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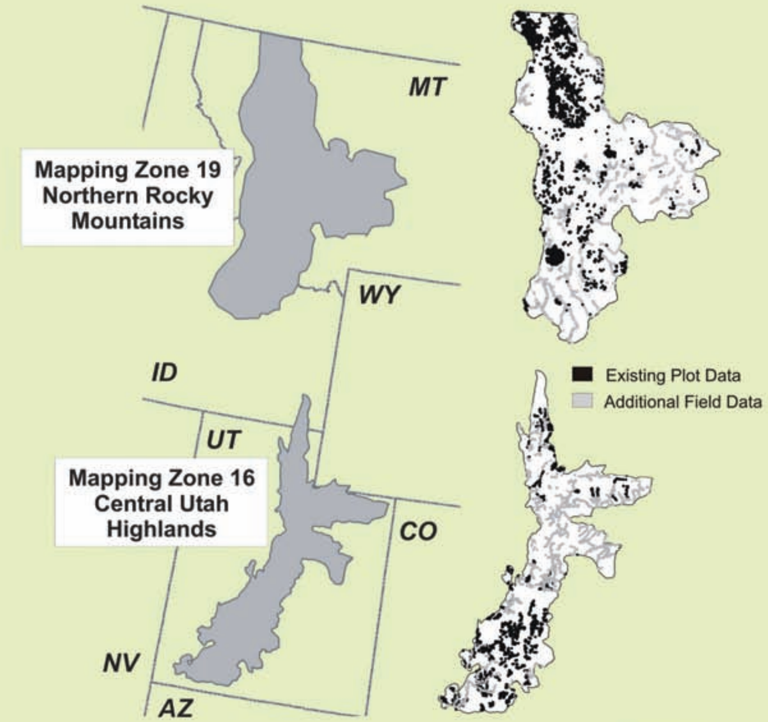
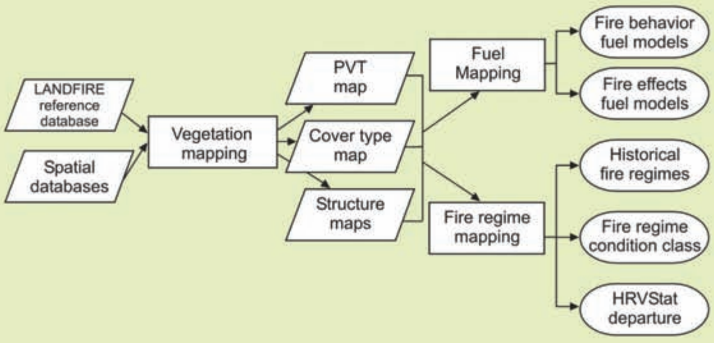
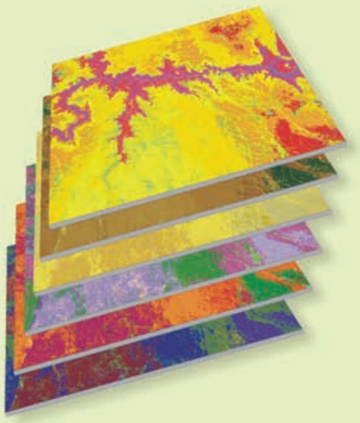
The LANDFIRE Prototype Project:

Nationally Consistent and Locally Relevant Geospatial Data for Wildland Fire Management







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Abstract

The Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, began in April of 2002 and ended in April of 2005. The project was funded by the U.S. Department of Agriculture Forest Service and U.S. Department of the Interior. The objectives of the LANDFIRE Prototype Project were to develop the methods, tools, and protocols for producing consistent and comprehensive digital maps of current vegetation composition and structure, wildland fuel, historical fire regimes, and fire regime condition class (FRCC) to be applied across the entire United States at a 30-meter spatial resolution. The LANDFIRE Prototype Project was conducted in two large study areas: the first in the highlands of central Utah and the second in the northern Rocky Mountains of Idaho and Montana. The LANDFIRE Prototype Project involved the compilation of a large field-referenced database to serve as training data for developing predictive landscape models; the development of Landsat image catalogs and biophysical gradient layers to serve as spatial predictors for mapping vegetation and wildland fuel characteristics; the development of vegetation and fuel map unit classifications; the development of a suite of vegetation dynamics models for simulating vegetation development over time; the implementation of a landscape succession model (LANDSUMv4) for simulating historical fire regimes and vegetation reference conditions; and the development of maps of surface and canopy fuel and fire effects fuel models for application in wildland fire management planning. This report describes the scientific foundations of LANDFIRE and provides details on the methods and results of the LANDFIRE Prototype Project.

Key words and phrases: Mapping wildland fuel, Mapping fire regimes, Geographic Information Systems, Remote sensing, Fire ecology, Fire behavior, Wildland fire management

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Contents

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Chapter 1

Executive Summary

Matthew G. Rollins, Robert E. Keane, and Zhiliang Zhu

Geospatial data describing wildland fuel and current as well as historical vegetation conditions are essential for planning, implementing, and monitoring projects supported by the National Fire Plan and the Healthy Forests Restoration Act. Scientifically credible, consistent, and standardized spatial data allow fire and land managers to accurately identify the amount and locations of lands or communities with hazardous fuel build-up or extreme departure from historical conditions. These data also facilitate the prioritization of ecosystem restoration and hazardous fuel reduction treatments to protect ecosystems, property, and people. Moreover, these data may be used during specific wildland fire incidents to maximize firefighter safety, pre-position resources, and evaluate fire behavior under a variety of weather conditions.

The Landscape Fire and Resource Management Planning Tools Prototype Project, or "LANDFIRE Prototype Project," was a three-year project that began April 1st, 2002 and ended April 1st, 2005. The project was funded by the United States Department of Agriculture Forest Service and United States Department of the Interior, with an annual cost of approximately $2 million. The objectives of the LANDFIRE Prototype Project were to develop the methods, tools, and protocols for producing consistent and comprehensive digital maps of current vegetation composition and condition, wildland fuel, historical fire regimes, and fire regime condition class (FRCC) for the entire U.S. at a 30-meter spatial resolution. The LANDFIRE Prototype Project was conducted in two large study areas: the first in the central Utah highlands and the second in the northern Rocky Mountains of Idaho and Montana.

The LANDFIRE Prototype Project involved various government agencies, universities, and private institutions. The two principal partners in the effort were the U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (MFSL) in Missoula, Montana and the U.S. Department of the Interior Geological Survey, USGS Center for Earth Resources Observation and Science (EROS) in Sioux Falls, South Dakota. Additional partners included the University of Montana (Missoula) Numeric Terradynamic Simulation Group (NTSG) and Systems for Environmental Management (SEM), also in Missoula, Montana. MFSL mapped biophysical settings, wildland fuel, historical fire regimes, and historical vegetation composition and structure. MSFL also conducted most ecosystem and landscape modeling. EROS mapped existing vegetation composition and structure; developed a quality assurance, quality control, and accuracy assessment system; and developed the LANDFIRE data-dissemination system. NTSG developed the daily weather DAYMET database used as a foundation for mapping biophysical gradient layers, and SEM created the LANDFIRE reference database and provided valuable expertise on the classification, mapping, and modeling of vegetation and fuel.

As mentioned above, LANDFIRE methods were tested in the central Utah highlands and revised based on problems and limitations encountered. These revised methods were then tested on the second study area in the northern Rocky Mountains of Montana and Idaho. In April 2004, one year prior to completion of

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the LANDFIRE Prototype Project, the Wildland Fire Leadership Council chartered the national implementation of the LANDFIRE Project (LANDFIRE National). It is important to emphasize here that the information presented in this report refers specifically to methods, procedures, and results from the LANDFIRE *Prototype* Project. LANDFIRE National is an ongoing effort involving most of the original collaborators and with the addition of The Nature Conservancy, NatureServe, and the Student Conservation Association to assist in vegetation modeling, vegetation map unit classification development, and field data collection, respectively. Lessons learned during the prototype process provide the foundation for the current mapping of vegetation, fuel, and fire regimes across the United States through LANDFIRE National. Visit www.landfire.gov for a detailed description of LANDFIRE National and to learn about and access the various LANDFIRE National data products.

The design criteria for the LANDFIRE Prototype Project resulted from several organizational meetings between the LANDFIRE team and USDA and USDOI fire management staffs. Agency fire management imposed abbreviated timelines and solid deadlines, required that LANDFIRE methodology be based on a strong scientific foundation, and required that the products be scalable to local applications with minimal modification. These conditions contributed to the following design criteria:

The LANDFIRE Prototype Project must be:

- based on the best available science,
- able to be implemented consistently across the nation,
- mapped at a 30-meter pixel size,
- reliant on no new field data collection,
- repeatable in time and space,
- scalable in application,
- developed within a three-year development timeline, and
- tested for accuracy.

Given these design specifications, we then developed a set of guiding principles that we used to direct the development of all LANDFIRE data layers. These principles allowed us to set boundaries for the development of every LANDFIRE product. These guidelines were as follows:

- Development should be targeted at mid-level map classifications.
- All themes must be identifiable, scalable, mappable, and model-able.
- Mapping applications must incorporate the biophysical gradients that determine the distribution of vegetation and disturbance regimes across landscapes.
- The primary development tool should be simulation modeling.
- The timespan for historical reference conditions would be 1600 AD to 1900 AD.

Many databases and computer models were developed to create the geospatial data layers describing vegetation and wildland fuel for the LANDFIRE Prototype Project to demonstrate that the methods and protocols could be applied nationwide. These products can be summarized by the following categories:

- **Databases**: LANDFIRE reference database, wildland fuel inventory database, vegetation development database, and map attribute tables
- **Computer models**: LANDFIRE-BGC, WXFIRE, LANDSUMv4, and HRVStat
- **Biophysical gradient maps**: 38 variables describing direct and indirect gradients affecting the distribution of vegetation and historical fire regimes
- **Vegetation maps**: existing vegetation, potential vegetation, canopy height, and canopy cover
- **Wildland fuel maps**: fire behavior fuel models, fire effects fuel models, and canopy fuel
- **Fire regime maps**: simulated historical fire return interval and severity, fire regime condition class, and indices of departure from historical conditions

The 24 core LANDFIRE Prototype Project spatial data layer products comprise a comprehensive set of data that may be implemented in broad- or mid-level prioritization of hazardous fuel mitigation efforts or in project-level planning of specific land and wildland fire management projects. See Chapter 2, table 1 for a detailed list of the LANDFIRE Prototype Project products.

The primary goal of the LANDFIRE Prototype Project was to develop a high-resolution map of FRCC for the entire nation. The computation of FRCC requires a comparison of current conditions with historical conditions to quantify departure. Current conditions are described using maps of vegetation composition (cover types) and structure (structural stages) derived from a supervised classification of Landsat imagery using continuous maps of biophysical gradients and an extensive collection of geo-referenced plot data called the LANDFIRE reference database. Historical conditions were described using a spatially explicit landscape fire succession model called LANDSUMv4. Vegetation composition and structure were described using a cover type and structural stage classification developed specifically for LANDFIRE. The biophysical gradient layers were created from two ecosystem simulation models that compute variables describing the fundamental physical processes that govern vegetation dynamics. These models used the DAYMET national weather database, which has a 1-km^2 spatial resolution and daily temporal resolution spanning 18 years. Biophysical gradient layers created from these models were also used to construct a data layer describing biophysical settings (potential vegetation types) that was then used to facilitate Landsat imagery classification and as an input layer for simulating historical reference conditions.

Historical reference conditions were simulated over a timespan of thousands of years using a spatially explicit landscape fire succession model, called LANDSUMv4, which simulates vegetation development using deterministic succession pathways for different biophysical settings and simulates fire using a pixel-to-pixel cell percolation or spread approach. The time series of simulated historical vegetation conditions was compared with imagery-derived current conditions using the area occupied by biophysical setting/cover type/structural stage combinations within square (0.81 km^2) spatial reporting units. Fire regime condition class was mapped using methods consistent with the Interagency Fire Regime Condition Class Guidebook. In addition, we created a statistical program called HRVStat that computes another, more statistically robust index of departure with a corresponding measure of statistical significance. Fire severity and fire return interval information simulated over time was summarized over the entire simulation period to create simulated historical fire regime maps.

Several additional data layers were developed as part of the LANDFIRE Prototype Project to provide critical information to wildland fire management for planning and implementing hazardous fuel mitigation and ecosystem restoration projects. We developed a refined set of fire behavior fuel models specifically for LANDFIRE that was better suited for distinguishing subtle differences in fuel characteristics resulting from fuel treatments, and we mapped the original 13 fuel models in addition to the refined set based on an expert system and an integrated vegetation database describing cover type, structural stage, and biophysical settings. Maps of canopy fuel, including canopy height, canopy cover, canopy bulk density, and canopy base height, were mapped based on statistical landscape modeling (specifically, regression trees) using Landsat imagery and the biophysical gradient layers. Fire effects fuel models were developed and mapped using the same approach as that used for fire behavior fuel model mapping. Maps of fire behavior fuel models and canopy fuel can be used in real-time wildfire applications, such as modeling fire growth or quantifying fire and fuel hazard using the suite of available fire behavior models, which include FARSITE, FlamMap, and NEXUS. Fire effects fuel models represent actual estimations of loading by fuel category for fire effects applications, such as estimating fuel consumption and smoke production using CONSUME or FOFEM.

The main strengths of the LANDFIRE Prototype Project included:

- a standardized, open source, repeatable method for developing consistent and comprehensive maps for use in wildland fire management;
- use of existing databases from government and non-government sources;
- the combination of remote sensing, ecosystem simulation, and biophysical gradient modeling to accurately map vegetation, fuel and fire regimes;
- a robust, straightforward, biophysically-driven statistical approach;
- a quantitative accuracy assessment;
- the automation of individual LANDIFRE tasks and processing steps;
- comprehensive coverage across all administrative boundaries and ownerships; and
- a seamless, Internet-based database dissemination tool.

The comprehensive, consistent, and automated methods developed through the LANDFIRE Prototype Project complement an integrated approach to wildland fire management and facilitate comparison of potential treatment areas using equivalent databases across the entire United States. The LANDFIRE system does not preclude the use of locally developed fire and fuel information in planning and management activities.

Please refer to the individual chapters of this report for a detailed description of each aspect of the LANDFIRE Prototype Project, information on the scientific background, and specific details regarding the individual procedures for creating the LANDFIRE data products.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

The Authors

Matthew G. Rollins is a Landscape Fire Ecologist at the USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (MFSL). His research emphases have included assessing changes in fire and landscape patterns under different wildland fire management scenarios in large western wilderness areas; relating fire regimes to landscape-scale biophysical gradients and climate variability; and developing predictive landscape models of fire frequency, fire effects, and fuel characteristics. Rollins is currently science lead for the LANDFIRE Project, a national interagency fire ecology and fuel assessment being conducted at MFSL and the USGS Center for Earth Resources Observation and Science (EROS) in Sioux Falls, South Dakota. He earned a B.S. in Wildlife Biology in 1993 and an M.S. in Forestry in 1995 from the University of Montana in Missoula, Montana. His Ph.D. was awarded by the University of Arizona in 2000, where he worked at the Laboratory of Tree-Ring Research.

Robert E. Keane is a Research Ecologist with the USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory. Since 1985, Keane has developed various ecological computer models for the Fire Effects Project for research and management applications. His most recent research includes the development of a first-order fire effects model, construction of mechanistic ecosystem process models that integrate fire behavior and fire effects into succession simulation, restoration of whitebark pine in the Northern Rocky Mountains, spatial simulation of successional communities on landscapes using GIS and satellite imagery, and the mapping of fuel for fire behavior prediction. He received his B.S. degree in Forest Engineering in 1978 from the University of Maine, Orono, his M.S. degree in Forest Ecology in 1985 from the University of Montana, and his Ph.D. degree in Forest Ecology in 1994 from the University of Idaho.

Zhiliang Zhu is a Research Physical Scientist with the USDOI Geological Survey Center for Earth Resource Observation and Science (EROS). Zhu's research work focuses on mapping and characterizing large-area land and vegetation cover, studying land cover and land use change, and developing remote sensing methods for the characterization of fire fuel and burn severity. His role in the LANDFIRE Prototype Project has been to design and test a methodology for the mapping of existing vegetation cover types and vegetation structure and to direct research and problem-solving for all aspects of the methodology. He received his B.S. degree in Forestry in 1982 from the Nanjing Forestry University in China, his M.S. degree in Remote Sensing in 1985, and his Ph.D. degree in Natural Resources Management in 1989, both from the University of Michigan.

Chapter
2

An Overview of the LANDFIRE Prototype Project

Matthew G. Rollins, Robert E. Keane, Zhiliang Zhu, and James P. Menakis

Introduction

This chapter describes the background and design of the Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, which was a sub-regional, proof-of-concept effort designed to develop methods and applications for providing the high-resolution data (30-m pixel) needed to support wildland fire management and to implement the National Fire Plan and Healthy Forests Restoration Act. In addition, this chapter provides synopses of the many interrelated procedures necessary for development of the 24 LANDFIRE Prototype products (see table 1 and appendix 2-A). Throughout this chapter, direction is provided for where, in this report and elsewhere, additional detailed information is available.

It is important to emphasize that the information presented in this report refers specifically to methods, procedures, and results from the LANDFIRE Prototype Project. National implementation of the methods developed during the LANDFIRE Prototype Project (LANDFIRE National) was chartered by the Wildland Fire Leadership Council in April of 2004 and continues on schedule. Approaches and methods for the national implementation of LANDFIRE differ slightly from those detailed in this report because the LANDFIRE National team used the wealth of knowledge gained from developing the LANDFIRE products for the two prototype study areas to improve the processes for national implementation. With the exception of the first three chapters, each chapter in this report describes in detail a major procedure required for successful creation of the LANDFIRE Prototype products. The final section of each chapter (again, with the exception of the first three chapters) contains the LANDFIRE Prototype technical team's recommendations for national implementation, which have been incorporated into the procedures and methods for LANDIFRE National.

Background

Status of Wildland Fire in the United States

A history of fire suppression and land use practices has altered fire regimes and associated wildland fuel loading, landscape composition, structure, and function across the United States over the last century (Brown 1995; Covington and others 1994; Frost 1998; Hann and others 2003; Leenhouts 1998; Pyne 1982; Rollins and

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Table 1—LANDFIRE Prototype products created for mapping zones 16 and 19.

	Mapped products	Description	Relevant chapter in this report
1	Map Attribute Tables	Plot locations and associated themes used to develop training sites for mapping vegetation and wildland fuel.	4
2	Potential Vegetation Type	A map that identifies unique biophysical settings across landscapes. Used to link the process of succession to the landscape.	7
3	Existing Vegetation	Mapped existing vegetation.	8
4	Structural Stage Density/Cover	Percent canopy closure by life form of existing vegetation.	8
5	Structural Stage Height	Height by life form (in meters) of existing vegetation.	8
6	Fire Interval	The mean interval between wildland fires (simulated using LANDSUMv4).	10
7	Fire Severity 1	Probability of an area to experience non-lethal wildland fire (simulated using LANDSUMv4).	10
8	Fire Severity 2	Probability of an area to experience mixed-severity wildland fire (simulated using LANDSUMv4).	10
9	Fire Severity 3	Probability of an area to experience stand-replacing wildland fire (simulated using LANDSUMv4).	10
10	FRCC Vegetation-Fuel Class	Mapped combinations of vegetation and structure that represent seral stages of vegetation communities.	11
11	Fire Regime Condition Class (FRCC)	Discrete index (1-3) describing departure of existing vegetation conditions from those of the simulated historical reference period. Developed using Interagency FRCC Guidebook methods.	11
12	FRCC Departure Index	Index (1-100) describing the difference between existing vegetation and historical vegetation conditions. Developed using Interagency FRCC guidebook methods.	11
13	HRVStat Departure	Index (0-1) describing the difference between existing vegetation and simulated historical vegetation conditions. Developed using the HRVStat multivariate time series analysis program.	11
14	HRVStat Significance Index	Index (0-1) describing the confidence in the HRVStat departure index. Developed using the HRVStat multivariate time series analysis program.	11
15	Fire Behavior Fuel Models	Wildland fuel models for modeling the rate of spread, intensity, size, and shape of wildland fires. Serves as FARSITE/FLAMMAP input.	12
16	Canopy Base Height	Height from the ground to the bottom of the vegetation canopy. Required for predicting the conversion of surface fires to crown fires. Serves as FARSITE/FLAMMAP input.	12
17	Canopy Bulk Density	Metric that describes the density of crown fuels. Required to model the spread of crown fires. Serves as FARSITE/FLAMMAP input.	12
18	Canopy Height	Height of the dominant existing vegetation. Serves as FARSITE/FLAMMAP input.	8
19	Canopy Cover	Density of the dominant existing vegetation. Serves as FARSITE/FLAMMAP input.	8
20	Slope	Slope in percent. Serves as FARSITE/FLAMMAP input.	5
21	Aspect	Aspect in degrees. Serves as FARSITE/FLAMMAP input.	5
22	Elevation	Elevation in meters. Serves as FARSITE/FLAMMAP input.	5
23	Fuel Loading Models	Classification based on fuel loading that provides inputs to models that predict the effects of wildland fires (including smoke production).	12
24	FCCS Fuelbeds	Classification based on fuel loading across several fuel strata. Provides inputs to models that predict fire effects (including smoke production).	12

others 2001). As a result, the number, size, and severity of wildfires have departed significantly from that of historical conditions, sometimes with catastrophic consequences (Allen and others 1998; Leenhouts 1998; U.S. GAO 1999; U.S. GAO 2002b). Recent examples of increasing wildland fire size and uncharacteristic severity in the United States include the 2000 Cerro Grande fire near Los Alamos, New Mexico that burned 19,200 hectares and 239 homes; the 2000 fire season in the northwestern United States during which over 2 million hectares burned; and the 2002 Biscuit (Oregon), Rodeo-Chediski (Arizona), and Hayman (Colorado) fires that burned over one-half million hectares and cost nearly $250 million to suppress (U.S. GAO 2002b). More recently, the 2003 fire season was distinguished by catastrophic wildland fires that began in early summer with the Aspen Fire north of Tucson, Arizona in which 322 homes were burned. This was followed by large, severe fires in the northern Rocky Mountains of western Montana and northern Idaho and arson-caused wildland fires that burned over 304,000 hectares and 3,640 homes in southern California.

The National Fire Plan and Healthy Forests Restoration Act

In response to increasing severity of wildland fire effects across the United States over the last decade, the secretaries of Agriculture and Interior developed a National Fire Plan for responding to severe wildland fires, reducing hazardous fuel buildup, reducing wildland fire threats to rural communities, and maximizing wildland firefighting efficiency and safety for the future (USDA and USDOI 2001; U.S. GAO 2001; U.S. GAO 2002a; U.S. GAO 2002b; www.fireplan.org). To implement this plan, the United States Department of Agriculture Forest Service (USFS) and Department of Interior (USDOI) developed both independent as well as interagency management strategies, with the primary objectives focused on hazardous fuel reduction and restoration of ecosystem integrity in fire-adapted landscapes through prioritization, adaptive planning, land management, and maintenance (USDA and USDOI 2001). In 2003, President George W. Bush signed the Healthy Forests Restoration Act into law. The main goals of the act are to reduce the threat of destructive wildfires while upholding environmental standards and encouraging early public input during review and planning processes for forest management projects (www.healthyforests.gov).

Importance of Nationally Consistent Spatial Data for Wildland Fire Management

The factors that affect wildland fire behavior and effects are inherently complex, being dynamic in both space and time. The likelihood that a particular area of a landscape will burn is often unrelated to the probability that a wildland fire will ignite in that area because wildland fires most often spread into one area based on the complex spatial arrangement and condition of fuel across landscapes. Spatial contagion in the process of wildland fire highlights the critical need for data that provide a comprehensive spatial context for planning and monitoring wildland fire management and hazardous fuel reduction projects. Furthermore, nationwide, comprehensive, consistent, and accurate geospatial data are critical for implementation of the National Fire Plan and the Healthy Forests Restoration Act (U.S. GAO 2002a; U.S. GAO 2002b; U.S. GAO 2003; U.S. GAO 2005). Specifically, consistent and comprehensive geospatial data are necessary for the following:

- planning wildland fire management with a landscape perspective,
- allocating resources across administrative boundaries,
- strategic planning for hazardous fuel reduction,
- tactical planning for specific wildland fire incidents, and
- monitoring the geographic consequences of wildland fire management.

The LANDFIRE process provides standardized, comprehensive mapped wildland fuel and fire regime information to address the objectives listed above. LANDFIRE maps were created using consistent methods over all ecosystems and geographic areas, which allows for reliable representation of “wall-to-wall” wildland fire hazard across entire regions and administrative areas. The spatial components of LANDFIRE ensure that individual areas within landscapes may be considered with a spatial context and therefore analyses can incorporate the potential influence of adjacent areas where wildland fires may occur more frequently or with different ecological or socioeconomic effects.

History of LANDFIRE

In 2000, the United States Department of Agriculture Forest Service Missoula Fire Sciences Laboratory developed coarse-scale (1-km grid cells) nationwide maps of simulated historical fire regimes and current departure from these historical conditions (Hardy and others 2001; Schmidt and others 2002). These data were designed to assist landscape and wildland fire management at national levels (for example, 10,000,000s – 100,000,000s km^2) and to facilitate comparison of wildland fire hazard between regions and states (Schmidt and others 2002). These coarse-scale, nationwide data layers include mapped potential natural vegetation groups, existing vegetation, historical fire regimes, departure from historical fire regimes, fire regime condition class (FRCC), national fire occurrence histories, and wildland fire risk to structures (Schmidt and others 2002). These data layers rapidly became the foundation for national-level, strategic wildland fire planning and for responding to national- and state-level concerns regarding the risk of catastrophic fire. Specifically, FRCC became a key metric for assessing fire threats to both people and ecosystems across the United States (U.S. GAO 2004).

While well-accepted and valuable for comparative analyses at the national level, the coarse-scale FRCC data lacked the necessary spatial resolution and detail for regional planning and for prioritization and guidance of specific local projects. In addition, the coarse-scale FRCC maps relied heavily on expert opinion, which led to inconsistent classification of vegetation across regional boundaries. Further, the low resolution and scale incompatibilities in underlying data resulted in overestimates of the number of areas with highly departed conditions (Aplet and Wilmer 2003).

As a result of the coarse-scale FRCC data's shortcomings, U.S. Government Accountability Office (formerly General Accounting Office) reports stated that federal land management agencies lacked adequate information for making decisions about and measuring progress in hazardous fuel reduction (U.S. GAO 2002b). The U.S. GAO (2002b) stated, "The infusion of hundreds of millions of dollars of new money for hazardous fuel reduction activities for fiscal years 2001 and 2002 and the expectation of sustained similar funding for these activities in future fiscal years accentuate the need for accurate, complete, and comparable data." United States GAO reports (U.S. GAO 1999, U.S. GAO 2002a, U.S. GAO 2002b, U.S. GAO 2003) have pointed to three main information gaps in wildland fire management planning:

- Federal land agencies lack information for identifying and prioritizing wildland-urban interface communities within the vicinity of federal lands that are at high risk of wildland fires.
- Federal land agencies lack adequate field-based reference data for expediting the project planning process, which requires complying with numerous environmental statutes that address individual resources, such as endangered and threatened species, clean water, and clean air.
- Federal agencies require consistent monitoring approaches for measuring the effectiveness of efforts to dispose of the large amount of brush, small trees, and other vegetation that must be removed to reduce the risk of severe wildland fire.

The LANDFIRE Prototype Project

The LANDFIRE Prototype Project started in 2001 and was funded by the United States Department of Agriculture Forest Service and Department of the Interior, with an annual cost of approximately $2 million. The project's purpose was to develop methods and tools for creating the baseline data needed to implement the National Fire Plan and to address the concerns of the GAO. LANDFIRE was designed specifically to provide the spatial data required to implement the National Fire Plan at regional levels and to fill critical knowledge gaps in wildland fire management planning. To achieve these objectives, LANDFIRE integrates information from extensive field-referenced databases, remote sensing, ecosystem simulation, and biophysical modeling to create maps of wildland fuel and fire regime condition class across the United States (Rollins and others 2004).

The main strengths of the LANDFIRE Prototype Project approach included:

- a standardized, repeatable method for developing comprehensive fuel and fire regime maps (see appendix 2-A for an outline of the procedures followed in developing the data products of the LANDFIRE Prototype Project);
- a combination of remote sensing, ecosystem simulation, and biophysical gradient modeling to map fuel and fire regimes;
- a robust, straightforward, statistical framework and quantitative accuracy assessment; and
- a seamless, Internet-based data-dissemination system.

In addition to the strengths of the approach, the main strengths of the LANDFIRE Prototype data included:

- a resolution fine enough (30-m pixel) for wildland fire managers to evaluate and prioritize specific landscapes within their administrative units;

- national coverage, ensuring that the data may be used for regional and national applications;
- comprehensive and consistent methods, allowing for both an integrated approach to wildland fire management and the ability to compare potential treatment areas across the entire United States through equivalent databases; and
- the ability to monitor the efficacy of hazardous fuel treatments as LANDFIRE updates become available over time.

Study Areas

The LANDFIRE Prototype Project was implemented within two large areas in the western United States: the central Utah highlands and the northern Rocky Mountains (fig. 1). These prototype landscapes were chosen because each represents a wide variety of vegetation assemblages that are common in the western U.S. They were chosen also because pre-processing of the Landsat satellite imagery had already been completed as part of the USGS Multi-Resolution Land Characteristics (MRLC) 2001 project (Homer and others 2002; landcover.usgs.gov/index.asp).

As the LANDFIRE Prototype depended on imagery solely from the MRLC 2001 project, LANDFIRE adopted the use of MRLC mapping zones to divide the United States into workable spatial areas. Use of these delineation units ensured that the LANDFIRE timetable requirements would be met by the MRLC image processing schedule.

Central Utah Highlands mapping zone — The 69,907 km^2 Central Utah Highlands mapping zone begins at the northern tip of the Wasatch Mountains in southern Idaho and extends through central Utah to the southern border of the state (fig. 1). Elevations range from 980 m to 3,750 m. Vegetation communities range from alpine forb communities in the Uinta and Wasatch Mountains in the northern portion of the mapping zone to desert shrub communities in the southern deserts. Extensive areas of pinyon-juniper/mountain big sagebrush and both evergreen and deciduous shrub communities are found at mid-elevations throughout the Central Utah Highlands mapping zone. The climate of the this mapping zone is highly variable. Thirty-year average temperatures range from –4°C in the high Uinta Mountains to 15°C in the southern deserts. Average annual precipitation varies from 10 cm in the southwestern deserts to nearly 2 meters in the northern mountains (Bradley 1992).

Northern Rocky Mountains mapping zone — The 117,976 km^2 Northern Rocky Mountains mapping zone begins at the Canadian border in northern Montana and extends south into eastern Idaho (fig. 1). Elevations range from 760 m to 3,400 m. Vegetation communities range from alpine forbs in the highest mountain ranges to prairie grasslands east of the Rocky Mountain front. Forest communities are prevalent, with spruce-fir communities found near the timberline and extensive forests of lodgepole pine, western larch, Douglas-fir, and ponderosa pine at middle elevations. Thirty-year average annual temperatures range from –5°C in the

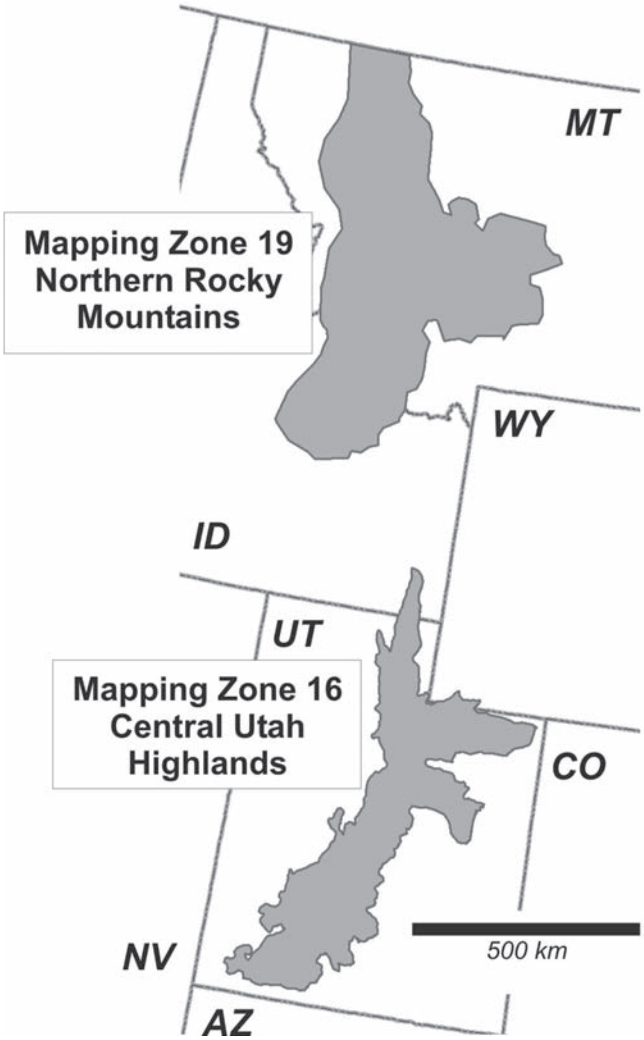

Figure 1—The study areas for the LANDFIRE Prototype Project were located in the central Utah highlands (Mapping Zone 16) and the Northern Rocky Mountains (Mapping Zone 19). LANDFIRE used mapping zones delineated for the Multiple Resolution Land Cover (MRLC) 2001 Project (http://landcover.usgs.gov/index.asp). All of the 24 core LANDFIRE Prototype products were produced for each zone. Lessons learned in the central Utah study area resulted in refinements that were applied in the northern Rocky Mountains.

high mountains of Glacier National Park to 15°C in the valley bottoms. Average precipitation varies from 14 cm in the valley bottoms to approximately 3.5 meters in the northern mountains (Arno 1980).

Methods

Many interrelated and mutually dependent tasks had to be completed to create the suite of databases, data layers, and models needed to develop scientifically credible, comprehensive, and accurate maps of fuel and fire regimes (see fig. 2, table 2, and appendix 2-A). After a brief introduction, each of these tasks is detailed below. First, the LANDFIRE reference database (LFRDB) was compiled from existing, georeferenced, ground-based databases from both government and non-government sources. Second, mapped biophysical gradients, potential vegetation types (PVTs), cover types (CT) (existing vegetation composition), and structural stages (SS) (existing vegetation structure) were mapped using the LFRDB, existing geospatial data, ecological simulation, Landsat imagery, and statistical landscape modeling at 30-meter pixel resolution to describe the existing vegetation and biophysical environment of each prototype study area. Third, succession pathway models and disturbance frequencies were entered into the LANDSUMv4 landscape fire succession model (described in the *LANDFIRE Fire Regime Modeling* section below) to simulate disturbance dynamics and vegetation development over time. These simulations served to quantify both the historical reference conditions and the range and variation of fire regime characteristics critical for determining current departure from historical conditions. Fourth, wildland fuel characteristics were mapped using field-referenced data, biophysical data, Landsat imagery, and LANDFIRE vegetation products.

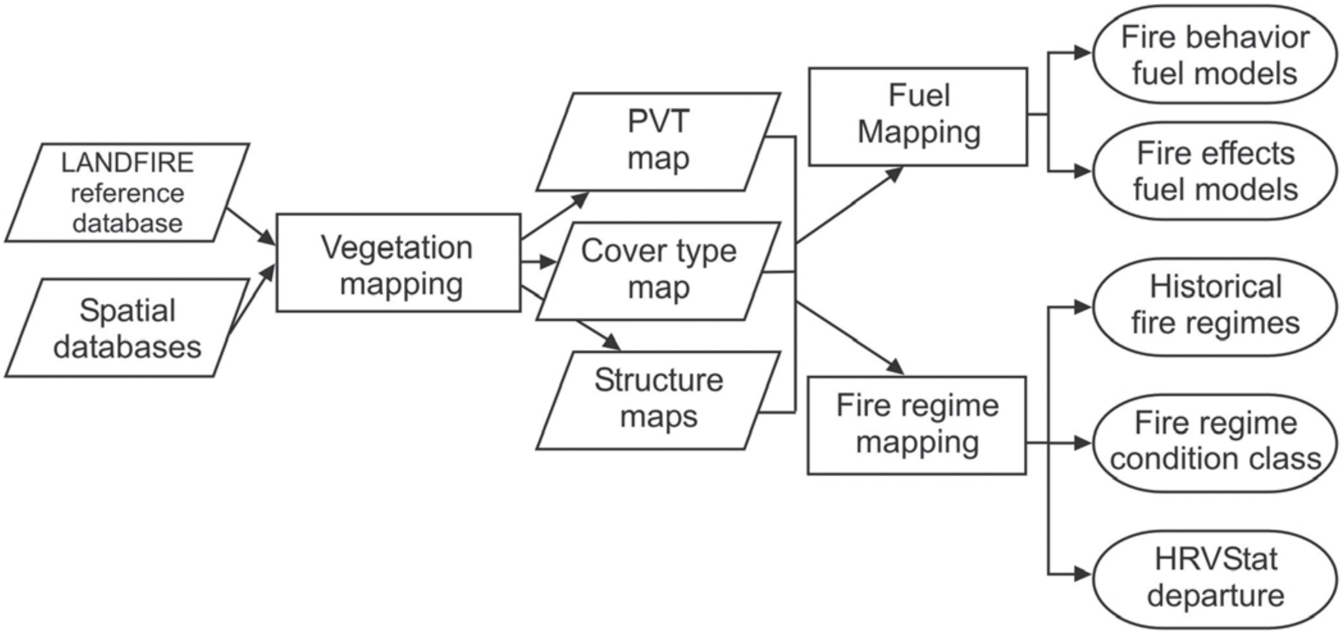

Figure 2—An overview of the LANDFIRE Prototype Project procedures. The LANDFIRE mapping processes began with the creation of the LANDFIRE reference database, which is comprised of a set of all available georeferenced plot information from within each mapping zone. The reference and spatial databases were used in a classification and regression tree-based machine learning framework for creating maps of biophysical settings (potential vegetation types), existing vegetation composition (cover type), and vegetation structure (canopy height and density). These core vegetation maps formed the foundation for the simulation of historical fire regimes and the subsequent calculation of current departure from historical vegetation conditions. In addition, the vegetation maps served as the basis for mapping wildland fuel for simulation of fire behavior and effects.

Table 2—Tasks essential for the creation of the LANDFIRE Prototype products. The first column directs the reader to the appropriate chapter sections containing general descriptions of the project's individual tasks. The second column directs the reader to the appropriate chapter in this GTR containing detailed background and procedural information about the project's individual tasks. Corresponding inputs/dependencies, methods for completion, and outputs/products are also listed for each task.

Task / chapter section heading	Chapter in this report	Inputs/dependencies	Methods for completion	Outputs/products
Compiling the LANDFIRE Reference Database	4	• Existing georeferenced field databases • Automated conversion utilities	• Compiled data from existing field databases. • Re-projected and reformatted data from native format into LFRDB format. • Produced attribute tables for all LANDFIRE mapping applications.	• Map attribute tables used as training data for mapping biophysical settings, vegetation, and fuel. • Data for accuracy assessment, quality control, and product evaluation.
Developing the Physiography and Biophysical Gradient Layers	5	• Topographic data from USGS • STATSGO soils data • DAYMET daily weather data • WXFIRE ecosystem simulator	• Derived simulation units. • Implemented WXFIRE. • Evaluated and processed output.	• Thirty-eight biophysical gradient layers used for mapping biophysical settings, vegetation, and fuel. • Data for comparing mapped themes using biophysical information consistently across mapzones.
Developing the LANDFIRE Vegetation Map Unit Classifications	6	• LFRDB • LANDFIRE design criteria • Existing national classification systems • Literature review	• Synthesized existing classifications describing potential vegetation, existing vegetation, and structure. • Compiled hierarchical classifications • Developed keys/queries to implement classifications in LFRDB to produce map attribute tables.	• Custom LANDFIRE classifications meeting design criteria that vegetation classes are identifiable, scaleable, mappable, and model-able. • Rules/keys for implementing classifications in LFRDB. • Lists of vegetation types to be used in vegetation mapping and modeling and fuel mapping.
Mapping Potential Vegetation	7	• Biophysical gradient layers • PVT classification • LFRDB	• Developed training sites based on map attribute tables from LFRDB. • Compiled biophysical gradient layers for use as spatial independent variables. • Developed classification trees predicting PVT. • Created final map in ERDAS/Imagine.	• Maps of PVT. • Maps of probabilities of CT by PVT. • Stratification for vegetation succession modeling. • Simulation units for LANDSUMv4. • Basis for stratification for mapping wildland fuel.
Mapping Existing Vegetation	8	• MRLC 2001 Landsat Image Catalog • Biophysical gradient layers • Existing vegetation classifications • LFRDB	• Developed training sites based on map attribute tables from LFRDB. • Compiled 3 dates of Landsat imagery and biophysical gradient layers for use as mapped predictor variables. • Developed classification and regression trees predicting CT and SS. • Created final map in ERDAS imagine.	• Maps of existing vegetation composition and structure. • Current baseline for comparison with reference conditions to determine ecological departure. • Description of the current successional status of landscapes across mapping zones. • Foundation for wildland fuel mapping.
Developing Succession Pathway Models	9	• VDDT model • LFRDB • Vegetation classifications • PVT and existing vegetation maps • Vegetation development workshops	• Conducted workshops for developing modeling frameworks. • Evaluated disturbance probabilities and transition times from literature. • Assigned local ecologists to derive and refine models using VDDT. • Compiled models in the vegetation and disturbance development database.	• Evaluation and refinement of classification systems. • Set of vegetation development models for each mapped PVT. • Parameters used to simulate fire effects and post vegetation recovery in LANDSUMv4. • Historical reference conditions for evaluation of ecological departure.

(continued)

Table 2—(Continued)

Task / chapter section heading	Chapter in this report	Inputs/dependencies	Methods for completion	Outputs/products
Simulating Historical Landscape Composition	10	• LFRDB • Succession pathway models (VADDD) • Parameter database (VADDD) • PVT and existing vegetation maps • LANDSUMv4 model	• Divided landscape into simulation units and landscape reporting units. • Parameterized LANDSUMv4 with information from VADDD. • Ran LANDSUMv4. • Compiled and summarized results.	• Time series of historical vegetation conditions for simulation period. • Maps of simulated historical fire intervals. • Probability maps of fire severity. • Reference conditions for comparison with current conditions to evaluate ecological departure.
Estimating Departure using Interagency RCC Guidebook Methods	11	• Cover type map • PVT Map • SS map • Reference conditions from LANDSUMv4	• Implemented Interagency FRCC Guidebook methods adapted to LANDFIRE map classification systems. • Quantified reference conditions based on LANDSUMv4 output. • Calculated departure and created discrete FRCC classes.	• Consistently mapped FRCC across each map zone. • Consistent baseline information for determining relative levels of ecological departure across broad regions.
Estimating Departure Using HRVStat	11	• HRVStat statistical software • Cover type map • PVT Map • SS map • Reference conditions	• Compiled input analysis database for HRVStat including reference conditions and current CT and SS. • Determined departure from reference conditions. • Determined frequency distribution of departure estimates using time series of historical vegetation conditions. • Compiled final HRVStat departure and confidence maps.	• Multivariate, statistically robust measure of ecological departure. • Measure of the significance of the measurement of ecological departure (p-value). • Ecological departure mapped as a continuous variable. • Consistently mapped ecological departure across each map zone.
Mapping Surface Fuel	12	• LFRDB • Vegetation classifications • PVT map • CT and SS maps • Look-up tables and rule sets for assigning fuel models	• Compiled fuel mapping database as a subset of the LFRDB. • Created look-up tables and rule sets to link fuel models to biophysical settings and vegetation composition and structure. • Compiled final maps in ArcGIS.	• Maps of fire behavior fuel models for simulating potential fire spread and intensity. • Maps of fire effects models for simulating the effects of fires on vegetation.
Mapping Canopy Fuel	12	• LFRDB • FUELCALC model • biophysical gradient layers • MRLC 2001 Landsat Image Catalog • PVT maps • Existing vegetation maps	• Populated fuel mapping database with FUELCALC output. • Developed training sites from fuel database. • Compiled Landsat imagery, biophysical gradients, and LANDFIRE vegetation maps for use as mapped predictor variables. • Developed regression trees predicting CBH and CBD. • Created final maps in ERDAS imagine.	• Maps of canopy fuels for simulating the initiation and behavior of crown fires.

Compiling the LANDFIRE Reference Database

The LFRDB comprised a compilation of all existing georeferenced field data available for the prototype mapping zones (fig. 3). This database of georeferenced plot information formed the foundation for most phases of the LANDFIRE Prototype Project. The database was designed in Microsoft ACCESS and had a three-tiered hierarchical structure (Caratti, Ch. 4). Existing data were entered into the database and incorporated into the FIREMON database structure (Lutes and others 2002). The data were then further summarized and reformatted to ensure consistency across the entire database. This involved steps such as converting geographic coordinates to the LANDFIRE map projection, converting measurement units to metric, ensuring that all vegetation cover estimates represent absolute cover as opposed to relative cover, and populating fields that can be used for quality assurance and quality control (Caratti, Ch. 4). The final step in developing the LFRDB was classifying each plot to the appropriate CT, PVT, and SS using the LANDFIRE map unit classification systems (Long and others, Ch. 6) and assigning appropriate fuel characteristics using the LANDFIRE fuel map unit classification systems (Keane and others, Ch. 12). LANDFIRE map attribute tables describing georeferenced vegetation and fuel types were then used as training databases for developing most LANDFIRE products.

For inclusion in the LFRDB, all field data needed to be georeferenced and quantify at least one LANDFIRE mapping attribute (for example, CT or SS). All field data were evaluated for suitability and assigned quality control indices based on summary image overlay, logic checking, and associated metadata (Caratti, Ch. 4). Sources of data for the LFRDB include but are not limited to the following:

- Forest Inventory and Analysis (Gillespie 1999)
- Forest Health Monitoring (USDA Forest Service 2003)
- Landscape Ecosystem Inventory Systems (Keane and others 2002a)
- ECODATA (Jensen and others 1993)
- FIREMON fire monitoring data (Lutes and others 2002)
- Interior Columbia River Ecosystem Management Project (Quigley and others 1996)
- Natural Resources Conservation Service (USDA 2002)
- National Park Service fire monitoring database (USDI 2001)

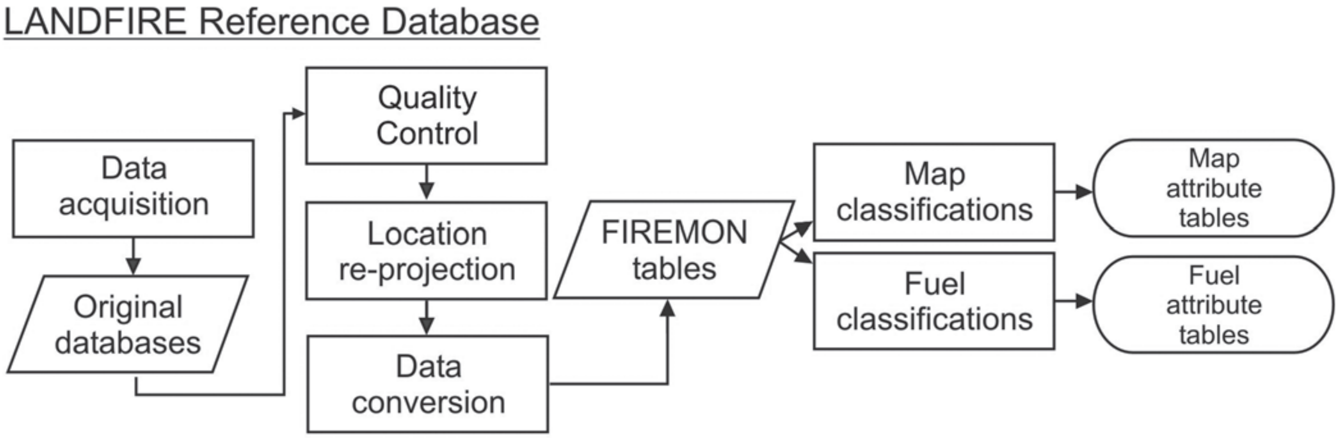

Figure 3—The procedure for developing the LANDFIRE reference database. Existing georeferenced plot data were acquired from numerous sources, including USDA Forest Service Forest Inventory and Analysis data, State GAP programs, and additional government and non-government sources. These data were processed through automated quality control and re-projection procedures and compiled in the FIREMON database architecture. The custom LANDFIRE vegetation classes (cover type, PVT, structural stage, and surface fuel models) were determined for each plot using sets of dichotomous sequence tables. The final stage of compiling the reference database was the development of map attribute tables that are implemented as training databases in the LANDFIRE mapping processes.

The LFRDB was used to classify, map, and evaluate each of the LANDFIRE products. For example, the LFRDB was used to classify existing vegetation communities and biophysical settings (Long and others, Ch. 6), to map PVTs (Frescino and others, Ch. 7), to map cover types (Zhu and others, Ch. 8), to evaluate and quantify succession model parameters (Long and others, Ch. 9 and Pratt and others, Ch. 10), to develop maps of wildland fuel (Keane and others, Ch. 12), and to evaluate the quality of LANDFIRE products (Vogelmann and others, Ch. 13).

Developing the Physiography and Biophysical Gradient Layers

Several spatial data layers provided baseline information for the LANDFIRE Prototype Project and served mainly as independent spatial predictor variables in the LANDFIRE mapping processes (fig. 4). We used topographic data from the National Elevation Database (NED) to represent or derive gradients of elevation, slope, aspect, topographic curvature, and other topographic characteristics (Holsinger and others, Ch. 5). The National Elevation Database, developed by the USGS Center for Earth Resources Observation and Science (EROS), was compiled by merging the highest-resolution, best-quality elevation data available across the United States into a seamless raster format. More information about the NED may be found at http://ned.usgs.gov/.

Topographic variables represent indirect biophysical gradients, which have no direct physiological influence on vegetation dynamics (Müller 1998); however, the addition of even indirect gradients has been shown to improve the accuracy of maps of vegetation (Franklin 1995). We used an ecosystem simulation approach to create geospatial data layers that describe important environmental gradients that directly influence the distribution of vegetation, fire, and wildland fuel across landscapes (Rollins and others 2004). The simulation model WXFIRE was developed for the purpose of employing standardized and repeatable modeling methods to derive landscape-level weather and ecological gradients for predictions of landscape characteristics such as vegetation and fuel (Keane and others 2002a; Keane and Holsinger 2006). WXFIRE was designed to simulate biophysical gradients using spatially interpolated daily weather information in addition to mapped soils and terrain data. The spatial resolution is defined by a user-specified set of spatial simulation units. The WXFIRE model computes biophysical gradients - up to 50 - for each simulation unit, where the size and shape of simulation units are determined by the user.

The implementation of WXFIRE requires the three following steps: 1) develop simulation units (the smallest unit of resolution in WXFIRE), 2) compile mapped daily weather, and 3) execute the model (Holsinger and others, Ch. 5). Using the DAYMET daily weather database, WXFIRE was executed over 10 million simulation units

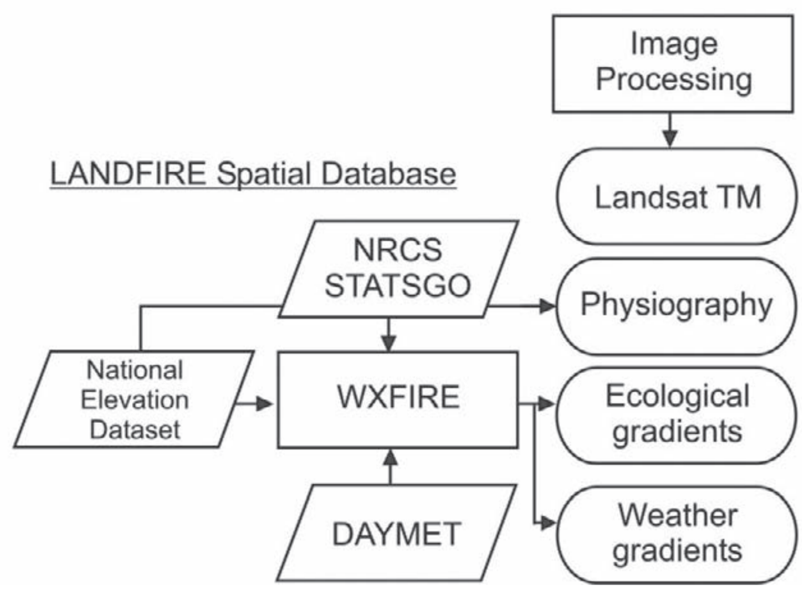

Figure 4—The procedure for developing the LANDFIRE base geospatial data layers. Topographic information from the National Elevation Database, soils information from the NRCS STATSGO database, and data from the DAYMET daily weather database were input into the WXFIRE weather and ecosystem model. WXFIRE was used to develop 38 gradients describing the factors that define the distribution of vegetation across landscapes. These gradients were incorporated into the LANDFIRE mapping processes to increase the overall accuracy of mapped products. Three dates of Landsat imagery from the MRLC 2001 project were used as the basis for mapping existing vegetation composition and structure. All information included in the LANDFIRE spatial database was developed using strict design criteria to ensure that these data could be developed consistently across the entire United States.

for Zone 16 and over 26 million for Zone 19 (Thornton and others 1997). Thirty-eight output variables from WXFIRE describing average annual weather and average annual rates of ecosystem processes (such as potential evapotranspiration) were then compiled as raster grids and used in developing the final LANDFIRE products (Holsinger and others, Ch. 5). Specifically, these layers were used as a basis for mapping PVT, CT, and SS (Frescino and Rollins, Ch. 7 and Zhu and others, Ch. 8) and for mapping both surface and canopy wildland fuel (Keane and others, Ch. 12). Additionally, biophysical gradient layers facilitated comparison of map units across mapping zones during the map unit development. For example, an equivalent CT in two different mapping zones should have similar biophysical characteristics. Vast differences in biophysical characteristics may indicate that a new CT should be developed.

Developing the LANDFIRE Vegetation Map Unit Classifications

The LANDFIRE Prototype Project developed vegetation map unit classifications that, combined with rule sets (keys), allowed the linkage of LFRDB plot data to geospatial data layers in a systematic, hierarchal, and scaleable framework. These hierarchal classification systems were directly related to the predictive landscape modeling of PVT, CT, and SS (Frescino and Rollins, Ch. 7 and Zhu and others, Ch. 8) for defining the developmental stages within succession models for landscape fire regime modeling (Long and others, Ch. 9 and Pratt and others, Ch. 10) and for mapping surface and canopy fuel (Keane and others, Ch. 12). In order for LANDFIRE to be successful, the LANDFIRE vegetation map units need to be:

- **identifiable** – Map units must be easily identifiable in the field, and the process for assigning map units based on existing plot data (such as FIA) needs to be efficient and straightforward.
- **scalable** – Map unit classifications must have a hierarchy that is flexible for addressing the spatial scales used in landscape- to national-level assessments (for example, 100,000s to 1,000,000s km^2). This flexibility in spatial scale also facilitates links with existing classifications.
- **mappable** – Only map units that can be delineated using remote sensing and biophysical modeling will be mapped.
- **model-able** – Map units must fit into the logical frameworks of the vegetation and landscape simulation models that are essential for the creation of many LANDFIRE products.

The LANDFIRE Prototype Project vegetation map unit classifications were based on combinations of extensive literature review, existing national vegetation classifications and mapping guidelines, development of vegetation succession models, summaries from the LFRDB, and classifications from other existing fuel and fire regime mapping projects (Long and others, Ch. 6). Each of the classifications is composed of two types of units (map and taxonomic) with several different nested levels possible (Long and others, Ch. 6). Map units are collections of areas defined in terms of component taxonomic and/or technical group characteristics. Map units may exist at any level of a hierarchical map unit classification based on physiognomic or taxonomic units or technical groups (Brohman and Bryant 2005). Taxonomic units were used to define and develop map units from the LFRDB and may also be used by land managers to scale the LANDFIRE CT map unit classification to floristically finer scales. Hierarchically nested, taxonomically defined map units allowed the vegetation map units to be aggregated or disaggregated to suit multiple purposes (such as vegetation modeling or fuel mapping). Taxonomic information was also used to link the LANDFIRE classifications to other existing vegetation classification systems (Long and others, Ch. 6). The individual classifications are described below.

Cover type map unit classification — The LANDFIRE cover type (CT) map unit classifications described existing vegetation composition in each mapping zone (Long and others, Ch. 6). Generally, CT map units were distinguished by dominant species or species assemblages. Records in the LFRDB were classified to CT based on indicator types with the highest relative canopy cover. The LANDFIRE Prototype CT map unit classification was based on the National Vegetation Classification System (NVCS) and the USDA Forest Service Existing Vegetation Classification and Mapping Guide (Brohman and Bryant 2005; Grossman and others 1998; Long and others, Ch. 6) but was modified to meet the LANDFIRE classification criteria listed above. By using NVCS and the Forest Service Existing Vegetation Classification and Mapping Technical Guide (Brohman and Bryant 2005), the LANDFIRE CT map unit classification quantitatively combined both physiognomic and floristic systems and adhered to important Federal Geographic Data Committee classification standards (FGDC 1997). The LANDFIRE vegetation map units were used for mapping existing vegetation and vegetation structure (Zhu and others, Ch. 8), modeling succession (Long and others, Ch. 9), parameterizing the LANDSUMv4 model (Pratt and others, Ch. 10), quantifying departure from historical conditions (Holsinger and others, Ch. 11), and for mapping wildland fuel (Keane and others, Ch. 12).

Structural Stage Map Unit Classification — The LANDFIRE structural stage (SS) map unit classification was based on summary analyses of vegetation characteristics contained within the LFRDB. The two main criteria for developing custom SS map units were that these map units had to be useful for describing vegetation developmental stages in succession models and they needed to be relevant for describing vegetation structure for mapping wildland fuel. In addition, LANDFIRE SS map units had to be distinguishable using Landsat imagery. The structural stages of forest CTs were broken into four SS map units based on a matrix of independently mapped canopy cover (CC) and height class (HC) map units (Long and others, Ch. 6). Structure classification of non-forest CTs was composed of only two map units describing canopy density. Height status was not included in these SS map units because most growth in non-forest areas occurs relatively swiftly in the first couple of years after regeneration and then levels out over time; therefore, height status is less relevant to vegetation succession in non-forest types than in forest types (Long and others, Ch. 6). LANDFIRE structural stages were used to develop models of vegetation development (Long and others, Ch. 9) and for mapping wildland fuel (Keane and others, Ch. 12).

Potential Vegetation Type Map Unit Classification — Potential vegetation type (PVT) is a site classification based on environmental gradients such as temperature, moisture, and soils (Pfister and others 1977). Potential vegetation types are analogous to aggregated habitat types or vegetation associations and are usually named for the late successional species presumed to dominate a specific site in the absence of disturbance (Cooper and others 1991; Daubenmire 1968; Frescino and Rollins, Ch. 7; Keane and Rollins, Ch. 3; Pfister and Arno 1980).

The LANDFIRE PVT map unit classification was created based on summaries from the LFRDB, extensive literature reviews, and existing PVT classifications (Long and others, Ch. 6). We began with PVT classifications that already existed for each of the prototype mapping zones (such as the USDA Forest Service regional classifications) and then refined these PVT classifications through expert opinion and data from the LFRDB. The resultant map unit classification was based on the presence of indicator types across gradients of shade tolerance, plant water relationships, and ecological amplitude. The LANDFIRE Prototype Project PVT map units were used to link the ecological process of succession to landscapes (Long and others, Ch. 9), to guide the parameterization and calibration of the landscape fire succession model LANDSUMv4 (Pratt and others, Ch. 10), and to stratify vegetation communities for wildland fuel mapping (Keane and others, Ch. 12).

Mapping Potential Vegetation

We mapped PVT using a predictive landscape modeling approach (fig. 5). This approach employs spatially explicit independent or predictor variables and georeferenced training data to create thematic maps (Franklin 1995; Keane and others 2002a; Rollins and others 2004). For the LANDFIRE Prototype, the training data were created by implementing the PVT map unit classification as a set of automated queries that access the LFRDB and classify each plot to a LANDFIRE PVT based on vegetation composition and condition (Long and others, Ch. 6). Each georeferenced plot and its assigned PVT were overlaid with the 38 biophysical gradients using GIS software. This resulted in a PVT modeling database where PVT was the dependent variable and the biophysical gradient layers were the predictor variables (Frescino and Rollins, Ch, 7).

In the LANDFIRE Prototype, we used classification trees (also known as decision trees) along with the PVT modeling database to create a spatially explicit model for mapping PVT within GIS applications. Classification trees, used as an analog for regression, develop rules for each category of a dependent variable (in this case, PVT). Classification trees for mapping PVTs were developed using the See5 machine-learning algorithm (Quinlan 1993; www.rulequest.com) and were applied within an ERDAS Imagine™ interface (ERDAS 2004; Frescino and Rollins, Ch. 7). See5 uses a classification and regression tree (CART) approach for generating a tree with high complexity and pruning it back to a simpler tree by merging classes (Breiman and others 1984; Friedl and Bradley 1997; Quinlan 1993).

Maps of PVT are a principal LANDFIRE Prototype product (table 1). In addition, the LANDFIRE PVT maps were used with the LFRDB to create layers that represent the probability of a particular CT to exist in a specific area (Frescino and Rollins, Ch, 7), used in the mapping of CT (Zhu and others, Ch. 8). The PVT map also facilitated linkage of the ecological process of vegetation succession to the simulation landscapes used in modeling historical reference conditions. In the LANDFIRE Prototype, vegetation ecologists created succession pathway models for individual PVTs that

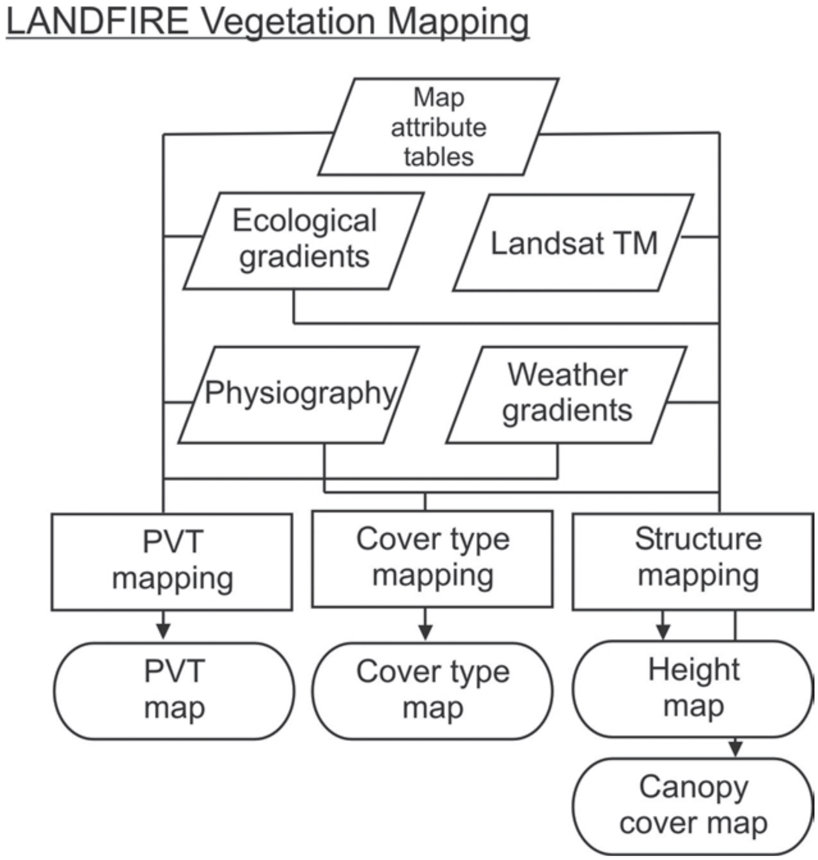

Figure 5—The LANDFIRE vegetation mapping process. Information from the LANDFIRE reference and spatial databases was used in a classification and regression tree framework and then implemented within ERDAS IMAGINE™ mapping software to create all mapped vegetation products. The mapping of potential vegetation was based purely on biophysical gradients including weather, topography, and soil information. Landsat imagery was used to create all maps of existing vegetation composition and structure.

served as input to the LANDSUMv4 landscape fire succession model used to simulate historical fire regimes and reference conditions (Long and others, Ch. 9; Pratt and others, Ch. 10). Maps of PVT were also used for stratification purposes in wildland fuel mapping (Keane and others, Ch. 12).

Mapping Existing Vegetation

Maps of existing vegetation composition and structure at spatial resolutions appropriate for wildland fire management are principal LANDFIRE products (table 1). Maps of existing vegetation serve as a benchmark for determining departure from historical vegetation and for creating maps of wildland fuel composition and condition. Satellite imagery was integrated with biophysical gradient layers and the LFRDB to create maps of CT, canopy closure (CC), and height class (HC) map units (HC) (fig. 5). Structural stage (SS) is an integration of CC and HC as described above in the *Structural Stage Map Unit Classification* section.

Mapping Cover Type

Many mapping algorithms have been developed for deriving vegetation maps from satellite imagery (Cihlar 2000; Foody and Hill 1996; Homer and others 1997; Knick and others 1997). For the LANDFIRE Prototype Project, we created maps of CT using a training database developed from the LFRDB, Landsat imagery, biophysical gradient layers (described above in Developing the Physiography and Biophysical Gradient Layers), the PVT map (for limiting the types of vegetation that may exist in any area) and classification tree algorithms similar to those described above for mapping PVT (Zhu and others, Ch. 8).

The LANDFIRE team developed maps of CT using a hierarchical and iterative set of classification models, with the first model separating more general land cover types (for example, life form) and subsequent models separating more detailed levels of the vegetation map unit classification until a final map of CT map units resulted. Specifically, life form information from the

MRLC 2001 program (Homer and others 2002) was used as a stratification to create separate models for mapping CT. An iterative approach was implemented where mapping models were developed using a "top-down" approach for successively finer floristic levels in the LANDIRE vegetation map unit classification (Long and others Ch. 6). The LFRDB, biophysical settings layers, and ancillary data layers were incorporated to guide the mapping process.

Mapping Structural Stage

We used empirical models for estimating canopy closure (CC) using satellite imagery and biophysical gradients. Though often considered unsophisticated and criticized for lack of focus on mechanistic processes, empirical models have proved more successful than other types of models in applications involving large areas (Iverson and others 1994; Zhu and Evans 1994). We used regression trees, applied through a Cubist/ERDAS Imagine interface, to map CC and HC separately. Model inputs included elevation data and derivatives, spectral information from Landsat imagery, and the 38 biophysical gradient layers. Similar to PVT and CT mapping, a training database was developed using the LFRDB that contained georeferenced values for CC and HC for each plot. The resultant maps represented these two structure variables continuously across each prototype mapping zone. Prior to the LANDFIRE Prototype Project, CC and HC had been modeled successfully using CART for Zone 16 as well as several additional areas (Huang and others 2001).

The final SS layer was developed by combining CC and HC map units into SS map units and assigning SS map units to combinations of PVT and CT. Structural stage assignments were based on the SS map unit classification (Long and others, Ch. 6). This integrated height and density information was used as an important determinant of wildland fuel characteristics and successional status of existing landscapes. The SS map units also formed the structural framework for the vegetation modeling described in the next section and in detail in Long and others, Ch. 9.

Modeling Fire Regimes

In the LANDFIRE Prototype Project, historical and current vegetation composition and structure were compared to estimate departure from historical conditions. To characterize historical conditions, we used the PVT map and succession pathway modeling as key input to the LANDSUMv4 landscape fire succession model (fig. 6). We then used two separate methods for estimating departure from historical conditions: the Interagency FRCC Guidebook method (Hann and others 2004) and the HRVStat spatial/temporal statistics software (Holsinger and others Ch. 11; Steele and others, in preparation).

The Interagency FRCC Guidebook provides detailed methods for estimating departure from historical conditions based on estimation of historical vegetation condition and disturbance regimes. The FRCC classification, established by Hann and Bunnell (2001), is defined as: a descriptor of the amount of "departure from the historical natural regimes, possibly resulting in alterations of key ecosystem components such as species composition, structural stage, stand age, canopy closure, and fuel loadings." Fire regime condition class is a metric for reporting the number of acres in need of hazardous fuel reduction and is identified in the National Fire Plan and Healthy Forests Restoration Act as a measure for evaluating the level of efficacy of wildland fuel treatment projects. In the FRCC Guidebook approach, low departure (FRCC 1) describes fire regimes and successional status considered to be within the historical range of variability, while moderate and high departures (FRCC 2 and 3, respectively) characterize conditions outside of this historical range (Hann and Bunnell 2001; Schmidt and others. 2002). Detailed description of how the Interagency FRCC Guidebook methods were implemented in the LANDFIRE Prototype Project follow in the below section titled *Estimating Departure using Interagency FRCC Guidebook Methods*.

Developing Succession Pathway Models

Succession pathway models were created using the multiple pathway approach of Kessell and Fischer (1981) in which succession classes are linked along pathways defined by stand development and disturbance probabilities within a PVT. Succession pathways describe the seral status of vegetation communities in the context of disturbances such as wildland fire, forest pathogens, and land use (Arno and others 1985). These pathways link seral vegetation communities or succession classes (described by combinations of PVT-CT-SS) over time. Each succession class is parameterized with disturbance probabilities and transition times. Transition times required to move from one seral succession class to another define the development of vegetation across landscapes over time. Disturbance probabilities determine the type and severity of disturbance. Pathways associated with disturbances determine where the post disturbance vegetation community trends over time.

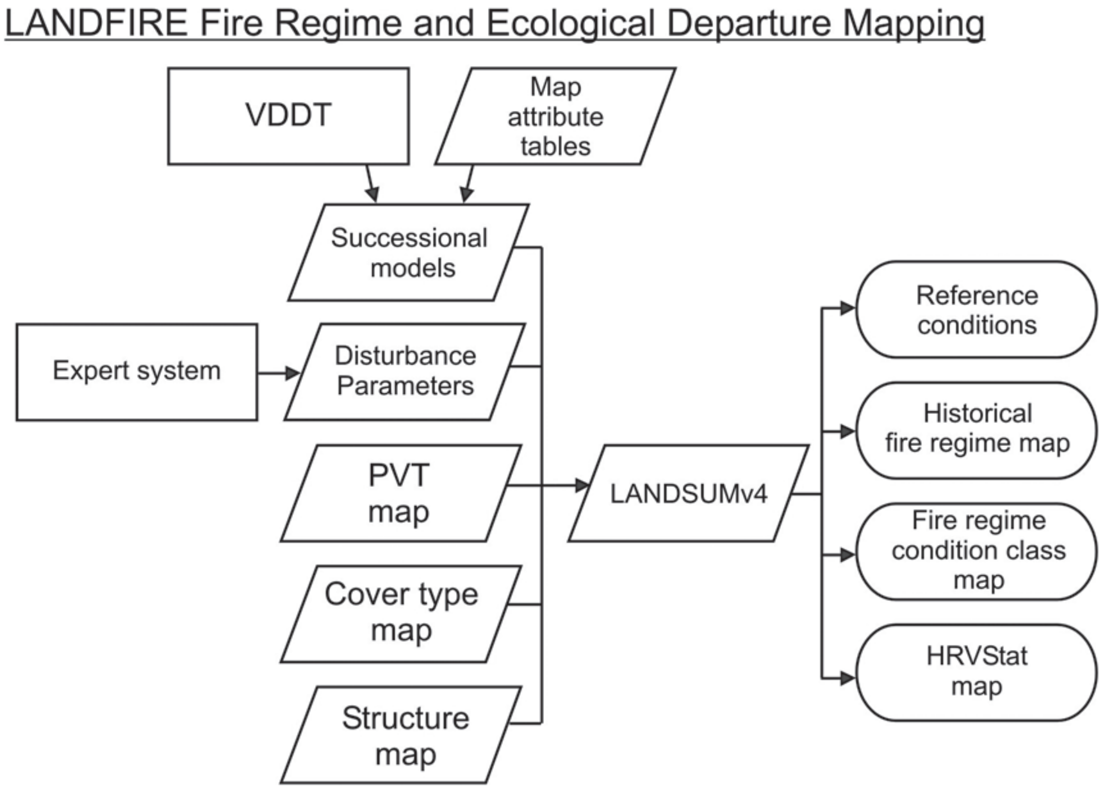

Figure 6—The LANDFIRE fire regime and ecological departure mapping procedure. Succession models were developed for each mapped PVT. These models, along with the PVT map and a suite of disturbance and weather parameters developed from empirical modeling or acquired from expert opinion, were implemented within the LANDSUMv4 landscape fire succession model to simulate spatial time series of vegetation characteristics and wildland fire. This information was summarized using the Interagency Fire Regime Condition Class Guidebook methods and the HRVStat software application to create maps of simulated historical fire regimes and departure from historical vegetation conditions.

We used a computer model called the Vegetation Dynamics Development Tool (VDDT; Beukema and others 2003) to build succession pathway models for each PVT defined in the LANDFIRE Prototype PVT map unit classifications. Specialists in forest and rangeland ecology facilitated this succession pathway modeling process (Long and others, Ch. 9). Based on the list of PVTs mapped for each zone, the specialists used VDDT to construct succession models. The existing vegetation map legends that describe both dominant species and structural stage were used to define the stages of vegetation development over time, called succession classes. Summaries from the LFRDB provided a list indicating which succession classes were most likely to occur in each PVT. An extensive literature search formed the basis for the input parameters (primarily transition times and disturbance occurrence probabilities) for each model. Each specialist used the VDDT software to both construct succession models and evaluate the behavior of each model. Final models were then reformatted and loaded into a relational database called the Vegetation and Disturbance Dynamics Database (VADDD) (Long and others, Ch. 9; Pratt and others, Ch. 10). This database was constructed specifically to facilitate the compilation and conversion of the succession pathway models into the proper format for LANDSUMv4.

Simulating Historical Landscape Composition

The fourth version of the Landscape Succession Model (LANDSUMv4) is a spatially explicit application where vegetation succession is modeled deterministically and disturbances are modeled stochastically over long simulation periods. LANDSUMv4 output is summarized for user-defined landscape reporting units to spatially describe simulated historical vegetation composition and structure and fire regimes (Keane and others 2002b).

LANDSUMv4 simulates succession using the LANDFIRE succession models described above. In LANDSUMv4, ignition of wildland fires is simulated based on separate probabilities by succession class and defined as a part of initial model parameterization. Simulated fires then spread across the landscape based on simple topographic and wind factors.

LANDSUMv4, stochastically simulates fire effects based on the distribution of fire severity types as specified during model parameterization. These effects are determined based on the information contained in VADDD. Finally, LANDSUMv4 outputs the amount of area in each succession class in each landscape reporting unit every 50 years over the simulation period. Landscape reporting units for the LANDFIRE Prototype Project were fixed at 900-m by 900-m to register with the 30-m grid cell size of the other LANDFIRE layers and to be comparable with the coarse-scale maps produced by Schmidt and others (2002). For detailed information on the background and implementation of LANDSUMv4 in the LANDFIRE Prototype Project, see Keane and Rollins, Ch. 3 and Pratt and others, Ch. 10.

Estimating Departure using Interagency FRCC Guidebook Methods

Comparison of current vegetation condition with that of the historical or reference period forms the foundation of FRCC calculation. Calculating FRCC using the Guidebook approach involves four distinct steps: 1) evaluate current vegetation conditions, 2) compute reference vegetation conditions, 3) calculate departure, and 4) estimate FRCC. For the LANDFIRE Prototype, current vegetation conditions were assessed by landscape reporting unit using the PVT, CT, and SS maps. Reference conditions for this analysis were estimated by executing the LANDSUMv4 model for a simulation period of several thousand years and reporting the area of each succession class every 50 years during the simulation period.

Calculation of FRCC begins with determining similarity, a concept addressed in depth by Hann and others (2004) and at www.frcc.gov. For the prototype, this simple metric was calculated by comparing current conditions with those of the reference period in the same reporting unit for each individual PVT. Percent composition of each PVT-CT-SS combination in the FRCC vegetation-fuel class map was compared with that of the reference conditions for a given landscape reporting unit. The lesser of the two percentages is defined as the similarity. That is, if a reporting unit currently has a smaller percent composition of a PVT-CT-SS combination than the reference conditions (modeled by LANDSUMv4) then the similarity equals the percent composition of the current PVT-CT-SS combination. Conversely, if the percent composition of a PVT-CT-SS combination in the reference conditions is less than that of the current conditions, the similarity value equals the percent composition of the reference conditions. For each PVT in a reporting unit, the similarity values were totaled and departure was calculated by subtracting the aggregate similarity from 100. For details regarding the scientific background of and specific methods for FRCC calculation, see Holsinger and others, Ch. 11 and visit www.frcc.gov

Estimating Departure using HRVStat

HRVStat is a multivariate statistical approach to rigorously evaluate patterns of succession classes (PVT-CT-SS) over the LANDSUMv4 simulation period – the estimated historical conditions – for comparison with those of current conditions. One important aspect of HRVStat that distinguishes it from the FRCC Guidebook approach is that it evaluates the variance structure of all PVT-CT-SS combinations as they fluctuate across landscapes through time to compute departure (Holsinger and others, Ch. 11; Keane and others 2006; Steele and others, in preparation).

The LANDSUMv4 output and current conditions based on the CT and SS maps were compiled into a custom HRVStat analysis database. This database consisted of the area in each succession class in each landscape reporting unit over the LANDSUMv4 simulation period. The HRVStat method involved a two-step process (Holsinger and others, Ch. 11). First, HRVStat determined the extent to which current vegetation in a reporting unit differed from simulated reference conditions. In addition, the amount of area in each succession class for each reporting unit was compared with the same for every other reporting unit. This process provided information on the variance structure from the entire simulation period to estimate a pixel based confidence measure for departure across the entire mapping zone. Secondly, for each reporting unit, a frequency distribution of departure measurements was derived, and the proportion of values in the departure distribution greater than or equal to the current departure estimate formed the basis for determining the significance level, or p-value. This significance level served as a measure of confidence in the departure estimate for each reporting unit. From this information we then created maps of departure (as a continuous variable) and significance (Holsinger and others, Ch. 11; Steele and others, in preparation).

Mapping Wildland Fuel

The various wildland fuel layers developed through the LANDFIRE Prototype Project were selected for development because they provide critical input to existing fire modeling software used for strategic and tactical planning, such as FOFEM (Reinhardt and Keane 1998), BEHAVE (Andrews and Bevins 1999), NEXUS (Scott 1999), and FARSITE (Finney 1998) (fig. 7). When implemented within these existing models, these fuel layers may be used to simulate fire intensity, spread rate, and severity for current conditions or (with slight modifications based on treatment level) used to predict fire behavior of fuel characteristics that result as a consequence of fuel treatment activities.

Mapping Surface Fuel

Surface fuel classifications represent biomass components that occur on the ground (less than 2 meters above) and integrate all factors that contribute to the behavior and effects of fires burning near the ground’s surface. For the LANDFIRE Prototype Project, we mapped four surface fuel model classifications to provide the inputs essential for implementing the fire behavior and fire effects applications used in wildland fire management planning (Keane and others, Ch. 12). The 13 fire behavior fuel models described by Anderson (1982) and the additional new 40 Scott and Burgan fire behavior fuel models (Scott and Burgan 2005) were mapped to facilitate the modeling of fire behavior variables such

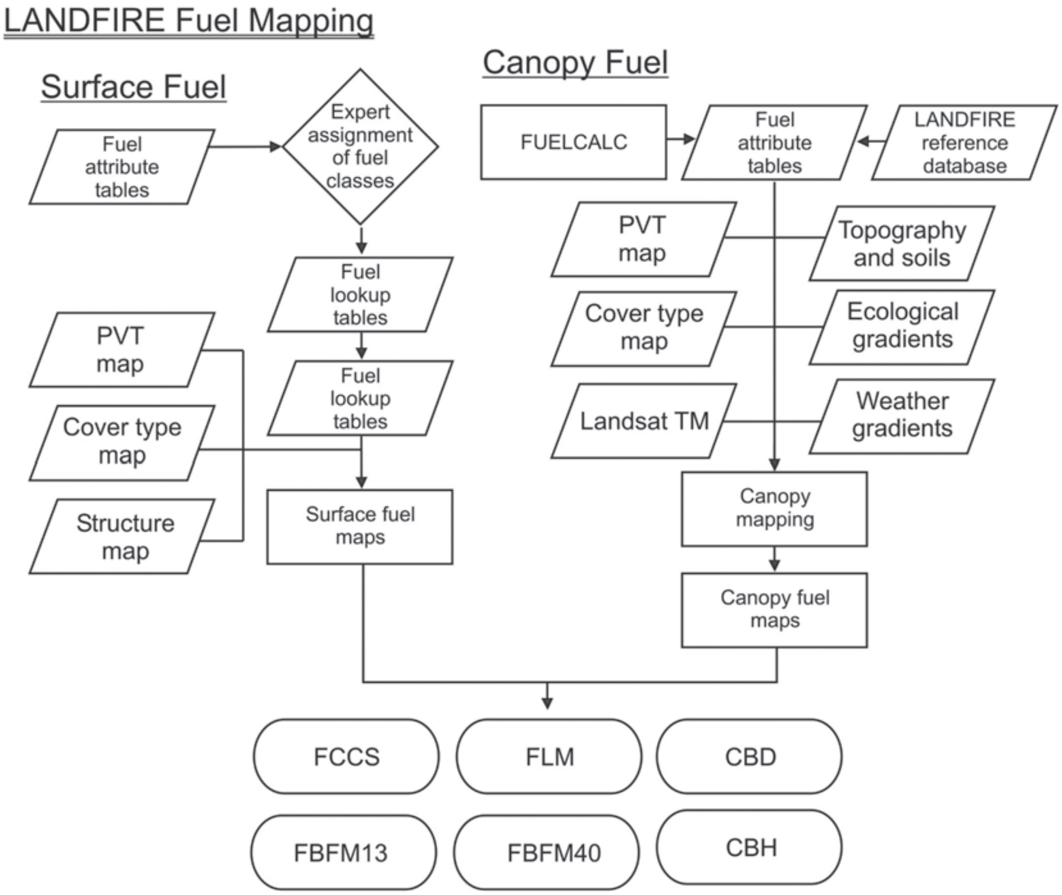

Figure 7—The LANDFIRE fuel mapping procedure. Surface fuel was mapped using a rule-based approach in which combinations of LANDFIRE map classes were matched with both fire behavior fuel models and fire effects models. These look-up tables and the LANDFIRE vegetation maps were used to create the final LANDFIRE surface fuel maps. Canopy fuel (crown base height and crown bulk density) was mapped with a predictive landscape modeling approach using Landsat imagery and a suite of biophysical gradient layers.

as fire intensity, spread rate, and size using models such as FARSITE and NEXUS (Finney 1998; Scott 1999). The Fuel Characterization Classification System fuel beds (Sandberg and others 2001) and the fuel loading models (Lutes and others, in preparation) were mapped to facilitate the spatially explicit modeling of fire effects such as vegetation mortality, fuel consumption, and smoke production (Keane and others, Ch. 12).

The following is a general description of procedures that were used for mapping surface fuel during the LANDFIRE Prototype Project; see Keane and others, Ch. 12 for detailed descriptions of these procedures. First, the LANDFIRE fuel database was compiled from the LFRDB by summarizing all georeferenced fuel data to the PVT-CT-SS combinations. Each PVT-CT-SS combination was assigned to each of the four surface fuel model classification systems based on data contained within the LFRDB. Information gaps resulting from lack of fuel data in the LFRDB were filled using either information from the literature or estimates from local fire behavior experts. Next, the LANDFIRE fuel database was converted to a rule set and implemented within a GIS to create the four surface fuel maps.

All surface fuel maps were created using similar classification protocols in which a fuel model category was directly assigned to a PVT-CT-SS combination. The rule set approach allowed the inclusion of additional detail by augmenting the PVT-CT-SS stratification with other biophysical and vegetation spatial data. For example, a rule set might assign the Anderson Fuel Model 8 to a specific PVT-CT-SS combination on slopes less than 50 percent and the Anderson Fuel Model 10 to the same combination on slopes greater than 50 percent (Keane and others, Ch. 12).

Mapping Canopy Fuel

Canopy fuel represents the amount and arrangement of live and dead biomass in the canopy of the vegetation. Characteristics of canopy fuel are important for estimating the probability and characteristics of crown fires, and the spatial representation of canopy fuel is important for assessing fire hazard on forested landscapes (Chuvieco and Congalton 1989; Keane and others 1998; Keane and others 2001). Spatially explicit maps of canopy fuel provide the critical input to simulation models of wildland fire required to simulate the initiation, spread, and intensity of crown fires across landscapes (Finney 1998).

Maps of canopy height (CH), canopy cover (CC), canopy bulk density (CBD), and canopy base height (CBH) were produced through the LANDFIRE Prototype Project. These layers are required input (along with maps of elevation, aspect, slope, and surface fuel models) for the FARSITE fire behavior model to simulate wildland fire behavior (Finney 1998). FARSITE is currently used by many fire managers to plan prescribed burns as well as to manage wildland fires. It is designed to model fire behavior over a continuous surface. These same canopy characteristics may also be used in NEXUS to calculate the critical wind threshold for propagating a crown fire (Scott 1999).

Canopy height and canopy cover map layers were developed from the stand height and canopy closure layers created by the EROS team using satellite imagery and statistical modeling (Zhu and others, Ch. 8). We calculated CBD and CBH for each georeferenced plot in the LFRDB using FUELCALC, a prototype program developed by Reinhardt and others at the Missoula Fire Sciences Laboratory in Missoula, Montana (Reinhardt and Crookston 2003). FUELCALC computes a number of canopy fuel characteristics for each field referenced plot based on allometric equations relating individual tree characteristics to crown biomass. Georeferenced values of CBD and CBH were implemented along with Landsat imagery and biophysical gradient layers within CART to create mapped CBD and CBH using an approach identical to that used in the mapping of existing vegetation composition and structure (Keane and others, Ch. 12).

Conclusion

Throughout the course of the LANDFIRE Prototype Project – from fall of 2001 to spring of 2005 – many lessons were learned that have proved valuable for the successful implementation of LANDFIRE mapping methods and procedures across the entire United States. The LANDFIRE team has refined the prototype processes and applications to ensure that LANDFIRE National will meet its objective of creating nationally comprehensive and consistent data for wildland fire management. In addition, LANDFIRE Prototype products have been successfully used in fire management applications, including hazard analyses for communities in the Color Country area of southern Utah and fire behavior analyses at the regional to local levels during the 2003 fire season in the northern Rocky Mountains. LANDFIRE National products will be available for the western U.S. in 2006, for the eastern U.S. in 2008, and for Alaska and Hawaii in 2009.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Appendix 2-A – LANDFIRE Prototype Project procedure table

1. LANDFIRE reference database (LFRDB)

1.1. Determine the geographic extent of existing plot data.

1.1.1. Acquire existing plot data from mapping zone for mapping LANDFIRE attributes.

1.1.2. Extract plot locations and convert coordinates to LANDFIRE map projection.

1.1.3. Conduct cursory quality assurance / quality control (QA/QC) on data to eliminate data with irreconcilable geospatial or information content errors.

1.1.4. Plot locations of useful data on LANDFIRE mapping zones to determine spatial gaps in coverage of the reference data.

1.1.5. Acquire additional field data in areas of mapping zones lacking sufficient field-referenced data.

1.2. Convert existing plot data into the relevant FIREMON and LANDFIRE attribute tables.

1.2.1. Create a separate directory for each data set.

1.2.2. Build an Access database for each data set.

1.2.3. Import empty LANDFIRE attribute tables into the Access database.

1.2.4. Develop data conversion queries to populate each LANDFIRE attribute table.

1.2.5. Develop data append queries to insert data into each FIREMON and LANDFIRE attribute table.

1.2.6. Document the data conversion process and populate the FIREMON Metadata (MD) table.

1.2.7. Create a subdirectory for all digital plot photos.

1.3. Conduct QA/QC procedures for all plot data.

1.3.1. Check again for geospatial errors in the data. Examples include plots located well outside the known study area for a particular database and plots located in bodies of water.

1.3.2. Check for information content errors. Examples include null values in required fields such as plot locations, duplicate records and/or plot locations, and erroneous plant species heights.

1.3.3. Visually inspect LANDFIRE cover types (CTs) with the Multi-Resolution Land Characteristics (MRLC) 2001 Landsat data and the 1992 National Land Cover Dataset (NLCD) Landsat imagery.

1.3.4. Visually inspect plots for gross differences in LANDFIRE CTs and NLCD land cover types.

1.3.5. Difference the Normalized Difference Vegetation Index (NDVI) values from the MRLC 2001 and the MRLC 1992 Landsat data.

1.3.6. Determine appropriate thresholds that suggest major land cover change.

1.3.7. Examine reference data plots that have values above these thresholds by overlaying them on the MRLC 2001 imagery.

Appendix 2-A — (Continued)

1.4. Populate the combined LFRDB

1.4.1. Create an Access database with empty FIREMON and LANDFIRE attribute tables as the LFRDB for each mapping zone.

1.4.2. Link FIREMON and LANDFIRE attribute tables from each data set to the LFRDB for each mapping zone.

1.4.3. Write append queries to add data from each linked table to its associated table in the LFRDB for each mapping zone.

1.4.4. Assign a LANDFIRE CT to each plot using the LANDFIRE CT map unit classification for each mapping zone.

1.4.5. Assign a LANDFIRE potential vegetation type (PVT) to each plot using the LANDFIRE PVT tables and queries for each mapping zone.

1.4.6. Assign a LANDFIRE structural stage (SS) to each plot using the LANDFIRE SS classification for each mapping zone.

1.4.7. Create the LANDFIRE map attribute table (MAT) with the PVT, CT, and SS assignments for each plot.

1.4.8. Develop data summary queries used in subsequent LANDFIRE tasks. Examples include plot counts by PVT/CT/SS, constancy cover tables by PVT/CT/SS, and fuel loading by PVT/CT/SS.

1.4.9. Place all digital plot photos and metadata documents for the LFRDB into one photo directory and one documents directory.

1.4.10. Connect the FIREMON database application to the LFRDB to hyperlink plot photos and metadata documents.

2. Mapping biophysical gradients

2.1. Acquire data to develop input layers for WXFIRE.

2.1.1. Acquire Digital Elevation Model (DEM) layer to create elevation, aspect, slope, and topographic shading layers.

2.1.2. Acquire STATSGO soils coverage and associated tabular data.

2.1.3. Acquire NLCD layer to create Ecophysiological Site layer.

2.1.4. Acquire DAYMET weather database.

2.1.5. Acquire Landsat imagery for leaf-on reflectance date to create Leaf Area Index (LAI) layer.

2.2. Create terrain-related layers.

2.2.1. Create Slope layer using Arc/Info SLOPE command with PERCENTRISE as units of slope.

2.2.2. Create Aspect layer using Arc/Info ASPECT command.

Appendix 2-A — (Continued)

2.2.3. Create Topographic Shading layer using Arc/Info HILLSHADE command. (Azimuth and altitude data were developed using NOAA Solar Position calculator, assuming summer solstice as the date and using center coordinates for each zone.)

2.3. Create Soil Texture layers (percent sand, percent silt, percent clay).

2.3.1. Using STATSGO database, compute four soil textures (percent sand, percent silt, percent clay, and coarse fragment).

2.3.2. Weight each soil texture by the layers' depths and spatial extent for each of soil sequences within STATSGO polygons.

2.3.3. Remove coarse fragment proportion from the composition of soil textures and rescale sand, silt, and clay components to comprise 100 percent of soil texture estimates.

2.3.4. Calculate average slope in STATSGO database from high and low values for each STATSGO polygon and associated sequences and classify average slope into 4 classes:
(1) ≤ 4 percent; (2) >4 percent and ≤8 percent; (3) > 8 percent and ≤ 15 percent; and
(4) >15 percent.

2.3.5. Calculate average soil texture using data from step 2.3.3 for each slope class within each STATSGO polygon.

2.3.6. Classify Slope layer (from 2.2.1) into same 4 slope classes.

2.3.7. Partition STATSGO polygon coverage by Classified Slope layer and link this spatial layer with the STATSGO variables of soil texture by polygon and slope class (from 2.3.5).

2.4. Create Soil Depth layer.

2.4.1. Extract data on maximum depth per soil sequence from the STATSGO database.

2.4.2. Weight maximum depth per soil sequence by areal extent of sequences to calculate maximum soil depth per polygon.

2.4.3. Calculate Topographic Soil Index (TSI) for each pixel using the following relationship:

$$TSI = \ln\left(\frac{a}{\tan B}\right)$$

where a is upslope area (m^2) draining past a certain point per unit width of slope calculated using Arc/Info FLOWACCUMULATION and FLOWDIRECTION commands and B is local surface slope angle (degrees) calculated using Arc/Info SLOPE command with DEGREE as units of slope.

2.4.4. Integrate STATSGO Maximum Depth layer and TSI to calculate soil depth value for each pixel using scalars to adjust for skewed TSI distributions in the equation:

$$\text{Soil Depth} = \{M_1, M_2\} * TSI.$$

where M_1 is scalar used if pixel's TSI is ≤ mean across a mapping zone, and M_2 is used if TSI value is > mapping zone's mean.

Appendix 2-A — (Continued)

Calculate M_1 and M_2 by the formulas:

$$M_1 = \frac{\text{Ave. Max. Depth}}{0.5 * (LN_{mo} + LN_{me})} \text{ and } M_2 = \frac{\text{Max. Depth}}{LN_{\max}}$$

where ave. max. depth is mean value of the STATSGO Maximum Depth layer across each zone, and LN_{mo} and LN_{me} are the mode and mean of the natural log of TSI for each STATSGO polygon calculated using Arc/Info's ZONALMAJORITY and ZONALMEAN commands, respectively.

2.4.5. For Zone 19: increase data resolution using slope data from STATSGO database and Classified Slope layer.

2.4.5.1. Use slope classes calculated from STATSGO database in step 2.3.1.

2.4.5.2. Calculate average maximum depth for each slope class within each STATSGO polygon using data from step 2.3.2.

2.4.5.3. Link STATSGO polygon coverage partitioned by Classified Slope layer from step 2.3.7 with STATSGO average maximum depth by polygon and slope class data calculated in 2.4.5.2.

2.5. Create LAI layer.

2.5.1. Calculate corrected Normalized Difference Vegetation Index (NDVI) using LANDSAT leaf-on reflectance imagery and the equation:

$$NDVI_c = \left(\frac{NIR - RED}{NIR + RED}\right) * \left(1 - \frac{MIR - MIR_{\min}}{MIN_{\max} - MIR_{\min}}\right)$$

where NIR is near infrared (band 4), RED is infrared (band 3), and MIR is mid-infrared (band 5); MIR_{min} is minimum value in mid-infrared band in an open canopy; and MIR_{max} is maximum value in the mid-infrared band in a closed canopy.

2.5.2. Convert $NDVI_c$ layer to LAI using the equation:

$$LAI = \frac{1n(0.7 - NDVIc}{-0.7}$$

2.6. Create Weather layer.

2.6.1. Using any one of the DAYMET layers (for example, daily temperature), clip DAYMET layer to zonal boundary using Arc/Info GRIDCLIP command.

2.6.2. Use clipped DAYMET layer to obtain center coordinates for each 1-km pixel.

2.7. Create Ecophysiological Site layer.

2.7.1. For Zone 16, partition landscape by 4 elevational breaks using DEM: Site 1 – 0 to 4,000 ft mean sea level (MSL); Site 2 – 4,000 to 6,000 ft MSL; Site 3 – 6,000 to 9,000 ft MSL; and Site 4 – 9,000+ ft MSL.

Appendix 2-A — (Continued)

2.7.2. For Zone 19, reassign 21 broad CTs from NLCD to 4 general plant functional types and one non-vegetated class: water/barren. Reassign developed land CTs to plant functional types based on surrounding pixels using FOCALMAJORITY command.

2.8. Classify WXFIRE input layers.

2.8.1. Classify Elevation layer into 100-m ranges.

2.8.2. Classify Slope layer (from 2.2.1) into low (0-10%), moderate (10-30%), and high (>30%) slope classes.

2.8.3. Classify Aspect layer into SW (165° to 255°), NW (255° to 345°), NE (345° to 75°), and SE (75° to 165°) classes.

2.8.4. Classify Topographic Shading Index layer into 0.25 intervals.

2.8.5. Classify Soil Depth layer into 0.5-m intervals.

2.8.6. Classify LAI layer into 1.0 intervals.

2.9. Create simulation units for running WXFIRE model.

2.9.1. Combine classified input layers (terrain, soil depth, and LAI), and ecophysiological site and weather layers such that each unique combination forms one simulation unit using Arc/Info's COMBINE command.

2.9.2. Associate values from each input layer to each simulation unit.

2.9.3. Create ASCII file for input to WXFIRE model that lists all the simulation units in a mapping zone with their associated site, terrain, weather-coordinates, soils, and LAI values.

2.10. Run WXFIRE simulations and develop biophysical gradient layers.

2.10.1. Input ASCII file to WXFIRE model.

2.10.2. Link each record in ASCII output file from WXFIRE model to its geo-referenced simulation unit (from step 2.9).

2.10.3. Create individual biophysical gradient layers for each simulation unit.

3. Mapping potential vegetation type (PVT)

3.1. Prepare data for model building.

3.1.1. Prepare spatially explicit predictor layers (biophysical and topographic gradients).

3.1.1.1. Acquire biophysical and topographic gradients for 3-km buffered zone.

3.1.1.2. Scale all layers to unsigned 8-bit or 16-bit integers and output summary statistics for each layer.

3.1.1.3. Convert layer to unsigned 8-bit or 16-bit integer images.

Appendix 2-A — (Continued)

- 3.1.1.4. Quality-check all predictor layers.
  - 3.1.1.4.1. Check projections and row / column numbers for consistency.
  - 3.1.1.4.2. Check all images for erroneous numbers or patterns.
- 3.1.2. Prepare response data (PVT classes).
  - 3.1.2.1. Acquire LFRDB MAT with uniqueID, spatial reference, and PVT assignments for plots within zone boundary.
  - 3.1.2.2. Examine data spatially and non-spatially, looking for outliers or unusual spatial distributions.
  - 3.1.2.3. Evaluate number of available plots by PVT class to see if classes need to be collapsed or dropped.
  - 3.1.2.4. Label each PVT plot as forest or non-forest type using values 1 and 2, respectively.
- 3.1.3. Perform data extraction.
  - 3.1.3.1. Extract values from each predictor gradient for each X and Y plot coordinate and link to the LFRDB MAT.
- 3.1.4. Perform data exploratory exercises.
  - 3.1.4.1. View data spatially, looking for unusual spatial patterns or outliers.
  - 3.1.4.2. Import data into a statistical package (in other words, R) and examine data for outliers or unusual features.
    - 3.1.4.2.1. Examine summary statistics of response (box plots, etc.).
    - 3.1.4.2.2. Examine summary statistics of predictors (distributions, scatter plots, correlation matrices, and principal components).

3.2. Generate PVT life form (forest / non-forest) model and map.

- 3.2.1. Set up input files for the See5 application.
  - 3.2.1.1. Generate an ERDAS Imagine image (dependent variable) of training plots using forest / non-forest values.
  - 3.2.1.2. Use NLCD Mapping Tool and Sampling Tool to generate See5 .names input file.
  - 3.2.1.3. Delete .data and .test files that are output from the NLCD Sampling Tool.
  - 3.2.1.4. Export refined training data set to a comma-delimited file (.data) including the uniqueID, the predictor gradient values (in the same order as listed in the .names file) and dependent (forest / non-forest) value.

Appendix 2-A — (Continued)

- 3.2.2. Use See5 to build forest / non-forest model.
    - 3.2.2.1. From See5, open input files (.data and .names).
    - 3.2.2.2. Specify options (such as winnow, boosting, and misclassification cost).
    - 3.2.2.3. Run model with 10-fold cross-validation (for accuracy assessment).
    - 3.2.2.4. Run model without cross-validation (for generating .tree file for prediction).
- 3.2.3. Apply model across buffered zone.
    - 3.2.3.1. Use NLCD Mapping Tool to generate a Forest / Non-forest map with an associated map of confidence.

3.3. Extract value from predicted map of forest / non-forest and link to LFRDB MAT.

3.4. Generate 2 mask images of PVT life form (forest / non-forest).

- 3.4.1. Create a new image by recoding forest / non-forest image to forest – 1; non-forest – 0.
- 3.4.2. Create a new image by recoding forest / non-forest image to forest – 0; non-forest – 1.

3.5. Generate forest PVT model.

- 3.5.1. Set up input files for the See5 application.
    - 3.5.1.1. Query data for forest PVTs, where predicted PVT life form is forest (life form = 1).
    - 3.5.1.2. Generate an ERDAS Imagine image (dependent variable) of training plots using forest PVT values from query.
    - 3.5.1.3. Use NLCD Mapping Tool and Sampling Tool to generate See5 .names file.
    - 3.5.1.4. Delete .data and .test files that are output from the NLCD Sampling Tool.
    - 3.5.1.5. Export a randomly selected 10% of the data set to a comma-delimited *.test file.
    - 3.5.1.6. Export remaining 90% of the data set to a comma-delimited *.data file.
- 3.5.2. Use See5 to build forest PVT classification tree.
    - 3.5.2.1. From See5, open input files (.data and .names).
    - 3.5.2.2. Specify options (such as winnow, boosting, and misclassification cost).
    - 3.5.2.3. Run model (no cross-validation) to generate .tree file for prediction.
- 3.5.3. Apply model across buffered zone.
    - 3.5.3.1. Use NLCD Mapping Tool and Classifier Tool to generate a map of forest PVTs with an associated map of confidence using the forest mask to limit prediction extent.

Appendix 2-A — (Continued)

3.6. Generate non-forest (shrub and herbaceous) PVT model.

  3.6.1. Set up input files for the See5 application.

    3.6.1.1. Query database for non-forest PVTs, where predicted PVT life form is forest (life form = 2).

    3.6.1.2. Generate an ERDAS Imagine image (dependent variable) of training plots using non-forest PVT values from query.

    3.6.1.3. Use NLCD Mapping Tool and Sampling Tool to generate See5 .names file.

    3.6.1.4. Delete .data and .test files that are output from the NLCD Sampling Tool.

    3.6.1.5. Export a randomly selected 10% of the data set to a comma-delimited *.test file.

    3.6.1.6. Export remaining 90% of the data set to a comma-delimited *.data file.

  3.6.2. Use See5 to build non-forest PVT classification tree.

    3.6.2.1. From See5, open input files (.data and .names).

    3.6.2.2. Specify options (such as winnow, boosting, and misclassification cost).

    3.6.2.3. Run model (no cross-validation) to generate .tree file for prediction.

  3.6.3. Apply model across buffered zone.

    3.6.3.1. Use NLCD Mapping Tool to generate a map of non-forest PVTs with an associated map of confidence using the non-forest mask to limit prediction extent.

3.7. Make final maps and assess accuracy.

  3.7.1. Combine forest and non-forest maps.

  3.7.2. Combine forest and non-forest error matrices.

  3.7.3. Calculate accuracy measures (for example, percent correctly classified, user and producer accuracy, and Kappa statistic).

4. Mapping existing vegetation

4.1. Conduct spatial QA/QC of field plot data

  4.1.1. Conduct QA/QC for non-Forest Inventory Analysis (FIA) data point identification.

    4.1.1.1. Convert map attribute coordinate data to point attribute (vector) data.

    4.1.1.2. Intersect vector coverage with NDVI Change layer

    4.1.1.3. Populate table with NDVI difference values. Large differences in NDVI values are likely to represent plots without recent major vegetation change. (such as ± 2 std dev. from mean NDVI value for table).

Appendix 2-A — (Continued)

4.1.1.4. Identify plots with a "distance to road" of > 30m.

4.1.1.5. If NLCD data for 2001 is available, compare CTs to NLCD classes to check for matches. If NLCD 2001 data is not available, try NLCD 1992 data (provided in LFRDB).

4.1.1.6. Flag values in MAT that require attention based on analyses performed in 4.1.

4.1.2. Identify questionable plots.

4.1.2.1. Overlay points onto imagery stratified by CTs.

4.1.2.1.1. Identify and flag points on roads or other similar types of locations (such as urban or agriculture) that should not be used for training.

4.1.2.1.2. Identify and flag those points that indicate change has occurred since the field data were obtained.

4.1.2.1.3. Identify plots with forest CTs located in relatively intact non-forest locations (and vice versa).

4.1.2.1.4. Identify plots typed as conifer located in relatively intact deciduous forest (and vice versa).

4.1.2.2. Flag questionable plots in MAT and omit from future analyses.

4.1.3. Develop a modified MAT storing only field plots that pass the QA/QC process in 4.1.2.

4.1.4. Conduct QA/QC for FIA data (same general process as in 4.1.1 but requires FIA analyst).

4.1.5. Isolate 2% of the sample points to be used for accuracy assessment using the 3x3 km, 2% block design.

4.2. Preprocess imagery.

4.2.1. Ensure that Landsat imagery used for LANDFIRE mapping is processed to the following specifications:

4.2.1.1. For each path/row, acquire and process 3 seasonally separate dates (spring, summer, and autumn) of Landsat scenes

4.2.1.2. Conduct geometric rectification to terrain precision correction level, resulting in less than ± 15m root mean square error (RMSE) spatial accuracy.

4.2.1.3. Conduct radiometric normalization to calibrate radiance values to at-satellite reflectance values.

4.2.1.4. Calculate NDVI and tasseled cap transformation values for each of the three dates of the data.

4.2.1.5. Develop preliminary maps of forest, shrub, and herbaceous CTs using methods listed in 3 (potential vegetation mapping) Provide the preliminary maps to the PVT mappers and vegetation modelers for internal use.

Appendix 2-A — (Continued)

4.2.2. Ensure that the PVT map and PVT probability layers are stored in data library

4.2.3. Conduct visual quality check on the PVT layers to ensure no obvious seam lines, dropped pixels, or other quality problems exist.

4.2.4. Assemble imagery, topographic data, biophysical gradient layers, PVT probability layers, and riparian-wetland mask (if available).

4.3. Map life form-specific CT

4.3.1. Extract digital values from the spatial layers (4.2.4) using field plots that have passed the visual QA/QC inspection process (4.1.3 and 4.1.4).

4.3.2. Determine if a "hierarchical approach" (mapping by high-level stratifications) is needed: if there are strong environmental differences between life form-specific CT classes, consider taking the hierarchical approach. For example, stratify desert shrub CTs from upland and riparian shrub CTs. If the hierarchical approach is needed, go to 4.3.2.1; otherwise, go to 4.3.3.

4.3.2.1. Recode field plot data to high-level CT groups and run decision tree model for high-level CT groups.

4.3.2.2. Model CTs with decision tree model under each of the high-level CT groups.

4.3.2.3. Calculate overall cross-validation accuracy by weighting and summarizing all CT groups

4.3.2.4. If weighted cross-validation is satisfactory, merge all CT groups into one CT map by major life form.

4.3.2.5. If weighted cross-validation is not satisfactory, consider rearranging high level groups or abandoning the approach.

4.3.3. Run decision tree model separately for forest, shrub, and herbaceous life forms.

4.3.4. Generate life form-specific cross-validation error matrices.

4.3.5. Generate life form-specific CT layers by applying decision tree models (create separate tree, shrub, and herbaceous layers).

4.3.6. Check for any visual and information content problems by examining CT maps and interpreting error matrices

4.3.7. Determine if there are any rare classes (< 30 field plots) and decide how to treat such rare classes.

4.3.7.1. Option 1: drop rare classes and re-run decision tree models.

4.3.7.2. Option 2: re-run decision tree models without the rare classes and then "burn" rare class field plots onto the map.

4.3.7.3. Option 3: merge rare classes with floristically similar classes (solicit feedback from Vegetation Working Group).

4.3.7.4. Option 4: retain the rare classes in the map.

Appendix 2-A — (Continued)

4.3.8. Determine if other major mapping errors exist and correct by altering input parameters (if possible) as well as field-referenced data.

4.3.9. Apply water, urban, and agriculture masks to life form-specific CT maps.

4.3.10. Merge the 3 life form-specific CT layers to form one CT layer.

4.4. Map life form-specific canopy height (CH)

4.4.1. Assign life form-specific CH classes to plots in modified MAT (4.1.3 and 4.1.4).

4.4.2. Extract digital values from the spatial layers, including life form-specific CTs (4.3.10), and use field plots classified to CH class values from 4.4.1 above.

4.4.3. Run decision tree models separately for the three life forms (tree, shrub, and herbaceous).

4.4.4. Generate life form-specific cross-validation error matrices for CH classes.

4.4.5. Generate life form-specific CH class maps using decision trees.

4.4.6. Check for errors in the three life form-specific CH maps, ensuring ranges of CH values are logical for their corresponding CTs.

4.4.7. Mask each CH map with water, urban, and agriculture masks.

4.5. Map life form-specific canopy cover (CC)

4.5.1. Map tree CC

4.5.1.1. Create training set of forest CC using 1-m digital ortho-photography quadrangles or 1-m satellite imagery.

4.5.1.2. Establish the relationship between Landsat data and plot data using regression trees.

4.5.1.3. Apply the regression-tree relationship to generate a spatial per-pixel estimate of tree canopy for all pixels.

4.5.1.4. Generate cross-validation error matrices, evaluate error and R^2 values, and determine effectiveness of the regression tree models.

4.5.1.5. Recode continuous tree CC data to CC classes defined by the Vegetation Working Group.

4.5.1.6. Apply land cover masks: water, urban, and agriculture.

4.5.2. Map shrub and herbaceous CC, option 1:

4.5.2.1. Extract digital values from the spatial layers using field plots that have shrub or herbaceous CC associated with them. Use the modified MAT (4.1.3 and 4.1.4).

4.5.2.2. Stratify digital values based upon dominant life form and run regression models.

4.5.2.3. Generate life form-specific error assessments based on cross-validation analysis.

Appendix 2-A — (Continued)

    - 4.5.2.4. Determine effectiveness of the regression tree models based on error analysis and determine whether changes need to be made to both field data and independent spatial layers.
    - 4.5.2.5. Generate life form-specific CC maps by applying the regression tree models.
    - 4.5.2.6. Recode continuous variables to CC classes defined by the Vegetation Working Group.
    - 4.5.2.7. Apply land cover masks: water, urban, and agriculture.
- 4.5.3. Map shrub and herbaceous CC, option 2:
    - 4.5.3.1. Recode plot CC values in modified MAT (4.1.3 and 4.1.4) into CC classes defined by Vegetation Working Group.
    - 4.5.3.2. Extract digital values from the spatial layers (4.2.4) using binned shrub or herbaceous field plots from step 4.5.3.1.
    - 4.5.3.3. Stratify digital values based upon dominant life form (shrub and herbaceous vegetation) and run decision tree models.
    - 4.5.3.4. Generate life form-specific error assessments based on cross-validation analysis.
    - 4.5.3.5. Determine effectiveness of the decision tree models based on error analysis and determine whether changes need to be made to both field data and independent spatial layers.
    - 4.5.3.6. Generate life form-specific CC layers by applying the decision tree models.
    - 4.5.3.7. Apply land cover masks: water, urban, and agriculture.
- 4.5.4. Map shrub and herbaceous CC, option 3:
    - 4.5.4.1. Measure field spectral bands (corresponding to Landsat red and NIR bands) from multiple shrub and grass sites and derive field NDVI values.
    - 4.5.4.2. Estimate percent shrub and herbaceous CC for sites where field spectral data has been acquired (1-m^2).
    - 4.5.4.3. Determine relationship between field percent CC estimates and field-measured NDVI values.
    - 4.5.4.4. Estimate continuous shrub and grass CC through application of relationship described in step 4.5.4.3 to Landsat NDVI to standardize Landsat CC estimates (stratified by life form using NLCD 2000 data and/or LANDFIRE CT data).
    - 4.5.4.5. Recode continuous shrub or herbaceous variables to CT classes defined by the Vegetation Working Group.
    - 4.5.4.6. Apply land cover masks: water, urban, and agriculture.
- 4.5.5. Refine and normalize CC estimates.

Appendix 2-A — (Continued)

4.5.5.1. Normalize individual tree, shrub, and herbaceous CC values such that tree, shrub, and herbaceous CC values combined do not exceed 100% per pixel.

4.5.5.2. Locate zones of low confidence using confidence layers and other sources of information.

4.5.5.3. Mask out zones of low confidence for shrub and grass CTs where forest is the dominant CT.

4.6. Generate merged CT and SS maps

4.6.1. Revisit, and revise if necessary, the merged CT map (4.3.10) by using forest, shrub, and herbaceous percent CC as reference. Ensure that CTs match life form CC maps.

4.6.2. Produce a Federal Geographic Data Committee (FGDC) -compatible metadata file for the final merged CT map (4.6.1) using a mapping zone metadata template for CT.

4.6.3. Generate a single CH layer using the CT data layer (4.6.1) for life form masking stratification.

4.6.4. Produce an FGDC-compatible metadata file for the final merged Canopy Height layer (4.6.3) using a mapping zone metadata template for CH.

4.6.5. Generate a single CC layer using the CT layer (4.6.1) for life form masking stratification.

4.6.6. Produce an FGDC-compatible metadata file for the final merged Canopy Cover layer (4.6.5) using a mapping zone metadata template for CC.

4.7. Conduct cross-validation and accuracy assessments

4.7.1. Summarize all cross-validation errors and accuracy tables for the mapping zone; provide information to the Accuracy Working Team.

4.7.2. Extract the final CT, CC, and CH class values and labels (from 4.6.1, 4.6.3, and 4.6.5) using withheld plot locations (4.1.5). Provide extracted data to the Accuracy Working Team.

4.7.3. Evaluate error matrices, overall accuracy, and user and producer accuracy.

5. Mapping ecological departure

5.1. Acquire and develop input layers.

5.1.1. Acquire vegetation layers: PVT, CT, and SS.

5.1.2. Create Landscape Reporting Unit (LRU) layer by building grid of 900-m x 900-m squares.

5.1.3. Acquire polygon coverage that partitions zone into smaller units – termed simulation landscapes – used in LANDSUMv4 simulations.

5.2. Calculate ecological departure and index of significance using HRVStat approach.

5.2.1. Acquire data for historical reference conditions of vegetation patterns, developed using LANDSUMv4 model, including year, LRU, PVT, succession class, and area (m^2).

Appendix 2-A — (Continued)

5.2.1.1. Partition data into series of files, which function as LANDSUMv4 output for each simulation landscape within a zone.

5.2.1.2. Remove agriculture and urban CTs from reference conditions database.

5.2.2. Combine CT and SS layers to represent current succession classes using ArcInfo's COMBINE command.

5.2.3. Combine Succession Class layer with LRU and simulation landscape layers.

5.2.4. Join historical reference conditions with current succession class data for each unique LRU within each simulation landscape of zone data. Create series of ASCII files with these data for each simulation landscape.

5.2.5. Convert ASCII files from text to binary format.

5.2.6. Run the HRVStat program. The HRVStat program outputs ASCII text files containing calculations of departure, observed significance level, and classified HRVStat departure for each LRU within each simulation landscape file.

5.2.7. Link HRVStat ASCII output files to LRU layer to develop individual layers of ecological departure, observed significance level, and classified HRVStat departure.

5.3. Calculate ecological departure using FRCC Guidebook approach.

5.3.1. Isolate analysis to individual simulation landscapes.

5.3.2. Combine values for LRU, PVT, CT, and SS. Combined CT and SS information form succession classes.

5.3.3. Concatenate the LRU, PVT, CT, and SS fields to create unique IDs for LRU/PVT/succession class and LRU/PVT combinations.

5.3.4. Calculate current fire regime (CFR) by dividing the area of each succession class within an LRU/PVT combination into the total area (m^2) of the LRU/PVT combination.

5.3.5. Access the LANDSUMv4 files for each simulation landscape.

5.3.5.1. Create unique IDs for the LANDSUMv4 data corresponding to those of the CFR data.

5.3.5.2. Calculate the 90th percentile for each LRU/PVT/succession class combination and then export to historical fire regime (HFR) database.

5.3.6. Join HFR database records for the current simulation landscape with CFR database records using the LRU/PVT/succession class field.

5.3.7. Compute similarity, which is the smaller of CFR or HFR.

5.3.8. Total the similarity values across each LRU/PVT combination.

5.3.9. Compute departure as 100 – similarity. This represents the estimated ecological departure for a PVT in an LRU.

Appendix 2-A — (Continued)

5.3.10. Compute departure for entire LRU on an area-weighted basis. Weighting factors are derived by dividing the area (m^2) of each individual PVT into the area of each LRU (constant at 81 ha or 900 x 900 meters).

5.3.11. Merge all individual simulation landscapes together to create map for entire zone.

6. Mapping surface fuel models

6.1. Acquire rectified CT, PVT, and SS layers.

6.2. Combine these layers in a GIS format.

6.3. Export combined vegetation data and import into Access.

6.3.1. Assign CT, PVT, and SS names to the coded information from GIS layers.

6.4. Build rule sets for Anderson's (1982)13 fire behavior fuel models and Scott & Burgan's (2005) 40 fire behavior fuel models.

6.4.1. Use Forest Vegetation Simulator-Fire and Fuels Extension (FVS-FFE) documentation on variant fuel rules from Reinhardt and Crookston (2003).

6.4.2. Use additional information, such as local fire and fuel plans, fire behavior studies, other fuel research.

6.4.3. When necessary, consult local experts.

6.4.4. Compare rate of spread and flame length for each fuel model to ensure that fuel models are not illogically assigned to a specific vegetation combination. For example, we would not assign a FBFM 3 in grass systems that are only 1 foot tall.

6.4.5. Construct logical crosswalks between combined vegetation layers and fuel models.

6.4.5.1. Timber-dominated systems are usually assigned timber FBFMs.

6.4.5.2. Herbaceous systems are usually assigned grass FBFMs. Shrub systems can be assigned timber, shrub, or grass models, depending on composition and structure.

6.5. Apply rule set to vegetation combinations and assign surface fuel models in Access table.

6.5.1. Use key to assign fuel models to each combination of vegetation attributes.

6.5.2. Map fire behavior fuel models by linking the combination database to a GIS layer.

7. Mapping canopy fuel

7.1. Prepare data for model building.

7.1.1. Prepare spatially explicit predictor layers (biophysical and topographic gradients and Landsat satellite imagery).

7.1.1.1. Acquire biophysical and topographic gradients for 3-km buffered zone (as unsigned 16-bit images).

Appendix 2-A — (Continued)

- 7.1.1.2. Acquire Landsat imagery.
- 7.1.1.3. Quality-check all predictor layers.
    - 7.1.1.3.1. Ensure all layers are unsigned 8-bit or 16-bit integers.
    - 7.1.1.3.2. Check projections and row/column numbers for consistency.
    - 7.1.1.3.3. Check all images for erroneous numbers or patterns.

7.1.2. Prepare response data (canopy bulk density [CBD] and canopy base height [CBH]).

- 7.1.2.1. Set up input table for FUELCALC program, including field-referenced tree attributes from LFRDB.
- 7.1.2.2. Run the FUELCALC program.
- 7.1.2.3. Link FUELCALC output with LFRDB table (or FIA table).

7.1.3. Perform data extraction.

- 7.1.3.1. Extract values from each predictor gradient for each X and Y plot coordinate and link to the LFRDB MAT.

7.1.4. Perform data exploratory exercises.

- 7.1.4.1. Import coordinates into ArcMap and view data spatially, looking for unusual spatial patterns or outliers.
- 7.1.4.2. Import all data into a statistical package (in other words, R) and examine data for outliers or unusual features.
    - 7.1.4.2.1. Examine summary statistics of response (histograms, box plots, etc.).
    - 7.1.4.2.2. Examine summary statistics of predictors (distributions, scatter plots, correlation matrices, and principal components).
- 7.1.4.3. Create another variable, CBDx, in database with value: CBD * 100.
- 7.1.4.4. Create another variable, CBHx, in database with value: CBH * (0.3048 * 10).

7.2. Use NLCD Mapping Tool to set up input files for Cubist application.

7.2.1. Generate an ERDAS Imagine image (dependent variable) of training plots using CBDx/CBHx values.

- 7.2.1.1. Import Access table with X/Y coordinates (Albers) and CBDx/CBHx data into Arcmap.
- 7.2.1.2. Define extent identical to that of predictor layers.

Appendix 2-A — (Continued)

    - 7.2.2. Use NLCD Mapping Tool and Sampling Tool to generate Cubist .names input file.
        - 7.2.2.1. Set dependent (response) variable as the CBDx image.
        - 7.2.2.2. Set independent (predictor) variable as the list of imagery, gradient, and topographic layers used for modeling (in the refined data set).
        - 7.2.2.3. Specify sampling process: set sample to random and set number of samples to 99% training and 1% validation.
        - 7.2.2.4. Set name and location of output files.
        - 7.2.2.5. Select model as Cubist.
        - 7.2.2.6. Review .names file to make sure all variables are specified and all discrete variables have codes.
    - 7.2.3. Export .data input file from Access to Cubist.
        - 7.2.3.1. Delete .data and .test files that are output from the NLCD Sampling tool.
        - 7.2.3.2. Export refined training data set from Access to a comma-delimited file (.data), including the predictor gradient values and dependent (CBD) value.
- 7.3. Use Cubist to build model.
    - 7.3.1. From Cubist, open input files (.data, .names).
    - 7.3.2. Specify options
    - 7.3.3. Run cubist model with test data set (generating a .rules file for prediction).
    - 7.3.4. Run multiple models with different options and select the model with the highest accuracy.
- 7.4. Apply model across buffered zone.
    - 7.4.1. Use NLCD Mapping Tool to generate a map of CBDx/CBHx with associated map of confidence.
    - 7.4.2. Analyze output maps.
    - 7.4.3. Check accuracy and run diagnostics.

Chapter 3

The Scientific Foundation of the LANDFIRE Prototype Project

Robert E. Keane and Matthew Rollins

Introduction

The Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, originated from a recent mapping project that developed a set of coarse-scale spatial data layers for wildland fire management describing fire hazard and ecological status for the conterminous United States (Hardy and others 2001; Schmidt and others 2002; www.fs.fed.us/fire/fuelman). Schmidt and others (2002) used linear succession transition pathways to estimate vegetation conditions that occurred on historical landscapes represented by combinations of land cover types and structural stages from existing vegetation databases. The comparison of current landscape conditions with these historical successional sequences provided a means for assessing departure and for creating an index, called Fire Regime Condition Class (FRCC), that reflects the magnitude of departure (see Hann 2004 and www.frcc.gov).

Although maps generated from this coarse-scale mapping project provided fire management with a first-ever picture of ecosystem conditions across the lower 48 states or conterminous U.S., they contained problems that limited their use at finer resolutions and for smaller areas. First, the maps were developed with a large grain size (pixel size) of 1 km square. Very few field-referenced data sets are compatible with this large pixel size, making it difficult to develop empirical predictive models to increase or assess accuracy. Second, the project was limited to existing spatial data layers, including the land cover type and stand structure maps, to describe current and historical conditions. The legends of these layers tended to have categories that were broad and therefore difficult to describe uniquely with any degree of accuracy (Schmidt and others 2002). Moreover, the existing map layers used in this project were developed at different map scales and with varied resolution and detail because they were created from various independent efforts that had disparate objectives. As a result, it was often difficult to rectify the broad and sometimes inconsistent map categories between maps. Last, the majority of the data layers were based on models that were parameterized using ecologists' and managers' estimates rather than with data collected in the field. Because of these limitations, the coarse-scale mapping products could be used only for large, regional assessments and were essentially useless for finer-scale applications such as national forest management plan revision and implementation or local wildland fire hazard assessments.

The inability of the coarse-scale mapping project to aid in finer applications spurred the U.S. Department of Agriculture (USDA) Forest Service (FS) Fire and Aviation Management (FAM) to explore the possibility

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of developing a set of data layers that could be used at multiple scales, from national planning to local fuel treatment design. To make regional and local comparisons possible, it was essential that each layer be constructed in a manner ensuring that all areas of the country receive the same rigor and detail in the mapping effort.

In December of 1999, FAM met with scientists at the USDA FS Rocky Mountain Research Station (RMRS) Missoula Fire Sciences Laboratory (MFSL) to request the design and implementation of this national, fine-scale mapping project. The MFSL scientists wrote a proposal and study plan for this project and submitted both to FAM in March of 2000. In 2002, the project was funded by the United States Department of Agriculture Forest Service and Department of the Interior, with an annual cost of approximately $2 million. The MSFL scientists started the project in April of 2002 and called it the "LANDFIRE Prototype Project" (Rollins and others, Ch. 2). These methods and tools were tested in two large geographic areas (called prototype areas) during 2003 and 2004 and revisions to the process occurred during 2004 and 2005. The LANDFIRE Prototype Project was completed in April of 2005 and the results are currently being implemented across the nation. Meanwhile, the General Accounting Office (GAO) published two reports on the increasing threat of intense wildland fires across the nation (GAO 2002) and fire management's inability to cope with this emerging threat (GAO 2004), and GAO identified LANDFIRE as a viable project for generating the spatial data needed to plan and implement a national fire program (Rollins and others, Ch. 2).

This chapter documents the history, concepts, theory, and scientific foundation of the development of LANDFIRE products as they were applied to the two prototype areas. First, the background of the project is presented to detail the project's design criteria and guidelines. Then, the theory and development of each integrated LANDFIRE task is discussed in the context of the overall project. This chapter does not describe how each phase of LANDFIRE was accomplished (for this information, see Rollins and others, Ch. 2); rather, it describes the scientific background and concepts behind the design of LANDFIRE and the theory and ideas behind the development of the project's tasks. Although the methods and protocols presented here were implemented and refined for two prototype areas only (Rollins and others, Ch. 2), this report is written with the perspective that these methods will eventually be applied throughout the entire United States.

Background

Project Objectives

The primary objective of the LANDFIRE Prototype Project was to develop a fine-scale (30 meter) digital map (spatial data layer) of Fire Regime Condition Class (FRCC). FRCC is an ordinal index with three categories indicating how far the current landscape has departed from historical conditions (Hann 2004) (see www.frcc.gov for complete details). This data layer can be used to identify those areas that are in need of treatment to reduce wildland fire hazard and protect homes and lives. Fire management can then use this information to allocate funding, fire fighting resources, and personnel to these areas for implementation of restoration activities and fuel reduction treatments (Laverty and Williams 2000) (see www.fireplan.gov for details).

The FRCC layer's primary use lies in fire management planning and resource allocation, with limited use in designing and implementing possible treatments. We therefore identified several secondary objectives of the LANDFIRE Prototype Project aimed at creating spatial and software products to aid fire management in implementing the National Fire Plan's Cohesive Strategy (Laverty and Williams 2000). For example, we specified the development digital maps of wildland fuel (surface and canopy) and of vegetation composition and structure as important data for designing fuel treatments. We eventually identified 24 core data layers to be developed as LANDFIRE Prototype products (see table 1 in Rollins and others, Ch. 2).

Design Specifications

A set of design criteria was developed during the initial LANDFIRE organizational meetings with USDA FS MSFL scientists and FAM. Most of these criteria resulted from the abbreviated timelines and solid deadlines imposed by FAM and other fire management agencies. Other criteria were imposed as a result of FAM's condition that LANDFIRE be based on a strong scientific foundation and be scalable to local applications with minimal modification.

The design criteria for the LANDFIRE Prototype are listed below and are detailed in the following paragraphs. According to the design criteria, the LANDFIRE Prototype Project must be:

- based on the best available science,
- able to be implemented consistently across the nation,

- mapped at a 30-meter pixel size,
- reliant on no new field data collection,
- repeatable in time and space,
- scalable in application,
- developed within a three-year development timeline, and
- tested for accuracy.

Fire and Aviation Management's overriding design specification was that the products generated from LANDFIRE must be based on *the best available science*. This meant that the many tools, methods, programs, models, and protocols used in LANDFIRE to produce the FRCC maps needed to have a publication record, preferably in peer-reviewed journals, or in some way demonstrate acceptance by the scientific community. This limited the methods and procedures, especially those involving spatial analyses, to those that are citable in the literature. This specification implied that LANDFIRE development should have a minimal amount of subjectivity. We interpreted this to mean that each data layer and model should be developed using methods that are *repeatable* and objective. Some tasks in LANDFIRE required the creation of new methods that are not in the literature. In these cases, we developed the new methods from scientifically credible sources and prepared manuscripts for publication describing these methods.

To build LANDFIRE on a scientifically credible foundation, we based the development of all products in LANDFIRE on an extensive, plot-level database, called the LANDFIRE reference database (LFRDB) (fig. 1) (Caratti, Ch. 4). Every product generated by LANDFIRE was developed from legacy field data collected by resource professionals and screened for quality and consistency (the *LANDFIRE Prototype Design* section below gives additional detail on the database). This data compilation process ensured that each data layer could be easily recreated (*repeatable*), an especially important feature when additional data become available in the future. In addition, this process allowed for *accuracy assessment,* and the reference plot data could be used to *scale* LANDFIRE products for local applications by facilitating the development of additional, more detailed classifications of cover types, structural stages, and fuel models. A major complication arose from the design specification that, to reduce the costs of and time for project development, *no additional data be collected*. This meant no new data could be added to the database to supplement the ecosystems or geographic areas where data were lacking. This criterion was relaxed, however, when we found significant gaps in data coverage for the mapping of current vegetation conditions.

The second most important design standard was that LANDFIRE products must have the potential for *national implementation*. This meant that all ecosystems had to be mapped and modeled with the same degree of complexity and detail, ensuring that the FRCC categories would have the same meaning across the entire conterminous U.S. In other words, a "red" pixel in Maine would mean the same as a "red" pixel in Arizona. For LANDFIRE, we used the terms "consistent" and "comprehensive" to define this national implementation. *Consistent* means that we used the same methods of mapping and modeling for every pixel in the conterminous U.S., and *comprehensive* means that we used the same rigor (a thorough and wide-ranging approach) for all LANDFIRE tasks, regardless of ecosystem or geographic area.

The *30-meter pixel size* condition specified by FAM was an important criterion because they wanted fine-scale applications to be possible for all LANDFIRE map products. This posed a significant scale problem because it is difficult to match map category and simulation model resolution for national implementation to the small spatial resolution of 30 meters; however, this pixel size matched the grain of the satellite imagery and digital elevation models that were used to map current vegetation conditions.

Another important criterion was that the project had to be developed so that it could be *repeated* every five to ten years to assess and monitor the efficacy of the National Fire Plan and the Cohesive Strategy (www.fireplan.gov) across the U.S. in a standardized format. By repeating the LANDFIRE process every five to ten years, fire management would have a vehicle by which to monitor the success of the National Fire Plan and Cohesive Strategy across multiple spatial scales. Subjective and arbitrary methods and protocols had no place in the creation of any LANDFIRE product because they are difficult to consistently replicate.

The specification that LANDFIRE include tools and methods to *scale* maps and models both upwards (coarser) and downwards (finer) presented a major challenge in the creation of many LANDFIRE products. Although important, this turned out to be a time-consuming design requirement because it required that all products have the ability to be scaled both in geospatial and management applications. For example, the vegetation data layers needed to be developed so that refinement and additional detail in the vegetation classification categories could be remapped on smaller landscapes with relative ease. This stipulation also meant that tools were needed that integrate the LANDFIRE products into value-added

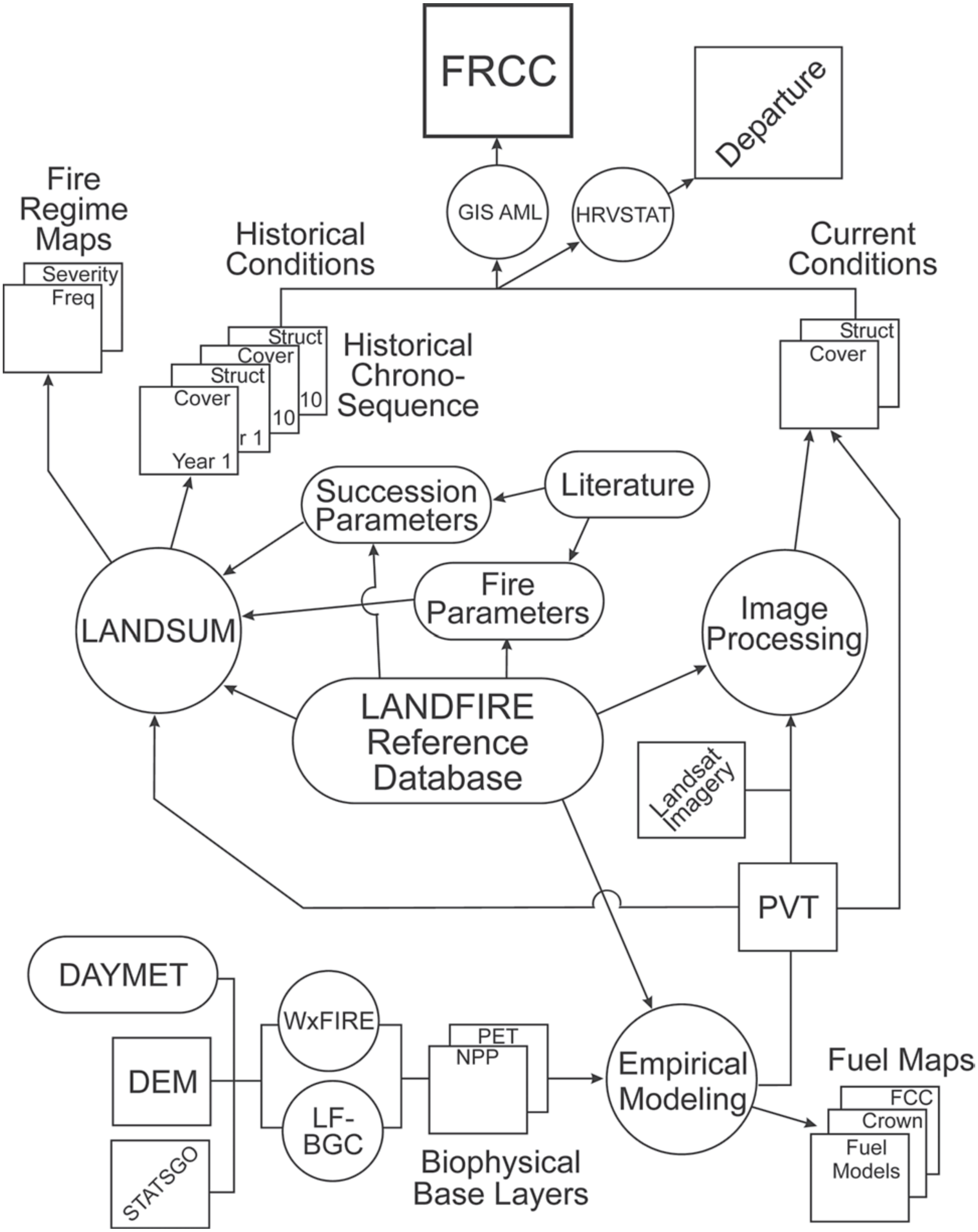

Figure 1—Flow chart of all LANDFIRE software and products culminating in the creation of the FRCC layers. All squares in the figure are digital maps, circles are analysis tasks involving software, and ovals are data sources. The acronyms are defined as follows: DEM - digital elevation model, PVT - potential vegetation type, PET - potential evapotranspiration, NPP - net primary productivity, and GIS AML - geographic information systems macro language. All other acronyms are program names that are detailed in this report.

products that have more specific meaning and utility for fire management, especially at local scales. For example, the LANDFIRE fuel layers can be used in the Fire Hazard Rating Model (FIREHARM), to create spatial data layers of expected fire behavior and effects. Moreover, all of LANDFIRE analysis programs and models are open source so that they can be modified for local situations and applications.

As specified by FAM, the entire LANDFIRE Prototype Project needed to be completed in *three years*. This included the final 24 map layers, the analysis software, and the final draft manuscripts of all chapters presented in this report. This timeline required that the entire process had to be developed within the first 18 months and implemented within the first prototype mapping zone during the following six months. Revisions and refinements needed to be made, and the second prototype area had to be mapped during the following six months. The chapters in this report were written during the last six months. This accelerated timeline dictated the detail of analysis for many LANDFIRE tasks and prevented a more thorough investigation of a few aspects of the project.

The last design requirement specified that every data layer be *assessed for accuracy* to ensure and document the quality and precision of LANDFIRE products. As mentioned, we created the LFRDB to serve as a foundation for meeting the accuracy assessment requirement. There is, however, a wide range of accuracy assessments: from thematic accuracy (Is this pixel mapped correctly?) to classification accuracy (How often does this classification fit real field data?) to model accuracy (How often does the statistical mapping model predict the correct answer?). FAM identified thematic accuracy as the primary target. The estimation of this measure has many problems, however, including the possibility of field data having 1) inaccurately georeferenced plot coordinates, 2) errors in data measurement and entry, and 3) inexperience and inconsistency within field crews (Vogelmann and others, Ch. 13). We therefore attempted to report as many types of accuracy measures as possible, using the reference database and data from other modeled sources, to provide a more complete assessment of accuracy. The main three measures of accuracy that we calculated for most LANDFIRE products were 1) thematic accuracy or the accuracy of a pixel being mapped correctly, 2) landscape accuracy or the accuracy of pixel summaries across large areas, and 3) model accuracy or the accuracy of the statistical models used to build the maps (Vogelmann and others, Ch. 13).

Guiding Principles

Given these design specifications, we then developed a set of principles that we used to guide the development of all LANDFIRE data layers. These principles were a direct outgrowth of the design specifications, and they allowed us to set boundaries for the development of every LANDFIRE product. These guidelines were as follows:

- Development should be targeted at mid-scale map classifications.
- All themes must be identifiable, scalable, mappable, and model-able.
- Mapping applications must incorporate the biophysical gradients that determine the distribution of vegetation and disturbance regimes across landscapes.
- The primary development tool should be simulation modeling.
- The timespan for historical reference conditions would be 1600 AD to 1900 AD.

Development should be targeted at mid-scale – The mid-scale development target was chosen because of the national implementation design specification. It was unrealistic to develop and map classifications of vegetation at finer scales for several reasons. First, national vegetation classifications that are scalable to local applications are nonexistent or, at best, incomplete, especially for mapping purposes (Anderson and others 1998; Grossman and others 1998). Next, most existing classifications do not provide for the shared dominance of two or more species in a consistent manner for the entire nation (Long and others, Ch. 6). In addition, many rare vegetation types that are important to management have not been sampled in the field and were therefore under-represented in the LANDFIRE reference database, making it difficult to map rare vegetation types at a national scale. Last, there was not enough time to develop the detail in our simulation models required for fine-scale mapping. For these reasons, we decided to aim for a mid-scale target in the development of all LANDFIRE intermediate and final products, including map categories, model elements, and fuel classes.

In keeping with this mid-scale development, we chose to use the USGS Center for Earth Resources Observation and Science (EROS) mapping zones (Rollins and others, Ch. 2) to define the spatial extent which guided the design of all vegetation classifications and simulation models. To that end, we decided that a vegetation class must occur in at least five percent of the mapping zone to warrant its mapping. This restriction eliminated from consideration many vegetation types which, although important for local applications, are uncommon across an entire mapping zone. It is doubtful that we could have mapped these types anyway as there were so few representative data for these in the LFRDB. It is important to note that the mid-scale development target concerned mainly the vegetation and fuel classifications that were mapped across the nation, not the spatial and temporal resolution of the maps; we still had to meet the fine-scale design specification of a 30-meter spatial resolution.

All themes must be identifiable, scalable, mappable, and model-able — The categories within the vegetation map unit classification mapped by the LANDFIRE Prototype team served as the building blocks used to construct all LANDFIRE Prototype maps and models. It was essential that the design of the classification match the detail provided by the 1) imagery used to map existing conditions, 2) empirical models used to assign attributes to vegetation categories, and 3) simulation models used to determine historical conditions (Long and others, Ch. 6; Zhu and others, Ch. 8; Pratt and others, Ch. 10). For LANDFIRE, we specified that classification categories must meet four criteria to warrant their mapping. First, the classification categories had to be *identifiable* on the ground and in the LFRDB, meaning that we had to be able to construct a key that would uniquely identify the classes from commonly sampled vegetation characteristics, especially those present in the reference database. Moreover, field crews needed to be able to use the LANDFIRE key to accurately identify the vegetation classification type on the ground. Second, the classifications had to be *scalable;* similar categories needed to have the ability to “collapse” to form a coarser classification, or the ability to expand so that additional, finer-scale categories could be added with little effort. Third, map categories had to be *mappable,* meaning that the methods used to map entities had to be able to detect this classification category. For example, we did not map upland willow shrubland types if the Landsat imagery (EOSAT 1992; http://landsat.gsfc.nasa.gov/) could not distinguish them from other shrubland types. Lastly, the vegetation categories needed to be consistent in scale and detail with the simulation model entities used to estimate historical conditions (*model-able*). Categories that included both shade-tolerant and shade-intolerant tree species, for example, were not included in the classification because they could not be used to simulate seral states in models of vegetation succession (Long and others, Ch. 6; Long and others, Ch. 9).

Methods must stress those ecosystem processes that govern mapped entities — LANDFIRE National ultimately depends on a set of core data layers that are consistent and comprehensive across the entire nation. We employed these layers as the raw material to construct other data layers used to create the LANDFIRE mapping products. It was especially important that these core layers represent those fundamental biophysical processes that govern vegetation, fuel, and fire dynamics. In addition, we wanted to incorporate all possible existing national 30-meter scale layers into the LANDFIRE Project to ensure that our GIS library had the latest mapping technology; however, upon researching the availability, extent, and quality of possible core data layers, we found very few that had national coverage and fine-scale resolution (30-meter). The only two sets of nationally consistent data layers that fit LANDFIRE’s needs were the USGS National Elevation Database (ned.usgs.gov/), which served as the LANDFIRE Digital Elevation Model (DEM), and the extensive catalog of Landsat data from the USGS Multi-Resolution Land Characteristics (MRLC) 2001 project (landcover.usgs.gov/index.asp).

Given the lack of comprehensive, nation-wide GIS data layers, we decided to create our own set of base layers, called *the biophysical gradient layers,* because we wanted these layers to be consistent in design, extent, and detail so that we could use them in complex analyses and minimize error resulting from independent and sometimes incompatible sources. Creating our own layers also allowed us the opportunity to build a GIS library of consistent data layers describing those fundamental processes that govern vegetation, fuel, and fire dynamics. The LANDFIRE Prototype’s *core* layers were data we obtained from elsewhere and the *base* layers were those we built to describe basic ecosystem processes.

The biophysical gradient layers were developed using a *process-based approach* that emphasized the creation of layers describing the fundamental biophysical drivers influencing the vegetation, fuel, and fire characteristics that we were to map. Having previously used this approach to map vegetation and fuel characteristics on the Kootenai National Forest, we found that it increased map accuracies from 10 to 30 percent (Keane and others 2002a; Rollins and others 2004). In this approach, we used spatially explicit biophysical gradients to augment the mapping of vegetation and fuel composition and structure. Incorporating these gradients in our mapping process allowed for increased discrimination between mapped categories because the gradients represent the causal mechanisms that physically determine the distribution of vegetation and fuel across landscapes. For example, average annual soil water availability is often a better indicator of growing conditions than average annual precipitation, especially for fine-scale applications.

Several databases were needed to build this biophysical gradient base layer library. First, we needed the DEM (ned.usgs.gov/) to represent topography across the nation. Next, we needed a daily weather database for the entire nation with a temporally deep record. The DAYMET national weather database (www.daymet.org) was selected because of its national coverage at 1-km^2 resolution and 18-year daily resolution weather record (Running and Thornton 1996; Thornton and others 1997; Thornton and White 1996). The STATSGO layer was used to represent soil because of its national scope; however, because it was developed at very coarse scales, we performed several procedures to compile the layers for LANDFIRE analyses (Holsinger and others, Ch. 11). Lastly, we needed a set of simulation models that could take the DEM, DAYMET weather data, and STATSGO information and produce mechanistic maps that best discriminate vegetation dynamics. We used the LANDFIRE Biogeochemical Cycles (LFBGC) model (Thornton and others 2002; Thornton and White 1996; White and others 2000) to simulate ecosystem processes, the WXFIRE model to simulate weather and climatic processes (Keane and Holsinger 2006), and a landscape succession model called LANDSUMv4 to generate historical chronosequences (Keane and others 2006*;* Pratt and others, Ch.10; Keane and others 2002b). We found no other existing layers that met our design criteria and development guidelines.

The primary development tool should be simulation modeling — The use of simulation modeling as the primary development tool was an important guiding principle in LANDFIRE because it was used to create the biophysical layers, as previously discussed, and also to quantify historical landscape conditions. Simulation modeling provides a comprehensive and consistent method to create fine-scale data layers across large domains such as the conterminous U.S. The LFBGC and WXFIRE models were used to map basic ecosystem processes. In addition, we used a spatial model that simulates fire and vegetation dynamics to generate chronosequences of historical landscape conditions. The LANDSUMv4 model, recreates historical landscapes using fire and succession parameters quantified from the LFRDB (Keane and others 2002b; Keane and others 2006; Pratt and others, Ch. 10).

The timespan for historical reference conditions would be 1600 AD to 1900 AD — Determining the benchmark years within which to frame the historical reference conditions posed a special challenge. The calculation of FRCC requires that current conditions be compared with historical reference conditions, yet these historical conditions differ according to the time span used to demarcate the historical temporal reference. The reference time span needed to be long enough to contain ample variation in fire and vegetation dynamics but short enough to ensure that the span is fully documented with field data and historical observations. We determined recent history to be a better reference for current conditions because climate, soil, and vegetation distributions are roughly similar and because recent history is the only era that contains field data of the resolution useful in LANDFIRE. We selected the year 1900 A.D. as the end of the historical period because it best represents the start of significant Euro-American influences on western U.S. landscape characteristics (Keane and others 2002c). The year 1900 marks the approximate start of the industrial revolution, the settlement of the West, the fire exclusion era, and active land management (Baron 2002). We used the findings of fire history studies to guide our determination of the start of the historical period, and we found most studies had recorded fires dating back to at least 1600 A.D., although some went back much further (Heyerdahl and others 1995; www.ngdc.noaa.gov/paleo/impd). This date of 1600 seemed the best compromise for all ecosystems and fire history findings. We concluded that this span of years best represented the historical reference conditions for use in managing today's landscapes. The historical reference years may need to be revisited when mapping the eastern portion of the U.S.

LANDFIRE Prototype Design ______

General Description

This chapter summarizes the scientific foundation underlying all phases of the LANDFIRE Prototype Project, and other chapters in this report detail each individual phase. A complete description of the procedures for creating the entire suite of LANDFIRE Prototype products is given in Rollins and others, Ch. 2. This chapter focuses on the *concepts* that were used to create the LANDFIRE products, rather than detail actual methods or processes.

The general flow of logic, product development, and analysis for the LANDFIRE Prototype can be followed in figure 1, and it illustrates the organization of the content in the following sections. In short, the computation of FRCC requires a comparison of current conditions to historical conditions. In the LANDFIRE Prototype Project, current conditions are described using maps of vegetation composition (cover types) and structure (structural stages) derived from a supervised classification of Landsat imagery and using continuous maps of biophysical gradients and Landsat imagery (fig. 1; Zhu and others, Ch. 8; Holsinger and others, Ch. 11). Vegetation composition and structure were described using cover type and structural stage classifications developed specifically for LANDFIRE. The biophysical gradient layers were created from two ecosystem simulation models that compute variables describing fundamental physical processes that govern vegetation dynamics (Holsinger and others, Ch. 5). These models used the DAYMET national weather database that, as mentioned above, has a 1-km^2 spatial resolution and daily temporal resolution spanning 18 years. Biophysical gradient layers created from these models were also used to construct a data layer describing potential vegetation types (PVTs) that was then used to aid in vegetation mapping and also used as an input layer for simulating historical reference conditions.

Historical reference conditions were simulated using LANDSUMv4, a spatially explicit landscape fire succession model that simulates vegetation development using deterministic succession pathways by potential vegetation type (PVT; described below) and simulates fire using a pixel-to-pixel cell percolation or spread approach (Keane and others 2001; Pratt and others, Ch. 10). This simulated, spatially explicit cover type/structural stage time series was compared with imagery-derived cover type/structural stage data layers describing current conditions using a GIS program that computes departure and ultimately FRCC (fig. 1) (Holsinger and others, Ch. 11). We also created a statistical program called the Historical Range and Variation Statistical Analysis Program (HRVStat; Steele and others, in preparation) that computes another index of departure with a corresponding measure of statistical significance. This departure index can be collapsed into the three classes to define FRCC.

Several secondary data layers – considered secondary because they were not used to compute the primary LANDFIRE product of FRCC – were developed using the intermediate layers created during this FRCC mapping process to aid fire management in planning and implementing ecosystem restoration and designing fuel treatments. We developed a new set of surface fire behavior fuel models specifically for LANDFIRE to distinguish subtle differences in fuelbeds resulting from fuel treatments (Scott and Burgan 2005). These represented a significant improvement over the original thirteen fire behavior fuel models of Anderson's (1982). Maps of these fuel models were created from the cover type, structural stage, and PVT maps (Keane and others, Ch. 12). The canopy fuel characteristics of bulk density and canopy base height were mapped using statistical landscape modeling (specifically, regression trees) using the biophysical layers, whereas canopy height and canopy closure maps were created using Landsat imagery (Quinlan 1993; Zhu and others, Ch. 8; Keane and others, Ch. 12). We also mapped fuel models representing actual estimations of loading (live and dead biomass per unit area) by fuel category for fire effects simulations using complex statistical modeling using the biophysical layers. Two classifications of fire effects fuel models were used: the Fuel Characterization Class System (FCCS; Cushon and others 2003; Sandberg and others 2001) and the Fuel Loading Models (FLMs) created by Lutes and others (in preparation). The FLMs were not yet developed at the conclusion of the prototype mapping effort but will be available for the national LANDFIRE implementation.

Creating the LANDFIRE Reference Database

As previously mentioned, we based all products in the LANDFIRE Prototype on an extensive, plot-level database called the LANDFIRE reference database (LFRDB) (fig. 1) (Caratti, Ch. 4). This ensured that each data layer could be recreated and revised, an especially important feature when additional data become available in the future. This data compilation process provided a source for accuracy assessment, and the reference plot data could be used to scale LANDFIRE products to finer scales by facilitating the development of additional, more detailed classifications of cover types, structural stages, and fuel models. Every product generated by LANDFIRE was developed from this legacy field data collected by diverse resource professionals and screened for quality and consistency.

The creation of the LFRDB was the most expensive task in LANDFIRE, but once created, the database became the foundation of nearly every task in the prototype effort. We used the database for many purposes, including:

- developing training sites for imagery classification;

- parameterizing, validating, and testing simulation models;
- developing vegetation classifications;
- creating empirical models;
- determining data layer attributes;
- describing mapped categories; and
- assessing accuracy of maps, models, and classifications.

The LANDFIRE reference database was actually composed of data from two separate sources: Forest Inventory and Analysis (FIA) and legacy ecological data. Through its Forest Service programs, the FIA has been collecting valuable tree data on fixed and variable radius plots for several decades and provided access to these valuable data for LANDFIRE tasks. The legacy data source was created by locating all possible georeferenced ecological data collected for any purpose and by any organization and then reformatting the data into LANDFIRE database structure (Caratti, Ch. 4).

Mapping Current Vegetation Composition and Structure

The creation of a national 30-m map of existing vegetation composition and structure presented substantial challenges. We quickly recognized that there were neither enough expertise nor computer resources to create these maps at MFSL. The EROS team had been collaborating with scientists at MFSL since 1980, researching fire-oriented remote sensing such as the development of national fuel and fire danger digital maps (Burgan 1984; Burgan and others 1998). Because the remote sensing scientists at EROS are internationally renowned, we asked them to collaborate, with the specific task of creating the current vegetation maps. We agreed that the MFSL team would develop all the fire, fuel, and biophysical layers, whereas the EROS team would develop the vegetation maps describing current or existing conditions. These vegetation layers were compared to historical reference conditions to determine FRCC. However, before any area was mapped, historical or current, a comprehensive and consistent vegetation classification was needed to define the map elements that describe vegetation composition and structure.

Developing vegetation classifications — The first and most important step in this collaborative effort was to develop classifications for vegetation composition and structure. In our previous attempts at large, regional classifications (Keane and others 1996a; Keane and others 1996b; Hann and others 1997; Schmidt and others 2002), we found that, for several reasons, it was difficult to use existing vegetation classifications to map vegetation across large areas. The most significant problem lay in the fact that existing classifications rarely match the resolution and detail of the entities that can be mapped using Landsat imagery. For example, some rangeland classifications stratify cover types by sagebrush species, but EROS scientists found it difficult to differentiate between these types using the Landsat imagery. Second, most existing classifications are limited to particular ecosystems or geographic areas. The Society of American Foresters' (SAF) classification of forest types (Eyre 1980) does not include types for rangeland species, for example. Further, most existing national vegetation classifications were developed for description rather than for mapping; the one exception is the National Vegetation Classification System (NVCS) (Anderson and others 1998; Grossman and others 1998); however, we found that this classification was difficult to scale to the detail required by LANDFIRE, and it was difficult to key plots from the LFRDB to the NVCS types.

We decided to create our own vegetation classification process using a top-down approach in which our categories were designed to be:

- *important to management*. The classification categories had to be useful to land management for mid-scale analyses.
- *conducive to modeling*. The categories needed to adequately represent stages of vegetation development to be compatible with our modeling approach.
- *distinguishable from satellite imagery*. The categories needed to represent cover types that can be easily detected with remotely sensed data.
- *identifiable using plot data*. The classification must have a key that will uniquely identify each category from data in the LFRDB (see LANDFIRE guidelines above).

Rather than construct or use a system that classified all vegetation types within the conterminous U.S., we decided to first identify those vegetation types that we could successfully distinguish through satellite imagery and identify in the reference database. We developed classification categories for forests and rangelands based on a blend of many national efforts (Holdridge 1947; Kuchler 1975; Eyre 1980; Loveland and others 1991; Running and others 1994; Shiflet 1994; Bailey 1995; Grossman and others 1998) and synthesized lists of categories within the context of the two prototype mapping zones. We based the vegetation composition on dominant plant cover and called the classification categories *cover* *types*. We then used the cover type categories to name the potential vegetation types (discussed below); therefore, these categories needed to discriminate between successional stages based on relative shade tolerance and ecological amplitude (Long and others, Ch. 9).

We generated a list of cover types for the central Utah prototype area (Zone 16) by conducting a series of informal workshops with ecologists and members of the LANDFIRE team (Long and others, Ch 6). First, we reviewed the national classifications and devised a list of possible categories, keeping in mind our mid-scale objective. We determined that the selected cover types had to meet the minimum area guideline for mid-scale mapping (occupying at least five percent of a mapping zone) as well as meet the above mentioned guideline that "all themes must be identifiable, scalable, mappable, and model-able." We then created a set of keys to identify the cover type of each plot in the LFRDB based on the predominance of plant cover by species. Next, we inspected the plot distribution by cover type and merged or deleted cover types that were represented by less than 50 plots. We also modified the key to reduce the number of plots that were unclassified and misclassified (Caratti and others, Ch. 4). Categories were also eliminated or merged to distribute plots evenly across all classification categories.

We then submitted this preliminary list of cover types and the keyed reference database plots to the EROS team for evaluation. They assessed whether the imagery could successfully distinguish between cover type categories and sent suggestions and a modified list back to MFSL to evaluate whether the suggestions and modified list fit within the modeling framework. This process continued until we mutually agreed upon on a final cover type list for the prototype areas. We then cross-referenced the LANDFIRE vegetation classification with all other national classifications to provide linkages to other mapping efforts (Long and others, Ch. 6). In the end, we were satisfied that the final list represented those types that we could successfully identify, scale, map, and model using the reference database and Landsat imagery.

For the northern Rockies prototype area (Zone 19), we decided to use a bottom-up approach in which we aggregated classes in the NVCS using the classification's inherent hierarchy. We based the final level of aggregation on the above mentioned guideline that "all themes must be identifiable, scalable, mappable, and model-able." We sent this aggregated list to the EROS scientists for their review, and both teams mutually agreed upon a final set of cover types (Long and others, Ch. 6). Both approaches (top-down and bottom-up) have advantages and disadvantages, and the choice for the national effort will depend on the ability of NVCS to meet the needs of the LANDFIRE Project.

The structural stage classification proved easier to develop because it contained far less detail than the cover type classifications (Long and others, Ch. 6). After much discussion with the scientists at EROS, we were convinced that there was little chance of successfully using commonly accepted structural stage classifications because Landsat imagery has difficulty detecting subtle changes in forest strata (see Lavigne 1992, O'Hara and others 1996a, O'Hara and others 1996b, Oliver and Larson 1990, and Pfister 1981 for examples of structural stage classifications). We therefore decided to base our structural stage classification on two structural components that the EROS team had some success in mapping: canopy cover and canopy height. These two attributes are mapped using a statistical modeling approach in which cover and height are regressed against Landsat imagery spectral values and other ancillary data layers (Zhu and others, Ch 8). We constructed a four-category forest structure classification with two categories of height (short and tall) and two categories of cover (low and high), and the thresholds delineating categories were based on cover type (Long and others, Ch. 6). We used a similar approach for shrublands and grasslands. We then constructed mock succession pathways using these structure categories and found that they were consistent with our modeling approach for creating the historical reference time series.

Describing biophysical settings — Many studies have shown that augmenting a satellite imagery classification with a quantitative description of the biophysical environment (temperature, elevation, and precipitation, for example) improves the mapping of ecological characteristics such as vegetation and fuel (Keane and others 2002a; Rollins and others 2004). Moreover, our landscape modeling approach for quantifying historical reference conditions was predicated on the assumption that the landscape is stratified into settings that represent broad environmental categories and that these categories also represent similar succession and disturbance responses, such as plant associations and habitat types. We needed to invent a classification of biophysical settings that would be useful to both the mapping and modeling efforts, and this biophysical classification must also be useful for scaling LANDFIRE products to finer scales for local land management applications. In addition, a biophysical classification was needed for simulation of historical vegetation reference conditions. This classification had to correlate with the potential vegetation types that would eventually inhabit the area in the absence of disturbance because this is the premise for simulating succession in LANDSUMv4. Most importantly, each plot in our LFRDB needed to be keyed to a specific biophysical setting category. This last criterion ultimately guided the biophysical classification.

We wanted the biophysical settings classification to be based on fundamental, process-oriented environmental gradients. Austin and Smith (1989) define these as direct gradients and resource gradients. Direct gradients, such as temperature and humidity, have a direct physiological impact on vegetation, but these gradients are not consumed by vegetation. On the other hand, the energy and matter used or consumed by plants, such as light, water, and nutrients, define resource gradients. Direct and resource gradients are important for mapping vegetation and ecosystem characteristics because they can fundamentally define the potential species' niches. Indirect gradients, such as slope, aspect, and elevation, have no direct physiological influence on plant dynamics, yet we included them in the biophysical mapping effort because they can be proxies for other unknown or immeasurable gradients. Of course, these biophysical gradients needed to be spatially explicit, and this requirement involved identifying and creating a suite of environmental spatial data layers that describe major climate and ecosystem variables, such as temperature and evapotranspiration, that might be useful for mapping and modeling. The layers that represent major biophysical gradients are used for a variety of tasks in LANDFIRE including 1) the creation of the potential vegetation type layer used by the LANDSUMv4 model (Frescino and others, Ch. 7) and in fuel mapping (Keane and others, Ch. 12), 2) the mapping of existing vegetation composition and structure (Zhu and others, Ch. 8), and 3) the statistical mapping of canopy fuel and fuel models (Frescino and others, Ch. 7).

As mentioned above, we found very few existing, nationally consistent data layers that met the LANDFIRE design criteria. The few biophysical data layers that have a national extent often have pixel sizes of 1 km or greater (Hargrove and Luxmore 1998). Finer resolution data were available but highly localized and variable in quality and consistency. It was evident that there were not enough independently developed, 30-meter national gradient databases to create the set of biophysical layers required by LANDFIRE. We then turned to simulation modeling as the primary tool for creating a comprehensive and consistent set of useful biophysical gradient layers.

In the mid 1990s, we created a prototype system called Landscape Ecosystem Inventory System (LEIS) that used data from local weather stations with various input data layers to simulate and summarize a wide variety of climate and ecosystem processes (Keane and others 1997a; Keane and others 2002a; Rollins and others 2004). This system used a collection of software, including the mechanistic ecosystem process model Biome-BGC (Running and Coughlan 1988; Running and Gower 1991; Thornton and White 1996; White and others 2000), to create biophysical layers that were then used to map fuel and vegetation. The addition of biophysical layers to predict ecosystem attributes increased mapping accuracies by over 20 percent. Although the accuracy of the estimates of the actual values of the biophysical variables was sometimes low, the precision was high because relative differences between the variables across landscapes were spatially consistent. This spatial representation of the relative differences was highly important because the biophysical gradients were used as spatial predictors in the mapping process, rather than an accurate portrayal of the actual values of the biophysical variables. However, the LEIS system was built for regional – not national – applications, so we needed to modify several pieces of software to meet LANDFIRE needs.

We redesigned two of the major programs in LEIS to access the 1-km national DAYMET weather database built by Thornton and others (1997) so that the simulated environmental gradient data layers would be nationally consistent and comprehensive. For LANDFIRE purposes, we modified the WXGMRS program in LEIS to create the WXFIRE program and modified the Biome-BGC model to create the LFBGC model (fig. 1). The WXFIRE program scales the DAYMET weather data to 30 meters using physical principles and then summarizes weather into climate descriptors over the 18-year record (for complete documentation, see Keane and Holsinger 2006). It also simulates some ecosystem processes, such as soil water fraction and evapotranspiration, and computes annual summaries. The LFBGC program simulates ecosystem processes to compute carbon, water, and nitrogen fluxes over time, and then outputs summaries of these fluxes for the 18-year DAYMET daily record (Running and Coughlan 1988; Thornton 1998). These two programs (WXFIRE and LF-BGC) provided us with the ability to create consistent and comprehensive spatial data layers for LANDFIRE mapping and modeling tasks, especially regarding the biophysical settings.

We encountered several issues when designing a system for classifying biophysical settings. Our first approach was to stratify landscapes into biophysical units based on simulated weather, climate, and ecosystem process variables (outputs from WXFIRE and LFBGC) using an unsupervised approach (Hargrove and Luxmore 1998; Hessburg and others 1999; Hessburg and others 2000). This stratification involved creating a suite of environmental gradient spatial data layers, such as temperature and evapotranspiration, using the WXFIRE and LF-BGC software. We performed an unsupervised clustering classification on every pixel in the biophysical layers for the prototype mapping zones and mapped the resultant clusters as unique biophysical settings. This approach created a landscape stratified by categories of similar biophysical conditions. That is, this map had the advantage of dividing the landscape into areas that reflect unique climate, soil, and topographic conditions

We found the results from the unsupervised biophysical classification somewhat disappointing because we could not find significant correlations between the biophysical clusters and a vegetation-based classification, as required for the LANDSUMv4 succession modeling effort to produce simulated historical conditions. We found the connection between the unsupervised clusters of similar environmental conditions and the vegetation that these biophysical characteristics support was either missing or highly variable when we correlated with the field data from the reference database to potential vegetation classification categories (for example, contingency statistics between biophysical clusters and LANDFIRE potential vegetation type classifications were low and variable). These results were frustrating as we had planned to use the unsupervised biophysical settings layer to scale the LANDFIRE vegetation maps and models to local applications. For example, a new, more detailed potential vegetation type map could be created from the biophysical setting clusters by reassigning the plots in the LFRDB a new potential vegetation type category using a more complex and detailed key. These results caused us to switch from an unsupervised to a supervised approach for mapping biophysical settings.

The supervised approach required that we develop complex statistical models directly from the field data and then implement these models in space using the simulated environmental gradient layers (Fresino and Rollins, Ch. 7). The plot data in the LFRDB had to be keyed to a biophysical classification that is useful for both the LANDFIRE mapping and modeling efforts. We reviewed a number of biophysical classifications, such as terrain models, habitat types, plant associations, and fire groups, but found few existing classifications that had complete coverage across the conterminous U.S. (Pfister 1980; Pfister 1989). Moreover, very few of the plots in the LFRDB could be keyed to existing biophysical categories, which would facilitate national implementation. The biophysical settings classification needed to be keyed from consistently collected plot data attributes to satisfy the design criteria that LANDFIRE be based on the best available science, be repeatable, and be objective.

Creating the potential vegetation type classification — We decided to develop our own biophysical classification based on the potential vegetation approach used in habitat type classifications (Pfister 1989; Pfister and Arno 1980; Pfister and others 1977) and other site classifications based on climax vegetation (Daubenmire 1962, 1966; Ferguson and others 1989). In concept, the PVT approach assumes that the climax vegetation that would eventually develop on a stand in the absence of disturbance and this climax community can be used to uniquely identify environmental conditions and can therefore provide the foundation for a biophysical classification. This approach has a long history in vegetation mapping, and potential vegetation type classifications have been developed for most of the forests of the western U.S. (Ferguson and others 1989; Pfister 1981; Pfister and Arno 1980). The approach has had limited success in non-forested environments because extensive disturbance histories in rangelands has eliminated many climax indicator species; yet overall, this approach was fitting for LANDFIRE because it provided a vegetation-based classification of potential plant communities needed for simulation modeling.

We modified this approach extensively to match the scale and limitations of the LFRDB and mapping efforts. First, we assumed that the potential vegetation for forested ecosystems could be keyed from plot data based on the shade tolerance of tree species according to the hypothesis that the tree species with the highest shade tolerance will, without disturbance, eventually become dominant on a given plot. Following Daubenmire's theory (1966), the tree species with the highest shade tolerance will have a high fidelity to unique biophysical settings. The *potential natural vegetation* (PNV) approach to classifying vegetation integrates disturbance into succession dynamics as classification criteria and, as such, was not useful for the LANDFIRE effort because it was incompatible with the LANDSUMv4 modeling structure. We made no inference that the shade-tolerant species will become the climax species since the term climax has many limitations and is often misconstrued. Climax is often associated with plant communities rather than species, and many ecologists have noted that climax vegetation is an unrealistic endpoint since climate, genetics, and exotic migrations, among other factors, are in constant flux and thus making a stable climax community impossible (Hironaka 1987; Huschle and Hironaka 1980). For this reason, we do not assume that the shade-tolerant species will become climax; rather, we believe that the most shade-tolerant species is an indicator of distinctive environmental conditions.

For lack of a better term, we named our biophysical classification after PVTs, assuming that these shade-tolerant species best indicate potential vegetation under the current climate regime, not an ultimate climax community (fig. 1). This PVT approach facilitates the mapping of unique biophysical settings and also allows these settings to be directly linked to the succession pathways that we use in our simulation modeling to determine historical reference conditions. A common misconception is that the PVT classification is a vegetation classification; however, the PVT classification is a biophysical classification that uses plant species' names as category names because the most shade-tolerant species are indicators of site conditions. This classification was useful because, in the LANDSUMv4 succession pathway protocols, the PVT classification categories had to match the existing cover type classification categories. For example, the Douglas-fir cover type category is keyed based on the dominance of Douglas-fir (Caratti, Ch. 4), but the Douglas-fir PVT is keyed from the presence of Douglas-fir on the plot. This is somewhat confusing for the user but is absolutely critical for LANDFIRE integration.

Each forested plot in the reference database was assigned a PVT based on the coverage or tree density data collected for that plot. We sorted all tree species present on a plot by shade tolerance using information in the literature (Burns and Honkala 1990; Fowells 1965; Minore 1979). We then identified the most shade-tolerant species on the plot that exceeded a designated abundance threshold (Caratti, Ch. 4) and matched this species with the associated cover type category used in the mapping of existing vegetation (Long and others, Ch. 6). For example, a plot having 50 percent canopy cover of ponderosa pine and 5 percent cover of Douglas-fir would have an existing cover type category of ponderosa pine but a PVT category of Douglas-fir. The matching of PVT and existing vegetation legends ensured logical combinations between maps and a consistent linkage for the development of the LANDSUMv4 modeling pathways used in simulating historical reference conditions.

As mentioned above, the rangeland ecosystems presented a special problem in the PVT determination since late successional species are rarely observed because of high frequency of disturbance such as grazing and fire (Bunting 1994; Sieg 1997; Westoby 1980). We therefore arranged the rangeland cover type categories along a moisture gradient from xeric to mesic communities, and this arrangement was used as the key criterion for classifying plots in the reference database (Long and others, Ch. 6). Presence, rather than dominance, however, was used to determine the rangeland PVTs in the key. There were some inconsistencies in this approach, so we used dominant species autecological characteristics to further refine the rangeland types (Long and others, Ch. 6). Although this approach had a number of additional flaws, most importantly the inability to consistently model successional development, it proved to be the best considering the limited resources and data available.

The mapping of PVT was performed by mapping zone, so it was important to ensure that PVTs were mapped consistently across zones (fig. 1). We did this by conducting a study that generated the set of WX-FIRE and LF-BGC simulated biophysical variables for 14 million 1-km pixels across the conterminous U.S. These pixel values were then used in complex clustering algorithms to create a national set of biophysical settings using a supervised approach (Hargrove and Luxmore 1998; Hessburg and others 1998). The resulting cluster map was used to guide the mapping of PVTs using the assumption that similar clusters across mapping zones should identify similar PVTs. This coarse-scale biophysical settings map was not finished by the end of the LANDFIRE Prototype but will be available for national LANDFIRE implementation.

Mapping existing cover type and structural stage with satellite imagery — Using all the classifications, digital map layers, and tools detailed above, we were able to map current vegetation conditions using the cover type and structural stage vegetation classifications. This complex task was performed by the EROS team using Landsat imagery (Zhu and others, Ch. 8; fig. 1). The team used the set of simulated biophysical data layers as covariates in the mapping process and also used landscape metrics and the PVT layer to guide cover type and structural stage mapping. Another aid that the EROS team found very useful was a summary from the LFRDB containing the distribution of plots across all cover type and structural stage categories, which was used to guide the selection of vegetation classes that were difficult to distinguish.

For the two prototype mapping zones, Landsat images were acquired on three different dates over the time period between 1999 and 2001 to capture several annual growth phases, such as growing season and dormant season, to maximize the ability to distinguish cover types. All images were corrected for terrain using NED, and the raw satellite digital numbers were converted to at-satellite reflectance for the six Landsat bands (Markham and Barker 1986). We used at-satellite reflectance-based coefficients to calculate values for tasseled-cap brightness, greenness, and wetness, which have been found useful for vegetation characterization

In the LANDFIRE Prototype Project, we created maps of cover types using a training database developed from the LFRDB, satellite imagery from Landsat, the biophysical gradient layers, the PVT map (for limiting the types of vegetation that may exist in any area) and classification and regression tree (CART; Breiman and others 1984; Quinlan 1993) algorithms similar to those used to map PVT. We selected CART-based classification methods for the following reasons. First, as a non-parametric alternative for regression, CART is more appropriate for broad-scale mapping than parametric methods (such as maximum likelihood estimation or discriminant analysis). Second, CART-based models may be trained hundreds of times faster than some other non-parametric classifiers like neural networks or support vector machines. Yet, CART is comparable to and performs similarly with regard to accuracy to these methods (Franklin 2003; Rollins and others 2004). Third, the CART framework explicitly represents logics and rules that may be interpreted in and incorporated into expert systems for further analysis. Neural networks and support vector machines work like "black boxes," with classification logics difficult to interpret or simply "invisible". Lastly, CART has been successfully used recently for modeling and mapping vegetation at broad scales, including the MRLC 2001 project (Zhu and others, Ch. 8).

The EROS team mapped cover types using a hierarchical set of classification models, with the first model separating broader land cover types (such as life form) and subsequent models separating more detailed levels of the vegetation classification. The LFRDB, biophysical settings layers, and other ancillary data layers were incorporated to guide the classification.

Regression trees in a CART framework and applied through a custom See5/ERDAS IMAGINE interface (ERDAS 2004; Quinlan 1993; Rulequest 1997) were used to map canopy closure and canopy height using spectral information from Landsat imagery and the 38 biophysical gradient layers. Again, a training database was developed using the LFRDB. The resultant maps represented canopy closure and canopy height continuously across each prototype mapping zone. When compared to standard, parametric linear regression, regression trees developed using CART have the advantage of being able to approximate complex nonlinear relationships (Quinlan 1993). The final structural stage layer was developed by assigning structural stage classes to combinations of PVT, cover type, and the continuous canopy closure and height class layers. Structural stage assignments were based on the classification described above (Long and others, Ch. 6).

A major problem arose when the MFSL scientists received the vegetation maps from EROS. The cover type and structural stage maps did not match the PVT maps for approximately 20 percent of the pixels. For example, there were mesic cover types such as Grand Fir being mapped in xeric PVTs such as Douglas-fir, which is ecologically impossible under our PVT approach and inconsistent with the succession pathways used in the LANDSUMv4 modeling effort. These inconsistencies occurred because the EROS scientists felt confident that their mapping of cover type, based on a set of computed statistics, was correct, whereas they had low confidence in the PVT maps. Finally, both EROS and MFSL members agreed that we should create a map of confidence using indices from zero to one for the mapping of cover type, structural stage, and PVT. These indices were derived from our statistical modeling and analysis results. Any pixel mapped to PVT or cover type with a confidence lower than 0.5 would be changed to the most appropriate category according to a set of rules built from a statistical analysis of LFRDB. This iterative process eventually created a set of consistent vegetation maps useful in LANDSUMv4 modeling and in the ultimate mapping of FRCC.

Many additional layers were developed by the EROS team for specific uses in the LANDFIRE Prototype Project. As mentioned, the cover type, structural stage, and corresponding confidence layers were used to revise the PVT map and used in the computation of FRCC. The scientists at EROS also created maps of canopy height from regression analyses of Lidar data and Landsat imagery, as well as maps of canopy cover from the imagery and reference database information (Zhu and others, 8). These layers were used to map canopy fuel and are described in Keane and others, Ch. 12).

Describing Historical Conditions

The calculation of FRCC requires that current vegetation conditions be compared with the range and variation of conditions that existed during the historical era identified in the LANDFIRE guidelines (1600-1900 A.D.) to calculate a departure statistic (Hann 2004). This historical range and variation (HRV) has several forms. Historical range and variation can refer to ecosystem characteristics such as landscape composition described by the cover type, the structural stage, or the fuel model. It can also refer to landscape structure characteristics such as pattern, patch distribution, and contagion. In the LANDFIRE Prototype, we used only landscape composition as described by the combination of PVT, cover type, and structural stage to describe HRV. Maps of PVT, cover type, and structural stage were used because the combination provided the finest resolution for describing landscape dynamics in LANDFIRE. We did not address any historical variation in landscape pattern or patch dynamics because of time and computer resource limitations.

The only way to quantify HRV over space and time is by developing a sequential set of data layers that spatially describe the vegetation conditions over many points in time. These sequential data layers are referred to as *spatially explicit historical chronosequences*. The challenge in the LANDFIRE Prototype was to find a set of existing maps of historical vegetation conditions that were directly comparable to the maps of current conditions created from Landsat imagery and biophysical gradients as part of the LANDFIRE Prototype. These historical reference layers needed to be consistent and comprehensive across the conterminous U.S. at a 30-meter pixel resolution and created using the same map categories, resolution, and accuracy.

We faced a major dilemna when it came to deciding which source to use for the representation of historical landscape composition. Temporally deep chronosequences that are spatially explicit across the entire nation are rare, and we found no historical spatial data that fit our design specifications. There were many fire history studies and some historical vegetation maps, but many ecosystems and geographic areas of the country were inconsistently sampled or not sampled at all (Heyerdahl and others 1995; Heyerdahl and others 2001). We found no national map sequences of historical vegetation. Most historical maps were highly localized to small geographic areas and limited to one point in time, usually circa 1900. It became clear that previously derived historical time series for the conterminous U.S. were not available for the computation of FRCC.

Using landscape simulation modeling – This deficit left simulation modeling as the only tool for creating a spatial historical record that would be consistent with the other elements of the LANDFIRE Prototype. For the last decade, MSFL scientists have been developing spatially explicit landscape models that simulate fire and vegetation dynamics (Keane 2000; Keane and Finney 2003; Keane and Hann 1998; Keane and Long 1997; Keane and others 1996b; Keane and others 2002b) and therefore have had a great deal of experience with these complex computer programs.

Simulation provides several advantages for quantifying HRV (Keane and Finney 2003; Keane and others 2004a). Simulation models can generate temporally deep chronosequences that are limited only by the amount of computing resources available to run the model. These sequential data layers can be designed to be consistent with the data layers developed for describing current conditions (PVT, cover type, and structural stage), and they can be reported over long intervals so temporal autocorrelation is minimized. Modeling also allows the integration of spatially and temporally limited field data, which are mostly point data, into the simulation framework as parameterization or validation sources for the creation of spatially explicit predictions. For example, data from local fire history studies can be used to quantify fire frequency and severity parameters in the LANDSUMv4 simulation model. Moreover, spatial models can be designed so that disturbance and succession dynamics are consistently modeled across the entire simulation area. These same models can also be used to generate chronosequences for other applications such as climate change research or a national fire management policy.

Simulation models also have their limitations. Most importantly, models are simplifications of reality, and it is easy to oversimplify model design such that the simulation results are meaningless. In addition, simulation models are difficult to test and validate, especially spatially explicit landscape models, because of the scarcity of field data that are appropriate in scale, accuracy, and detail for comparisons with model predictions. Complex simulation models also have difficulty computing accurate predictions because the varied algorithms implemented in models come from disparate sources and resolutions. The real strength of modeling is precision rather than accuracy because prediction errors tend to be the same across large spatial and temporal extents. Because mapping efforts such as LANDFIRE are more concerned with relative differences across large areas, we identified simulation modeling as an appropriate vehicle for generating the HRV spatial data layers.

The LANDSUMv4 model used in the LANDFIRE effort is in a class of models called *landscape fire succession models* (LFSMs) because they spatially simulate the complex processes of fire and vegetation succession across landscapes. We evaluated many LFSMs that were deemed appropriate for LANDFIRE implementation (Keane and others 2004a) and found most of them to be inadequate for various reasons, mainly because of the extensive input data required by most models. In addition, many complex LFSMs are difficult to parameterize and initialize because the suite of data layers required for these tasks are unavailable across the nation. Complex biogeochemical models for fire and vegetation dynamics, such as the Fire-BGC model (Keane and others 1996c), not only require extensive parameterization and initialization but also require vast amounts of computing resources to execute the program. When we identified the data sources available for parameterization and initialization (in essence, the LFRDB and map products) and evaluated the LFSMs in this context, we found that the LANDSUMv4 model best met the needs of the LANDFIRE Prototype (see Keane and others 1996b, Keane and others 1997c, and Keane and others 2002b for details).

LANDSUMv4 is the fourth version of the LANDSUMv4 model and was developed specifically for the LANDFIRE Prototype (Keane and others 2006) (fig. 1). It contains a deterministic simulation of vegetation dynamics in which successional communities are linked along multiple pathways of development that converge in an end-point community. Disturbances, except fire, are stochastically modeled at the stand level from probabilities specified by the user. Fire ignition is computed from fire frequency probabilities specified by PVT, cover type, and structural stage categories in model input files (Keane and others 2001). Fire is then spread across the landscape based on simplistic slope and wind factors. LANDSUMv4 does not mechanistically simulate fire growth because of the lack of fuel inputs, daily weather records, and computing resources. The effects of fires are stochastically simulated based on the fire severity types as specified in the input files. Finally, LANDSUMv4 outputs the historical composition by PVT, cover type, and structural stage for areas called landscape reporting units. We selected the size of the reporting unit to be 900 meters by 900 meters so that it was compatible with the 30-meter pixel size of the base maps and approximated the resolution of the coarse-scale maps produced by Schmidt and others (2002).

A significant LANDFIRE Prototype Project task involved estimating the succession and disturbance parameters needed to execute LANDSUMv4. Previous attempts at parameter quantification used the "Delphi" method in which local and regional experts (ecologists and land managers) collaborated through a series of workshops to build succession pathways and estimate pathway disturbance and development parameters using local knowledge rather than field data (Hann and others 1997). This approach proved productive because most of the experts were familiar with the literature and able to make realistic approximations. However, these workshops were difficult and expensive to stage, and the final results were often inconsistent between succession pathways and were incompatible with LANDFIRE modeling and mapping goals. For these reasons, we employed several vegetation, fire, and landscape ecologists to construct and parameterize the LANDSUMv4 succession pathways so that the entire modeling effort was consistent and comprehensive. Each ecologist constructed and parameterized succession pathways and disturbance parameters for an assigned a set of PVTs (see Keane and others 2006 for details on succession and disturbance parameters). These professionals used information from the literature, the LFRDB, and local area knowledge to perform this task and thoroughly documented their work (Long and others, Ch. 9).

An important end product of the LANDSUMv4 simulations was the creation of a set of four fire regime maps (fig. 1; Keane and others 2003; Keane and others 2004b). The fire frequency map details the number of fires over the entire landscape, whereas the three fire severity maps represent the probabilities of stand-replacing fires, mixed severity fires, and non-lethal surface fires, respectively. These maps provide a useful reference for locating those areas that tend to experience frequent fire so that fuel treatments can be located and scheduled. They also represent an important scaling tool for fire management in that they can be used to plan the frequency and severity of proposed burn treatments.

Calculating FRCC — The computation of FRCC from the comparison current conditions to historical reference conditions presented a unique set of challenges. In the LANDFIRE Prototype Project, we coded the field methods of Hann (2004) into a GIS program that uses the LANDSUMv4 simulated historical chronosequences to determine the range of landscape conditions and then compares this range to current conditions to compute an index of departure from historical conditions (fig. 1). This departure index ranges from zero to 100 in which an index of 100 represents the current landscape as being totally departed from simulated historical conditions. FRCC is then computed by grouping the index into classes (see Holsinger and others, Ch. 11). FRCC was computed for divisions of the LANDFIRE mapping zones called *landscape reporting units*. These

900-meter by 900-meter landscape delineations served as the smallest units for evaluating departure (Holsinger and others, Ch. 11). Hann's (2004) methodology is the only approach officially accepted by FAM for computing FRCC and so, to be consistent with FAM's protocol, the final FRCC map created by the LANDFIRE Prototype Project used these methods. However, because of the many limitations to Hann's approach, we determined that a complete exploration of the computation of departure from historical conditions was warranted to ensure a scientifically credible protocol.

The idea that historical ecological data can be used as a reference to inform land management's decisions regarding today's landscapes is somewhat new and has only recently been put into practice (Hessburg and others 1999; Keane and others 2002b; Landres and others 1999; Reed and others 1998; Swetnam and others 1999). Although the theory is sound and well-founded, its implementation in land management is still in its infancy. There are few standardized methods and protocols for quantitatively comparing historical reference conditions with current conditions and evaluating their differences. Standard parametric statistics are not always appropriate for historical time series since the chronosequences are autocorrelated in time and in space. Also, HRV has to be evaluated across all elements or mapping entities that comprise the landscape; in LANDFIRE, the elements evaluated over time are cover type and structural stage combinations by PVT. These combinations are correlated to each other because a decrease in the area of one combination will result in increases in the areas of other combinations on the simulation landscape. In addition, these combinations are correlated in space because simulated fire spread will tend to burn contagious pixels. It is also difficult to ascertain the thresholds of departure that determine whether human intervention via fuel treatments is warranted. We therefore explored an entirely new, alternative, statistically based method for comparing the simulated historical chronosequences with the imagery derived from existing conditions using indices of departure and a measure of statistical significance. In addition, these new methods could be compared with Hann's (2004) FRCC field method for computing departure so that either or both methods could be improved at a later date.

A set of complex statistical methods for computing departure from historical conditions were developed by Steele and others (in preparation) specifically for the LANDFIRE Project (fig. 1). They created a statistical technique that is sensitive to the autocorrelation of simulated data over time, space, and vegetation categories. This technique computes an index of departure that varies from zero (no departure) to one (most departed). In addition, a measure of statistical significance is computed as a probability value (p-value), also varying from zero to one. Steele and others (in preparation) implemented this statistical technique in the HRVStat program that compares summaries of simulated historical chronosequences with current conditions by reporting unit within the mapping zone and outputs a departure value and a p-value for each landscape unit or strata. By design, Steele and others (in preparation) created this program to work with any historical chronosequence, not only simulated time series, so that local land management offices can replace the simulated data with actual historical observations, if they exist. Moreover, this program can be used for reference sequences other than historical that are more germane to land management, such as climate change chronosequences' effects on exotics.

Another potentially fruitful area of HRV research exists in the determination of the size and shape of the reporting unit used as the context analysis landscape for calculating departure. The most perplexing problem we encountered while developing these protocols was deciding the size of the landscape for evaluation. Simulation results from landscapes that were too small did not adequately capture the full range of conditions within the area, whereas results from landscapes too large were not sensitive to subtle changes in cover type and structural stages, such as those caused by fuel treatments. We decided to use a 900-meter by 900-meter analysis landscape reporting unit because it closely matched the coarse-scale project by Schmidt and others (2002) and could thereby facilitate (limited) comparisons, and it fit well with the 30-meter grid cell resolution of the input layers. We are currently conducting a study to determine the characteristic landscape size appropriate for computing FRCC and departure statistics.

Ancillary LANDFIRE Prototype Products

The previously discussed LANDFIRE biophysical, vegetation, and historical data layers constitute a remarkable set of spatial data sources for describing vegetation characteristics and dynamics across the entire nation. However, the utility of these data layers is seriously limited because there are few applications that use these layers directly as inputs. For example, extensive expertise and funding would be required to create a map of fire hazard across a region from merely the mapped vegetation characteristics. Similarly, whereas the FRCC map may be used as a reference for the distribution of funding and resources to land management agencies and regions, it has little application in terms of designing, implementing, and monitoring fuel treatments. Additional layers and software tools were needed to provide local land management with applications that were consistent with all other LANDFIRE products. We therefore generated a set of fuel data layers and companion analysis models to aid fire managers in the design, implementation and monitoring of fuel treatments for their respective areas. These fuel layers were developed as ancillary products in the LANDFIRE process because they were not central to the computation of FRCC, but these products were critically important as they provided a means by which to use LANDFIRE products to more efficiently plan and design ecological restoration projects and fuel treatments for local applications.

Creating the LANDFIRE Fuel Layers

It was essential that the entire array of fuel characteristics be mapped in the LANDFIRE Prototype Project to ensure that fire hazard analyses be germane to fire management. Both surface and canopy fuel had to be mapped so that they could be used in fire behavior and fire effects predictive models. Since fuel is highly variable and complex, many fire applications use classifications of fuel as inputs instead of using actual fuel loading sampled in the field. Fuel classifications contain fuel classes with representative fuel loading for a set of fuel components, and these fuel classes are often referred to as "fuel models". To complicate matters, most fire behavior simulation models require fuel models that are actually abstract representations of expected fire behavior and therefore cannot be used to simulate fire effects (Anderson 1982). Moreover, existing fire behavior fuel models are quite broad and do not match the resolution needed to detect changes in fuel characteristics after fuel treatments (Anderson 1982). Because our design criteria specified that, with the implementation of the National Fire Plan, the LANDFIRE layers must be able to identify changes in FRCC and fire hazard, we needed to overcome these limitations. We therefore developed a new set of fire behavior fuel models and a new classification of fire effects fuel models to ensure that the fuel layers could be used for local to regional assessments and analyses.

A new set of fire behavior fuel models was created by Scott and Burgan (2005) using funding from – but developed independently of – the LANDFIRE effort. This suite of 40 models represents a significant improvement in detail and resolution over Anderson's original 13 (1982). The new fire behavior fuel models were developed independently of LANDFIRE because we wanted to ensure their use in accepted fire behavior applications such as BEHAVE (Andrews 1986; Andrews and Bevins 1999) and FARSITE (Finney 1998). Each model has a complete description and includes graphs showing fire behavior under different fuel moisture and weather conditions (www.fire.org).

Fire effects fuel models differ from fire behavior fuel models in that they represent real fuel loading by fuel category, not abstract representations of expected fire behavior. This loading information by fuel component is used to calculate important fire effects such as fuel consumption, soil heating, smoke, and tree mortality. Because there were no national classifications of fuel loading at the time of LANDFIRE's inception, we created our own. Our classification of Fuel Loading Models (FLMs) attempts to identify unique fuel loading models from an analysis of the variance of fuel loading by fuel category (Lutes and others, in preparation). Fuel loading categories include four downed woody size classes, live and dead shrub and herbaceous biomass, duff and litter depth, and crown fuel characteristics. Many studies have noted that high variation of fuel loading across temporal and spatial scales often precludes correlations with vegetation characteristics (see Brown and Bevins 1986 and Brown and See 1981). We examined this variance across and between fuel categories to identify clusters of fuel loading that might facilitate fire effects fuel model mapping. We gathered fuel loading data sets from past field efforts across the nation and reformatted them in the LFRDB and then performed complex clustering analyses to identify unique fuel loading clusters or models (Lutes and others, in preparation). Resultant fuel classes matched the mid-scale development framework specified in the project guidelines. The FLM maps were not available for the prototype effort because the FLM classification was not completed; however, the national LANDFIRE effort will map FLMs for use in fire effects models such as FOFEM (Reinhardt and others 1997; Reinhardt and Keane 1998) and CONSUME (Ottmar and others 1993).

Another classification of fuel loading was needed for finer-scale applications because the FLM classification is quite broad and meant for mid-scale analyses. We used the national Fuel Characterization Class (FCC) classification developed by Sandberg and others (2001) and Cushon and others (2003). This classification was developed through sampling fuel extensively in various vegetation, structure, and stand history combinations in forest and rangeland settings across the nation and then assigning the computed fuel loading to the categories within the classifications of vegetation and stand condition called default fuelbeds. We mapped these default fuelbeds from information collected in the intensive sampling effort using the PVT, cover type, and structural stage maps (Long and others, Ch. 6). Using software developed by the FCC effort, land managers can modify fuel loading for their default FCC fuel model to create a more site-specific, locally realistic fuel model for use in fire effects computer models.

Most fire behavior and effects predictive models require a quantification of several canopy characteristics to simulate crown fire initiation and propagation (Albini 1999; Rothermel 1991; van Wagner 1993). These characteristics include canopy bulk density, top height, base height, and closure. Fortunately, the EROS team mapped canopy top height and canopy closure using satellite imagery (Zhu and others, Ch. 8), but canopy bulk density and canopy base height had to be mapped at MFSL by calculating the two canopy attributes from tree inventory information in the reference database using the Fuel Calculation system (FUELCALC) program (Reinhardt and Crookston 2003). This program uses tree measurements of species, height, and diameter to compute the vertical distribution of crown biomass from a set of biomass equations. The program also contains an algorithm that computes the canopy base height from the vertical distribution of crown biomass (Reinhardt and Crookston 2003). These two canopy characteristics are then statistically modeled using complex statistical analyses from variables spatially represented in all LANDFIRE biophysical layers (Keane and others, Ch. 12). The statistical models are then implemented across the mapping zones using the biophysical layers. FUELCALC is still under development but will be released before the LANDFIRE Prototype Project is finished.

Creating analysis tools — Maps of fuel characteristics have limited use until they are linked with an appropriate application. An existing application that can be used directly with LANDFIRE products is the FARSITE fire growth model that simulates the spread of fire as it moves across landscapes (Finney 1998). The sister program to FARSITE, called FLAMMAP, is used for fire hazard analysis and computes fire behavior for every pixel based on user-defined weather scenarios. A drawback to these programs, however, is that FLAMMAP and FARSITE compute fire behavior from weather data with no temporal distribution. For example, crown fires are more important to fire management if they occur frequently due to a dry weather record, as in dense ponderosa pine stands, than if infrequently, as in crown fires of lodgepole pine forests found at high elevations. A tool was needed to analyze fire behavior and fire effects across a landscape over a temporal domain so that fire hazard could be assessed in time and space.

We initiated the development of the FIREHARM program to compute fire hazard across large landscapes over long time periods. This program accepts the fuel map inputs from LANDFIRE and then uses the DAYMET weather database to calculate the probability that a fire event could happen on any given day in the 18-year weather record. A fire event can be defined from fire danger (such as burning index, spread index, and energy release component), fire behavior (such as flame length, spread rate, and fire intensity), and fire effects (such as fuel consumption, soil heating, and tree mortality) variables. For example, a user might define a fire event as those days when fuel consumption is greater than 50 percent. The resultant maps of fire event probability can be used to target treatment locations, or they can be used with other layers to perform other estimations of fire hazard. The FIREHARM model is still in development and will be released sometime after LANDFIRE Prototype Project completion.

A last application that is still in development is the LANDFIRE decision support tool that uses LANDFIRE data layers as inputs to an expert system that uses fuzzy logic and decision uncertainty to prioritize the selection of areas for fuel treatment and restoration activities, depending on management objectives (Reynolds and Hessburg 2005).

Discussion

Despite our best efforts, some elements of subjectivity crept into LANDFIRE methods, and perhaps the task infused with the highest bias was the development of the vegetation map classification. It was difficult to avoid subjectivity in creating a comprehensive list of cover types that matched the sensitivity of the Landsat imagery and simulation models because of the wide variety of cover type classifications and vegetation communities possible for each individual mapping zone and the inherent variability of vegetation across the mapping landscape. One possible solution would be to use an existing cover type classification for the entire U.S. so that bias is minimized and the list of cover types remains constant across mapping zones. Yet this option poses problems. Often, the composition of a cover type can change across large regions, making it difficult to develop one classification key that fits all areas. Perhaps the best method would be to use an existing classification, determine the list of cover types to map according to each mapping zone, and then vary the keys to these cover types to reflect the subtle differences across zones.

The LANDFIRE task of assigning the new fire behavior fuel models to combinations of cover type, structural stage, and PVT also contained some subjectivity (Keane and others, Ch. 12). This was primarily the result of the lack of a comprehensive and consistent key, which precluded our ability to assign a fuel model to each plot in the LFRDB. In addition, since the fire behavior fuel model classification had been recently created, none of the plots in the reference database contained information about the new fuel models. Furthermore, the new fuel models could not be assigned to any plots in the reference database because of a lack of consistent key criteria. Without a link to field data, we had to assign a fuel model to each PVT-cover type-structural stage combination based on the best estimate by the authors of the fuel model classification (Scott and Burgan 2005) and by specialists on the LANDFIRE team (Keane and others, Ch. 12). Future efforts should attempt to derive a key that objectively assigns fuel models based on the data collected in the field or present in the reference database.

LANDFIRE products can be scaled to local applications using a variety of approaches. The biophysical layers can be used in concert with the field-referenced data to refine local vegetation maps and with the PVT maps to reflect environmental conditions. For example, precipitation can be used to create two Ponderosa Pine cover types, one including larch and one without larch, or elevation could be used to separate a LANDFIRE Sagebrush cover type into Mountain Sage and Black Sage LANDFIRE cover types. LANDFIRE fuel assignments to combinations of PVT, cover type, and structural stage can be linked to local digital maps of vegetation and biophysical settings to create a fine-scale fuel layer. In addition, local maps of vegetation conditions, such as basal area and tree density, can be augmented with the suite of LANDFIRE maps to improve fuel model assignments.

In addition to a host of other land management applications, LANDFIRE products can also be used to help prioritize, plan, and implement fuel treatments. Maps of vegetation and fuel can be used as inputs to a number of existing fine-scale computer models, such as SIMMPPLE (Chew 1997) or FVS-FFE (Reinhardt and Crookston 2003), to evaluate alternative fuel treatments and their effects on project landscapes. In addition, scenarios can be developed for the LANDSUMv4 model to simulate the effects of alternative management strategies. The FIREHARM program can use the LANDFIRE maps and DAYMET database to create data layers that show the probability of fire events, such as a crown fire or lethal soil heating, across small analysis landscapes. The set of LANDFIRE fuel layers can be used in FARSITE and FLAMMAP to simulate fire growth or predict fire hazard for local landscapes. Furthermore, fire regime maps can be used to prioritize, plan, locate, and schedule ecological landscape restoration and fuel treatments across small landscapes by identifying those areas that burn frequently and therefore needing treatment more urgently.

Conclusion

The LANDFIRE Prototype Project has created a process for mapping fire, fuel, and vegetation conditions across the entire United States by integrating satellite imagery, statistical analyses, and simulation modeling using scientifically credible methods. This process is currently being implemented through the national LANDFIRE effort with the complete set of LANDFIRE products scheduled to be delivered by 2008. The methods, procedures, and protocols implemented within this process ensure consistency across all regions, ecosystems, and land types and allow for future replications of the process to monitor the efficacy of the National Fire Plan and Healthy Forest Restoration Act. The LANDFIRE products can be scaled from local applications to national assessments and will facilitate detailed fuel and fire hazard analyses.

For further project information, please visit the LANDFIRE website at www.landfire.gov

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Chapter
4

The LANDFIRE Prototype Project Reference Database

John F. Caratti

Introduction

This chapter describes the data compilation process for the Landscape Fire and Resource Management Planning Tools Prototype Project (LANDFIRE Prototype Project) reference database (LFRDB) and explains the reference data applications for LANDFIRE Prototype maps and models. The reference database formed the foundation for all LANDFIRE tasks. All products generated by the LANDFIRE Prototype Project were developed from field-referenced data collected by resource professionals and screened for quality and consistency by the LFRDB team (Keane and Rollins, Chapter 3), ensuring that each LANDFIRE data layer could be recreated and improved upon with the availability of new data. Field-referenced data provided a means of assessing the accuracy of many LANDFIRE Prototype products. The LFRDB integrated field-referenced data collected for many separate projects that used different sampling methods and had varying sampling intensities. See appendix 2-A in Rollins and others, Ch. 2 for a table outlining, in part, the procedure used to build the LFRDB.

Field-referenced data play a critical role in any mapping project involving remotely sensed data (Congalton and Biging 1992). Field-referenced data are used to generate, test, and validate maps and models. Field-referenced data provide important field-referenced information that accurately describes that which is being remotely sensed or mapped, and field-referenced data points function as training sites in satellite imagery classifications (Jensen 1998; Verbyla 1995). In the LANDFIRE Prototype Project, we used field-referenced data coupled with Landsat imagery to model and map cover types (CT), canopy closure, and height (Zhu and others, Ch. 8). Field-referenced data were also used to model and map biophysical settings and wildland fuel (Frescino and Rollins, Ch. 7; Keane and others, Ch. 12).

In addition, field-referenced data serve another important purpose in the development of vegetation and fuel classifications. The distribution and occurrence frequency of cover types across landscapes – both summarized in the LFRDB – were used in the LANDFIRE Prototype Project to refine the CT classification (Long and others, Ch. 6). The PVT classification was also refined based upon field-referenced data and the relationship between vegetation occurrence and biophysical settings (Long and others, Ch. 6). Furthermore, reference data were used to develop database tables relating PVT, CT, and SS to attributes relevant to wildland fire management, such as fire behavior fuel models, fire effects fuel models, and canopy fuel characteristics (Keane and others, Ch. 12). Reference data were also integral in the development of succession pathway models (Long and others, Ch. 9), which ultimately served as the foundation for creating maps of simulated historical fire regimes and fire regime condition class (Pratt and others, Ch. 10; Holsinger and others, Ch. 11).

Finally, field-referenced data aid in both the quantitative and qualitative interpretation of maps and mapping classifications and in identifying and explaining the associated inaccuracies or inconsistencies. A common way to assess

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the accuracy of classified images and maps is to employ the reference data as a measure by which to assess the amount of the area that was classified correctly (Story and Congalton 1986). Reference data provided three measures of accuracy for most LANDFIRE data layers: 1) locational accuracy (the probability of a pixel being mapped correctly), 2) landscape accuracy (the accuracy of pixel summaries across large areas), and 3) model accuracy (the accuracy of statistical models used to build the maps) (Keane and Rollins, Ch. 3; Vogelmann, Ch. 13).

Reference Data Requirements

All field data were georeferenced within reasonable locational accuracy, preferably 30 meters or less. To be useful in the LANDFIRE Prototype, reference data were required to have a minimum set of fields applicable to at least one of the various LANDFIRE mapping tasks. Field-referenced data suitable for the LANDFIRE Prototype could, for example, include species composition data needed to map cover type and structure, have fuel attributes for developing fuel models, or contain tree data needed to map canopy fuel. Table 1 lists some of the variables required for the LFRDB.

A critical element in acquiring LANDFIRE data was obtaining these from field plots that were sufficiently representative of all land ownerships and ecosystems. We acquired the data through three separate yet coordinated efforts. First, with cooperation and support from the Forest Inventory and Analysis (FIA) program, we obtained forest vegetation data collected on permanent FIA inventory plots (Gillespie 1999). We selected only FIA plots which occurred within one condition and used all subplot data (Interior West Forest Inventory and Analysis 2004). FIA plot variables used by the LFRDB included tree species, diameter at breast height (DBH), tree height, crown ratio, height to live crown base, and crown class. FIA data were stored in the database without geographic coordinates to preserve the confidentiality of the plot locations (Interior West Forest Inventory and Analysis 2004). Analyses requiring coordinates were conducted by FIA personnel stationed at the Missoula Fire Sciences Laboratory (Missoula, MT).

Table 1—Examples of variables included in the LANDFIRE reference database.

Data type	Attributes
Plot	Georeferenced plot location Sampling date Digital plot photos Metadata
Vegetation	Species list Cover by species Cover by life form (tree, shrub, herb) Height by species Heights of individual trees Crown ratios (individual trees) Crown classes (individual trees) Diameters (individual trees) Tree density
Fuel	Fine (1-, 10-, and 100-hour) Coarse (1000-hour) Cover of live and dead shrubs Cover of live and dead herbs Base height of canopy fuel Height of shrubs Height of herbaceous vegetation

A second data acquisition effort involved the circulation of a formal request letter to federal agencies, soliciting additional reference data from the LANDFIRE Prototype mapping zones. In conjunction, the LFRDB team conducted an exhaustive search for existing field-referenced data relevant to LANDFIRE, relying heavily on cooperation from federal, state, and non-governmental organizations. Due to the diverse nature of field sampling methods and data storage procedures, the reference database team spent much time and effort converting these data into a common database structure.

Third, even after obtaining FIA data and other existing field-referenced data, large areas of the prototype mapping zones were under-represented, particularly those in the shrublands and grasslands. In response, the LFRDB team collaborated with the Southwest Regional Gap Analysis Project (Southwest ReGAP) (Utah State University 2004) to collect additional field-referenced data in under sampled areas of the prototype mapping zones.

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on the procedures followed to compile the LFRDB, which formed the foundation for nearly all modeling and mapping tasks in the LANDFIRE Prototype Project.

Data Acquisition

Zone 16—The three data sources for Zone 16 were FIA, Southwest ReGAP for the state of Utah, and the

Southern Utah Fuels Management Demonstration Project (Southern Utah Project). Utah field-referenced data from Southwest ReGAP included both plant species cover estimates and height measurements for each plot. The Southern Utah Project data included plant species cover estimates, height measurements, downed woody fuel transects, and individual tree measurements for each plot. .FIA data included individual tree measurements for each plot and were acquired from the national FIA Database (Miles and others 2001) and the Interior West FIA program (Interior West Forest Inventory and Analysis 2004).

Once all existing field-referenced data were acquired, we displayed the non-FIA plot locations for Zone 16 to identify obvious gaps in the reference data acquisition. Substantial portions of the central and northern areas of Zone 16 contained little or no reference data (fig. 1A). We contracted with Utah State field crews who, using the Southwest ReGAP field data collection protocols, collected additional field-referenced data in these areas (Utah State University 2004). These efforts helped fill gaps in data coverage, especially in non-forest vegetation types.

Zone 19—We drew from several sources for Zone 19 data acquisition. These data sets included information from the FIA Database; United States Department of Agriculture (USDA) Forest Service Northern Region ecosystem inventory database (ECODATA) (Jensen and others 1993); Bureau of Land Management (BLM) Fuels database from the Salmon and Challis, Idaho field offices (Gollnick-Waid 2001); United States Geological Survey (USGS) ECODATA database from Glacier National Park; and the USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, Missoula, Montana (MFSL) ECODATA database. All ECODATA plot databases included plant species cover estimates and height measurements, downed woody fuel transects, and individual tree measurements for each plot. The BLM Fuels Survey data included information on dominant and codominant plant species by life form, life form cover, fuel loading, and fire hazard.

Once all existing field-referenced data were acquired, we displayed the non-FIA plot locations within Zone 19 to determine deficiencies in the reference data acquisition for non-forested areas. Areas in the southern, eastern, and west-central portions of Zone 19 contained little or

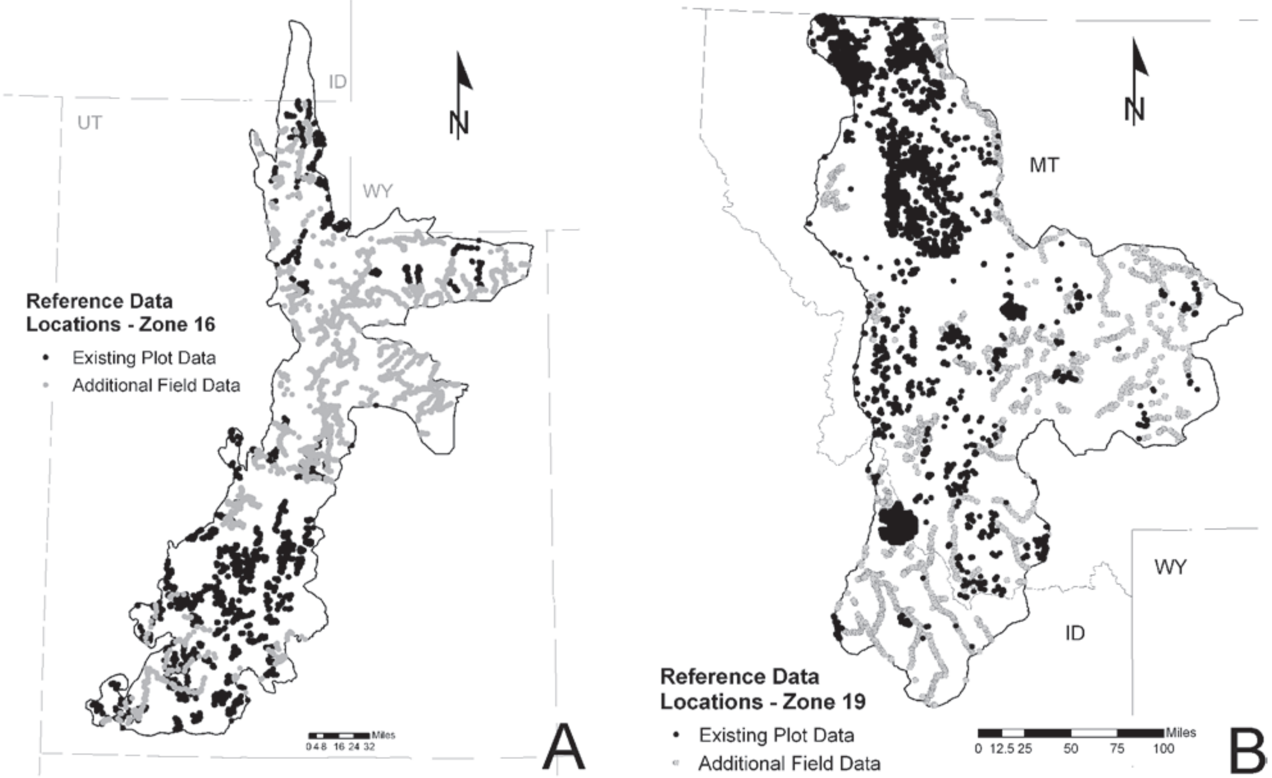


Figure 1—Field plot locations for non-FIA reference data within zones 16 (A) and 19 (B).

no reference data (fig. 1B). Again, we contracted with Utah State University field crews who, using the Southwest ReGAP field data collection protocols, collected additional field-referenced data in these areas (Utah State University 2004). As with Zone 16, these additional plot data filled in the data gaps, especially for non-forest vegetation types.

LANDFIRE Reference Database Structure

The LFRDB was composed of three levels (fig. 2), each containing data processed at the preceding level. Each data set was stored in a separate directory in its original data format (Level 3). Each directory contained the original data, metadata documentation, and any existing data-conversion queries or programs. We designed the data directory structure to follow the Fire Effects Monitoring and Inventory Protocol (FIREMON) plot identifier structure (Lutes and others, 2006; table 2). This enabled us to track summary data in the LANDFIRE attribute tables back to the original data and identify problems in the data-conversion process.

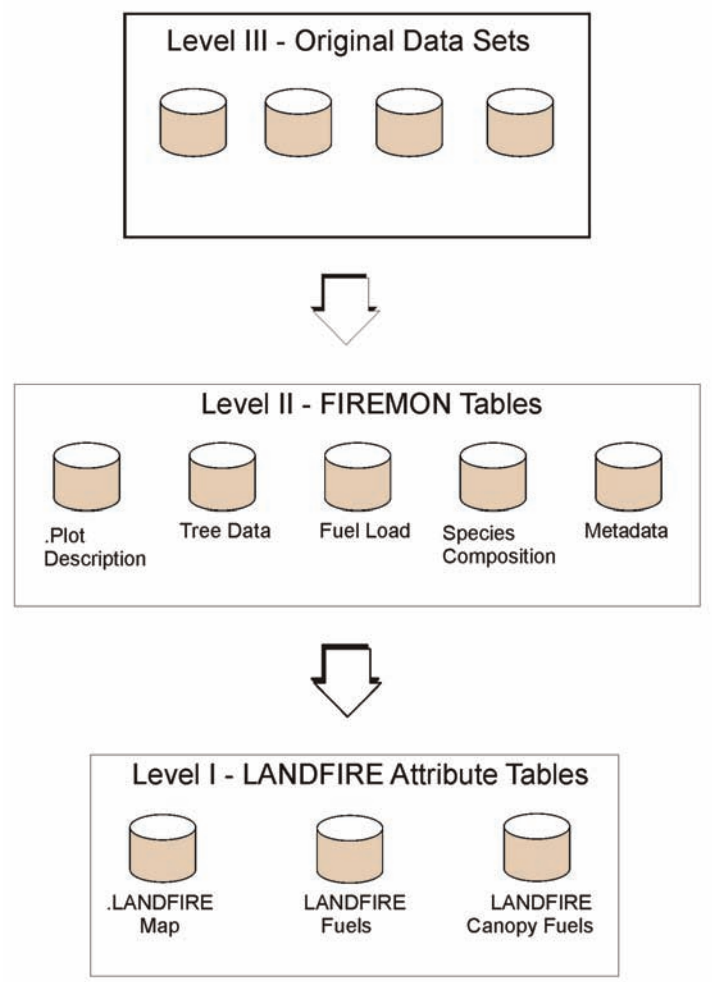


Figure 2—LANDFIRE reference database structure.

Table 2—LANDFIRE reference database data directory structure.

Directory name	Contents
FIREMON Registration ID	Subdirectories of data by major categories (such as agency)
FIREMON Project ID	Original data tables, FIREMON and LANDFIRE attribute tables
Metadata	Data conversion documents and sampling protocol documents

We then developed data-conversion routines for each data set that transformed all Level 3 data into a common database structure (Level 2) using the FIREMON database. FIREMON is a complete fire effects monitoring and inventory package that includes many field sampling methods designed to measure and describe vegetation and fuel. Most FIREMON field sampling methods are well-suited to conducting ecological inventory as well as monitoring fire effects. The FIREMON database contains a suite of tables that store collected plot data using a variety of standard vegetation and fuel sampling protocols. We used the database tables associated with the subset of FIREMON sampling methods relevant to LANDFIRE to store the LANDFIRE reference data (table 3). See appendix 4-A for a complete list of FIREMON tables and field descriptions used in the LFRDB.

We then populated the LANDFIRE attribute tables (Level 1) with data from the FIREMON database using a set of database queries (fig. 2). The LANDFIRE attribute tables were linked to the FIREMON tables and stored plot data and summary data used to develop, test, model, and map many of the LANDFIRE data layers. Level 1 attribute data included the LANDFIRE map table, the LANDFIRE fuel table, and the LANDFIRE canopy fuel table (table 4). We used the LANDFIRE map table data to model and map cover type, potential vegetation type, and structural stage; we used the LANDFIRE fuel table data to model and map fuel; and we used the LANDFIRE canopy fuel table data as input to the FUELCALC program (Keane and others, Ch. 12; Reinhardt and Crookston 2003). FUELCALC uses tree measurements and biomass equations to compute the vertical distribution of canopy biomass and uses an algorithm to calculate canopy base height (Reinhardt and Crookston 2003). FUELCALC output was used to

Table 3—FIREMON sampling methods used in the LANDFIRE reference database.

FIREMON sampling method	Type of data
Plot description (PD)	Geographic coordinates
	Life form canopy cover (tree, shrub, herbaceous)
	Hyperlinked digital plot photos
	Plant species codes (NRCS plants)
Species composition (SC)	Plant species cover
	Plant species height
	Individual tree height
	Individual tree DBH
Tree data (TD)	Individual tree live crown percent
	Individual tree crown class
	1-hr fuel
	10-hr fuel
	100-hr fuel
Fuel load (FL)	1000-hr fuel
	Live/dead shrub cover and height
	Live/dead herbaceous cover and height
Metadata (MD)	Metadata and comments
	Hyperlinked metadata documents

Table 4—LANDFIRE attribute tables.

Attribute table name	Contents
LANDFIRE map	Potential vegetation type, cover type, and structure
LANDFIRE fuel	Fuel loading
LANDFIRE canopy fuel	Canopy bulk density and canopy base height

model and map canopy bulk density and canopy base height. See appendix 4-B for a complete list of LANDFIRE map attribute tables and field descriptions.

Data-Conversion Process

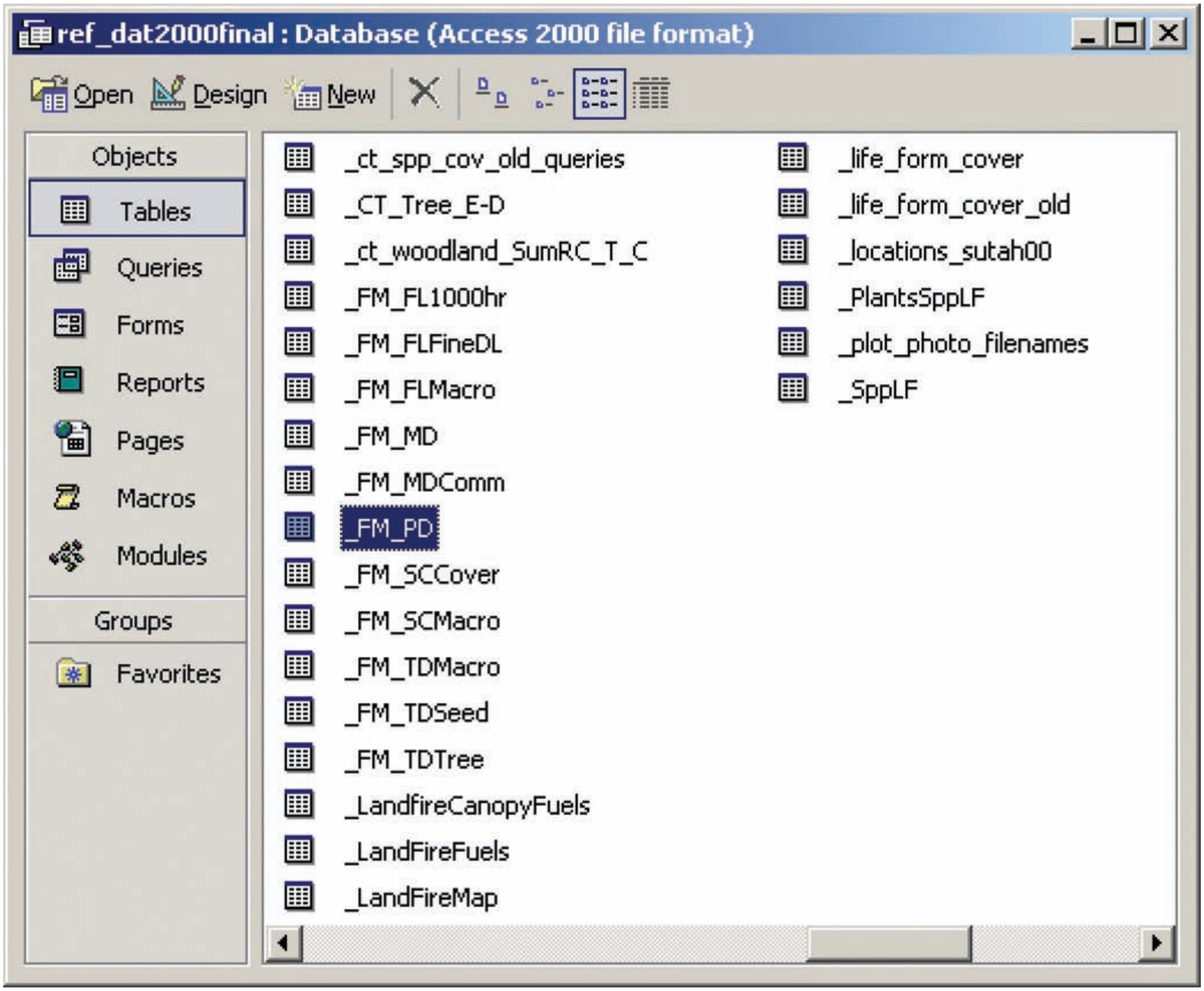
We compiled data collected from many different sampling methods into a common database structure so that vegetation and fuel data could be queried in a consistent manner. We acquired plant species data that had estimates of either relative or absolute cover. Some plant species data contained entire species lists, with cover and height values for each species, whereas other data recorded cover estimates for two to four dominant species by life form. We obtained tree data sampled on variable radius and fixed radius plots. Some tree data contained data only for mature trees, whereas other data included seedling and sapling measurements. All of the surface fuel data we acquired were sampled using variations of the planar intersect method (Brown 1974). Although different sampling protocols were used for each data set, we distilled this information into basic vegetation and fuel data within a common database structure.

The data-conversion process involved converting data from their original format into the formats of the FIREMON database tables and LANDFIRE attribute tables. This process involved four steps: 1) storing the original data sets in the LFRDB Level 3 directory structure; 2) populating a Microsoft Access database containing the original data tables plus the FIREMON and LANDFIRE attribute tables; 3) building a set of crosswalk tables, data format queries, and data append queries to convert the data and populate the FIREMON and LANDFIRE attribute tables; and 4) documenting the data-conversion process and populating the FIREMON metadata tables.

Data directories—We created a directory for each data set to store the original data, any existing documentation and metadata, the FIREMON data-conversion queries and tables, and the populated FIREMON tables. The naming convention for the directories and subdirectories followed the naming convention for the FIREMON plot identification key. The FIREMON plot identification key consists of four fields: Registration ID, Project ID, Plot ID, and Date. The Registration ID and Project ID fields are used to define a directory and subdirectory for each data set. For example, the directory “mfsl” contains all data acquired from the Missoula Fire Sciences Laboratory. The subdirectories “sutah00” and “sutah01” contain field-referenced data collected for the Southern Utah Fuels Demonstration Project during the 2000 and 2001 field seasons.

Original data tables—If the original data were not delivered in an Access database, we opened an empty Access database and imported the data tables, spreadsheets, or ASCII files. We then joined the tables within Access to maintain any relationships that existed between the data in their original format.

We then imported empty FIREMON and LANDFIRE attribute tables into the Access database containing the original data set. All FIREMON tables were prefixed with “_FM_” to distinguish them from the original data tables and to organize them for easier data management (fig. 3). LANDFIRE attribute table names were prefixed with a “_” for the same reasons (fig. 3). Only FIREMON tables compatible with the sampling methods used in the original data set were added to the Access database. The imported tables retained their relationships and maintained the referential integrity of the FIREMON database. This allowed for the identification of errors associated with invalid or duplicate plot keys and allowed for cascading deletions from and updates to the FIREMON and LANDFIRE attribute tables. These tables were then populated via data-conversion queries and subsequently used to error-check the data-conversion



ref_dat2000final : Database (Access 2000 file format)

_ct_spp_cov_old_queries
_CT_Tree_E-D
_ct_woodland_SumRC_T_C
_FM_FL1000hr
_FM_FLFineDL
_FM_FLMacro
_FM_MD
_FM_MDComm
_FM_PD
_FM_SCCover
_FM_SCMacro
_FM_TDMacro
_FM_TDSeed
_FM_TDTree
_LandfireCanopyFuels
_LandFireFuels
_LandFireMap
_life_form_cover
_life_form_cover_old
_locations_sutah00
_PlantsSppLF
_plot_photo_filenames
_SppLF

Figure 3—FIREMON tables within the Access database containing the Southern Utah Project year 2000 field data.

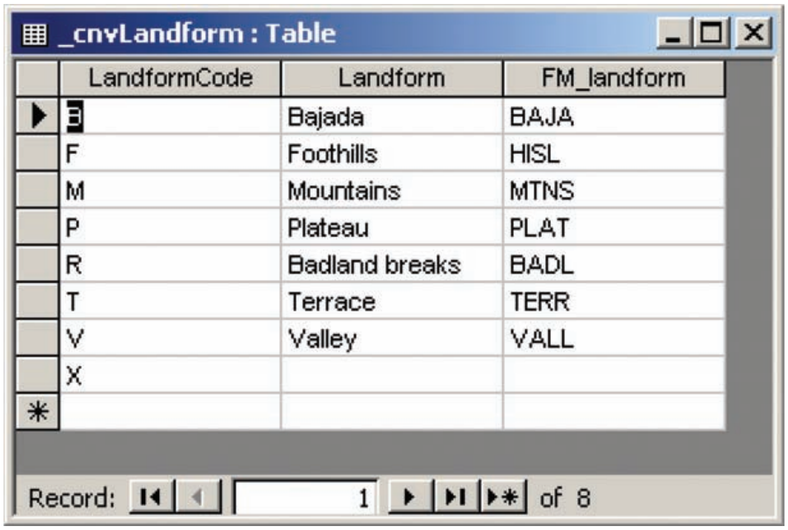
process. If errors were discovered, we emptied the FIREMON and/or LANDFIRE attribute tables, corrected the data-conversion queries, and repopulated the tables. Once the FIREMON and LANDFIRE attribute tables were loaded correctly, the data were added to the main LFRDB containing data from all data sets for that specific mapping zone.

Data-conversion queries—We created crosswalk tables to convert local codes in the original data set to standard FIREMON codes. We generated these tables by querying each applicable field in the original tables for all unique codes, creating a table from the results, and then adding a column for the FIREMON code. We populated FIREMON codes in each data-conversion table through queries or data entry. We then linked these data-conversion tables with database queries to format data for each FIREMON table. All conversion tables were prefixed with "_cnv" for easy identification in the Access database. Figure 4 illustrates a landform data-conversion table that converts the landform codes in the Southern Utah Project year 2000 data to the FIREMON landform codes. The field names containing FIREMON codes were prefixed with "FM" to distinguish these field names from field names in the original data tables (fig. 4).

Next we designed data format queries to format the original data for each FIREMON table. Each data format query was prefixed with "_format" to easily locate and identify these queries in the Access database. All necessary tables from the original data were joined with the appropriate data crosswalk tables so that the query results contained the standard FIREMON codes (fig. 5). Any numerical computations within fields, such as converting units or calculating new values, were incorporated as equations in the data format queries. Each data format query generated the FIREMON plot identifier fields plus any other relevant fields needed to populate the corresponding FIREMON table. The data format query results were then used to populate the corresponding FIREMON table (fig. 6).

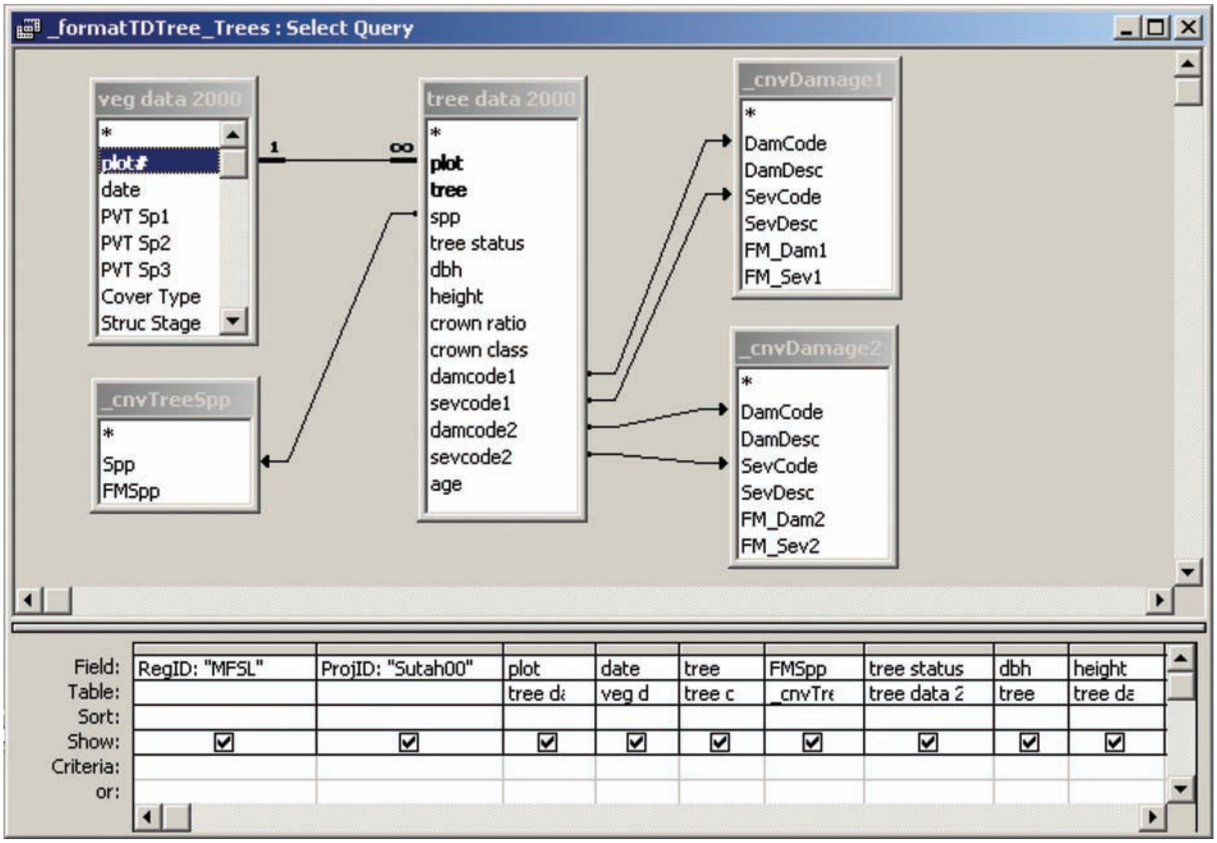
FIREMON and LANDFIRE attribute tables—We developed a set of append queries to add data from the data format queries into the appropriate FIREMON tables. We prefixed these query names with "_insert" to facilitate identification in the Access database. These queries used the Access Structured Query Language (SQL) INSERT INTO statement to append data from the data format query into the corresponding FIREMON table.

Specifically, within each Access database, we designed a form with two command buttons. This form facilitated the deletion and addition of records from and to the FIREMON tables when changes were made to the data format queries and the FIREMON tables had to be updated. One button deleted all of the records in the FIREMON tables and one button added all of the



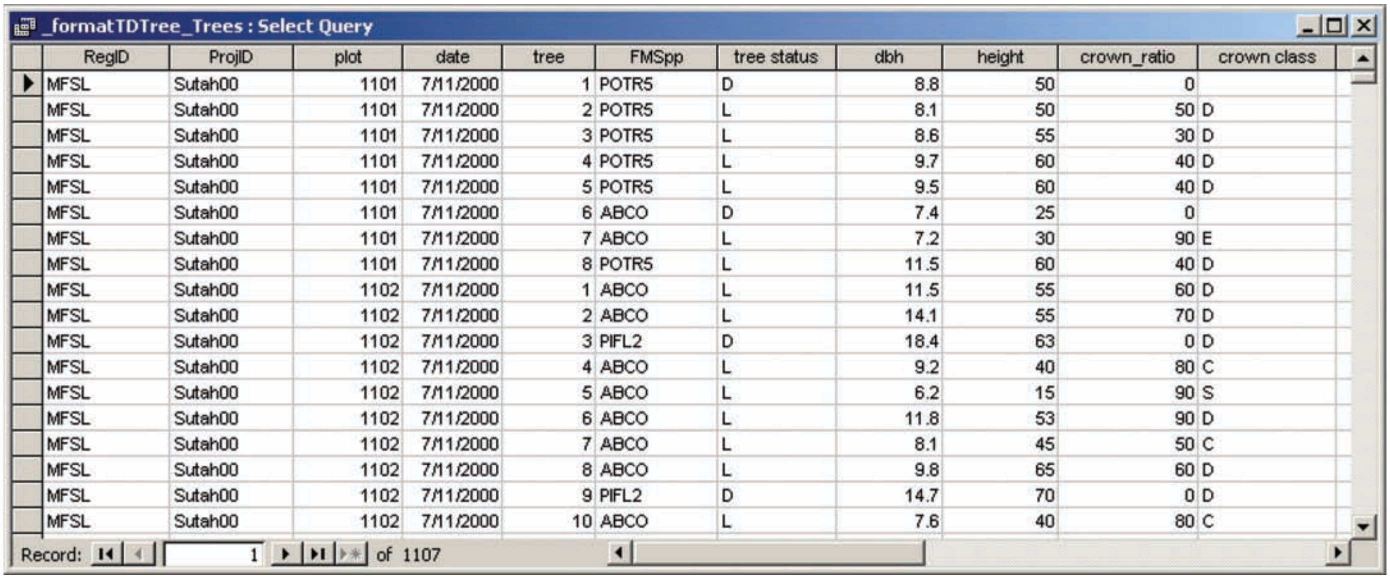
LandformCode	Landform	FM_landform
B	Bajada	BAJA
F	Foothills	HISL
M	Mountains	MTNS
P	Plateau	PLAT
R	Badland breaks	BADL
T	Terrace	TERR
V	Valley	VALL
X		

Figure 4—Data conversion table for landform codes in the Southern Utah Project year 2000 database.



Field:	RegID: "MFSL"	ProjID: "Sutah00"	plot	date	tree	FMSpp	tree status	dbh	height
Table:			tree dı	veg d	tree c	_cnvTre	tree data 2	tree	tree da
Sort:									
Show:	☑	☑	☑	☑	☑	☑	☑	☑	☑
Criteria:									
or:									

Figure 5—Data format query used to populate the FIREMON tree data (TDTree) table in the Southern Utah Project year 2000 database.



RegID	ProjID	plot	date	tree	FMSpp	tree status	dbh	height	crown_ratio	crown class
MFSL	Sutah00	1101	7/11/2000	1	POTR5	D	8.8	50	0	
MFSL	Sutah00	1101	7/11/2000	2	POTR5	L	8.1	50	50	D
MFSL	Sutah00	1101	7/11/2000	3	POTR5	L	8.6	55	30	D
MFSL	Sutah00	1101	7/11/2000	4	POTR5	L	9.7	60	40	D
MFSL	Sutah00	1101	7/11/2000	5	POTR5	L	9.5	60	40	D
MFSL	Sutah00	1101	7/11/2000	6	ABCO	D	7.4	25	0	
MFSL	Sutah00	1101	7/11/2000	7	ABCO	L	7.2	30	90	E
MFSL	Sutah00	1101	7/11/2000	8	POTR5	L	11.5	60	40	D
MFSL	Sutah00	1102	7/11/2000	1	ABCO	L	11.5	55	60	D
MFSL	Sutah00	1102	7/11/2000	2	ABCO	L	14.1	55	70	D
MFSL	Sutah00	1102	7/11/2000	3	PIFL2	D	18.4	63	0	D
MFSL	Sutah00	1102	7/11/2000	4	ABCO	L	9.2	40	80	C
MFSL	Sutah00	1102	7/11/2000	5	ABCO	L	6.2	15	90	S
MFSL	Sutah00	1102	7/11/2000	6	ABCO	L	11.8	53	90	D
MFSL	Sutah00	1102	7/11/2000	7	ABCO	L	8.1	45	50	C
MFSL	Sutah00	1102	7/11/2000	8	ABCO	L	9.8	65	60	D
MFSL	Sutah00	1102	7/11/2000	9	PIFL2	D	14.7	70	0	D
MFSL	Sutah00	1102	7/11/2000	10	ABCO	L	7.6	40	80	C

Figure 6—Query results for the data format query used to populate the TDTree table in the Southern Utah Project year 2000 database.

records to all of the FIREMON tables. The *Delete Records* button deleted all records from the FIREMON PD table, which then deleted all FIREMON records through cascading deletes. The *Add Records* button executed all the append queries in a sequence compatible with the referential integrity of the FIREMON tables.

Documentation and Metadata

We documented the data-conversion process for each data set using a table that mapped all the applicable FIREMON table names and field names to the original table names and field names. This data mapping table keeps a permanent record of the data-conversion process and facilitates the writing of data format queries for the FIREMON database structure. This table contains columns for the FIREMON table and field names, the original data table and field names, and any data-conversion algorithm or constant values applied to the field. Appendix 4-C contains the data mapping table for the Southern Utah Project year 2000 data set. Instances in which data-conversion algorithms or constants were applied to this data set include times at which we added MFSL and SUtah00 to the FIREMON Registration ID and Project ID fields, converting log diameters and decay classes from a row format to a column format, using a data-conversion table to convert local plant species codes to the Natural Resources Conservation Service (NRCS) plant codes (NRCS PLANTS Database 2005), and calculating absolute canopy cover from relative canopy cover.

Documents describing the field sampling protocols and the database structure for each data set were compiled as metadata for the LFRDB. We stored these documents in a metadata subdirectory for each data set. We also recorded any metadata pertaining to the data-conversion process in the FIREMON metadata tables (table 3). Metadata documents that were supplied with each data set were also stored in a documents directory associated with the main LFRDB

Quality Assurance and Quality Control (QA/QC)

Inaccurate reference data may introduce systematic or random bias into any type of mapping effort (Congalton 1992). We therefore implemented a set of systematic quality control measures to assure a high confidence level in the maintenance of data quality and accuracy standards. We developed QA/QC procedures to test for potential errors inherent within the reference data and to assess the quality of the reference data. We targeted three specific categories of QA/QC: 1) geospatial, 2) information content, and 3) land cover change detection.

Geospatial—We recognized that many incorrect plot coordinates result from human data entry errors and from samplers, who, in order to save time, record geographic coordinates along a road instead of from the actual plot center. Such locational inaccuracies were identified and corrected before the field-referenced data were used. We displayed data points using ArcGIS to visually inspect the distribution of plot locations for obvious problems resulting from coordinate errors, such as points occurring well outside the known perimeter of a particular data set. Data points were displayed with road network and hydrology coverages to identify problems such as sample points recorded on roads and in bodies of water. We also calculated the distance of field plots from the nearest road and noted plots positioned within 90 meters of a road.

Information content—We also identified errors related to the information collected at each sample point as numerous errors occur within the plot data, such as fields left empty and data recorded incorrectly. We sorted data records and scanned fields for null values in required fields to ensure that all plot identifiers and plot locations were unique. In addition, we assessed the quality of plant species data and determined the level of information provided, such as whether the data contained full or partial plant species lists. We also noted whether heights were provided for each species, flagging plots with species heights exceeding the normal range.

Land cover change detection—Plot data used for LANDFIRE Prototype Project were collected over a variety of dates ranging back to the late 1980s. Over time, land cover changes rendered some plot information obsolete. We therefore evaluated older data sets for land cover changes resulting from either natural or human causes. We used Landsat imagery from the Multi-Resolution Land Characteristics (MRLC) 1992 and 2001 projects and the 1992 National Land Cover Data Set (NLCD) (Vogelmann and others 2001) in this evaluation.

MRLC 1992 and MRLC 2001 data consist of a collection of terrain-corrected Landsat imagery covering all of the United States. The 1992 NLCD is a classified Landsat product delineating land cover types across the conterminous United States. MRLC 2001 Landsat imagery and NLCD 1992 land cover data were used for the LANDFIRE vegetation classification, providing a means to visually evaluate field-referenced data for errors. Each reference point was selected by life form (for example, forest, shrub, or herbaceous), overlaid onto both the 2001 Landsat imagery and the 1992 NLCD land cover data, and then visually interpreted for validity. This subjective point evaluation was adequate for identifying obvious plot errors, such as lodgepole pine-dominated plots situated in the middle of a large, homogeneous herbaceous area.

To detect reference data errors due to land cover change, we compared the difference between the Normalized Difference Vegetation Index (NDVI) of the MRLC 1992 and the MRLC 2001 image data sets. NDVI is a widely used vegetation index calculated as a ratio between the measured reflectance in the red and near infrared spectral bands of the Landsat imagery. This index has been shown to be highly effective in providing reliable quantification of vegetation cover (Goward and others 1991). The differencing of these NDVI data over time provides an excellent spatial representation of vegetation change. We extracted data values from the resultant images of the NDVI of MRLC 2001 Landsat data minus the NDVI of MRLC 1992 Landsat imagery. Changed areas within the differenced images assume strongly positive or negative values, especially when the changes are great (for example, the clear-cutting of a forest, mortality caused by insect defoliation, or forest regeneration). The differenced images were evaluated to determine the appropriate threshold values that depicted major change. The differenced NDVI values were extracted for each reference data point, and those points with values above the defined thresholds were flagged as areas of possible change. These points were then examined in greater detail by overlaying on the MRLC 2001 imagery, and a decision was made as to whether these points should be used in LANDFIRE analyses.

LANDFIRE Reference Database Content

The LFRDB included a subset of tables from the FIREMON database plus the LANDFIRE attribute tables. The plot description (PD), tree data (TD), fuel load (FL), species composition (SC) and metadata (MD) tables comprise the FIREMON subset in the LFRDB (table 3). Figure 7 shows the relationships between the FIREMON tables and the LANDFIRE attribute tables.

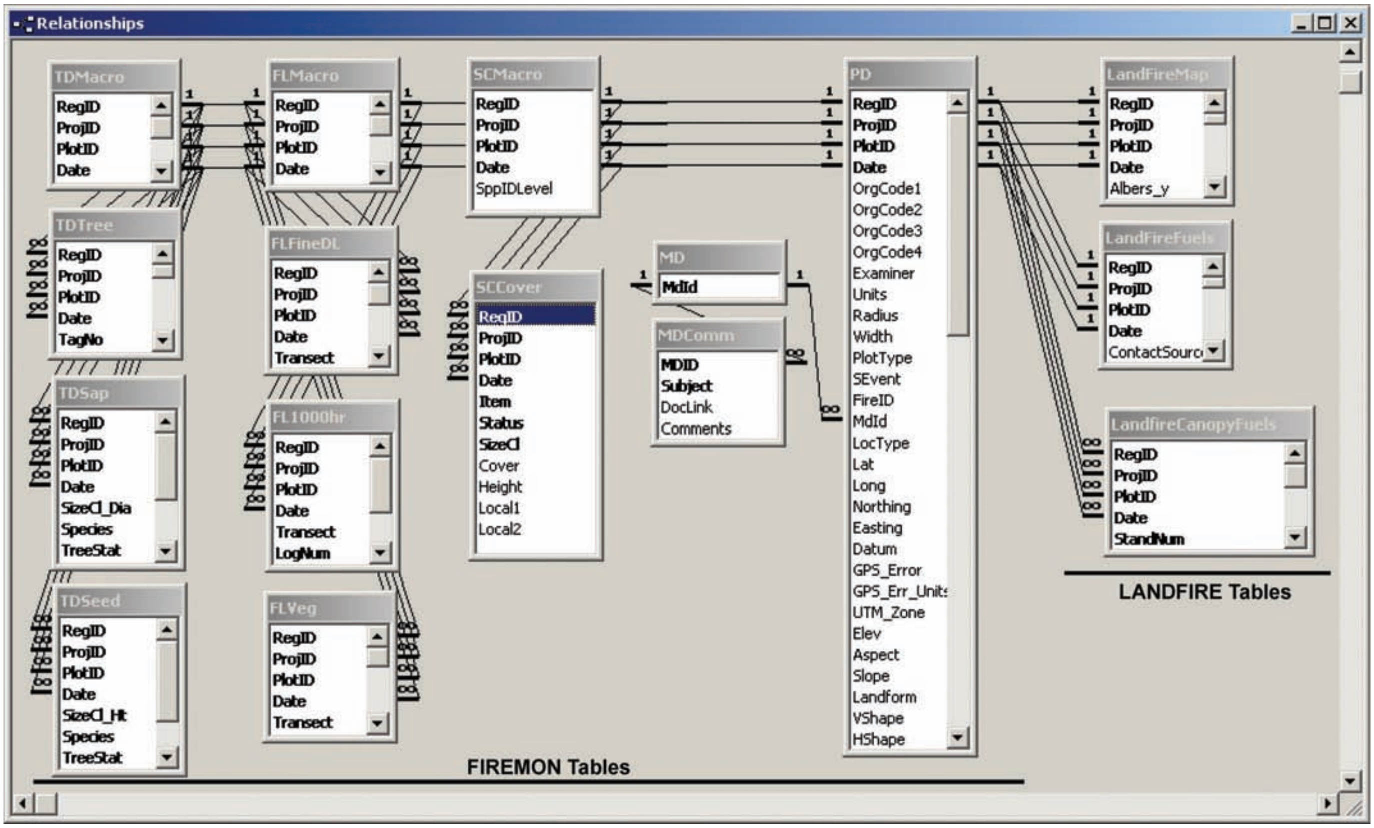


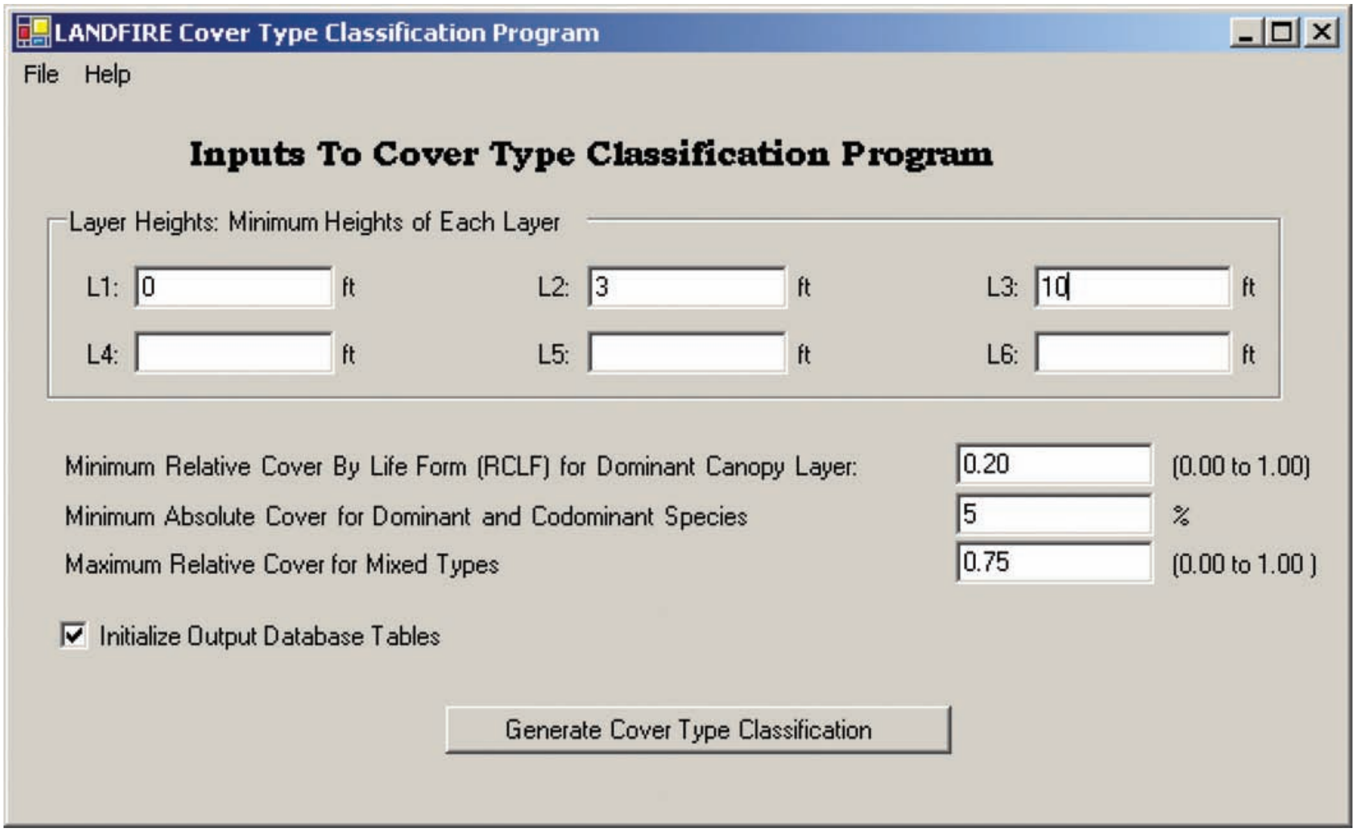
Figure 7—LANDFIRE reference database relationships view showing FIREMON tables and LANDFIRE attribute tables.

We linked FIREMON tables from each data set separately to the LFRDB. We then developed a set of append and update queries for data management purposes. Append queries insert the data from each linked FIREMON table into the appropriate LFRDB table. Each append query is prefixed with "_insert" followed by the table name to which it adds data. Update queries modify the LANDFIRE map table by assigning a PVT, CT, and SS to each plot. All update queries are prefixed with "_update" followed by the table and field in which they update. These queries are run only after the cover type program and PVT queries are executed (see below sections on cover type and potential vegetation type). Linked tables were deleted after all required append queries were run and the data were successfully appended to the reference database tables. This procedure was repeated for each data set within a mapping zone until all plot data for the mapping zone were added.

Cover Type

We assigned a cover type (for example, Ponderosa Pine, Douglas-fir, etc.) to each plot in the reference database using differing methods for FIA and non-FIA data. Plot data including plant species cover and height information were processed with a computer program to assign a LANDFIRE cover type based on the dominant overstory plant species. FIA plots were assigned a cover type based on the dominant tree species by basal area.

Plant species cover and height data—A LANDFIRE cover type classification program was developed to assign a LANDFIRE cover type to each plot having plant species cover and height data. This program consists of a Windows graphical user interface (GUI) front-end (fig. 8) called *covertypewin.exe* and a console application called *covertype.exe*. These two programs are .NET



Inputs To Cover Type Classification Program

Layer Heights: Minimum Heights of Each Layer

L1: 0 ft
L2: 3 ft
L3: 10 ft
L4: ft
L5: ft
L6: ft

Minimum Relative Cover By Life Form (RCLF) for Dominant Canopy Layer: 0.20 (0.00 to 1.00)
Minimum Absolute Cover for Dominant and Codominant Species 5 %
Maximum Relative Cover for Mixed Types 0.75 (0.00 to 1.00)

☑ Initialize Output Database Tables

Figure 8—Cover type classification program graphical user interface (GUI) – front end.

executables and run under the Microsoft .NET Framework version 1.0 (Microsoft .NET 2005). Covertypewin.exe is the GUI portion of the package and invokes the console application covertype.exe, which then determines the cover type assignment for each plot.

There are several user inputs to this program (fig. 8). *Layer heights* are used to specify the lower height of up to six vegetation strata (for example, <1 m, 1 to 3 m, etc.). *Minimum relative cover by life form (RCLF) for dominant canopy layer* specifies the minimum RCLF value, determining which stratum or combination of strata occupies the dominant canopy. For example, if this parameter is set to .20 (20 percent) and tree species in the upper stratum (>3 m) occupy only 10 percent RCLF, the next lower stratum is added to the dominant canopy layer. If tree species in these two strata occupy at least 20 percent RCLF, then these strata are considered to occupy the dominant canopy (in other words, >1 m). This parameter is used primarily to determine the dominant canopy layer on forested plots where overstory and understory species coexist. *Minimum absolute cover for dominant and codominant species* specifies the cover threshold for determining dominant and codominant species. *Maximum relative cover for mixed types* specifies the relative cover value used to determine whether a plot falls in a mixed cover type (such as Pinyon – Juniper) or a single species cover type (such as Juniper). The *Initialize output database tables checkbox* indicates whether the program will delete the current contents of the output table before program execution.

This program requires one configuration file, three lookup tables, two input data tables, and generates one output table. Two of the three lookup tables associate dominant and codominant plant species with a LANDFIRE cover type. The other lookup table determines “tie-breakers,” based on successional development, when two or more cover types have equal cover. For example, a tie between Douglas-fir and Ponderosa Pine cover types went to the later successional cover type of Douglas-fir. The input data tables contain plot life form cover values (tree, shrub, and herbaceous) and individual plant species’ canopy cover and height values. The output table, *cover type classification,* is populated with the LANDFIRE cover type, dominant and codominant plant species, and their associated cover values. The configuration file sets the database paths for the input and output data tables.

The LANDFIRE cover type classification program first determined the dominant life form on the plot based on the cover type classification rule set (Long and others, Ch. 6). Next, the program determined the dominant canopy layer. We stratified canopy layers using the FIREMON defaults of 0 to 1 m, 1 to 3 m, and greater than 3 m. Relative cover for each species in the dominant life form was totaled for each canopy layer until a minimum value was reached. We set this minimum value at 20 percent. The cover type was determined by totaling the canopy cover values for each species in the dominant layer by cover type and selecting the cover type that has the greatest canopy cover. Plots having cover types with equal cover in the dominant canopy layer were assigned the later successional cover type.

For cover types based on codominance, such as Pinyon – Juniper, the program calculated the relative cover of each codominant species to determine if both were greater than or equal to 25 percent. For example, in Zone 16, the Pinyon – Juniper cover type was distinguished from the Juniper cover type based on each species having at least 25 percent cover.

This program also determined the dominant and codominant plant species on a plot. These plant species were within the dominant life form, typically within the assigned cover type and dominant canopy layer, and had the greatest absolute cover values. If there was only one species on the plot in the assigned cover type, the codominant species was determined as the species with the next greatest canopy cover within the dominant life form. Ties went to the later successional species. We set the minimum cover value at zero and reported a dominant and codominant plant species, when possible, and their associated cover values.

FIA tree data—FIA tree data include tree species codes, DBH, and trees per acre. We developed Access queries to calculate the basal area for each species on a plot, calculated the basal area by LANDFIRE cover type, and assigned the cover type having the greatest basal area. Plots having cover types with equal basal area were assigned the later successional cover type.

For cover types based on codominance, such as Pinyon-Juniper, we calculated the relative basal area of the codominant species to determine if it is greater than or equal to 25 percent. For example, in Zone 16, mixed pinyon-juniper plots were distinguished from juniper-dominated plots. The criterion for distinguishing the Pinyon – Juniper cover type from the Juniper cover type was that pinyon and juniper must each have at least 25 percent relative cover.

We then identified the dominant and codominant tree species as those having the greatest basal area within the LANDFIRE cover type. If there was only one species on the plot in the assigned cover type, the codominant species was selected as the species with the next greatest basal area. Ties went to the later successional species for reasons described above.

Potential Vegetation Type

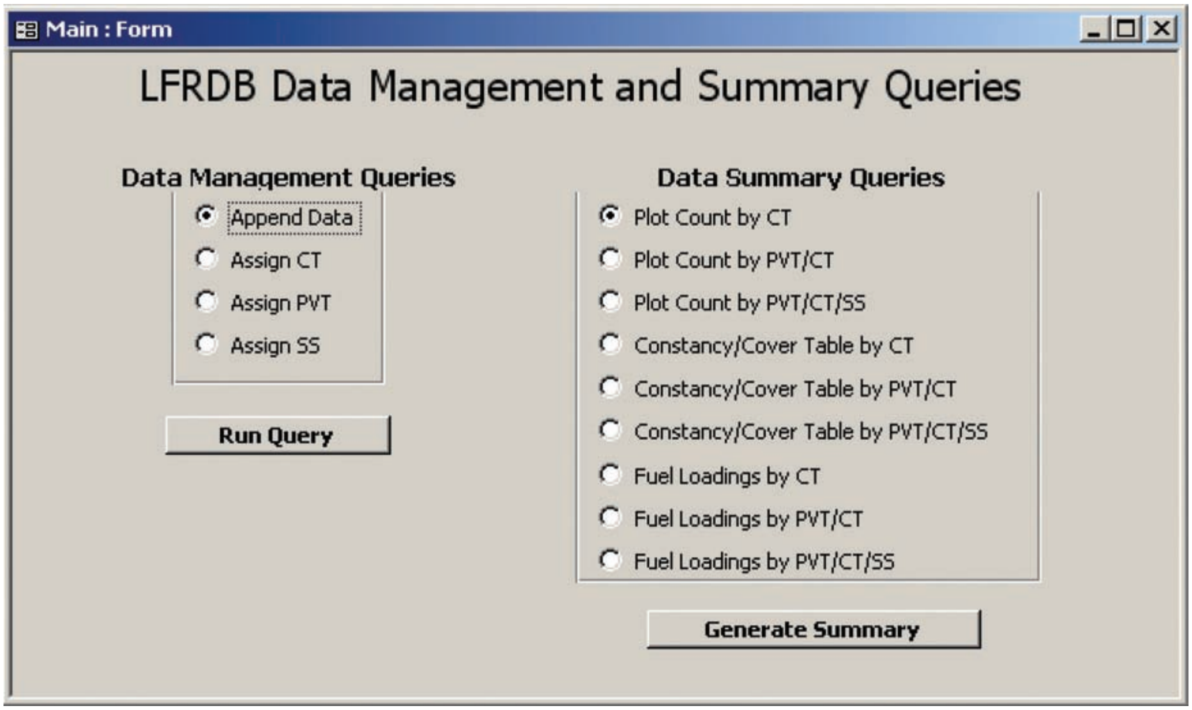
The LANDFIRE potential vegetation type (PVT) classifications (Long and others, Ch. 6) were based on two levels of indicator species, one associating plant species with each Level 2 PVT and one associating plant species with each Level 3 PVT. The indicator species were ordered in these tables by shade tolerance (more to less) within forest PVTs or by a moisture gradient (xeric to mesic) within shrubland or herbaceous PVTs (Long and others, Ch. 6). We developed a set of database queries for assigning LANDFIRE PVTs to plots based on the presence of these indicator species.

The first set of database queries assigned a Level 2 PVT sequence number to each plot based on the PVT Level 2 indicator species list (Long and others, Ch. 6). First, each plant species that was in the PVT classification and present on a plot was assigned a Level 2 PVT sequence number. Then, the lowest sequence number on the plot determined the Level 2 PVT for the plot. A minimum cover percentage level for shrub indicator species (greater than or equal to 10 percent) was used to prevent plots with an herbaceous cover type from being assigned a shrubland PVT, such as in plots having shrub species present yet a total shrub cover of less than 10 percent.

The second set of database queries assigned a Level 3 PVT sequence number to each plot based on the PVT Level 3 indicator species list (Long and others, Ch. 6). Again, each plant species that was in the PVT classification and present on a plot was first assigned a Level 3 PVT sequence number. Then the lowest sequence number on the plot determined the Level 3 PVT for the plot. We then concatenated the Level 2 and Level 3 PVT labels to generate the proper PVT label.

Data Management and Summary Queries

Data management queries involved appending data to the reference database tables and updating the LANDFIRE map table with PVT, CT, and SS assignments for all plots. We created data summary queries to assist in the development of the potential vegetation classification, the cover type classification, succession pathway models, and fuel model classifications. These data summary queries included plot counts by CT, PVT / CT, and PVT / CT / SS; constancy cover tables by CT, PVT / CT, and PVT / CT / SS; and fuel loading by CT, PVT / CT, and PVT / CT / SS. We built a form within the LFRDB to automate the data management and data summary tasks (fig. 9). Automating these tasks facilitated database plot record updates as modifications were made to the PVT, CT or SS classifications.



LFRDB Data Management and Summary Queries

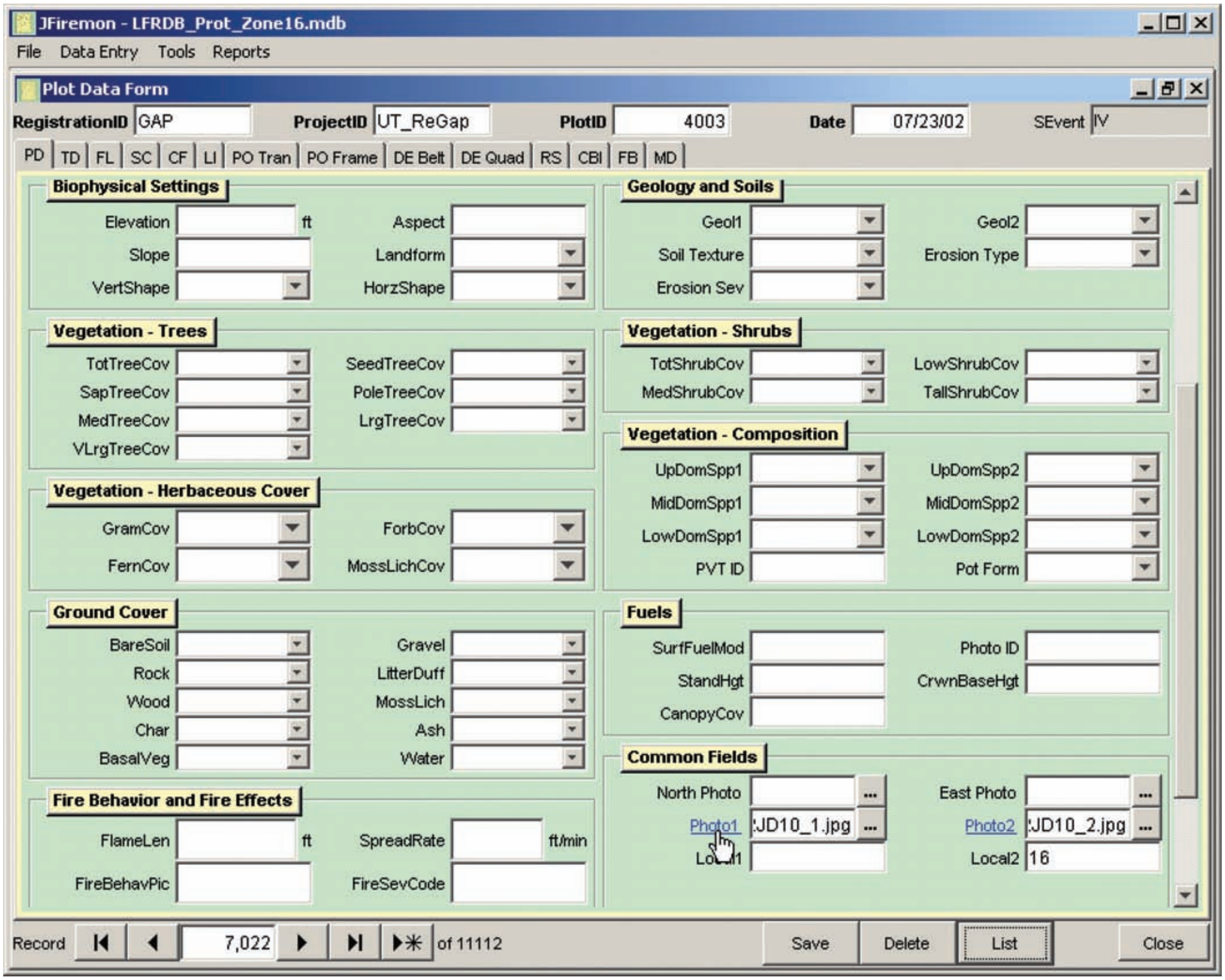
Data Management Queries
● Append Data
○ Assign CT
○ Assign PVT
○ Assign SS

Data Summary Queries
● Plot Count by CT
○ Plot Count by PVT/CT
○ Plot Count by PVT/CT/SS
○ Constancy/Cover Table by CT
○ Constancy/Cover Table by PVT/CT
○ Constancy/Cover Table by PVT/CT/SS
○ Fuel Loadings by CT
○ Fuel Loadings by PVT/CT
○ Fuel Loadings by PVT/CT/SS

Figure 9—Form for automating data management and data summary tasks.

FIREMON Database Application

The FIREMON database application has two features that were applicable to the LFRDB: plot photo and metadata document hyperlinks. The FIREMON database application was connected to the LFRDB using the *Configuration and Settings* menu. This menu also set the directory path for the FIREMON documents and photos directories. The FIREMON plot description (PD) data entry form allowed the LANDFIRE team to view hyperlinked photos (fig. 10). For each mapping zone, we placed all acquired digital plot photos into a photo directory. The digital image (photo) file names were added to the FIREMON PD photo fields during the data-conversion process. These photos could then be viewed via the plot photo hyperlink on the PD form. The FIREMON MD data entry form allowed the team to view hyperlinked documents (fig. 11). For each mapping zone, we placed all associated metadata documents into a documents directory. The document file names were added to the MD table document link field in the LFRDB for each mapping zone. These documents could then be viewed via the document hyperlink.



JFiremon - LFRDB_Prot_Zone16.mdb

Plot Data Form

RegistrationID GAP
ProjectID UT_ReGap
PlotID 4003
Date 07/23/02
SEvent IV

Photo1 :JD10_1.jpg
Photo2 :JD10_2.jpg
Local2 16

Record 7,022 of 11112

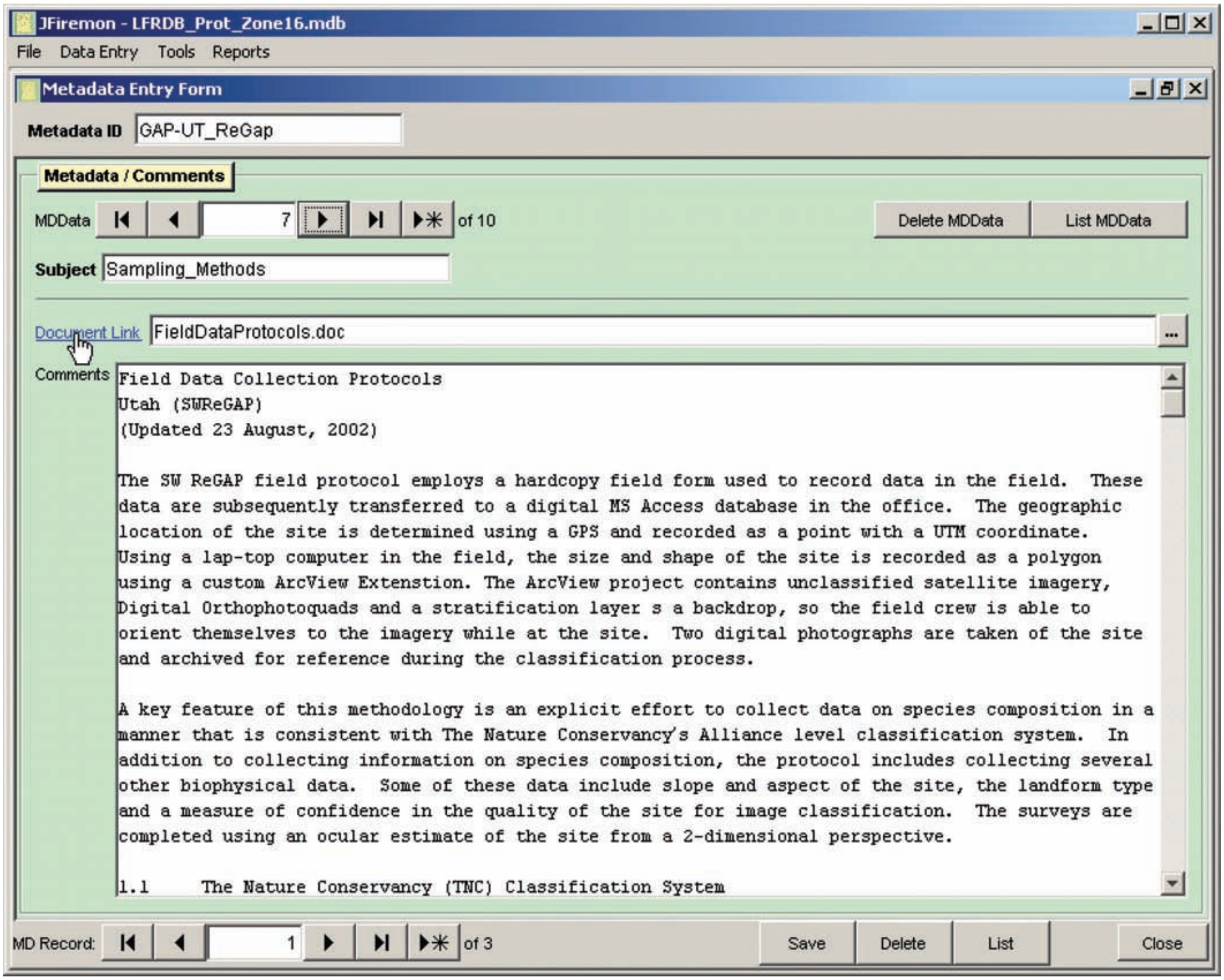
Figure 10—FIREMON plot description form illustrating the plot photo hyperlink.

Results and Discussion

Reference Database Implementation

The FIREMON database was designed to be flexible, and it proved to be fully capable of storing the primary data elements required for the LFRDB. One accommodating feature of FIREMON is that many of the fire monitoring and ecosystem inventory sampling methods employ standard field sampling techniques The flexibility of the FIREMON database allowed customization of the core data tables to store data from a diverse set of field-referenced databases. For example, the FIA, ECODATA, and Southern Utah Project tree data were easily added to the FIREMON TD tables; The ECODATA, Utah field-referenced data from Southwest ReGAP, and Southern Utah Project plant species composition and cover data were easily added to the FIREMON SC tables; The FIREMON PD table accommodated all locational information and site data; and the FIREMON MD tables stored all metadata on field sampling protocols and the data-conversion process.

Additional LANDFIRE attribute tables were easily integrated into the FIREMON database and linked to the FIREMON PD table. These tables were developed specifically for LANDFIRE modeling and mapping tasks and facilitated reference data dissemination to specific LANDFIRE teams. For example, data from the LANDFIRE map attribute table were used to model and map cover type and vegetation structure (Zhu and others, Ch. 8) and to model and map potential vegetation (Frescino and Rollins, Ch. 7). In addition, these data



Metadata ID: GAP-UT_ReGap

MDData: 7 of 10

Subject: Sampling_Methods

Document Link: FieldDataProtocols.doc

Comments:

Field Data Collection Protocols
Utah (SWReGAP)
(Updated 23 August, 2002)

The SW ReGAP field protocol employs a hardcopy field form used to record data in the field. These data are subsequently transferred to a digital MS Access database in the office. The geographic location of the site is determined using a GPS and recorded as a point with a UTM coordinate. Using a lap-top computer in the field, the size and shape of the site is recorded as a polygon using a custom ArcView Extenstion. The ArcView project contains unclassified satellite imagery, Digital Orthophotoquads and a stratification layer s a backdrop, so the field crew is able to orient themselves to the imagery while at the site. Two digital photographs are taken of the site and archived for reference during the classification process.

A key feature of this methodology is an explicit effort to collect data on species composition in a manner that is consistent with The Nature Conservancy's Alliance level classification system. In addition to collecting information on species composition, the protocol includes collecting several other biophysical data. Some of these data include slope and aspect of the site, the landform type and a measure of confidence in the quality of the site for image classification. The surveys are completed using an ocular estimate of the site from a 2-dimensional perspective.

1.1 The Nature Conservancy (TNC) Classification System

MD Record: 1 of 3

Figure 11—FIREMON metadata form illustrating the document hyperlink.

were used to refine the existing and potential vegetation classifications (Long and others, Ch. 6). Data in the LANDFIRE map attribute and fuel attribute tables were used to map fire behavior fuel models (Anderson 1982; Scott and Burgan 2005), fire effects fuel models (Keane and Rollins, Ch. 3; Keane and others, Ch 12; Lutes and others, in preparation; Sandberg and others 2004), and canopy fuel. These tables were used to map fire behavior and effects fuel models based on spatially explicit layers of PVT, CT, and SS. (Keane and others, Chapter 12). The LANDFIRE canopy fuel attribute table was also used as input to the FUELCALC program, and FUELCALC output was used to model and map canopy bulk density and canopy base height (Keane and others, Chapter 12).

In addition to using the FIREMON database to store field-referenced data, we developed a simple and efficient data-conversion process. The *Access Query Design Window* provided a relatively easy way for reference database team members to build the SQL statements required for the data-conversion process. This process was easy to teach resource personnel with limited database skills and was effective as a data migration and data cleaning tool. Our method proved adaptable enough to convert a wide range of data into a common database structure. In addition, our process provided an easy way to track plot records from the LANDFIRE attribute tables back to the original data stored in the data directories for each data set.

Reference Data Acquisition and Applications

Zone 16—Approximately 11,000 plots were compiled in the LFRDB for Zone 16. The initial acquisition of existing data sets for Zone 16 produced only three viable data sets: FIA tree data, Southern Utah Project data, and Utah field-referenced data from Southwest ReGAP. Since FIA data is fairly extensive in forested areas, the limiting factor was the acquisition of non-forest vegetation data. The Southern Utah Project data adequately covered the southern portion of Zone 16. The initial Utah data acquired from Southwest ReGAP contained very little reference data for the northern and central portions of Zone 16. A strategic partnership between the Southwest ReGAP project and the LANDFIRE Prototype Project was crucial in obtaining additional field-referenced data for Zone 16.

Concerning applications, all data sets acquired for Zone 16 included vegetation data used to model and map potential vegetation, cover type, and structure. In addition to use in mapping vegetation cover and structure, all FIA tree data were used for modeling and mapping canopy fuel (canopy bulk density and canopy base height). A limited number of plots in the Southern Utah Project data set had tree data used for modeling and mapping canopy fuel and downed woody fuel transect data used for mapping fire behavior and effects fuel models.

Zone 19—Approximately 12,500 plots were compiled in the reference database for Zone 19. The initial data acquisition for Zone 19 produced several viable data sets in addition to the FIA tree data, due in part to existing ECODATA plots from the USDA Forest Service Northern Region ecology program and USGS and MFSL research in and around Glacier National Park. We acquired data for thousands of BLM fuel inventory plots, as well; however, these were heavily concentrated around Salmon and Challis, Idaho. Moreover, many of the ECODATA plots were concentrated around the Flathead National Forest and Glacier National Park. We lacked field-referenced data for many non-forested areas in the southern and eastern portions of Zone 19. Therefore, it was crucial to contract with the Utah field crews from Southwest ReGAP for additional field-referenced data collection.

All data sets for Zone 19 included vegetation data used to model and map potential vegetation, cover type, and structure. In addition to use in mapping vegetation and structure, all FIA tree data were used for modeling and mapping canopy fuel. All ECODATA data sets had tree data for modeling and mapping canopy fuel and downed woody fuel transect data for mapping fire behavior and effects fuel models.

Limitations of Acquired Data

Some of the existing data sets obtained for the LANDFIRE Prototype proved limited in utility. For example, the data sets acquired from research projects -- MFSL and USGS ECODATA plots for Glacier National Park -- provided the most accurate data for mapping existing and potential vegetation and fuel models, yet these data were geographically limited. Second, FIA tree data provided valuable plot data for forest ecosystems, including individual tree measurements used for modeling and mapping potential vegetation, cover type, canopy height, canopy cover, and canopy fuel. In order to maintain nationally consistent FIA data, however, we used only the FIADB data tables that are available nationally; we did not use FIADB seedling and understory vegetation data as these are not collected across the country. Third, the Utah data collected for Southwest ReGAP and for additional Zone 19 reference plots were useful for modeling and mapping potential vegetation, cover type and structure. However, because height data were not always collected for every plant species recorded, only a subset of data collected using the Southwest ReGAP sampling protocols could be used to model and map structure. Lastly, although there were approximately 4,000 data points in the BLM dominant and co-dominant species data sets, most of the data were tightly clustered geographically, limiting their utility for mapping vegetation and fuel across the entire extent of Zone 19.

Recommendations for National Implementation

Cooperation with Outside Agencies

Projects requiring extensive field-referenced data, such as LANDFIRE, must rely heavily on existing data sources since there is not enough time or money to collect new reference data. We initially solicited data via a formal data request letter sent to agency personnel, but this effort yielded only a few small and limited data sets. Nonetheless, a formal data request letter will be necessary for the national implementation of LANDFIRE and will likely generate some high-quality data sets. We do, however, caution against relying primarily on such a letter to generate the quantity and quality of data required for a project the size and scope of LANDFIRE. We discovered that the most efficient and effective way to obtain high-quality, well-distributed data is through cooperation with agencies that have already collected similar reference data. All major field-referenced data contributions for the LANDFIRE Prototype Project were obtained through new or existing relationships with outside agencies and research projects.

It is of particular importance to have cooperation from FIA in light of the confidential nature of FIA plot locations. The Interior West FIA program provided the LANDFIRE Prototype Project with one part-time FIA employee to facilitate data acquisition and perform tasks requiring the use of FIA plot coordinates. In addition, through this partnership we were able to acquire plot data other than those available from the FIADB. Furthermore, collaboration between LANDFIRE and the Southwest ReGAP Project gained the LFRDB team access to a wealth of data for Zone 16. Once we established a relationship with the Utah State Southwest ReGAP team, we were able to obtain all existing plot data as well as contract with their Utah field crews to acquire additional field-referenced data for zones 16 and 19. Contracting with other agencies' field crews capitalizes on their resources and expertise in field sampling, thereby saving investment in additional resources and training.

Data Triage

Data triage is critical to the timely delivery of reference data. It is easy to become overwhelmed by too much data and too little time for processing. For this reason, it is essential to concentrate on large, high-quality data sets with wide geographic coverage containing data elements pertinent to the LANDFIRE mapping tasks. We do not recommend spending much time on small data sets unless they have high quality data (such as certain data sets from intensive research projects) or until after the large data sets have been processed. Next, prior to data conversion, we recommend identifying all plot locations mistakenly recorded on roads, in water, or outside the known study area. Assessing the locations of existing reference data will also highlight areas in need of additional field data collection. Identifying these areas early in the process allows ample time to contract with field crews prior to the up-coming field season.

Keep it Simple

Most of the data sets we acquired for the LANDFIRE Prototype Project contained many more variables than were necessary for our purposes. We initially converted all original data that could populate the FIREMON database fields and recommend this as the first step in data conversion since all data elements of the original data set exist in a common database for use in the prototype effort. When time is a limiting factor, however, it is practical to first convert only the fields required to populate the LANDFIRE attribute tables. If time allows, the data-conversion queries may be modified and plot records updated in the LFRDB. We did spend a substantial amount of time converting data that were never used for the LANDFIRE Prototype, yet the prototype nature of the project required that we had all data available while the LANDFIRE mapping processes were being developed.

Because of the large quantity of field-referenced data and necessary distribution across LANDFIRE mapping teams, the LANDFIRE National will require a true multi-user relational database management system capable of accommodating more data than Microsoft Access and operating efficiently under a distributed computer network. Although a database with greater flexibility than that of Access should ultimately be used for LANDFIRE National, the Access reference database used in the prototype effort proved satisfactory for our purposes. If, for LANDFIRE National, a separate LFRDB were built for each mapping zone, Access would be able to accommodate the large amount of plot data and the entire data-conversion process described in this chapter could be applied.

Conclusion

In conclusion, the use of existing databases to meet the broad-scale mapping objectives of the LANDFIRE Prototype Project worked well. Existing databases from both government and non-government sources provided excellent information for successfully completing the LANDFIRE mapped products. In this prototype effort, however, we found that field data for non-forested areas were rare relative to those of forested areas. This scarcity of data for non-forested areas may pose more of a limitation in other areas of the United States than it did in the two study areas of the LANDFIRE Prototype Project. For this reason, it may be necessary to collect additional data in non-forested areas for national implementation of the LANDFIRE methods.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

The Author

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Appendix 4-A—FIREMON tables and fields in the landfire reference database

Plot description (PD)

Field name	Description
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
OrgCode1	Organization code 1
OrgCode2	Organization code 2
OrgCode3	Organization code 3
OrgCode4	Organization code 4
Examiner	Name of FireMon crew boss or lead examiner
Units	Units of measurement (english or metric)
Radius	Radius/length of the macroplot in feet (meters)
Width	Width of macroplot in feet (meters)
PlotType	Type of plot: C=Control, M=Measured
SEvent	Sampling event - reason why plot is being measured at this time
FireID	Fire behavior database key-id
MdId	Metadata Key-Id
LocType	Type of Location L=Lat/Long, U=UTM
Lat	Latitude of plot center
Long	Longitude of plot center
Northing	UTM Northing of plot center
Easting	UTM Easting of plot center
Datum	GPS datum
GPS_Error	GPS error (meters or feet)
GPS_Err_Units	Units for GPS Error: ft = feet, m=meters
UTM_Zone	UTM zone
Elev	Elevation above mean sea level - feet (meters)
Aspect	Aspect of plot in azimuth - degrees
Slope	Average slope (rise/run)*100 - percent
Landform	Landform code
VShape	Shape of plot perpendicular to contour
HShape	Shape of plot parallel to contour
Geol1	Primary surficial geology code
Geol2	Secondary surficial geology code
SoilTex	Soil texture
EType	Erosion type
ESev	Erosion severity
TreeC	Total tree cover - percent
SeedC	Seedling cover - percent
SapC	Sapling cover- percent
PoleC	Pole cover - percent
MedC	Medium tree cover - percent
LTreeC	Tree cover - percent
VLTreeC	Very large tree cover - percent
ShrubC	Total shrub cover - percent
LShrubC	Low shrub cover - percent
MShrubC	Medium shrub cover - percent
TShrubC	Tall shrub cover - percent
GramC	Graminoid cover - percent
ForbC	Forb cover - percent
FernC	Fern cover - percent
MossC	Moss and lichen cover - percent
USpp1	Most dominant species in upper layer
USpp2	Second most dominant species in upper layer
MSpp1	Most dominant species in middle layer
MSpp2	Second most dominant species in middle layer

Appendix 4-A — (Continued)

LSpp1	Most dominant species in lower layer
LSpp2	Second most dominant species in lower layer
PVTId	Potential vegetation type code
PotForm	Potential life form code
BSoilGC	Bare soil ground cover - percent
GravelGC	Gravel ground cover - percent
RockGC	Rock ground cover - percent
DuffGC	Duff and litter ground cover - percent
WoodGC	Wood ground cover - percent
MossGC	Moss and lichen ground cover - percent
CharGC	Charred ground cover - percent
AshGC	Ash ground cover - percent
BVegGC	Basal vegetation ground cover - percent
WaterGC	Water ground cover - percent
FModel	Fire behavior fuel model (Anderson 1982)
PhotoID	Fuel photo series
SHT	Stand height: height of highest stratum which contains at least 10% of canopy cover - feet (meters)
CBH	Canopy fuel base height - feet (meters)
CanopyC	Percent canopy cover of forest canopy >6.5 feet - feet (meters)
FLength	Average flame length - feet (meters)
SRate	Spread rate; average speed of fire - feet/min (meters/min)
FBevPic	Picture code for fire behavior picture
FSC	Fire severity code
NorthPic	Code for plot photo taken in direction of due north
EastPic	Code for plot photo taken in direction of due east
Photo1	Code for plot photo 1
Photo2	Code for plot photo 2
Local1	Local code 1
Local2	Local code 2
Comments	Comments about plot

Species composition – macroplot (SCMacro)

Field name	**Description**
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
SppIDLevel	Plant species ID level; minimum cover recorded – percent
RegID	

Species composition (SCCover)

Field name	**Description**
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
Item	Item code
Status	Heath of species - (live or dead)
SizeCl	Size class
Cover	Canopy cover - percent
Height	Average height - feet (m)
Local1	Optional field 1
Local2	Optional field 2

Tree data – macroplot (TDMacro)

Field name	**Description**
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
MacroPlotSize	Macroplot size - acres (square meters)
MicroPlotSize	Microplot size - acres (square meters)
SnagPlotSize	Snagplot size - acres (suqare meters)
BreakPntDia	Break point diameter - inches (cm)

Appendix 4-A — (Continued)

Tree data – mature trees (TDTree)

Field name	Description
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
TagNo	Tree tag number
Species	Species code
TreeStat	Health of tree (live or dead)
DBH	Diameter at breast height - inches (cm)
Height	Tree Height - feet (m)
LiCrPct	Live crown percent
LiCrBHt	Live crown base height feet (m)
CrwnCl	Crown position class
Age	Tree age - years
GrwthRt	Tree growth rate (last 10 yrs radial growth) - inches (mm)
DecayCl	Decay class
Mort	Cause of mortality
DamCd1	Damage code 1
DamSev1	Severity code 1
DamCd2	Damage code 2
DamSev2	Severity code 2
CharHt	Bole char height - feet (m)
CrScPct	Crown scorch percent
Local1	Optional code 1

Tree data – saplings (TDSap)

Field name	Description
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
SizeCl_Dia	Size class
Species	Species code
TreeStat	Tree status
Count	Count number of trees by species, size class, and status
AvgHt	Average height - feet (m)
AvgLiCr	Average live crown percent
Local1	Local field 1

Tree data – seedlings (TDSeed)

Field Name	Description
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
SizeCl_Ht	Size class
Species	Species code
TreeStat	General health condition of sample tree
Count	Number of trees by species, size class, and status
Local1	Local field 1

Fuel load – macroplot (FLMacro)

Field name	Description
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
1HRTranLen	1-hr transect length - feet (m)
10HRTranLen	10-hr transect length - feet (m)
100HRTranLen	100-hr transect length - feet (m)
1000HRTranLen	1000-hr transect length - feet (m)
NumTran	Number of transects

Appendix 4-A — (Continued)

Fuel load – fine fuel, duff, and litter (FLFineDL)

Field name	**Description**
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
Transect	Line transect number
Slope	Slope of transect (rise/run)*100 - percent
1hr	Number of pieces 0 - 0.25 in. (0 - 0.635 cm) in diameter
10hr	Number of pieces 0.25 - 1.0 in. (0.635 - 2.54 cm) in diameter
100hr	Number of pieces 1- 3 in. (2.54 and 7.62 cm) in diameter
D/LDep1	Depth of duff/litter profile - inches (cm)
LitterPct1	Proportion of total profile depth that is litter- percent
D/LDep2	Depth of duff/litter profile - inches (cm)
LitterPct2	Proportion of total profile depth that is litter - percent
Local1	Local field 2

Fuel load – 1000-hr fuel (FL1000hr)

Field name	**Description**
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
Transect	Line transect number
LogNum	Log number
Dia	Diameter of log at line intersection - inches (cm)
DecayCl	Log decay class
Local1	Local field 1

Fuel load – vegetation (FLVeg)

Field name	**Description**
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
Transect	Line transect number
LiShC1	Live woody cover at point 1
DdShC1	Dead woody cover at point 1
ShHt1	Woody height at point 1
LiHeC1	Live non-woody cover at point 1
DdHeC1	Dead non- woody cover at point 1
HeHt1	Non-woody height at point 1
LiShC2	Live woody cover at point 2
DdShC2	Dead woody cover at point 2
ShHt2	Woody height at point 2
LiHeC2	Live non-woody cover at point 2
DdHeC2	Dead non- woody cover at point 2
HeHt2	Non-woody height at point 2

Metadata ID (MDID)

Field name	**Description**
MdId	Metadata ID

Metadata (MDComm)

MDID	Metadata ID
Subject	Metadata subject
DocLink	Hyperlink for metadata documen

Appendix 4-B—LANDFIRE attribute tables

LANDFIRE map

Field name	Description
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
Albers_y	Albers Northing of plot center
Albers_x	Albers Easting of plot center
Datum	Datum of coordinate system
LF_Zone	LANDFIRE zone - MRLC zone in which plot is located
Orig_CoverType	Cover type assigned in original data set
LF_CoverType	LANDFIRE cover type
LF_CoverTypeCode	LANDFIRE cover type code
DomSpp	Dominant plant species
DomSppC	Dominant plant species cover - percent
CoDomSpp	Codominant plant species
CoDomSppC	Codominant plant species cover - percent
TreeC	Tree cover - percent
ShrubC	Shrub cover - percent
HerbC	Herbaceous cover - percent
TreeHt	Average tree height weighted by canopy cover (ft.)
ShrubHt	Average shrub height weighted by canopy cover (ft.)
HerbHt	Average herbaceous height weighted by canopy cover (ft.)
Orig_StrucStage	Structural stage assigned in original data set
LF_StrucStage	LANDFIRE structural stage
LF_StrucStageCode	LANDFIRE structural stage code
Orig_PVT	Potential vegetation type assigned in original data set
LF_PVT	LANDFIRE potential vegetation type
LF_PVTCode	LANDFIRE potential vegetation type code
SoilTex	Soil texture
PhotoID	Plot photo filename identifier
Reference	Data reference
Loc_Meth	Method for determining plot location
Loc_Acc	Plot location accuracy (meters)
DistToRoad	Distance to nearest road (meters)
NLCD_Code	NLCD code
NLCD_Desc	NLCD description
LifeFormCover_QAQC	Codes for life form cover QA/QC
SppCover_QAQC	Codes for plant species data QA/QC
SppHeight_QAQC	Codes for plant species height QA/QC

LANDFIRE fuel

Field name	Description
RegID	Unique 4 character code for each FIREMON user
ProjID	Unique 8 character code for each project
PlotID	Unique number for each plot
Date	Sampling date
ContactSource	Contact person for data
DataSource	Source of data
DataSourceInfo	Information about source of data
DataComments	Data comments
ID1	Organization code 1
ID2	Organization code 2
ID3	Organization code 3
ID4	Organization code 4
Units	Measurement units (E or M)
Albers_y	Albers Northing of plot center
Albers_x	Albers Easting of plot center
Datum	Datum of coordinate system

Appendix 4-B — (Continued)

LF_Zone	LANDFIRE zone - MRLC zone in which plot is located
Slope	Elevation above mean sea level - feet (meters)
Aspect	Aspect of plot in azimuth - degrees
Elevation	Average slope (rise/run)*100 - percent
LocationComments	Comments on plot location
LandfirePVT	LANDFIRE potential vegetation type
CurrentLifeForm	Current life form on plot
PotLifeForm	Potential life form on plot
CoverType	Land cover type
HabitatType	Habitat type
BaileyProvince	Bailey Province
ICRBStructure	ICRB stand structure
VegDataFile	Vegetation data file
OverSpecies1	Dominant overstory species
OverSpecies2	Codominant overstory species
UnderSpecies1	Dominant understory species
UnderSpecies2	Codominant understory species
Graminoid1	Dominant graminoid species
Graminoid2	Codominant graminoid species
Shrub1	Dominant shrub species
Shrub2	Codominant shrub species
Forb1	Dominant forb species
Forb2	Codominant forb species
FuelbedDepth	Fuelbed depth
Carrier1	Primary fire carrier
Carrier2	Secondary fire carrier
VegComments	Vegetation comments
Event	Fire event
Pre/post	Pre/post fire effects
ActivityFuel	Activity fuel
EventComments	Event comments
1-hrBiomass	1-hr fuel biomass
10-hrBiomass	10-hr fuel biomass
100-hrBiomass	100-hr fuel biomass
3”<TotalBiomass	1-100-hr total fuel biomass
3”>TotalBiomass	1000-hr total fuel biomass
3”>SndBiomass	1000-hr sound fuel biomass
3”>RotBiomass	1000-hr rotten fuel biomass
3”-9”SndBiomass	3”-9” sound fuel biomass
3”-9”RotBiomass	3”-9” rotten fuel biomass
9”-20”SndBiomass	9”-20” sound fuel biomass
9”-20”RotBiomass	9”-20” rotten fuel biomass
20”+SndBiomass	20” and larger sound fuel biomass
20”+RotBiomass	20” and larger rotten fuel biomass
DWMethod	Downed woody sampling method
DWSource	Downed woody sampling method source
DWComments	Downed woody comments
DuffBiomass	Duff biomass
DuffBulkDen	Duff bulk density
DuffMethod	Duff method
DuffSource	Duff source
DuffComments	Duff comments
LitterBiomass	Litter biomass
LitterBulkDen	Litter bulk density
LitterMethod	Litter method
LitterSource	Litter source
LitterComments	Litter comments
LiveHerbBiomass	Live herbaceous biomass
DeadHerbBiomass	Dead herbaceous biomass

Appendix 4-B — (Continued)

HerbMethod	Herbaceous sampling method
HerbSource	Herbaceous sampling method source
HerbComments	Herbaceous comments
LiveShrubBiomass	Live shrub biomass
DeadShrubBiomass	Dead shrub biomass
ShrubMethod	Shrub sampling method
ShrubSource	Shrub sampling method source
ShrubComments	Shrub comments
OtherBiomass	Other biomass
OtherMethod	Other biomass sampling method
OtherSource	Other biomass sampling method source
OtherComments	Other comments
#ofTrans	Number of transects
1-hrLen	1-hr transect length
10-hrLen	10-hr transect length
100-hrLen	100-hr transect length
1000-hrLen	1000-hr transect length
1-hrQMD	1-hr fuel quadratic mean diameter
10-hrQMD	10-hr fuel quadratic mean diameter
100-hrQMD	100-hr fuel quadratic mean diameter
TransectComments	Transect comments
DecayCl1Den	Decay class 1 density
DecayCl2Den	Decay class 2 density
DecayCl3Den	Decay class 3 density
DecayCl4Den	Decay class 4 density
DecayCl5Den	Decay class 5 density
DecayClassComments	Decay class comments

LANDFIRE canopy fuel

Field name	**Description**
RegID	Unique code for each FIREMON user (up to 4 characters)
ProjID	Unique code for each project (up to 8 characters)
PlotID	Unique code for each plot
Date	Sampling date
StandNum	Stand number
Tag	Tree ID number
Spe	Tree ID - 2 character code
Dia	Diameter at breast height (inches)
Hgt	Tree height (feet)
C-HBC	Height to base of live crown (feet)
CC	Crown class (code = D, C, I, S, E, G)
TPA	Tree density (trees/acre)

Appendix 4-C—FIREMON data conversion table for Southern Utah Project year 2000 data, which shows how fields from the Sutah Access database are mapped and converted to fields in the FIREMON access database

FIREMON table	FIREMON field	Sutah00 table	Sutah00 field	Conversion
FL1000hr	RegID			MFSL
FL1000hr	ProjID			Sutah00
FL1000hr	PlotID	Down Wood 2000	Plot#	
FL1000hr	Date	Veg data 2000	Date	
FL1000hr	Transect	Down Wood 2000	Transect	
FL1000hr	LogNum	Log1-17		Horiz – vert
FL1000hr	Dia	Log1-17 dia		Horiz – vert
FL1000hr	DecayCl	Log1-17 dc		Horiz – vert
FL1000hr	Local1			
FLFineDL	RegID			MFSL
FLFineDL	ProjID			Sutah00
FLFineDL	PlotID	Down Wood 2000	Plot#	
FLFineDL	Date	Veg data 2000	Date	
FLFineDL	Transect	Down Wood 2000	Transect	
FLFineDL	Slope	Down Wood 2000	Slope	
FLFineDL	1hr	Down Wood 2000	1Hour	
FLFineDL	10hr	Down Wood 2000	10Hour	
FLFineDL	100hr	Down Wood 2000	100Hour	
FLFineDL	D/LDep1	Down Wood 2000	DuffLittDepth30	
FLFineDL	LitterPct1			
FLFineDL	D/LDep2	Down Wood 2000	DuffLittDepth60	
FLFineDL	LitterPct2			
FLFineDL				
	Local1			
FLMacro	RegID			MFSL
FLMacro	ProjID			Sutah00
FLMacro	PlotID	Down Wood 2000	Plot#	
FLMacro	Date	Veg data 2000	Date	
FLMacro	1HrTranLen			60
FLMacro	10HrTranLen			60
FLMacro	100HrTranLen			60
FLMacro	1000HrTranLen			60
FLMacro	NumTran			7
PD	RegID			MFSL
PD	ProjID			Sutah00
PD	PlotID	Site2000	Plot#	
PD	Date	Veg data 2000	Date	
PD	OrgCode1			
PD	OrgCode2			
PD	OrgCode3			
PD	OrgCode4			
PD	Examiner			
PD	Units			E
PD	Radius			37.2
PD	Width			
PD	PlotType			
PD	SEvent			
PD	FireID			
PD	MdId			
PD	LocType			
PD	Lat			
PD	Long			
PD	Northing	Location Data 2000	Northing	

Appendix 4-C — (Continued)

FIREMON table	FIREMON field	Sutah00 table	Sutah00 field	Conversion
PD	Easting	Location Data 2000	Easting	
PD	Datum			
PD	GPS_Error			
PD	GPS_Err_Units			
PD	UTM_Zone			12
PD	Elev	Location Data 2000	Elevation	
PD	Aspect	Site2000	Aspect	
PD	Slope	Site2000	Slope	
PD	Landform	Site2000	Landform	Table: _cnvLandform
PD	VShape			
PD	HShape			
PD	Geol1			
PD	Geol2			
PD	SoilTex	Site2000	Soil	
PD	EType			
PD	ESev			
PD	TreeC	Veg data 2000	Tot tree cover	
PD	SeedC			
PD	SapC			
PD	PoleC			
PD	MedC			
PD	LTreeC			
PD	VLTreeC			
PD	ShrubC	Veg data 2000	Shrub cover	
PD	LShrubC			
PD	MShrubC			
PD	TShrubC			
PD	GramC	Veg data 2000	Gramm cover	
PD	ForbC	Veg data 2000	Forb cover	
PD	FernC			
PD	MossC			
PD	USpp1			
PD	USpp2			
PD	MSpp1			
PD	MSpp2			
PD	LSpp1			
PD	LSpp2			
PD	PVTId	Veg data 2000	PVT Sp1, 2, 3	PVT Sp1 + PVT Sp2 + PVT Sp3
PD	PotForm			
PD	BSoilGC			
PD	GravelGC			
PD	RockGC			
PD	DuffGC			
PD	WoodGC			
PD	MossGC			
PD	CharGC			
PD	AshGC			
PD	BVegGC			
PD	WaterGC			
PD	FModel	Site 2000	FBFM nor	
PD	PhotoID			
PD	SHT	Site 2000	Stand ht	
PD	CBH	Site 2000	Cbh	
PD	CanopyC	Site 2000	FARSITE cc	
PD	FLength			
PD	SRate			
PD	FBevPic			

Appendix 4-C — (Continued)

FIREMON table	FIREMON field	Sutah00 table	Sutah00 field	Conversion
PD	FSC			
PD	NorthPic			
PD	EastPic			
PD	Photo1			
PD	Photo2			
PD	Local1			
PD	Local2			
PD	Comments			
SCCover	RegID			MFSL
SCCover	ProjID			Sutah00
SCCover	PlotID	Species 2000	Plot#	
SCCover	Date	Veg data 2000	date	
SCCover	Item	Species 2000	Species	Table: _cnvSpp
SCCover	SizeCl			
SCCover	Cover	Species 2000	Rc	Rc * Lifeform CC fraction
SCCover	Height	Species 2000	Ht	
SCCover	Local1			
SCCover	Local2			
SCMacro	RegID			MFSL
SCMacro	ProjID			Sutah00
SCMacro	PlotID	Species 2000	Plot#	
SCMacro	Date	Veg data 2000	Date	
SCMacro	SppIDLevel			
TDMacro	RegID			MFSL
TDMacro	ProjID			Sutah00
TDMacro	PlotID	Tree data 2000	Plot	
TDMacro	Date	Veg data 2000	Date	
TDMacro	MacroPlotSize			
TDMacro	MicroPlotSize			
TDMacro	BreakPntDia			
TDSeed	RegID			MFSL
TDSeed	ProjID			Sutah00
TDSeed	PlotID	Seedling Data 2000	Plot#	
TDSeed	Date	Veg data 2000	Date	
TDSeed	SizeCl_Ht	Seedling Data 2000	SizeClass	
TDSeed	Species	Seedling Data 2000	Species	
TDSeed	TreeStat			
TDSeed	Count	Seedling Data 2000	Number	
TDSeed	Local1			
TDTree	RegID			MFSL
TDTree	ProjID			Sutah00
TDTree	PlotID	Tree data 2000		
PJ Data 2000	Plot			
Plot No				
TDTree	Date	Veg data 2000	Date	
TDTree	TagNo	Tree data 2000		
PJ Data 2000	Tree			
PJ Number				
TDTree	Species	Tree data 2000		
PJ Data 2000	Spp			
Spp				
TDTree	TreeStat	Tree data 2000		

Appendix 4-C — (Continued)

FIREMON table	FIREMON field	Sutah00 table	Sutah00 field	Conversion
PJ Data 2000	Tree status			
Status				
TDTree	DBH	Tree data 2000		
PJ Data 2000	Dbh			
Dbh (in)				
TDTree	Height	Tree data 2000		
PJ Data 2000	Height			
Height (ft)				
TDTree	LiCrPct	Tree data 2000		
PJ Data 2000	Crown ratio			
Crnratio				
TDTree	LiCrBHt			
TDTree	CrwnCl			
TDTree	Age	Tree data 2000	Age	
TDTree	GrwthRt			
TDTree	DecayCl			
TDTree	Mort			
TDTree	DamCd1	Tree data 2000		
PJ Data 2000	Damcode1			
Damcode1				
TDTree	SevCd1	Tree data 2000		
PJ Data 2000	Sevcode1			
Sevcode1				
TDTree	DamCd2	Tree data 2000	Damcode2	
TDTree	SevCd2	Tree data 2000	Sevcode2	
TDTree	CharHt			
TDTree	CrScPct			
TDTree	Local1			

Chapter
5

Development of Biophysical Gradient Layers for the LANDFIRE Prototype Project

Lisa Holsinger, Robert E. Keane, Russell Parsons, and Eva Karau

Introduction

Distributions of plant species are generally continuous, gradually changing across landscapes and blending into each other due to the influence of, and interactions between, a complex array of biophysical gradients (Whittaker 1967; 1975). Key biophysical gradients for understanding vegetation distributions include moisture, temperature, evaporative demand, nutrient availability, and solar radiation. Models to predict plant community distributions across landscapes can be developed by identifying the unique set of biophysical gradients that drive the physiological responses of plant species across landscapes (Guissan and Zimmerman 2000). This method of incorporating information about ecological characteristics into analyses of vegetation distribution, termed gradient modeling, is a standard technique for describing ecosystem composition, structure, and function (Gosz 1992; Kessell 1976; Kessell 1979; Whittaker 1973) and has been applied extensively at varying scales, from local to regional (see Keane and others 2002 for a review of gradient modeling applications). The modeling process essentially involves developing empirical relationships between vegetation distributions and geospatial data describing biophysical gradients to enable extrapolation over space. Modeling accuracy becomes substantially improved by incorporating those biophysical gradients that directly affect vegetation dynamics such as temperature, light, and water (Austin 1980, 1985; Austin and Smith 1989; Franklin 1995). Recent efforts have further demonstrated that the accuracy of mapping vegetation and ecological characteristics using remote sensing techniques is greatly improved through the inclusion of biophysical gradient data as predictive variables (Franklin 1995; Keane and others 2002; Ohmann and Gregory 2002; Rollins and others 2004).

The Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, was conceived, in part, with the objective of developing methods and procedures for mapping vegetation composition and structure, wildland fuel, and historical conditions at a fine spatial grain (30-m) across the entire United States. This information will facilitate the identification of areas where current vegetation conditions are markedly different from simulated historical conditions (Rollins and others, Ch. 2; Keane and Rollins, Ch. 3). We used a gradient modeling approach to describe vegetation conditions by their potential vegetation type, existing cover type, and existing structural stage (Frescino and Rollins, Ch. 7; Zhu and others, Ch. 8). The overall framework was to use geospatial data representing biophysical gradient variables combined with field-referenced data describing vegetation composition in a classification and regression tree-based approach to map potential vegetation type (Frescino and Rollins, Ch.7) and then incorporate Landsat imagery to map existing vegetation composition, density, and height (Zhu and others, Ch. 8).

We assumed that our accuracy in modeling these vegetation characteristics would be optimized by using biophysical gradient information, which included climatically derived variables related to physiological

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In: Rollins, M.G.; Frame, C.K., tech. eds. 2006. The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. Gen. Tech. Rep. RMRS-GTR-175. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

responses of vegetation composition and structure (Austin and Smith 1989). Although geospatial data describing biophysical gradients may exist in certain specific locations, we could not rely on the availability of these data across the nation at spatial scales that met the LANDFIRE design criteria of national consistency (Keane and Rollins, Ch. 3); therefore, we relied on simulation of biophysical gradient data. A number of biogeochemical simulation models and statistical techniques were available to estimate biophysical gradients across spatial domains (Keane and Holsinger 2006; Kessell 1979; Thornton and White 2000; Thornton 1998; White and others 1997). We chose to use the simulation model WXFIRE to develop biophysical gradient data because the model represents a balance of sophistication and computational efficiency. WXFIRE simulates a suite of gradients proven to describe both biotic and abiotic characteristics and processes that directly influence ecosystem composition, structure, and function (Keane and others 2002; Keane and Holsinger 2006; Rollins and others 2004).

We implemented the LANDFIRE methods in two large prototype areas to test the feasibility of national application of the LANDFIRE design criteria and guidelines. The study areas were based on mapping zones developed for the USGS Multi-Resolution Land Characteristics (MRLC) 2001 project (landcover.usgs.gov/index.asp). We first applied our methods to Zone 16, located in central Utah, and then, based on lessons learned, applied refined methods in Zone 19, located in the northern Rocky Mountains (see fig. 1 in Rollins and others, Ch. 2). Most of the biophysical gradient layers were derived using the WXFIRE simulation model implemented with data from the DAYMET weather database, which comprises daily weather data across the conterminous United States (Thornton and others 1997; Thornton and others 2002; Thornton and Running 1999). We also acquired or derived ancillary geospatial data for use as predictors in vegetation gradient modeling (for example, topography from the National Elevation Database). In this chapter, we describe our methods for creating the biophysical gradient layers, including the development of WXFIRE input and simulation procedures. We also describe the resulting biophysical gradient layers used for mapping potential vegetation type, existing vegetation, structural stage, and canopy fuel. (Frescino and Rollins, Ch. 7; Zhu and others, Ch. 8; Keane and others, Ch. 12). Further, the LANDFIRE biophysical gradient layers could potentially be applied in other land management purposes, such as hydrological studies or quantification of thermal cover for wildlife.

In the process of developing these protocols for the LANDFIRE Prototype Project, we identified numerous improvements that could be made to our methods, and we outlined a set of recommendations for future development of biophysical gradient layers. Hence, the methods described here do not necessarily reflect the protocols followed by LANDFIRE National (Rollins and others, Ch. 2).

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on the procedure followed in developing biophysical gradients, which served as spatial predictors in mapping models for nearly all mapping tasks in the LANDFIRE Prototype Project.

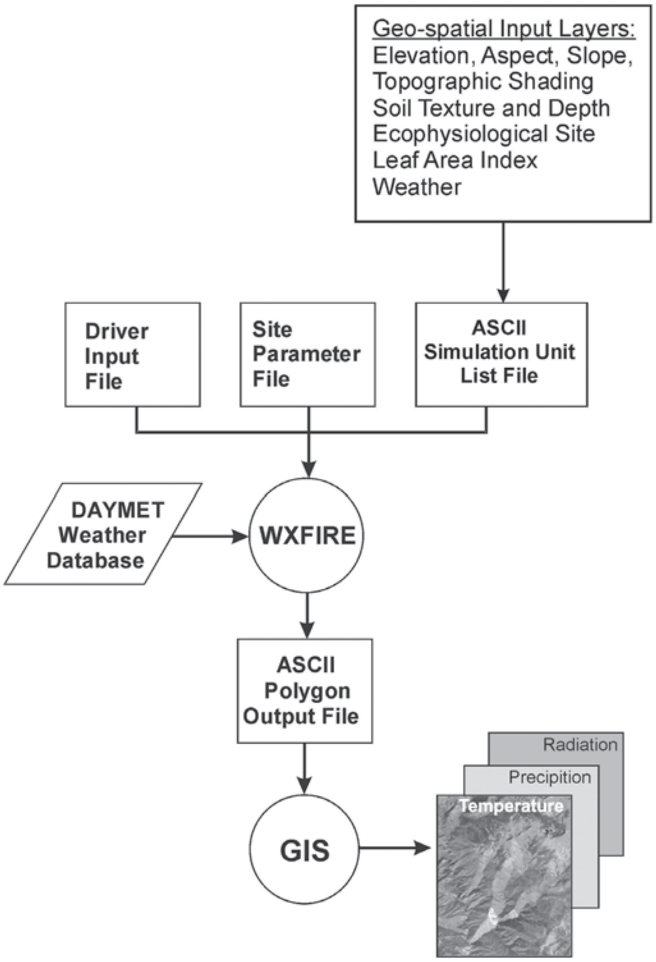


Figure 1—The flow and component diagram for the WXFIRE program.

Spatial Units used in Modeling

We applied numerous spatial units in creating biophysical gradients, ranging in spatial extent from large, regional mapping zones to simulation units of intermediate size to 30-m pixels. These various spatial units used in the WXFIRE modeling process require some initial explanation here for clarity. Detailed descriptions are provided in the following sections. At the broadest scale, we divided the U.S. into regional mapping zones ranging in size from five to fifteen million ha, and we applied our protocols to mapping zones 16 and 19, which were six and ten million ha, respectively. Next, the mapping zones were divided into simulation units representing unique environmental conditions for the purposes of estimating biophysical gradients using the WXFIRE simulation model. Simulation units were derived by combining the key spatial WXFIRE inputs such as soils data and topography. Simulation units ranged in pixel size from 0.09-ha to 575-ha in Zone 16 and 0.09-ha to 144-ha in Zone 19.

Another spatial unit was developed for describing biophysical settings. The WXFIRE model required a set of data representing specific ecophysiological parameters for landscapes (table 1). These parameters could have been included in the development of simulation units because they describe unique environmental conditions. However, WXFIRE requires so many parameters (45) that, for expediency in model simulations, those ecophysiological parameters are simply assumed to be relatively homogenous over fairly broad areas or across spatial units termed ecophysiological 'sites' (Keane and Holsinger 2006). For example, albedo is an ecophysiological parameter required by the WXFIRE model, and it should be relatively constant across many simulation units in a landscape for many days of the year. WXFIRE runs far more efficiently by assigning albedo (along with the other 44 ecophysiological parameters) to a site, rather than determining unique parameter values for every simulation unit. Typically, one site encompasses many simulation units. As such, we identified ecophysiological sites across our mapping zones and then assigned unique values to all ecophysiological parameters for each site. The sites ranged in size from 6.25 to 4.6 million ha in Zone 16 and 6.25 to 2.2 million ha in Zone 19.

Overview of the Modeling Process

We developed biophysical gradient layers in several steps for each mapping zone (fig. 1). First, we collected and modified various topographic, soil, weather, and vegetation-related layers and grouped the values in these layers into classes to improve the computational efficiency of the model. We then partitioned each mapping zone into simulation units by spatially combining all of the classified input layers (fig. 1; table 2). That is, each unique spatial combination of the values for the input layers identified a distinct simulation unit. Next, we assembled the three input files needed to run WXFIRE, including: 1) the simulation unit file containing soil, topographic, weather, and vegetation-related data for all the simulation units in a mapping zone (*simulation unit list file*) (fig. 2); 2) a file specifying general simulation options (*driver file*), such as time frames for summarizing data; and 3) a parameter file describing the ecophysiological site conditions (*site file*). We then ran WXFIRE simulations and produced tabular data of biophysical gradients for each simulation unit. Finally, we linked the tabular data to the spatial layer of simulation units to create geospatial biophysical gradient layers for each mapping zone. In the following sections, we briefly discuss the WXFIRE and DAYMET computer models used to generate biophysical gradients and then cover in detail our process for developing those layers.

Computer Models for Developing Biophysical Gradient Layers

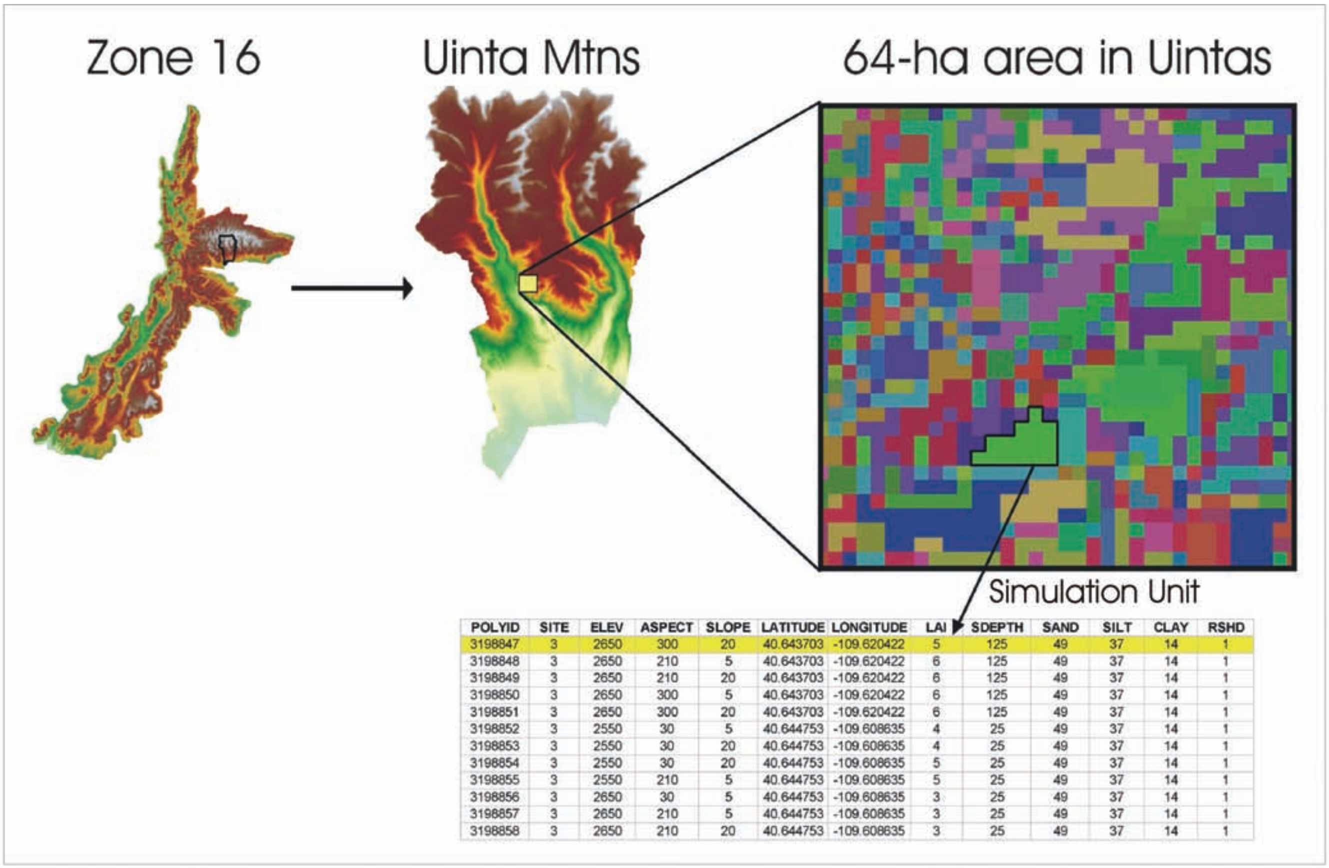
The WXFIRE model was developed with the goal of employing standardized and repeatable modeling methods to derive spatially explicit, climate-based biophysical gradients for predictions of landscape characteristics related to ecosystem management (Keane and others 2002; Rollins and others 2004). Keane and others' (2002) first model, WXGMRS, was built for a spatially explicit gradient modeling application called the Landscape Ecosystem Inventory System. The next generation of this model, WXFIRE, was used for creating biophysical gradient layers in the LANDFIRE Prototype Project (Keane and Holsinger 2006). The WXFIRE model is designed for simulating biophysical gradient data at any geographic extent or spatial resolution using spatial data layers of daily weather, soils, topography, leaf area index, and a suite of ecophysiological parameters. The WXFIRE model produces a broad array of biophysical gradients that can be categorized into two general types: 1) weather and climate variables and 2) ecosystem variables. The weather variables describe daily weather conditions (maximum daily temperature), whereas the climate variables summarize weather conditions over broader temporal periods (decades) to describe the climatic regime of the study area (for example, solar radiation flux to the ground). The ecosystem variables describe how climate variables interact with vegetation.

Table 1—Parameters required in the ecophysiological site input file for WXFIRE (Keane and Holsinger 2006) for a montane site (1,800 – 2,700 m) in Zone 16.

Ecophysiological parameter	Units	Value
Julian date of start of pre-greenup period	Jday	135
Julian date of initiation of greenup period	Jday	149
Julian date of end of greenup period	Jday	190
Julian date indicating live fuels are frozen	Jday	300
LAI of the site in m2/m2	m^2/m^2	2.5
LAI conversion factor	index	3.54
Extinction coefficient	index	0.48
Rainfall interception coefficient	index	0.0005
Average site albedo (dim) for climax stand	index	0.18
Leaf water potential at stomatal opening	-MPa	-0.5
Leaf water potential at stomatal closure	-MPa	-1.65
Min vapor pressure deficit stomatal opening	Pa	500.0
Max vapor pressure deficit stomatal closure	Pa	4100.0
Maximum canopy conductance	m sec^{-1}	0.0065
Leaf boundary layer conductance	m sec^{-1}	0.0865
Leaf cuticular conductance	m sec^{-1}	0.00001
Maximum live foliar moisture content	percent	200.0
Minimum live foliar moisture conten	percentt	80.0
DBH of reference tree	cm	50.0
Bark conversion factor	cm bark/cm dbh	0.05
Live crown ratio	percent	50.0
Tree height	meters	25.0
Initial fuel moisture content - 1-hr woody	percent	20.0
Initial fuel moisture content - 10-hr woody	percent	20.0
Initial fuel moisture content - 100-hr woody	percent	25.0
Initial fuel moisture content - 1000-hr woody	percent	30.0
Initial fuel moisture content - live foliage	percent	120.0
Initial fuel moisture content - litter	percent	100.0
Initial fuel moisture content - duf	percent	150.0
Initial fuel moisture content - shrub	percent	100.0
Initial fuel moisture content - herb	percent	140.0
FOFEM cover type ID number	code	11
NFDRS fuel model number (a=1...z=26)	code	12
FBFM ID number from Anderson et al. (1982)	code	10
FLC fuel loading model ID number	code	122
Elevation of site	meters	2500.0
Aspect of site	degrees	180.0
Slope of site	percent	10.0
Latitude of site	decimal-deg	45.12345
Longitude of site	decimal-deg	120.12345
Depth of soil defining free rooting zone	meters	1.0
Percent sand in soil profile in FRZ	percent	50.0
Percent silt in soil profile in FRZ	percent	30.0
Percent clay in soil profile in FRZ	percent	20.0
Average wind speed	m sec^{-1}	10.0
Topographic shading reduction factor	m sec^{-1}	1.00

Table 2—Spatial input data for developing simulation units for the WXFIRE simulation model.

Layer name	Description	Data scale or resolution	Source
Aspect	Direction of exposure in azimuths	30-m pixel	Derived (ESRI 2002)
DAYMET	Daily weather data	1-km pixel	Derived (Nemani et al. 1993)
Elevation	Digital Elevation Model (DEM) (m)	30-m pixel	Thornton et al. 1997
LAI	Leaf area index	30-m pixel	USGS 2002
Percent sand	Percent of sand in soil	1:250,000	SCS 1991
Percent silt	Percent of silt in soil	1:250,000	SCS 1991
Percent clay	Percent of clay in soil	1:250,000	SCS 1991
Shading	Ecophysiological site conditions	30-m pixel	Derived (ESRI 2002)
Site	Topographic shade index	30-m pixel	DEM & USGS NLCD
Slope	Slope derived from DEM in percent	30-m pixel	Derived (ESRI 2002)
Soil depth	Soil depth to bedrock (cm)	30-m pixel	Derived (Zheng et al. 1996)



POLYID	SITE	ELEV	ASPECT	SLOPE	LATITUDE	LONGITUDE	LAI	SDEPTH	SAND	SILT	CLAY	RSHD
3198847	3	2650	300	20	40.643703	-109.620422	5	125	49	37	14	1
3198848	3	2650	210	5	40.643703	-109.620422	6	125	49	37	14	1
3198849	3	2650	210	20	40.643703	-109.620422	6	125	49	37	14	1
3198850	3	2650	300	5	40.643703	-109.620422	6	125	49	37	14	1
3198851	3	2650	300	20	40.643703	-109.620422	6	125	49	37	14	1
3198852	3	2550	30	5	40.644753	-109.608635	4	25	49	37	14	1
3198853	3	2550	30	20	40.644753	-109.608635	4	25	49	37	14	1
3198854	3	2550	30	20	40.644753	-109.608635	5	25	49	37	14	1
3198855	3	2550	210	5	40.644753	-109.608635	5	25	49	37	14	1
3198856	3	2650	30	5	40.644753	-109.608635	3	25	49	37	14	1
3198857	3	2650	210	5	40.644753	-109.608635	3	25	49	37	14	1
3198858	3	2650	210	20	40.644753	-109.608635	3	25	49	37	14	1

Figure 2—Example of WXFIRE simulation units for a small landscape in the Uinta mountains of Zone 16 and associated WXFIRE tabular input, including: simulation unit identifier (POLYID), ecophysiological site (SITE), elevation (ELEV), aspect, slope, geographic coordinates for weather, LAI, soil depth (SDEPTH), percents sand, silt and clay, and topographic shading (RSHD).

For example, actual evapotranspiration can describe the moisture available for vegetation development much better than average annual precipitation because it integrates phenology, temperature, and soil water dynamics. Keane and Holsinger (2006) provide extensive documentation of WXFIRE, including structure and formats of all input and output files, complete descriptions of all model algorithms, and guides on preparing and executing the program.

DAYMET is a computer model that extrapolates daily spatial surfaces of temperature, precipitation, radiation, and vapor pressure deficit across large regions (Thornton and others 1997, Thornton and others 2002; Thornton and Running 1999). The DAYMET model requires digital elevation data, minimum and maximum temperature, and precipitation from ground-based meteorological stations. The DAYMET model extrapolates station-based weather data across broad regions using a spatial convolution method with a truncated Gaussian weighting filter (Thornton and others 2002). The DAYMET weather database was compiled for the entire nation using over 1,500 weather stations and served as a key input to the WXFIRE model. The DAYMET weather database contains gridded 1-km resolution daily data for daily minimum and maximum temperature (°C), precipitation (cm), solar radiation (W m^{-2}), and vapor pressure deficit (percent) from 1980 to 1997. At this time, the DAYMET model is unique in its ability to provide data at a temporal (18 years of daily data) and spatial (1-km) resolution across the conterminous U.S.

Input Layers for Developing WXFIRE Simulation Units

This section details the process used to create the spatial data input layers required by WXFIRE (fig. 1). Specifically, we describe the procedures used to synthesize information from existing spatial data layers, including a suite of terrain-related layers and layers of soils, leaf area index, weather and ecophysiological site. These input layers were subsequently used to develop simulation units and to compute the attributes for each simulation unit required as input into the WXFIRE model (table 2).

Developing terrain-related input layers—We classified continuous data describing slope, aspect, and topographic shading as input to the WXFIRE model. Each layer was derived using digital elevation models (DEM) from the National Elevation Database (http://edc.usgs.gov/products/elevation/ned.html) and standard algorithms for deriving topographic derivatives. We calculated slope as the rate of maximum change in a DEM from each cell relative to its neighbors using a 3x3 grid cell neighborhood and an average maximum technique (Burrough 1986; ESRI 2002). Aspect was calculated by identifying the direction of maximum rate of change in a DEM between each cell and its neighbors (ESRI 2002). The topographic shading layer represented how direct radiation to a landscape area was attenuated by the surrounding high topography. The topographic shading layer was created by developing a shaded relief grid from a DEM, projecting an artificial light source onto the surface, and determining reflectance values. Solar azimuth and altitude for the sun's position were required inputs for this process. We calculated azimuth and altitude using the National Oceanographic and Atmospheric Association Solar Position calculator (http://www.srrb.noaa.gov/highlights/sunrise/azel.html, assuming the summer solstice as the date and using the center coordinates for each mapping zone.

Developing soil-related input layers—WXFIRE required soil texture (percent) and soil depth (m) as input for each simulation unit. Soil texture was derived using the State Soil Geographic (STATSGO) geo-spatial data, which is composed of digitized polygons from 1:250,000 scale state soil maps (Natural Resources Conservation Service or NRCS 1995a). We explored the finer-scale Soil Survey Geographic (SSURGO) data but found that SSURGO has incomplete coverage across the two prototype regions and would not provide sufficient soils information for the national LANDFIRE mapping effort (NRCS 1995b). The STATSGO data structure consists of soil polygons, where each polygon has associated descriptions of soil sequence and soil layers in tabular format. Soil sequence represents the dominant kinds of soils (up to three taxonomic classes) contained in a polygon. Geographic locations for these soil sequences are not available but are instead represented as percents for each soil polygon. Soil information for the STATSGO polygons includes vertical composition (soil horizons) (up to six layers) for each soil sequence (soil taxonomic class).

The WXFIRE model required that soil texture be described in terms of percent sand, silt, and clay (Keane and Holsinger 2006). These data are not directly defined in the STATSGO attribute list but can be extracted from the database based on variables describing the percent by weight of particles passing through various sieve sizes and percent clay content (Thornton and White 2000). We first calculated four soil textures from the STATSGO database, including coarse fragment content and percent sand, silt, and clay. We computed the

Table 3—Soil texture calculations based on STATSGO attributes that describe the percent by weight of particles passing through various sieve sizes and percent clay content (Thornton and White 1999).

Soil texture	Equation using STATSGO attributes
Coarse fragment content	Percent passing No. 10 sieve
Percent sand	Percent passing No. 10 sieve – Percent passing No. 200 sieve
Percent clay	Percent clay weighted by percent passing No. 200 sieve
Percent silt	Percent passing No. 200 sieve – (percent clay – percent passing No. 10 sieve)

four soil textures according to criteria for soil particle variables, described in table 3, using a script for SAS software (SAS System for Windows 2001). STATSGO data provides only high and low values for these attributes by soil sequence and layer. We calculated an average for each of the soil textures, for example, percent sand = (No. 10 sieve high + No. 10 sieve low) / 2 – (No. 200 sieve high + No. 200 sieve low) / 2, and weighted the STATSGO variables by the layers' depths and by the aerial extent of sequences within STATSGO polygons. Since the WXFIRE model requires measures of percent sand, silt, and clay only, we removed the coarse fragment proportion from the composition of soil textures and rescaled the sand, silt, and clay components to comprise 100 percent of soil texture estimates. Our final results from this analysis were estimates of percent sand, silt, and clay for each of the STATSGO polygons in a mapping zone.

The soil depth layer was also derived using STATSGO data, but we modeled soil depth to a higher resolution using DEM data and hydrologic modeling. For this process, we first extracted the maximum depth per soil sequence from the STATSGO database and weighted these values by their aerial extent to calculate a maximum soil depth per polygon. We then calculated a topographic convergence index (TCI) for each pixel using the following relationship provided by Beven and Kirkby (1979):

$$TCI = \ln\left(\frac{a}{\tan B}\right)$$

where a is the upslope area (m^2) draining past a certain point per unit width of slope and is calculated by accumulating the weight for all cells that flow into each down-slope cell (ESRI 2002; Jenson and Domingue 1988; Tarboton and others 1991) and B is the local surface slope angle (degrees) calculated from a 3x3 grid cell neighborhood using an average maximum technique (Burrough 1986; ESRI 2002). Using methods developed by Zheng and others (1996), we integrated the STATSGO maximum depth layer (STATGO Max Depth) and TCI data to calculate a soil depth value for each pixel using scalars to adjust for skewed TCI distributions as follows:

$$\text{Soil depth} = \{M1, M2\} * TCI$$

where M_1 is the scalar used if a pixel's TCI value was less than or equal to its mean across a mapping zone and was calculated by:

$$M1 = \frac{\text{Ave. Max. Depth}}{0.5 * (LN_{mo} + LN_{me})}$$

where Ave. Max. Depth is the mean value of the STATSGO maximum depth layer across each mapping zone, and LN_{mo} and LN_{me} are mode and mean values for the natural log of TCI. M_2 is the scalar used if a pixel's TCI value is greater than or equal to its mean across a mapping zone and is calculated by:

$$M2 = \frac{\text{Max. Depth}}{LN_{\max}}$$

where Max Depth is the STATSGO maximum depth layer for each polygon and $LN_{\max}$ is the maximum natural log of TCI.

For Zone 19, we revised this process to improve data resolution by including slope in calculations of soil texture and depth. The STATSGO database provides high and low slope values for each STATSGO polygon. We calculated an average slope and classified the average slope into four classes: (1) ≤4 percent; (2) >4 percent and ≤8 percent; (3) >8 percent and ≤15 percent; and (4) >15 percent (N. Bliss, personal communication). We extracted the soil texture and soil depth variables by these four slope classes from the STATSGO database. We used the slope geospatial layer (percent) previously described and then classified slope into the above four classes. We partitioned the STATSGO polygons by the classified slope layer and linked this spatial layer with the STATSGO variables of soil texture and depth by slope. For the final soil depth layer, we followed with the process described above for integrating STATSGO maximum soil depth with TCI to obtain soil depth values for each pixel. The final products were soil textures and soil depth—with improved resolution by incorporating slope into calculations. Note, improving the soil layers' resolution also contributed to a large increase in the number of records in the simulation unit file for Zone 19 from that of Zone 16.

Developing leaf area index and weather input layers—We generated leaf area index (LAI) from Landsat imagery (30-m pixel resolution) for leaf-on reflectance based on methods developed by Nemani and others (1993). We first calculated a corrected normalized difference vegetation index (NDVI) as follows:

$$NDVI_c = \left(\frac{NIR - RED}{NIR + RED}\right) * \left(1 - \frac{MIR - MIR_{\min}}{MIR_{\max} - MIR_{\min}}\right)$$

where NIR is near infrared (band 4), RED is infrared (band 3), MIR is mid-infrared (band 5), MIR_{min} is the minimum value in mid-infrared band in an open canopy, and MIR_{max} is the maximum value in the mid-infrared band in a closed canopy. We then converted the $NDVI_c$ layer to LAI according to the following equation:

$$LAI = \frac{\ln(0.7 - NDVIc)}{-0.7}$$

Developing the ecophysiological site input layer—For Zone 16, we delineated ecophysiological sites by partitioning the landscape by elevational breaks corresponding to major vegetation changes (for example, landscapes dominated by pinyon pine vs. Douglas-fir). The four sites in Zone 16 included:

Site 1 – Mohave (0 to 1,200 m mean sea level),
Site 2 – Sagebrush (1,200 to 1,800 m MSL),
Site 3 – Montane (1,800 to 2,700 m MSL), and
Site 4 – Subalpine (2,700+ m MSL).

We assigned values to the sets of ecophysiological variables for each site based on previous synthesis efforts (Korol 2001; Hessl and others 2004; White and others 2000). Table 1 shows the ecophysiological parameters and associated values for the Montane site in Zone 16.

For Zone 19, we used a less subjective approach where we developed sites using the U.S. Geological Service/U.S. Environmental Protection Agency National Land Cover Database (http://edcwww.cr.usgs.gov/programs/lccp/natllandcover) and biome types described for national-level ecosystem simulation (Thornton 1998). The National Land Cover Database contains 21 broad cover types, and we summarized these cover types into five general plant functional types and one non-vegetated class: water/barren (table 4). Each of these plant functional types represented a site, and we assigned a set

Table 4—Changes made to National Land Cover Database (NLCD) land cover class definitions for the LANDFIRE site map.

NLCD land cover class	LANDFIRE plant functional types
Open water	Water/barren
Perennial ice/snow	Water/barren
Bare rock/sand/clay	Water/barren
Quarries/strip mines/gravel pits	Water/barren
Transitional	Closest natural vegetation
Low intensity residential	Closest natural vegetation
High intensity residential	Closest natural vegetation
Commercial/industrial/transportation	Closest natural vegetation
Deciduous forest	Deciduous broadleaf forest
Evergreen forest	Evergreen needleleaf forest
Mixed forest	Majority of surrounding deciduous broadleaf forest or evergreen needleleaf forest
Orchards/vineyards/other	Deciduous broadleaf forest
Shrubland	Shrub
Grasslands/herbaceous	Grass
Pasture/hay	Grass
Row crops	Grass
Small grains	Grass
Fallow	Grass
Urban/recreational grasses	Grass
Woody wetlands	Deciduous broadleaf forest
Emergent herbaceous wetlands	Grass

of ecophysiological parameters to each site. The five main plant functional types were C3-grass, evergreen needle leaf forest, deciduous broadleaf forest, shrub, and barren/water. Areas classified as human development, such as urban and agriculture, were assigned a cover type based on the dominant cover type in neighboring pixels. Similarly, areas classified as mixed forest were recoded to either evergreen needle leaf forest or deciduous broadleaf forest based on the dominant forest type in surrounding pixels.

Development of WXFIRE Simulation Units and Model Input Files

Simulation units were developed by combining all 11 spatial data layers described above and detailed in table 2. Ideally (given the available data) we would have combined all input layers for every 30-m pixel to obtain the best resolution possible in the biophysical gradient layers. However, the LANDFIRE prototype mapping zones were very large and would have required the simulation of 284 million records for Zone 16 and 289 million records for Zone 19. Our computer resources were insufficient to process this amount of data in a timely manner. Instead, we reduced the data sets to 10 million and 26 million records for mapping zones 16 and 19, respectively, by classifying input layers to a coarser attribute measurement resolution. That is, we classified spatial layers so that their measurement increments were in broader ranges. Table 5 shows the classification scheme for each of the terrain, soil depth, and LAI layers. For example, slope was grouped into three classes of low, moderate, and high slope. Note that the soil texture layers (sand, silt, and clay) were already at a coarse spatial resolution, so we maintained them in their original form (1:250,000 scale) and did not summarize to a broader attribute measurement resolution.

To create the simulation units for executing WXFIRE, we combined the classified input layers (terrain, soil depth, LAI) with ecophysiological site, soil texture and weather layers such that each unique combination formed one simulation unit. Prior to combining these layers, we re-sampled all input layers to a 25-m pixel size such that each layer nested within the 1-km DAYMET weather data layer. Accordingly, each simulation unit was geo-referenced at a 25-m pixel size and had a series of associated input data. Figure 2 provides an example of WXFIRE simulation units developed for a landscape in the Uinta Mountains of Zone 16. As input to the WXFIRE model, we created an ASCII simulation unit list file that contained records for all the simulation units in a mapping zone along with their associated ecophysiological site identifiers, terrain data, geographic coordinates for weather (latitude and longitude), LAI, and soil values.

WXFIRE Model Simulation and Development of Biophysical Gradient Layers

Using the various input files, the WXFIRE model calculated a series of biophysical gradients for each simulation unit and output the results to ASCII files. We linked each record in the ASCII output files to their corresponding simulation units to create geospatial data representing the biophysical gradients output from WXFIRE. We implemented the WXFIRE model using average annual time frames to consistently measure biophysical gradients across large regions that may have variable growing seasons and to match temporal periods commonly used in other gradient modeling analyses (Waring and Running 1998).

In the initial WXFIRE runs, we retrieved the DAYMET weather data in the model simulations in its native 1-km format in an effort to maximize model efficiency. However, we discovered a strong gridded pattern in the biophysical gradient layers—a direct artifact of the coarsely gridded DAYMET weather maps (fig. 3A). We revised the WXFIRE program to scale the temperature and precipitation maps to a finer resolution using a moving window technique to calculate dynamic lapse rates (fig. 3B) (Keane and Holsinger 2006). The

Table 5—Methods used for classifying input layers to coarser attribute measurement resolution, implemented to reduce the number of input records and computer processing time.

Input layer	Classification method	Number of categories
Elevation	100-m intervals	30+
Aspect	SW (165° to 255°; NW (255° to 345°); NE (345° to 75°); SE (75° to 165°)	4
Slope	Low (<10%); moderate (10% to 30%) and high (≥ 30%)	3
Topographic shading index	Every 0.25 (index)	4
Soil depth	0.5-meter classes	4
LAI	1.0 LAI intervals	9

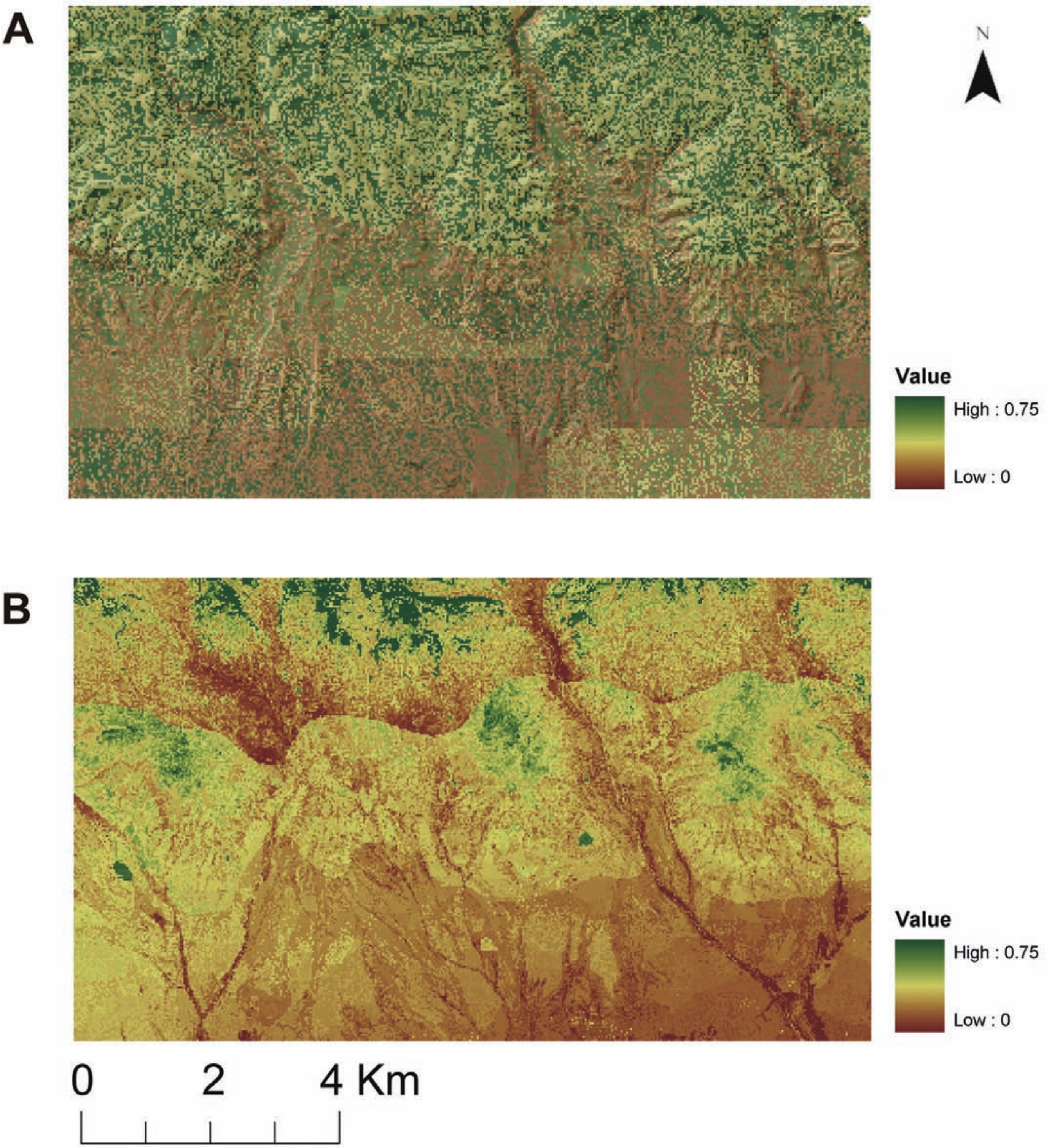


Figure 3—The biophysical gradient soil water fraction for an area in the Uinta mountains where: (A) shows results from initial model run using a static lapse rate calculation (the 1-km DAYMET footprint is particularly evident in southern area); and (B) shows final model run using dynamic lapse rates to scale down weather maps. Use of the dynamic lapse rate dramatically reduced the 1-km DAYMET footprint.

lapse rates were incorporated into linear regressions that adjusted the weather based on the difference in elevation between the coarse-scale DAYMET DEM and the elevation of the simulation unit. Solar radiation was also scaled to the simulation unit using geometric relationships of aspect and slope to sun zenith and azimuth angles (Keane and Holsinger 2006). We used the adiabatic lapse rate correction and the solar radiation adjustment in WXFIRE model runs for both mapping zones to minimize the DAYMET 1-km footprint pattern in output data layers, minimally affecting the efficiency of our model simulations and computational capacity.

Additional Topographic Layers for Gradient Modeling

Additional terrain-related layers were created as predictive layers for developing potential vegetation type, cover type, structural stage, and canopy fuel maps (Frescino and Rollins, Ch.7; Zhu and others, Ch. 8; Keane and others, Ch. 12). Although not part of WXFIRE input or output, we mention these layers in this chapter because they were important biophysical gradients for subsequent mapping applications. One of the terrain-related layers was topographic position index, which describes the exposure of a location in space compared to the surrounding terrain. Positive values expressed ridges or exposed sites, while negative values described sinks, gullies, valleys, or toe slopes. The topographic position index layer was developed using a moving window to describe relative location on a slope (Z. Zhang, personal communication). A topographic relative moisture index layer was developed to describe potential moisture conditions by combining relative slope position, slope configuration, slope steepness, and slope-aspect into a single scalar value based on methods defined by Haplin (1999) and Parker (1982). Finally, a landform layer was created based on reclassifying the topographic relative moisture index and slope. The landform layer described physiographic features such as valley flats, hills, and steep mountain slopes formed by erosion, sedimentation, mass movement, or glaciation (Neufeldt and Guralnik 1988).

Results and Discussion

Demonstration of Biophysical Gradient Layers

We developed thirty-one biophysical gradient layers from WXFIRE simulations to describe weather and climate variables and ecosystem variables (table 6). We created seven additional biophysical gradient layers describing topographic and soil conditions for use in subsequent vegetation and wildland fuel mapping (table 6). The mean, standard deviations, and ranges for each of the biophysical gradient variables in each mapping zone are presented in table 7.

Due to the large number of biophysical gradient layers that can be created by WXFIRE, we present only maps of a subset of the two variable types developed by WXFIRE: weather/climate variables and ecosystem variables. Average annual precipitation (cm) was an important weather/climate variable because it directly influences plant productivity and limits vegetation distributions (fig. 4). Another key weather/climate variable was degree-days, which reflects the heat load to a simulation unit (fig. 5). Potential evapotranspiration (kg H_2O yr^{-1}) is an example of an ecosystem variable modeled in WXFIRE (fig. 6). Potential evapotranspiration integrates temperature, precipitation, radiation, and relative humidity to estimate the maximum evapotranspiration through a vegetated surface. To better demonstrate the spatial patterns in the biophysical gradients, we also present a close-up view of important WXFIRE layers used in predicting potential vegetation type for forested areas of Zone 16 (fig. 7).

Limitations in Developing Biophysical Gradient Layers

The suite of biophysical gradient layers developed for the LANDFIRE Prototype Project must be considered in light of the limitations inherent to the simulation modeling process. Simulation modeling using WXFIRE was based on a set of algorithms that simplify and synthesize correlative relationships and mechanistic understandings of biophysical gradient variables (Keane and Holsinger 2006). The resulting geospatial data do not reflect direct and accurate measurements, but rather approximations of environmental conditions and ecosystem characteristics as they fluctuate across broad landscapes. Specifically, biophysical data developed using simulation modeling demonstrate the transition of biophysical gradients, emphasizing relative differences across large areas. In any given location, estimates for any one of the WXFIRE variables may not be particularly accurate; however, estimates will be consistently measured with high precision across landscapes. Care must therefore be taken to limit mapping applications to relative comparisons of variables across large landscapes and to forego expectation of spatial accuracy at any specific location. Keane and Holsinger (2006) present a detailed accuracy assessment of several WXFIRE weather outputs for several

Table 6—Biophysical gradients developed for the LANDFIRE Prototype Project, including weather, climate, and ecosystem variables simulated by the WXFIRE model and additional geographic variables.

Description	Biological significance
WXFIRE weather and climate variables	
Maximum daily temperature (°C)	Affects evapotranspiration and productivity
Minimum daily temperature (°C)	Limiting factor for plant tolerance
Precipitation (cm)	Directly affects productivity; limiting factor at lowest extreme
Average daily temperature (°C)	Affects evapotranspiration and productivity
Daytime daily temperature (°C)	Determines daily photosynthesis and respiration
Nighttime daily temperature (°C)	Important for dark respiration
Soil temperature (°C)	Affects water availability, soil respiration, nutrient availability
Relative humidity (%)	Determines photosynthesis and evapotranspiration rates
Total solar radiation (kJ m^{-2} day^{-1})	Directly affects photosynthesis
Solar radiation flux to the ground (KW m^{-2} day^{-1})	Dictates fuel moistures, duff moisture, understory response
Photon flux density in PAR (Umol m^{-2})	Incident photon flux density of photosynthetically active radiation
Days since last snow (days)	Good index of time that snow is on the ground
Days since last rain (days)	Index of precipitation environment
Degree-days (°C)	Reflects heat load at a stand
WXFIRE ecosystem variables	
Potential evapotranspiration (kg H_2O yr^{-1})	Potential evaporation and transpiration if no deficiency of water in the soil
Actual evapotranspiration (kg H_2O yr^{-1})	Water actually lost from plant surface due to evaporation and transpiration
Leaf-scale stomatal conductance (M sec^{-1})	Indicates how often stomates are open during the year
Leaf conductance to sensible heat (M sec^{-1})	Ability of foliage to transpire water
Canopy conductance to sensible heat (M sec^{-1})	Ability of canopy to transpire water
Soil water fraction (index)	Indicates amount of water available for plant growth
Water potential of soil and leaves (-MPa)	How tightly leaf holds moisture--high value indicates plant may be water stressed
Volumetric water content (Scalar)	Indicates soil moisture availability
Growing season water stress (-MPa)	Reflects extent of soil drying during the year
Maximum annual leaf water potential (-MPa)	Soil water availability and evapotranspiration
Snowfall (kg H_2O m^{-2} day^{-1})	Amount of snowfall aids in water balance for site
Soil water lost to runoff and ground (kg H_2O m^{-2} day^{-1})	Water that is not stored on-site for plant growth
Soil water transpired by canopy (kg H_2O m^{-2} day^{-1})	Amount of water lost from plants through their stomata by transpiration
Evaporation (kg H_2O m^{-2} day^{-1})	Indicates loss of water other than evapotranspiration
NFDRS - 1-hr wood moisture content (%)	Illustrates fine fuel moisture regime
NFDRS - 10-hr wood moisture content (%)	Illustrates large fuel moisture regime
Keetch-Byram Drought Index	Represents net effect of evapotranspiration and precipitation to produce cumulative moisture deficiency in deep duff and upper soil layers
Additional terrain and soils data	
Elevation (m)	Indirectly affects plant response to climate
Aspect (degrees)	Indirectly affects radiation, water, temperature
Slope (percent)	Indirectly affects soil water, radiation
Landform	Indirectly affects water storage
Topographic relative moisture index	Index reflecting ability of site to hold water
Topographic position index	Index describing topographic setting
Soil depth (cm)	Affects soil water availability

Table 7—Mean, standard deviation, minimum, and maximum values for biophysical gradients in mapping zones 16 and 19.

	Zone 16				Zone 19			
Parameters	**Mean**	**Std dev.**	**Min.**	**Max.**	**Mean**	**Std dev.**	**Min.**	**Max.**
Daily max. temperature (°C)	12.82	3.22	1.76	25.59	10.51	2.46	0.13	15.73
Daily min. temperature (°C)	–2.34	2.51	–11.99	7.95	–3.24	2.02	–12.13	1.96
Daily precipitation (cm)	58.12	20.45	19.49	234.12	64.24	30.32	20.05	282.96
Daily ave. temperature (°C)	5.24	2.82	–5.11	16.72	3.64	2.17	–5.39	8.46
Daily ave. daytime temperature (°C)	8.65	2.99	–2.02	20.69	6.73	2.28	–2.80	11.56
Daily ave. nighttime temperature (°C)	3.15	2.72	–7.00	14.31	1.75	2.11	–7.08	6.66
Daily ave. soil temperature (°C)	0.48	0.26	–0.46	1.52	0.33	0.20	–0.49	0.77
Relative humidity (%)	58.75	2.46	51.91	94.42	61.86	2.74	0.00	72.36
Total solar radiation (kJ m^{-2} day^{-1})	1,181.93	232.14	68.12	1,300.00	1,275.34	115.69	24.60	1,300.00
Solar radiation flux to the ground (KW m^{-2} day^{-1})	67.57	47.62	1.45	178.41	77.67	38.12	0.49	148.14
Photo flux density (Umol m^{-2})	2,426.40	403.88	154.97	2,600.00	2,563.84	197.05	0.00	2,600.00
Days since snowfall (days)	0.91	0.05	0.77	1.00	0.89	0.05	0.69	0.98
Days since rain (days)	1.43	0.17	0.92	1.86	1.32	0.12	0.00	1.63
Degree-days (°C)	2,985.47	819.01	586.67	6,831.58	2,544.67	567.04	641.29	3,878.23
Potential evaporation (kg H_2O yr^{-1})	1,478.25	166.85	434.12	1,997.15	1,120.80	164.02	0.00	1,563.33
Actual evapotranspiration (kg H_2O yr^{-1})	533.67	175.54	147.75	1,852.90	555.52	136.84	0.00	1,646.15
Leaf-scale stomatal conductance (M sec^{-1})	1,199.61	985.41	258.63	12,000.00	2,673.45	2,858.55	0.00	12,000.00
Leaf conductance to sensible heat (M sec^{-1})	9.31	0.36	7.90	10.34	16.43	10.42	9.02	96.40
Canopy conductance to sensible heat (M sec^{-1})	5.60	5.37	1.16	20.65	19.41	17.30	1.56	192.77
Soil water fraction (index)	0.38	0.09	0.04	0.86	0.30	0.16	0.00	0.89
Water potential of soil and leaves (-MPa)	–2.66	1.32	–9.82	–0.01	–4.57	2.58	–9.99	–0.01
Volumetric water content of soil (Scalar)	0.17	0.04	0.02	0.41	0.13	0.07	0.00	0.43
Growing season water stress (-MPa)	–165.70	124.58	–560.00	–0.38	–146.64	160.54	–560.00	–0.19
Maximum annual leaf water potential (-MPa)	–9.62	1.37	–10.00	–0.17	–9.50	1.84	–10.00	–0.10
Snowfall (kg H_2O m^{-2} day^{-1})	0.83	0.53	0.00	5.16	0.83	0.70	0.07	7.10
Soil water lost to runoff and groundwater (kg H_2O m^{-2} day^{-1})	0.18	0.30	0.00	5.57	0.38	0.64	0.00	29.74
Soil water transpired by canopy (kg H_2O m^{-2} day^{-1})	0.91	0.50	0.04	4.62	0.32	0.28	–27.69	3.27
Evaporation (kg H_2O m^{-2} day^{-1})	0.55	0.09	0.06	1.13	1.20	0.22	0.12	2.12
1-hour wood moisture content (%)	16.69	3.50	11.47	100.00	17.88	3.02	12.40	35.00
10-hour wood moisture content (%)	18.37	3.27	12.84	100.00	15.95	3.52	11.41	35.00
Keetch-Byram Drought Index	70.27	48.11	1.83	800.00	45.17	26.89	2.66	255.33

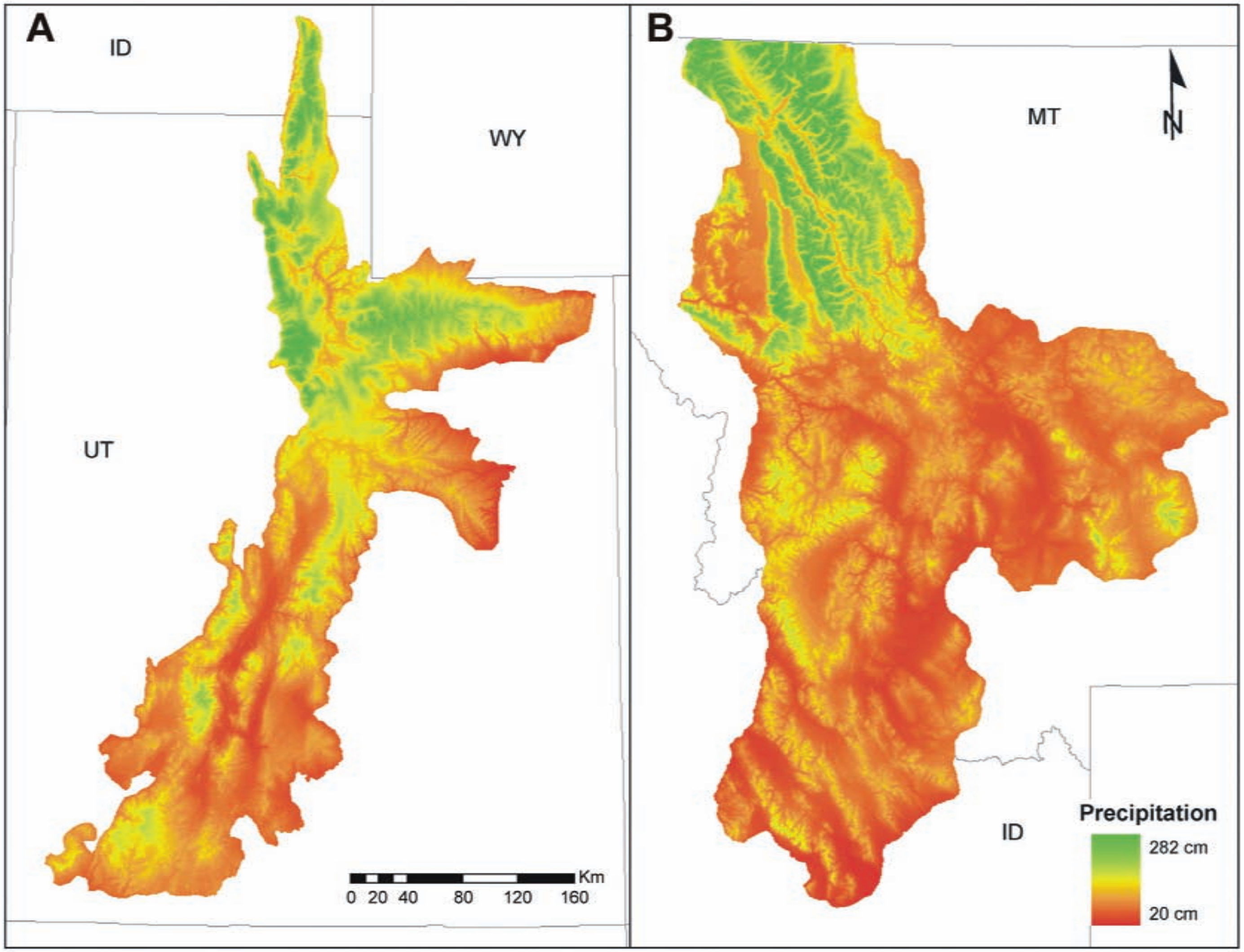


Figure 4—Average annual precipitation (cm) as simulated by WXFIRE for mapping zones 16 and 19.

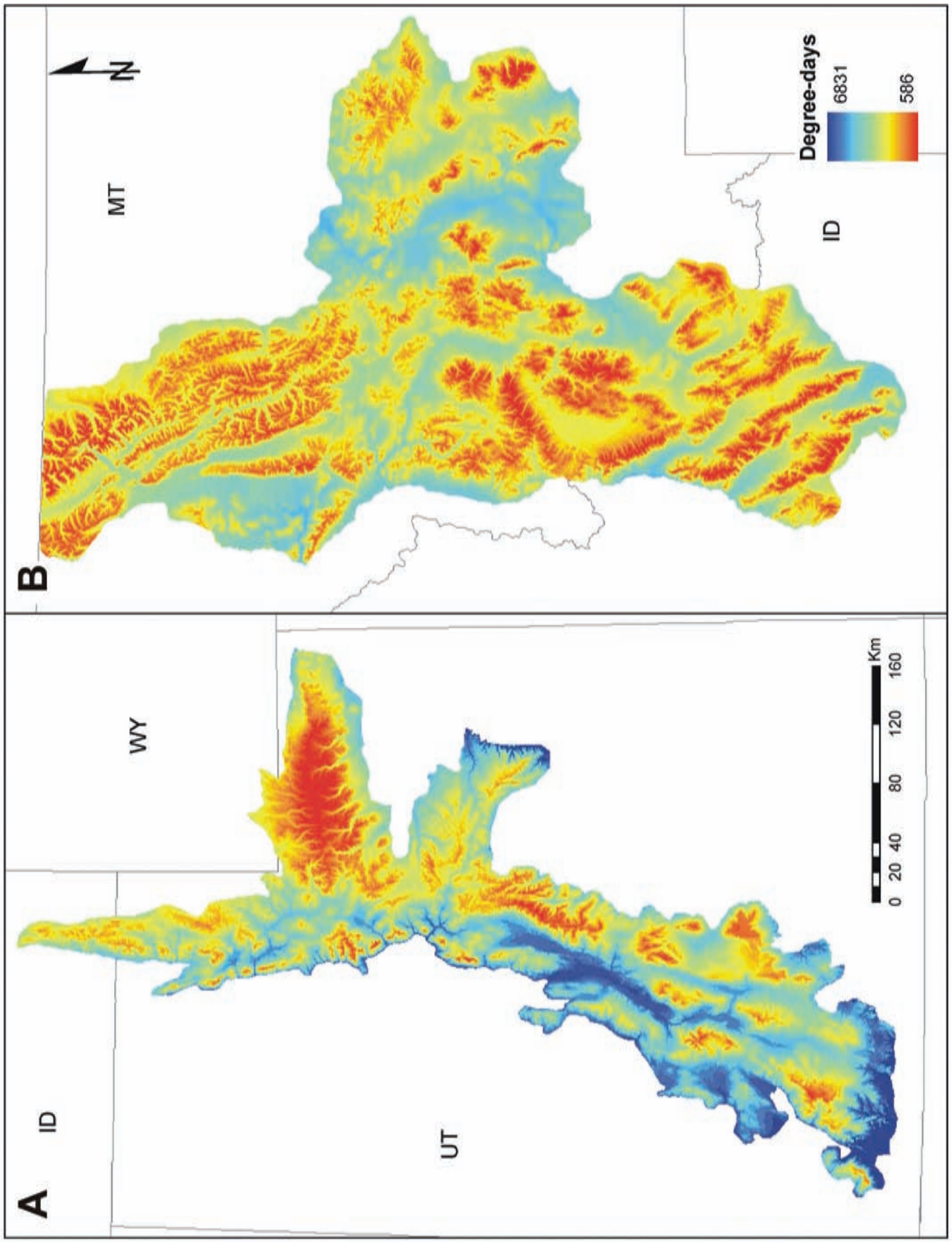


Figure 5—Degree-days (describing heat load of stand) as predicted by WXFIRE for mapping zones 16 and 19.

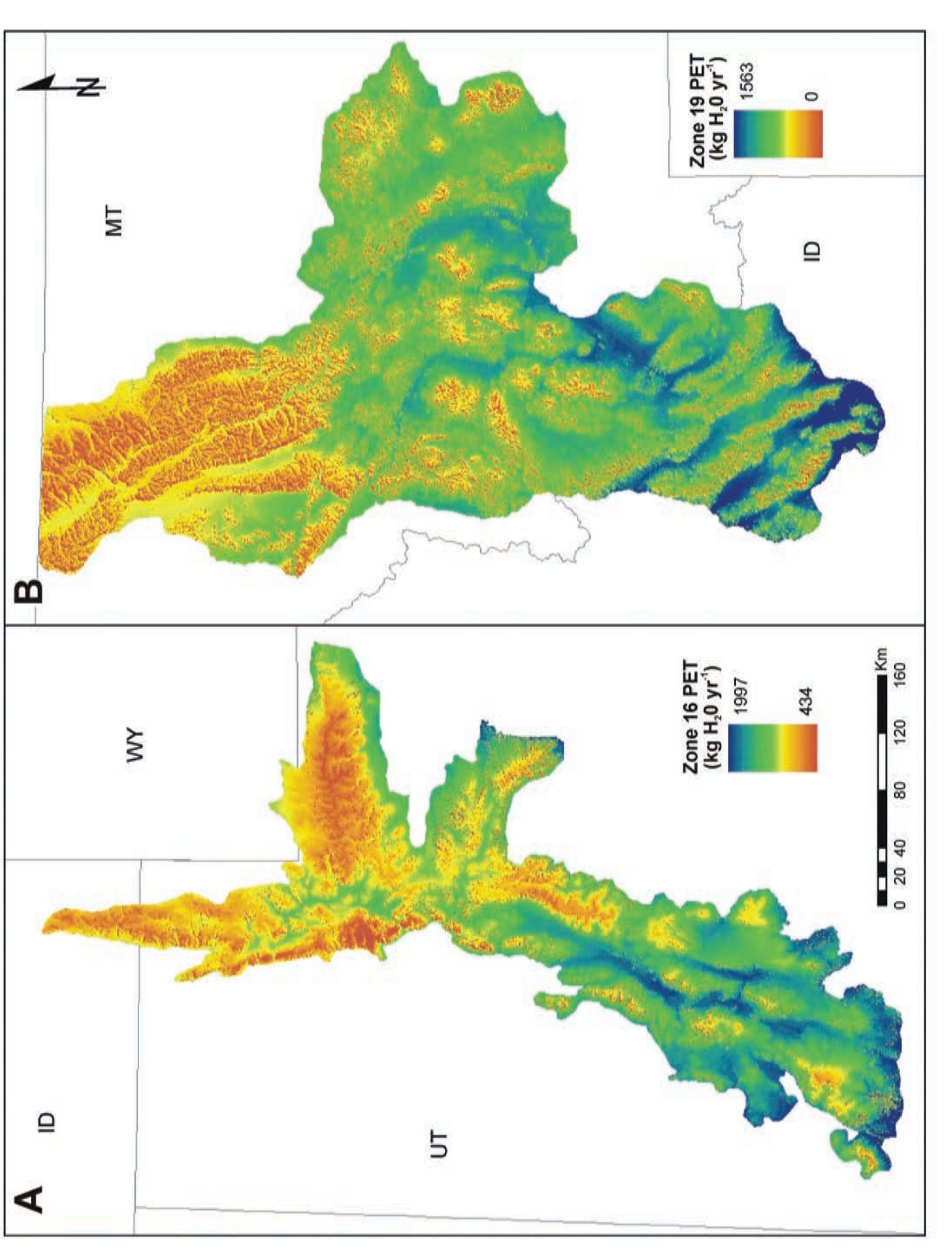


Figure 6—Potential evapotranspiration as predicted by WXFIRE for mapping zones 16 and 19.

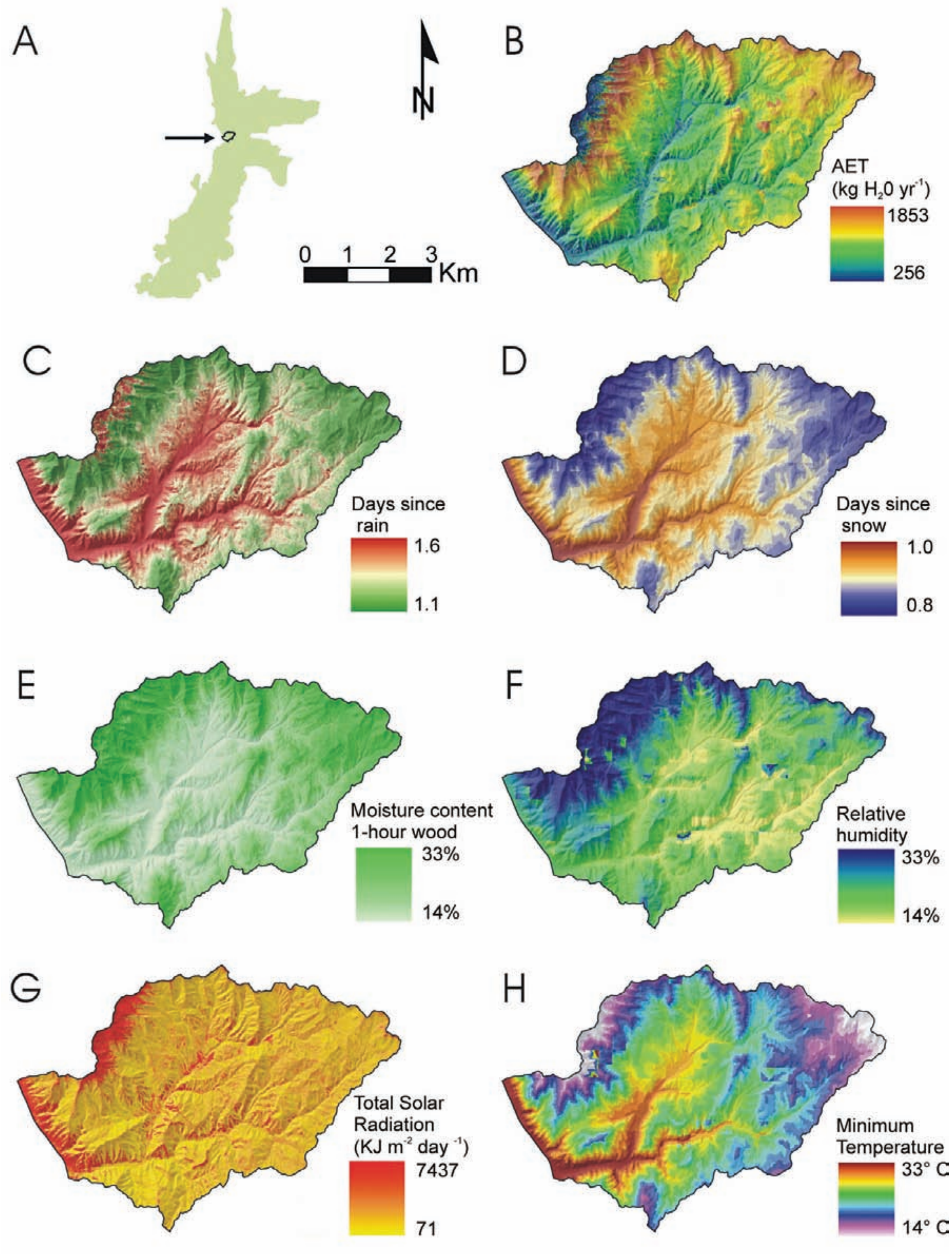


Figure 7—Higher resolution view of key WXFIRE layers used in predicting PVT for forested areas of Zone 16: (A) Zone 16 showing watershed of interest; (B) actual evapotranspiration; (C) days since rain; (D) days since snow; (E) moisture content of 1-hour wood; (F) relative humidity; (G) total solar radiation; and (H) minimum temperature.

landscapes in the two prototype mapping zones. They found that these biophysical gradients had a high level of precision but lacked a high degree of accuracy. WXFIRE model predictions were limited most by the difficulty of accurately quantifying the simulation units and site parameters due to the low quality and consistency of available GIS layers (Keane and Holsinger 2006).

The quality of biophysical gradient data was also constrained by the interpolation of weather data by the DAYMET model and by the integration of that weather data into biophysical gradient estimates. The WXFIRE model relies strongly on predictions of the DAYMET weather model. The DAYMET model offers extensive weather data for the conterminous United States at a high mapping resolution; however, it has limited spatial accuracy and temporal depth (Thornton and others 1997). In many parts of the country, weather stations are scarce, and this sparse distribution reduces the DAYMET model's ability to accurately interpolate weather between stations. In addition, the DAYMET data set spans 18 years (1980-1997), which, although substantial, is relatively short for generalizing the variability in weather patterns over time. For example, if our weather data set extended back one hundred years, we would have data from the drought years of the 1930s and relatively wet years of the 1950s. If such an extensive climate data set were available, spatial variability would likely be different in our suite of biophysical gradient layers—particularly for parameters calculated using non-linear equations, such as actual evapotranspiration (Keane and Holsinger 2006). An 18-year period possibly captured the range of variability in weather for some locations, but in other areas, this narrow time window may reflect only a relatively homogenous weather period, missing the full magnitude of variability.

Additionally, the WXFIRE model calculates weather outputs as annual averages (in other words, data were summed across daily values in a year and averaged across 18 years), which was not the ideal approach for predicting plant species distribution. Plant phenology most closely corresponds to seasonal or daily changes in weather conditions (White and others 2000), not annual time periods. However, the appropriate seasonal or daily time frames that affect vegetation dynamics will vary across regional landscapes. For example, the primary growing season of whitebark pine in alpine habitats ranges from approximately July to October, while sagebrush communities, on average, range from April to October. We used annual time period to capture the potential range of all plant species in a mapping zone; however, with weather data generalized to the coarser annual time frame, the resulting biophysical gradients were less robust for predicting vegetation distributions.

Another limitation in the development of the biophysical gradients for the LANDFIRE Prototype Project is related to the issue of scale, both in terms of spatial resolution and attribute measurement resolution. Our goal was to produce moderate resolution spatial data, which for the biophysical data layers, corresponds roughly to a 30-m resolution. The biophysical gradient layers produced for mapping zones 16 and 19 had a pixel size of 30-m, but the actual spatial resolution of the simulated data was much coarser. The reduced spatial resolution was a result of the limited availability of high resolution input layers for WXFIRE and limited computer resources. We chose only those geospatial data sources that were complete and contiguous across the conterminous United States. The base data layers used to create the WXFIRE input files had a wide variety of spatial resolutions and mapping scales. Weather and soil texture data for the nation were available only at spatial resolutions greater than 30-m. Other input layers were available at a 30-m resolution (for example, topographic data) but could not be fully utilized because we lacked the computer resources to execute model simulations for the large amount of records created at these fine resolutions. Consequently, we classified our finer-scale data layers to broader ranges in their measurement increments leading to coarser attribute measurement resolution. We also assumed that ecophysicological sites were homogenous across broad landscapes and thereby omitted smaller patches in the gradient patterns, decreasing spatial resolution. Moreover, WXFIRE was constructed, for lack of alternatives, under the assumption that the ecophysiological parameters match the simulation units in spatial and temporal scale (Keane and Holsinger 2006), which is rarely true. For example, maximum canopy conductance derived from the ecophysiological site layer has a significantly coarser resolution than terrain-related data.

The true resolution of these biophysical gradient layers was difficult to determine for several reasons. First, the core data layers that were used as input to the WXFIRE model were of varying resolution. Second, the WXFIRE model integrated multiple algorithms and equations for calculation of each biophysical gradient layer. Third, WXFIRE required additional ecophysiological site parameters for simulation—also at varying resolutions. We can illustrate the difficulty in assessing resolution from these compounding influences with the example of potential evapotranspiration (kg H_2O yr^{-1}) calculation. Calculations of potential evapotranspiration required data from six input layers: DAYMET weather, elevation, aspect, slope, ecophysiological site (albedo and others, see Keane and Holsinger 2006), and topographic shading (table 8). The original resolution of these input layers ranged from 30 m to 1 km, although the terrain-related layers (elevation, aspect, slope, and topographic shading) were classified to coarser attribute measurement resolutions (table 5). Actual simulation of potential evapotranspiration involved calculating several variables as inputs to a complex algorithm, and these variables represent processes which introduce additional modifications to data resolution. Specifically, weather data were interpolated from stations across the mapping zone in the DAYMET weather database. These weather data were also scaled down from 1-km data to the simulation unit, and the extent of scaling varied depending on size of the simulation unit. Finally, the actual algorithm to calculate potential evapotranspiration required the input of ecophysiological parameters of varying scale. For example, the ecophysiological parameter albedo can vary over small distances in real landscapes and over short time spans as species change due to phenology. However, we mapped albedo over large areas for broad categories of vegetation types that were considered static instead of dynamic. Overall, the resulting spatial resolution of the potential evapotranspiration layer depended on the integration of all the multiple data inputs and individual processing steps. Perhaps the best method for assessing data resolution would be through accuracy assessments using field-based data. However, observed data for potential evapotranspiration and other ecosystem, weather, and climate WXFIRE variables were not available. The effect of data resolution could also be assessed using sensitivity analysis such as Monte Carlo simulation, and such analyses would be worthwhile to perform in the future. In an effort to inform some understanding of the scale of the data layers, we have presented the data inputs required for modeling each of the biophysical gradients (table 8), the associated data resolution or scale for these input layers (table 2), and the classification scheme of input layers (table 5).

Recommendations for National Implementation

Many of the decisions made in the LANDFIRE Prototype Project aimed to minimize computation time while maintaining information content. Without constraints, it would be ideal to model each 30-m pixel on the landscape. For the LANDFIRE Prototype, however, that would have been intractable due to limited resources, the number of processes required, and narrow time-frames. For instance, we classified input layers and grouped pixels with similar values to create broad simulation units so that the model could be run one time and the outputs applied to many pixels. The overall scheme of this classification and creation of unique simulation units was sufficient, but the details implemented contained some flaws, such as in the soil depth layer's derivation and the DAYMET weather grid inclusion for creating simulation units. We suggest making changes to various phases of the biophysical gradients creation process to increase the quality of output while working within the general simulation framework developed during the LANDFIRE Prototype Project.

Improving Simulation Models

Early in the LANDFIRE Prototype Project, we explored using an ecosystem process model called LF-BGC, in addition to the WXFIRE simulation model (Thornton 1998). LF-BGC is a version of Biome-BGC adapted for the LANDFIRE Project that simulates carbon, water, and nitrogen fluxes to simulate a set of carbon budget metrics and ecophysiological characteristics. The version of LF-BGC available for the LANDFIRE Prototype Project, however, was designed primarily to produce biophysical gradient layers at a 1-km resolution, based on the scale objectives of Biome-BGC. We attempted to create higher-resolution biophysical gradient layers (30 m) by using higher-resolution inputs but discovered that more sophisticated model modifications were needed. A subsequent version of the LF-BGC model was developed that successfully creates higher-resolution biophysical gradient layers. Due to time constraints, however, we were unable to develop the layers with this new version. For the national implementation of LANDFIRE, we recommend incorporating the LF-BGC model to develop a more extensive set of biophysical gradient layers.

The LF-BGC and WXFIRE simulation models have many similarities, including file input, processing, and biophysical gradient output, and we suggest that the two models be combined into a single model executable for the national implementation of LANDFIRE. A number of factors should make this combination straightforward and a logical step towards optimizing model efficiency. First, both LF-BGC and WXFIRE are written in the C+ programming language and contain many equivalent calculations. Second, LF-BGC and WXFIRE have similar required inputs, differing in that WXFIRE requires more physical site information: slope, aspect, and hillshade. These three variables predominantly control the scaling of incoming radiation and its derivatives. Third, both models extract DAYMET weather data—the most time-consuming and process-intensive

Table 8—Data inputs used by WXFIRE to model each of the biophysical gradients. Note: units for each of the biophysical gradient variables are provided in table 7. Diamonds indicate that the input variable was applied in the calculation of the WXFIRE output variable.

WXFIRE variable	DAYMET	Elevation	Aspect	Slope	Soil depth	Soil texture	LAI	Site	Topo. shading
Soil water transpired by canopy	◆	◆	◆	◆	◆	◆		◆	◆
Soil water fraction	◆	◆	◆	◆	◆	◆		◆	◆
Daily maximum temperature	◆	◆							
Daily precipitation	◆	◆					◆	◆	
Daily minimum temperature	◆	◆							
Relative humidity	◆								
Daily average temperature	◆	◆							
Daily average soil temperature	◆	◆							
Daily average daytime temperature	◆	◆							
Daily average nighttime temperature	◆	◆							
Corrected average daily radiation	◆		◆	◆				◆	◆
Shortwave radiation	◆		◆	◆			◆	◆	◆
Photo flux density	◆		◆	◆			◆	◆	◆
Days since snowfall	◆	◆					◆	◆	
Days since rain	◆	◆					◆	◆	
Potential evapotranspiration	◆	◆	◆	◆				◆	◆
Actual evapotranspiration	◆	◆	◆	◆	◆	◆	◆	◆	◆
Degree-days	◆	◆							
Leaf-scale stomatal conductance	◆	◆	◆	◆	◆	◆		◆	◆
Leaf conductance to sensible heat	◆	◆	◆	◆	◆	◆		◆	◆
Canopy conductance to sensible heat	◆	◆	◆	◆	◆	◆		◆	◆
Volumetric water content of soil	◆	◆	◆	◆	◆	◆	◆	◆	◆
Growing season water stress	◆	◆	◆	◆	◆	◆	◆	◆	◆
Water potential of soil and leaves	◆	◆	◆	◆	◆	◆	◆	◆	◆
Maximum annual leaf water potential	◆	◆	◆	◆	◆	◆	◆	◆	◆
Snowfall	◆	◆							
Soil water lost to runoff & groundwater	◆	◆	◆	◆	◆	◆	◆	◆	◆
Evaporation	◆	◆	◆	◆	◆	◆	◆	◆	◆
1-hour wood moisture content	◆	◆	◆	◆				◆	
10-hour wood moisture content	◆	◆	◆	◆				◆	
Keetch-Byram Drought Index	◆								

step for executing either model. If the two models were combined, this call to DAYMET would only occur once. Fourth, the ecosystem variables (see table 6) calculated in WXFIRE are dependent on a site file and LAI data that both represent current land cover. The same (and more) ecosystem variables are output from LF-BGC, and, by combining models, we would no longer require current land cover information.

The process of combining WXFIRE and LF-BGC should be relatively seamless and significantly improve model outputs and efficiency. The unique variables output by WXFIRE, namely the climate derivatives, can readily be added to the LF-BGC model. This procedure can be done with minimal change to the core LF-BGC program and without affecting the stand-alone output. This proposed combination of the models would remove a major source of problems and error and virtually cut simulation times and computing resource needs in half.

In addition to combining the models, we suggest a change in the way that LF-BGC is parameterized and executed. During exploratory simulations, LF-BGC was run with the evergreen needle leaf forest plant functional type (PFT) across simulation units in Zone 16. Our goal in using this model was not to calculate the actual net primary productivity (NPP), but to represent the relative differences in potential NPP across landscapes in order to delineate unique biophysical settings. We chose to simulate the PFT with the narrowest ecological amplitude to maximize the information content of the output and selected only one to remain within our deadlines. This logic could be applied for most areas of the U.S.; however, some landscapes may exist that cannot sustain an evergreen needle leaf PFT. Sole use of the evergreen needle leaf PFT for LF-BGC simulations does not provide enough information to distinguish unique biophysical settings in such landscapes. Assuming that efficiency is improved and resources are increased for the national effort, we suggest adding the C3 grass (cool season) PFT to the simulation protocol. By modeling the two plant functional types with the narrowest (evergreen needle leaf) and broadest (C3 grass) ecological amplitudes, we can achieve a more complete picture of the biophysical gradients that exist across the entire United States.

Improving Model Input Layers

To minimize the number of unique simulation units, we classified much of the input data to broad categories. Classification served to minimize the number of simulations while attempting to remain within the bounds of model sensitivity. We propose a number of changes to the methods for creating the input layers used to create simulation units.

We derived soil depth from STATSGO slope groups that were further divided with a topographic convergence index (TCI). The derived soil depth layer showed a very speckled pattern or *pixelation* and contained a definite footprint of the hydrologic modeling that carried through to final biophysical gradient layers in the form of linear hydrologic features. Further examination determined that the pixelation of the soil depth layers was the dominant determinate of the size and shape of simulation units. This pattern was due largely to characteristics of the soil depth layer that were undesirable. The input of flow accumulation to the soil depth derivation process resulted in long, linear artifacts in the simulation units resulting from limitations in the flow direction grid. We explored different flow direction layers of varying complexity, but all created the same artifacts in the final layers. The multiple flow direction layers, in addition to the high degree of pixelation in the depth values, reduced our confidence in the derived soil depth values. We recommend eliminating the TCI soil depth calculation and using the soil depth information taken directly from STATSGO but modified by slope group, as with the soil texture information. In addition, we recommend exploring techniques to modify the soil depth estimation according to the coarse fragment proportion.

Reducing the soil depth layer complexity would provide the flexibility to increase the number of categories in our other model input layers and thereby improve the characterization of ecologically important and unique physical patches on the landscape for creating simulation units. We advocate increasing the number of classes in the terrain-related layers as follows:

- **Aspect**—Divide into eight classes: north 338 – 22, northeast 23 – 67, east 68 – 112, southeast 113 – 157, south 158 – 202, southwest 203 – 247, west 248 – 292, and northwest 293 – 337.
- **Slope**—Divide into five classes: <4 percent, 5 – 14 percent, 15 – 29 percent, 30 – 79 percent, and 80 – maximum percent.
- **Hillshade**—Divide (as a value between 0 and 1) into ten classes with the maximum class value representing each class (in other words, 0.1, 0.2, and so forth).

As in the prototype effort, the value assigned to the pixel should be the midpoint of the class range for aspect and slope.

We also propose a change in the extraction and handling of the DAYMET weather data. For the LANDFIRE Prototype Project, the center coordinates of 1-km DAYMET pixels were used to create simulation units and to extract weather data for each simulation unit within a 1-km pixel. A lapse rate was applied based on the elevation difference between the simulation unit and DAYMET pixel. A significant 1-km artifact of this DAYMET grid remained in many output layers, even when various smoothing techniques were implemented. We propose removing the DAYMET grid from the suite of layers used to create simulation units and employing a more sophisticated smoothing process to scale the weather data down to better represent our 30-m simulation units Specifically, we suggest applying a lapse rate based on bilinear interpolation to the four surrounding DAYMET pixels closest to the center coordinates for each simulation unit.

The ecophysiological site and LAI data layers were created based on current land use and land cover data, and these layers were used to determine unique simulation units for developing the biophysical gradient layers. When the site and LAI layers were used to create simulation units, they not only generated artifacts but had no bearing on biophysical attributes that define environmental site potential or biophysical setting. For these reasons, we recommend omitting these layers in the creation of unique simulation units. In combining the WXFIRE and LF-BGC models, the ecophysiological site and LAI inputs could be eliminated because they are inherent to the BGC PFT parameterization and will represent more generic potential rather than current land use and land cover.

Improving Simulation Unit Development

We propose some changes to the protocol for defining the simulation units with respect to reducing data volume and increasing simulation efficiency. We identified three major limitations in our methods, the removal of which would improve the quality of the simulation units. First, as stated in the previous section, the ecophysiological site, LAI, and the 1-km DAYMET layers should not be used to create simulation units. These layers impose artificial footprints and are not physical features that affect the biophysical potential of a landscape patch. Second, by removing the DAYMET grid as a controlling factor in creating simulation units, we can maintain the data at its native resolution rather than re-sampling all data to 25 m. Following these two changes to the input data used to create simulation units, we propose changes in the delineation methods aimed towards reducing the overall number of simulation units through classification and combination of the input layers.

In our proposed method for creating simulation units, we first assume that the following: First, executing the model to create biophysical gradient layers for each 30-m pixel is computationally problematic. Second, model input layers can be classified within the bounds of model sensitivity, thereby decreasing data volume without losing information. Third, physical limits—regarding the size of the simulation units—can be imposed without losing desired spatial detail. We suggest first combining the following input layers with new class definitions: elevation, slope, aspect, hillshade, soil depth, and soil texture (sand, silt, and clay). This combination would assign a unique identification number to each unique combination of the variables. We then suggest grouping adjacent like pixels based on the combined output. This aggregation would separate any pixels that have the same biophysical gradient properties but are separated in geographic space. We then propose applying a minimum mapping unit of ~1 ha to these simulation units to reduce the total number. Because the DAYMET weather data is interpolated to scale it to the 30-m DEM, a maximum size for simulation units should be imposed, such that the units are less than 1 km; we propose using a maximum axis length of 750 m. This set of steps represents small changes, but it would result in a significant reduction in the number of simulation units. Additionally, we expect that the gain in biophysical information through these new methods would significantly improve the quality of the output biophysical gradient layers.

Conclusion

Integration of remote sensing, simulation modeling, and gradient analysis proved to be an efficient and successful approach for mapping broad-scale vegetation, wildland fuel, and fire regime characteristics in the LANDFIRE Prototype Project. The ability of remote sensing and ecosystem simulation to portray spatial distributions of biophysical gradients enables the efficient construction of reasonably accurate maps that are critical for both fire managers and ecologists. While there were a variety of limitations encountered during the application of the LANDFIRE Prototype Project biophysical gradient modeling approach, the lessons learned will prove valuable when LANDFIRE methods are applied across the entire United States.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Chapter
6

Developing the LANDFIRE Vegetation and Biophysical Settings Map Unit Classifications for the LANDFIRE Prototype Project

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Introduction

The Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, required a system for classifying vegetation composition, biophysical settings, and vegetation structure to facilitate the mapping of vegetation and wildland fuel characteristics and the simulation of vegetation dynamics using landscape modeling. We developed three separate, fully integrated vegetation and biophysical settings map unit classifications that quantified, categorized, and described vegetation and environmental conditions; these include: cover type (CT), potential vegetation type (PVT) and structural stage (SS). We used a rule-based approach to implement these map unit classifications in the LANDFIRE reference database (LFRDB), which is a field-based database comprised of existing field data from the prototype mapping zones (Caratti, Ch. 4). We used the LFRDB to create training databases to develop maps of CT, PVT, and SS (Frescino and Rollins, Ch. 7; Zhu and others, Ch. 8). These vegetation-based maps formed the foundation for the mapping of fire regime condition class (FRCC), fire behavior fuel models, fuel loading models, fuel characteristic classes, and canopy fuel characteristics (Pratt and others, Ch. 10; Holsinger and others, Ch. 11; Keane and others, Ch. 12). The map unit classifications also formed the building blocks for the development of succession pathway models for simulating historical fire regimes (Long and others, Ch. 9).

In this chapter, we refer to our process of categorizing the biophysical settings, vegetation composition, and vegetation structure as a "classification" process. Several design criteria were developed to ensure that the LANDFIRE map unit classifications were sufficient for successfully completing the LANDFIRE vegetation, wildland fuel, and fire regime products. We refer to the complete list of units in each classification as a "map legend." We call the results of each classification a "map unit" or refer to them by the appropriate mapping classification topic such as "cover type" or "potential vegetation type" or "structural stage."

The biophysical and vegetation map unit classifications provided guidelines for many of the LANDFIRE Prototype mapping and modeling tasks. The CT classification describes existing vegetation composition and was used to describe the dominant species within vegetation communities that are differentiated by unique species compositions. The PVT classification is a biophysical classification that uses indicator plant species to identify the unique biophysical characteristics of a site. A biophysical classification describes environmental conditions such as water availability, nutrient status, and average annual temperature. The SS classification describes important stages of canopy development, and the classes are often referred to as *stand structure types*. These classifications defined the specific map classes that were quantified in LANDFIRE vegetation mapping.

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Research has shown that the integration of a biophysical classification (PVT) with stand structure (SS) and species composition (CT) classifications can uniquely describe other ecological characteristics, such as wildland fuel characteristics, fire regimes, and wildlife habitat (Keane and others 1998). In addition, such integration facilitates the modeling of vegetation succession needed to simulate the historical landscape composition that may be used for determining departure from historical conditions (Hardy and others 1998; Keane and others 1998).

We designed the LANDFIRE vegetation map unit classifications to contain a comprehensive list of consistently categorized vegetation characteristics that may be used beyond the scope of the prototype study areas across the entire nation. All lands, federal and non-federal, and all vegetative communities, forest, shrubland, and herbaceous, within the LANDFIRE Prototype Project study areas were classified with the same level of detail and consideration.

Each individual CT, PVT, and SS map unit had to meet the following LANDFIRE guidelines:

- **Identifiable** – The CT, PVT, and SS classes must be able to be identified in the field and from existing field databases (such as the Forest Inventory and Analysis [FIA]). Additionally, all classes must be able to be identified by nationally standard terminology used in vegetation classifications and descriptions of vegetation map units.
- **Scalable** – The CT, PVT, and SS classes must be hierarchical with regard to floristic and spatial scale. The aggregation and disaggregation of classes must be straightforward.
- **Mappable** – The CT, PVT, and SS classes must be able to be delineated accurately on a map using standardized remote sensing techniques combined with biophysical gradient modeling.
- **Model-able** – The CT, PVT, and SS classes must fit into the framework of the landscape simulation models critical for producing several of the LANDFIRE products, including maps of historical fire regimes, departure from historical conditions (Holsinger and others, Ch. 11), fire behavior fuel models, and fire effects fuel models (Keane, Ch. 12).

We used established vegetation classifications, biophysical classifications, extensive literature review, vegetation modeling science, classifications from other fuel and fire regime mapping projects, and reference data contained in the LFRDB (Caratti, Ch. 4) in the development of LANDFIRE Prototype Project map unit classifications and to guide the development of the multi-level hierarchy in which we embedded our classes. Multiple levels of CT and PVT allowed us to aggregate or disaggregate the classes to support multiple LANDFIRE tasks using a single classification scheme. Multiple levels also allowed linkage between the LANDFIRE map classifications and existing classifications such as the Society of American Foresters (SAF) classification (Eyre 1980), the Society of Range Management (SRM) classification (Shiflet 1994), and the National Vegetation Classification System (NVCS) (Grossman and others 1998).

We developed an iterative process to ensure that ecologically reasonable combinations, based on literature review and expert knowledge, would result when maps created with our classes were combined for use in succession pathway development, landscape succession simulation, and fuel mapping (see appendix 2-A in Rollins and others, Ch. 2 for a LANDFIRE Prototype procedure table). We also developed a coding protocol for the map legends, which can be found in appendix 6-A. The individual biophysical and vegetation mapping classifications and associated hierarchical structures developed for prototype zones 16 and 19 are described below.

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on the development of vegetation map units, which was a critical intermediate step for nearly all mapping tasks in the LANDFIRE Prototype Project.

Cover Type

The LANDFIRE Prototype Project required maps of cover type (CT) representing existing distinct vegetative communities that, when combined with maps of PVT and SS, allowed for characterization of the variation in wildland fuel and fire regimes across the prototype study areas. One intent of the LANDFIRE Prototype Project was to develop a standard methodology for the development of a LANDFIRE CT classification that would be applicable across the nation and repeatable (for consistency) by other teams. In addition, field data from the LFRDB were classified to CT and used as a training database for mapping existing vegetation from Landsat imagery.

Although several authors have created classifications of existing vegetation (Eyre 1980; Grossman and others 1998; Shiflet 1994), these classifications would not suffice for use in the LANDFIRE Prototype or LANDFIRE National effort without modification or customization. No single, existing vegetation classification met the LANDFIRE design criteria and guidelines (Keane and Rollins, Ch. 3). For example, classifications such as the NVCS (Grossman and others 1998) rely on the organization of plants by morphological characteristics and do not necessarily provide the class divisions required to delineate distinct and comprehensive mapping categories. In addition, vegetation classifications based on floristics, which can describe vegetation characteristics or spatial distribution of species, have many more classes than were needed for LANDFIRE maps. Inconsistencies were also found within some of the available classifications when they were applied across several states; for example, the USGS GAP Analysis Program vegetation class mapping methodologies (Merchant and others 1998) are inconsistent across state boundaries. Finally, some of the classifications serve specific purposes and therefore exclude many vegetation types; for example, the SAF cover types were developed primarily to describe forests and woodlands (Eyre 1980). Furthermore, several of the existing classifications include types composed of two or more species with different physiognomies and more importantly, different successional roles, which made these problematic for use in vegetation modeling or succession pathway development. For example, the SRM cover type number 509, "Oak-Juniper Woodland and Mahogany-Oak" (Shiflet 1994) is identified by multiple species that have different successional roles. To simplify the process of succession pathway development, we avoided grouping different seral species within a CT. LANDFIRE CT classes were designed to be represented with a single dominant species that characterized a primary stage in successional development (Long and others, Ch. 9).

Despite our reservations with available classifications, we attempted to integrate the logic and content of existing classifications into the LANDFIRE classification development. At times, we used the current classes as they were, sometimes we modified them, and other times we used them simply as general guidelines to create unique sets of CT map legends specifically suited to meet LANDFIRE design criteria and guidelines.

After our review of several CT classifications, we approached the development of a LANDFIRE CT classification using two fundamentally different methods. The approach used for Mapping Zone 16 in the central Utah highlands was a top-down method that partitioned general vegetation types (forest, woodland, shrub, and herbaceous) into classes based on differences within these types. This top-down approach, or *divisive* method, is most aptly used for large areas where relationships and patterns are already understood (Brohman and Bryant 2005). Because the classes are more conceptual in nature, fewer observations are required for their development (Brohman and Bryant 2005). As a result, Zone 16 plot data was used only to fine-tune map units, not direct the classification. The second classification methodology, used for Zone 19 in the Northern Rockies, focused on groupings based on shared characteristics. In this bottom-up approach, we used Zone 19 plot data to specify the type to be grouped, which, in our case, was the dominant species of the plot. This agglomerative method is often used to quantify unknown relationships and patterns using empirical data (Brohman and Bryant 2005). As this was a prototype effort to develop nationally consistent maps, we decided to test both methodologies to determine which approach, conceptually based or data-driven, would prove most useful. The following sections describe these two distinct approaches used in the development of the LANDFIRE CT classification.

Mapping Zone 16: Central Utah Highlands—The general approach for Zone 16 was to construct a list of CTs applicable to 11 western states. We expected detailed descriptions of these CTs to vary significantly between different parts of the West because of regional differences in species composition. We assumed at the outset that the western U.S. list and associated descriptions of the CTs would be refined once applied to Utah and further refined when applied to other parts of the West.

Through consultation with vegetation ecologists and mapping experts, we established general guidelines for the CT classification development. We determined that a set of approximately 50 western CTs would be suitable to map existing vegetation for the LANDFIRE Prototype. These types had to have at least one percent coverage of the western U.S. in order to describe a mid- to broad-scale vegetative community. We placed emphasis on the creation of a CT legend for non-forest vegetation, which had been inadequately represented in previous national mapping efforts. We represented each CT with an individual dominant species, such as ponderosa pine or bluebunch wheatgrass, and we attempted to avoid the use of mixed life form, phenological, and morphological classes when grouping the dominant species into CTs and when these CTs were arranged into coarser hierarchical levels. Finally, we decided to use CT names that describe the dominant species, as opposed to using generic vegetation terminology. Generic terminology such as *chaparral*, for example, comprises many species, and a term such as *Pacific* comprises many geographical regions.

We developed the original legend of non-forest and forest CTs from expert knowledge of western vegetation and then improved this legend based on reviews of key literature that described similar CTs and on other existing CT classifications. We relied heavily upon the SAF cover types (Eyre 1980), the SRM cover types (Shiflet 1994), and a list of USGS Gap Analysis Program (GAP) (Merchant and others 1998) land cover classes that we compiled from western GAP state maps and standardized classes provided by the University of Idaho and BLM National Science Technology Center. Essentially, most of the western SAF, SRM, and GAP types were linked to the LANDFIRE CT legend to ensure this legend included the major vegetation types of the western U.S. A few of these were not assigned to LANDFIRE CTs because they were either too fine spatially or had wide-ranging descriptor species, which meant that the presence of a particular species did not indicate a discrete CT useful to the LANDFIRE mapping effort. With significant assistance from Forest Service Region 4 ecologists, we also adjusted sagebrush CTs to be compatible with the classification used for the sagebrush map prepared by the NatureServe for the USGS (Reid and others 2002).

We followed the Federal Geographic Data Committee (FGDC 1997) standards for vegetation classification as closely as possible when developing CT legends and the classification hierarchy, and we used hierarchical levels similar to the NVCS (Grossman and others 1998), such as class, subclass, and group, to describe our hierarchy. Although the FGDC standards do not include mapping applications, we found that FGDC guidelines for vegetation classification were useful in the development of the LANDFIRE map unit classification. When necessary, however, we altered FGDC vegetation classification definitions to better suit the requirements of the LANDFIRE Prototype Project. For example, the LANDFIRE Prototype Project defined barren as less than 10 percent cover of vegetation, whereas FGDC defined it as less than 20 percent vegetation cover. If we had used the FGDC definition of barren, we would have classified many functioning, arid plant communities that fully occupy their sites as essentially devoid of vegetation. Furthermore, because some of these communities will sustain wildland fire, particularly in years when high precipitation causes abundant growth of herbaceous fine fuel, we determined they must be included in the LANDFIRE CTs as vegetated communities.

To facilitate the creation of the CT maps (Zhu and others, Ch. 8), we developed a classification key or sequence table for assigning LANDFIRE CTs to LFRDB plots (Caratti, Ch. 4). We assigned "dominant species" to each CT according to expert knowledge and the descriptions provided with each SRM, SAF, and GAP cover type classification. We used the dominant species to represent the CT, following an approach similar to that of Brohman and Bryant (2005) and their use of a "dominance type" in the *Existing Vegetation Classification and Mapping Technical Guide*. Specifically, we represented the CT by one important plant taxa in the uppermost layer of vegetation. Species defined as dominant usually had the greatest amount of canopy cover in the uppermost layer. The identification of a single dominant overstory species was adequate to describe the plot and therefore allowed us to delineate CTs using satellite image processing (which cannot identify lower strata vegetation). However, in the case of some shrub and grassland CTs, we employed a second species or species group when the important plant species could dominate more than one CT as a result of its wide-ranging distribution.

In our final step, we improved the western U.S. CT legend, added more dominant species to some CTs, and developed criteria for identifying dominant species using plot data from the central Utah mapping zone. We assigned each additional dominant species found in the plots to the most suitable CT based on distribution, occurrence, ecological characteristics, and/or habitat requirements of the species, as described in the Fire Effects Information System (http://www.fs.fed.us/database/feis). Furthermore, we divided graminoid communities into cool-season (C3 or C4) and warm season (C4) CTs according to the dominant photosynthetic pathway of the species with highest cover. We required the dominant species to be listed by complete scientific name (*Poa pratensis*), not just genera (such as *Poa*). We also required that all big sagebrush species be listed with variety or sub-species (for example, *Artemisia tridentata* ssp. *wyomingensis*). Comprehensive methodology detailing how the CTs were assigned to plots in the LFRDB can be found in Caratti, Chapter 4.

Mapping Zone 19: Northern Rockies—In contrast to the CT classification development for Zone 16, we implemented a data-driven approach for the creation of the Northern Rockies Zone 19 CTs. This bottom-up approach relied heavily on plot data found in the LFRDB. For a national classification, this approach would require enormous amounts of data and computing capacity to classify a single field-referenced database for the entire U.S.

We also developed guidelines that promoted consistency in CT criteria, even though the plots were to be classified independently for each zone. All CT and CT hierarchy development followed the same general principles, such as consideration of the predominance of a CT on the landscape, the ecological significance of a CT, and plot data availability. As in Zone 16, the objective of the CT map classification was to represent the CT with distinct yet nationally applicable criteria at a landscape-level. We attempted to avoid the use of mixed life form, phenological, and morphological classes when grouping the dominant species into CTs and when these CTs were arranged into coarser hierarchical levels. Mixed classes may have included species with different successional roles, making them difficult to use as representatives of single seral stages for succession models.

We used LFRDB plot data for Zone 19 to determine the set of dominant species that formed the foundation of our CT map classification and hierarchy development. To establish this set of dominant species, we first assigned life forms to plots based on criteria established by the LFRDB team (see Caratti, Ch. 4). Next we determined the dominant species on the plot to be the species within that life form that had the highest percent cover (or basal area if the plot was from FIA data). As for Zone 16, a complex rule set was developed to distinguish the uppermost dominant tree species from multiple layers in certain forest types (see Caratti, Ch. 4). The attributes for these dominant species became the starting point for the bottom-up CT classification.

We based the Zone 19 dominant species groupings on a number of taxonomic, physiognomic, succession, and site characteristics. We grouped some of dominant species into CTs, and we determined that other dominant species were CTs themselves because of their continuous and distinct distribution across the landscape. In essence, we selected the criteria for developing the CT classes based on whether they resulted in CT classes that met the four LANDFIRE design requirements. That is, they had to be identifiable, scalable, mappable, and modelable. This scalable, hierarchical system facilitated both mapping and succession modeling because CTs that were most suitable for the particular product could be selected. For example, if a CT at one level did not meet the needs of a certain LANDFIRE task, a level above or below could be used instead. As a result, the CTs used in processes described in other chapters (see, for example, cover type mapping in Zhu and others, Ch. 8) existed in more than one hierarchical level.

Potential Vegetation Type

The potential vegetation type (PVT) map classification was important to several LANDFIRE processes and products. Potential vegetation types describe and classify environmental site conditions, providing succession modelers with the biophysical settings (areas with common environmental site conditions) for which they then develop succession pathways describing vegetation development (Long and others, Ch. 9). Much in the same way as in the creation of the CT map, plot data from the LFRDB were classified to a PVT in order to provide a training database for mapping PVTs (Keane and Rollins, Ch. 3; Frescino and Rollins, Ch. 7). We used the PVT map as one of the predictor layers in the mapping of CT and SS, along with Landsat imagery and biophysical gradient layers (Zhu and others, Ch. 8). Potential vegetation type effectively limited the number of CTs that could occur on any site because certain existing vegetation types had high fidelity to specific PVTs. (Zhu and others, Ch. 8). Mapped PVT formed the foundation for the simulation of historical reference conditions that served as the baseline for characterizing the ecological departure of current systems from historical conditions (Keane and Rollins, Ch. 3; Pratt and others, Ch. 10; Holsinger and others Ch. 11). The PVT map was also used to spatially parameterize disturbance dynamics in the LANDSUMv4 fire-succession model (Pratt and others, Ch. 10). Finally, the PVT classes and map were used in the development of fuel maps (Keane and others, Ch. 12). The following section presents the background of the PVT concept, the LANDFIRE PVT mapping guidelines, and the development of the PVT map classification.

Quantitative descriptions of the biophysical environment can provide a process-oriented context for mapping and modeling important biological characteristics. Litter fall, for example, is greater on warm, moist sites than on cold, dry sites. Studies have shown that incorporating a quantitative description of the biophysical environment (such as temperature, elevation, and precipitation) with satellite imagery improved the mapping of ecological characteristics such as vegetation and fuel (Keane and others 2002; Rollins and others 2004). We recognized the need to develop a biophysical classification that would be useful for both LANDFIRE mapping and modeling and for scaling LANDFIRE products to finer scales for use in local land management applications.

Due to the lack of an existing national-scale PVT classification, we developed our own biophysical classification based on a revised habitat type classification approach

(Pfister 1989; Pfister and Arno 1980; Pfister and others 1977) and other site classifications based on climax vegetation (Daubenmire 1962, 1966; Ferguson 1989). In concept, the PVT approach assumes that a climax vegetation community would eventually develop on a site in the absence of disturbance). This approach has a long history in vegetation mapping, and PVT classifications have been developed for many of the forests of the western U.S. (Ferguson 1989; Pfister 1981; Pfister and Arno 1980). However, the approach has had limited success with non-forested environments because extensive disturbance histories in rangelands have eliminated many climax species that are indicators of biophysical settings. Also, non-forest systems don't lend themselves to a single climax species, but rather a group of species or vegetation communities. This type of classification, often based on late seral species and/or gradients of shade tolerance, provides the basis for LANDFIRE's biophysical classification.

We modified traditional approaches to PVT classification to match the scope and assumptions of the LFRDB development and LANDFIRE mapping tasks. Our objective was to identify the unique biophysical setting, not the climax vegetation or endpoint of succession. As noted above, the term *climax* is often associated with communities rather than species, and many ecologists have noted that climax vegetation is an unrealistic endpoint since climate, genetics, exotic migrations, and other factors are constantly changing such that a stable climax community is impossible (Hironaka 1987; Huschle and Hironaka 1980). We assumed that PVTs for forest ecosystems could be identified from plot data based on the most shade-tolerant tree species on a plot. The hypothesis is that the tree species with the highest shade tolerance will eventually become dominant in the absence of disturbance. Following the theory of Daubenmire (1966) (the principle of competitive exclusion), the tree species with the highest shade tolerance will also have a high fidelity of occurrence in unique biophysical settings. Again, we made no assumption that the most shade tolerant species was a *climax* species in our classification. We viewed the most shade-tolerant species found on a plot as a suitable indicator of the plot's distinctive environmental condition. We named our biophysical classification after PVTs because these shade-tolerant species best indicate the biophysical setting under the current climate regime, not the ultimate climax community. This approach not only ensured the mapping of unique biophysical settings but also allowed these settings to be directly linked to succession pathways in our simulation of historical reference conditions.

The CT map classification provided the building blocks for developing the final list of PVTs for the LANDFIRE Prototype Project. The PVTs were named according to CTs, and lists of CTs that could exist in each PVT were developed so that no inconsistencies or illogical combinations existed between the CT and PVT maps and so that each PVT could occur on the CT map as an existing vegetation type. Therefore, the CT map legend provided the resolution for all LANDFIRE PVTs. For example, a Dwarf Sagebrush PVT could be created only if there was a Dwarf Sagebrush CT. This was especially important to the LANDSUMv4 modeling effort for determining the historical range of landscape conditions (Pratt and others, Ch. 10).

Potential vegetation types were assigned to forested plots in the LFRDB based on the presence of a particular tree species as determined from the coverage or tree density data collected for that plot. Using the reference database, we sorted all tree species present (≥ 1 percent cover) on a plot by shade tolerance using autoecological information found in the literature (Burns and Honkala 1990; Fowells 1965; Minore 1979). We then matched the most shade-tolerant species with the comparable CT. Again, matching PVT and CT ensured logical combinations and a consistent linkage between maps for the development of the LANDSUMv4 succession pathways for simulating historical reference conditions (Pratt and others, Ch. 10)

Rangeland ecosystems presented a special problem for the PVT concept since residual late successional species are rarely observed in plot databases because of high frequency of disturbances such as grazing and fire (Bunting 1994; Sieg 1997; Westoby 1980). For this reason, we arranged the rangeland CTs along a moisture gradient from xeric to mesic communities, and this arrangement was used as the key criterion for classifying plots in the LFRDB. We had some problems uniquely assigning rangeland PVTs to plots because of overlap and limited coverage of some indicator species along the moisture gradient. To determine the PVT for some of the rangeland plots, we had to consider other ecological species characteristics, such as ecological amplitude. Presence of an indicator species at greater than ten percent cover, rather than dominance of that indicator species (species with highest cover on a plot), was used as a criterion for classifying the rangeland PVTs in the key. Additionally, a threshold of ten percent cover was used in the PVT key because when presence alone (greater than zero percent cover) was used to implement the key, as was initially done, none of the herbaceous rangeland PVTs were assigned to plots. Most herbaceous plots had a few shrubs on them, and the presence threshold of greater than zero percent that was employed initially always led to an assignment of shrub PVT, which we knew was not always accurate (Caratti, Ch. 4). Although this method for assigning PVTs to rangeland communities was based on a myriad of assumptions, most importantly the ability to consistently model successional development, it proved to be the best approach considering the limited resources and data available.

We created a nested hierarchy of the PVT categories to aggregate similar PVTs into one type and to facilitate the development of finer divisions of biophysical settings according to the modelers' and mappers' needs (Zhu and others, Ch. 8; Long and others, Ch. 9). The order of the hierarchical levels was also important as it influenced how relevant the classification would be for LANDFIRE purposes. For example, if we used a general forest PVT, such as Spruce – Fir, as our finest level of the hierarchy, we would not be able to divide this type any further to represent finer distinctions in the biophysical settings of Spruce – Fir forest PVTs.

Structural Stage

Structural stage (SS) map classifications delineate developmental stages of vegetative communities based on characteristics such as vegetation age, height, canopy closure, and canopy structure (Quigley and Arbelbide 1997). These characteristics are the key components in modeling vegetation succession, wildland fire behavior, and the effects of wildland fire. Arno and others (1985) classified forests based on the following stand characteristics: tree canopy coverage, average diameter at breast height of the dominant tree, basal area, and stand age. Quigley and Arbelbide (1997) used the processes approach, based on growth, development, competition, and mortality, to classify SS for the Interior Columbia Basin Ecosystem Management Project. Many professional foresters have used size classes (such as diameter at breast height) to represent seral stage or age, attributes which are primarily used to determine timber volumes. Foresters often assume the bigger and taller the stand, the older the stand or the later the seral stage. However, mapping efforts using diameter-breast-height and size classes have met with limited success and may not yield even enough information to adequately determine seral stage. The USGS Center for Earth Resources Observation and Science (EROS) team, responsible for producing the LANDFIRE SS maps, found that mapping canopy cover and height to indicate seral stage was more successful (Keane and Rollins, Ch. 3), and so these two attributes were used to create the LANDFIRE SS map.

The LANDFIRE SS map classification was critical for almost all phases of the project, especially for developing the succession pathway models and for mapping wildland fuel. This classification allowed modelers to assign seral stages to the various CTs that made up the succession pathways (Long and others, Ch 9). Additionally, the SS classes quantified the horizontal and vertical configuration of vegetation, enabling a more accurate assignment of wildland fire behavior models and fire effects models and a better overall representation of wildland fuel characteristics (Keane and others, Ch. 12).

We developed the existing SS map units using similar methodologies for both zones 16 and 19. We categorized continuous canopy cover (density) and height values into classes designed to yield the highest precision based on the mid-level resolution of Landsat imagery because we did not feel confident that the imagery had sufficient resolution to detect a more complex and detailed SS resolution. We determined the threshold values separately for each life form (forest, woodland, shrubland, and herbaceous) based on expert opinion. We then combined these two variables into a matrix that enabled us to describe both attributes with one value. The combination of the two attributes provided sufficient characterization of seral stage, which was then used to map wildland fuel (Keane and others, Ch. 12) and to parameterize and implement LANDSUMv4 (Pratt and others, Ch. 10).

Results and Discussion

Cover type

Mapping Zone 16: Central Utah Highlands—Fifty CT classes were created for the western United States. Table 1 provides a legend of these CTs and illustrates the hierarchical structure of the CT classification. The western U.S. CTs included 24 forest, 4 woodland, 15 shrubland, and 7 herbaceous types. Eight of the forest CTs were refined through examination of Zone 16 plot data, in addition to 2 woodland types, 14 shrubland types, and all 7 of the herbaceous types. Appendix 6-B provides a brief description of each western CT.

We assigned dominant species to each CT to enable identification (to meet the LANDFIRE guideline that all types be "identifiable") of a CT in the field or in a database. Species are commonly recorded in field data sets, especially the dominant species, because species are usually easily identified in the field, and the connection between dominant species and CT is a commonly understood concept.

Table 1—Western U.S. cover type legend. For Zone 16, the LANDFIRE Prototype Project used a “top-down” classification approach in which vegetation classes were developed for the entire western United States. Classes that were actually mapped for Zone 16 are denoted with a superscript b.

CT#[a]	Cover type	Class	Subclass	Group
1401	Riparian Hardwood[b]	Forest	Deciduous	Broadleaf
1405	Aspen – Birch[b]	Forest	Deciduous	Broadleaf
1406	Pacific Deciduous Forest [Other Broadleaf]	Forest	Deciduous	Broadleaf
1102	Pacific Broadleaf Evergreen Forest [Other Broadleaf Evergreen]	Forest	Evergreen	Broadleaf
1501	Larch	Forest	Deciduous	Needleleaf
1201	Ponderosa Pine[b]	Forest	Evergreen	Needleleaf
1208	Pacific Ponderosa Pine Complex	Forest	Evergreen	Needleleaf
1202	Foothill Pines	Forest	Evergreen	Needleleaf
1203	Western White Pine	Forest	Evergreen	Needleleaf
1204	Lodgepole Pine[b]	Forest	Evergreen	Needleleaf
1205	Douglas-fir[b]	Forest	Evergreen	Needleleaf
1206	Grand Fir – White Fir[b]	Forest	Evergreen	Needleleaf
1207	Pacific Silver Fir – Noble Fir	Forest	Evergreen	Needleleaf
1219	Red Fir	Forest	Evergreen	Needleleaf
1220	California White Fir	Forest	Evergreen	Needleleaf
1209	Western Hemlock	Forest	Evergreen	Needleleaf
1210	Mountain Hemlock	Forest	Evergreen	Needleleaf
1211	Spruce – Fir[b]	Forest	Evergreen	Needleleaf
1212	Sitka Spruce	Forest	Evergreen	Needleleaf
1213	Cedar	Forest	Evergreen	Needleleaf
1215	Redwood	Forest	Evergreen	Needleleaf
1216	Sequoia	Forest	Evergreen	Needleleaf
1217	Cypress	Forest	Evergreen	Needleleaf
1801	Timberline Pines[b]	Forest	Mixed Evergreen-Deciduous	Needleleaf
2401	Deciduous Oak	Woodland	Deciduous	Broadleaf
2101	Evergreen Oak	Woodland	Evergreen	Broadleaf
2201	Pinyon – Juniper[b]	Woodland	Evergreen	Needleleaf
2202	Juniper[b]	Woodland	Evergreen	Needleleaf
3704	Mountain Deciduous Shrub[b]	Shrubland	Deciduous	Broadleaf
3402	Riparian Shrub[b]	Shrubland	Deciduous	Broadleaf
3403	Exotic Riparian Shrub[b]	Shrubland	Deciduous	Broadleaf
3101	Mountain Big Sagebrush Complex[b]	Shrubland	Evergreen	Broadleaf
3102	Wyoming - Basin Big Sagebrush Complex[b]	Shrubland	Evergreen	Broadleaf
3103	Dwarf Sagebrush Complex[b]	Shrubland	Evergreen	Broadleaf
3104	Sand Sagebrush[b]	Shrubland	Evergreen	Broadleaf
3105	Blackbrush[b]	Shrubland	Evergreen	Broadleaf
3106	Rabbitbrush[b]	Shrubland	Evergreen	Broadleaf
3107	Chaparral[b]	Shrubland	Evergreen	Broadleaf
3108	Soft Chaparral [Coastal Sage Scrub]	Shrubland	Evergreen	Broadleaf
3301	Montane Evergreen Shrubs[b]	Shrubland	Evergreen	Mixed Broadleaf-Needleleaf
3701	Salt Desert Shrub[b]	Shrubland	Mixed Evergreen-Deciduous	Broadleaf
3702	Desert Shrub[b]	Shrubland	Mixed Evergreen-Deciduous	Broadleaf
3703	Dry Deciduous Shrub[b]	Shrubland	Mixed Evergreen-Deciduous	Broadleaf
4101	Warm Season Grasses[b]	Herbaceous	Perennial Graminoid	Grass
4102	Cool Season Grasses[b]	Herbaceous	Perennial Graminoid	Grass
4201	Native Forbs[b]	Herbaceous	Perennial Forb	Forb
4202	Exotic Forbs[b]	Herbaceous	Perennial Forb	Forb
4301	Wetland Herbaceous[b]	Herbaceous	Mixed Perennial Graminoid/Forb	Mixed Grass/Forb
4302	Alpine[b]	Herbaceous	Mixed Perennial Graminoid/Forb	Mixed Grass/Forb
4401	Annual Grasslands[b]	Herbaceous	Annual Graminoid	Grass

[a] Coding protocol can be found in appendix 6-A

[b] Refined with plot data and mapped in Zone 16.

While we adhered to the guideline that the CTs be "mappable," we could not logically follow some of the other initial guidelines developed for the Zone 16 CT mapping classification. For example, we did not name each CT according to an individual dominant species for several reasons. First, there are more plant communities dominated by individual species than needed for the mid-scale LANDFIRE Prototype map products. Second, in many plant communities, especially non-forest, mixes of species commonly dominate. Additionally, the subtle spatial patterns in many of these diverse plant communities cannot be mapped using current remote sensing technology because satellite technology cannot distinguish these as individual plant communities. Therefore, to maintain a mid-scale CT classification and adequately describe CT variability, we used generic names such as Desert Shrub or Chaparral to identify the CT. Lastly, we encountered difficulty in assigning unique CTs to plots dominated by non-forest species with broad ecological amplitude. To classify these systems, we had to either create a map unit with a relatively coarse floristic scale or use co-dominants in the classification process.

We recognized that categorizing grasses into two types only, warm season and cool season, was quite broad and may not be suitable for all LANDFIRE Prototype applications. For example, fire behavior fuel model mapping requires knowledge of leaf blade type, fine or coarse, to assign a grass fuel model; however, a mixture of both kinds of leaf blades may dominate both the warm and cool season grass CTs.

Overall, we found that the CTs served well in landscape succession models; that is, they met the LANDFIRE guideline of being "model-able." The number of map units in each classification was sufficient for modeling disturbance processes in each map zone. Although mapping accuracies may have increased had we used fewer classes (Vogelmann and others, Ch. 13), we needed to balance the need for high map accuracies with the need to provide useful types to modelers.

Allowing more than one dominant species to represent a CT did, however, create several problems. First, the Timberline Pine CT was composed of evergreen and deciduous tree species; we therefore created a mixed-leaf phenology map unit, which did not adhere to some of our initial classification guidelines (see above). In addition, some CTs contained species that play different successional roles. For example, the Mountain Deciduous Shrub CT includes Gambel oak, a long-lived, mid-seral species, in addition to other shrubs that show up early in the succession pathway. We did try to limit the number of CTs composed of different seral species because a single map unit was used to represent several different distinct stages in different succession pathways, and we did not want to expand individual CT's definitions beyond the LANDFIRE broad-scale mapping target (Brohman and Bryant 2005; Keane and Rollins, Ch. 3). Finally, some CTs, such as Montane Evergreen Shrubs and Mountain Deciduous Shrub, included species (in these examples, mountain mahogany and Rocky Mountain maple, respectively) that the modelers used so often in Zone 16 succession pathways that they should have been separate CTs.

We arranged the CTs within a hierarchy to address the "scalable" requirement. The hierarchy consists of three coarse mapping levels, a landscape-scale level, and a species-based level (described in table 2). We also tiered the LANDFIRE hierarchical levels to those of other classification systems (table 2). We created the three coarsest levels by aggregating characteristics of the CTs' dominant species, such as leaf type and leaf periodicity. Level 5, the species-based level, allows users to scale down the CTs and link them to other published and unpublished classifications.

The LANDFIRE fuel team found the map units developed for Zone 16 to be useful. Most of the CTs provided sufficient information for describing the fuel and fire characteristics of a site because many of the CTs were based on dominant species with similar growth forms and leaf types. In the cases where dominant species were lumped to form general CTs, such as Warm Season Grasses, the LANDFIRE fuel mapping team found it more difficult to determine the vegetative characteristics. For example, the warm-season perennial grassland contains both fine- and coarse-leaved graminoids. (Keane and others, Ch.12).

We developed a table (appendix 6-C) to relate LANDFIRE CTs to other classification systems. The most closely related SAF, SRM, and western U.S. GAP types are linked to corresponding CTs. Additionally, linkages of LANDFIRE CTs to the NVCS class, subclass, group, and alliance levels are found in appendix 6-D.

Mapping Zone 19: Northern Rockies—The Zone 19 CT map legend consists of 36 CTs (table 3) and includes 14 forest types, 15 shrub types, and seven herbaceous CTs.

Use of existing data (a main design criterion for the LANDFIRE Prototype) that had incomplete species lists or general taxonomic descriptions (for example, "*Pinus*") limited the level of detail that could be extracted from the data for the bottom-up CT classification approach used in Zone 19. Many plots simply did not have enough information to "identify" the CT. For example, one data set, representing approximately one-third of the reference

Table 2—LANDFIRE Zone 16 hierarchical structure and comparison with other classification systems.

Hierarchical level	LANDFIRE cover type classification	FGDC (FGDC 1997)	U.S. National Vegetation Classification System (NVCS) (Grossman and others 1998)	FS Ecosystem Management Coordination Staff (Brohman and Bryant 2003)
Class	Broad-scale map unit classes based on vegetation physiognomy (life form, structure, and canopy cover).	A level in the classification hierarchy defined by the relative percent canopy cover of the tree, shrub, dwarf shrub, herb, and nonvascular life form in the uppermost strata during the peak of the growing season.	Growth form and structure of vegetation (Forest, Woodland, Shrubland, Dwarf-shrubland, Herbaceous, Non-vascular, & Sparse vegetation).	Same definition as FGDC. Classification criteria are based on the following structural attributes: •Tree canopy cover •Shrub height and canopy cover •Herbaceous vs. non-vascular canopy cover
SubClass	Broad-scale map unit classes based on vegetation physiognomy, leaf phenology of woody plants, and leaf type and periodicity of herbaceous plants	Leaf phenology (evergreen, deciduous, mixed evergreen deciduous) and average height of herbaceous stratum (tall, medium, short).	Growth form characteristics, e.g., leaf phenology (e.g., Deciduous Woodland).	Same definition as FGDC. Classification criteria are based on the following structural attributes: •Leaf phenology (e.g., evergreen vs. deciduous) •Gross morphology (e.g., graminoid vs. forb) •Herb periodicity (e.g., annual vs. perennial)
Group	Broad-scale map unit classes formed by grouping cover types on broad leaf morphology.	Combinations of climate, leaf morphology, and leaf phenology.	Leaf types, corresponding to climate (e.g., Cold-deciduous woodland).	Same definition as FGDC. Classification criteria are based on the following structural attributes: •Climatic Regime (e.g., temperate, tropical, subpolar) •Leaf morphology (e.g., extremely xeromorphic) •Leaf phenology (e.g., cold- vs. drought-deciduous) •Presence of a sparse woody layer in grasslands.
Subgroup	N/A – Definition is problematic, particularly in forest plantations of native species (Brohman and others 2003)	A level of the hierarchy that splits Natural/Semi-Natural vegetation types from the Planted/Cultivated vegetation types.	Relative human impact (Natural/Semi-natural, or Cultural).	Same definition as FGDC. Classification criteria are based on the following structural attributes: •Natural/Semi-Natural - Areas dominated by native or established vegetation that has not been cultivated or treated with any annual management or manipulation regime. •Planted/Cultivated - Areas dominated with vegetation that has been planted in its current location by humans and/or is treated with annual tillage, a modified conservation tillage, or other intensive management or manipulation.

Table 2—(Continued)

Hierarchical level	LANDFIRE cover type classification	FGDC (FGDC 1997)	U.S. National Vegetation Classification System (NVCS) (Grossman and others 1998)	FS Ecosystem Management Coordination Staff (Brohman and Bryant 2003)
Formation	N/A – Difficult to apply because the plethora of attributes make many types that are not mutually exclusive, making it impossible to consistently assign plot or associations to formations (Brohman and others 2003).	Ecological groupings of vegetation units; broadly defined environmental and physiognomic factors.	Additional physiognomic and environmental factors, including hydrology (e.g., Temporarily Flooded Cold-deciduous Woodland).	Same definition as FGDC. Classification criteria are based on the following structural attributes: •Elevation zone (e.g., alpine, submontane) •Flooding regime (Cowardin 1979). •Leaf morphology (e.g., xeromorphic) •Tree crown shape (e.g., cylindrical) •Presence of sparse tree layer in shrublands •Leaf phenology and morphology of sparse tree layer in shrublands •Leaf phenology and morphology of sparse woody layer in grasslands •Shrub growth form (e.g., suffruticose, cushion, mat) •Presence of succulents in shrublands •Leaf phenology of shrubs (e.g., facultative-deciduous) •Plant height in herbaceous vegetation •Graminoid rooting habit (e.g., sod-forming vs. bunch)
Cover Type	Mid-level map unit classes that depict the distribution of one to several dominance types that cover a large geographic area. Grouping of dominance types are basedon combinations of factorsrelating to ecology, physiognomy, and succession.	N/A	N/A	N/A
Dominance Type or Dominant Species	Dominant Species or Species groups: A dominant species or a few dominant species that indicate a recurring landscape level (mid-) plant community. It is	N/A	N/A	Dominance Type: A recurring plant community “defined by the dominance of one or more species which are usually the most important ones in the [uppermost] layer of the community, but sometimes of a lower layer of higher coverage.” Dominance types are most simply defined by the single species with the greatest canopy cover in the uppermost stratum.

Table 2—(Continued)

Hierarchical level	LANDFIRE cover type classification	FGDC (FGDC 1997)	U.S. National Vegetation Classification System (NVCS) (Grossman and others 1998)	FS Ecosystem Management Coordination Staff (Brohman and Bryant 2003)
	defined by dominance of one or more plant taxa, which are usually the most important ones in the uppermost layer of the community and are usually determined from the plot data.			
Alliance	N/A – Difficult to delineate for this project as presently defined by FGDC 1997.	A physiognomically uniform group of Associations sharing one or more diagnostic (dominant, differential, indicator, or character) species, which, as a rule, are found in the uppermost stratum of the vegetation.	Dominant/diagnostic species of uppermost or dominant stratum (e.g., Populus deltoids Temporarily Flooded Woodland Alliance).	A group of associations with a characteristic hysiognomy and habitat and which share one or more pdiagnostic species, at least one of which is typically found in the uppermost or dominant stratum of the vegetation.
Association	N/A – Difficult to delineate for this project as presently defined by FGDC 1997.	A physiognomically uniform group of vegetation stands that share one or more diagnostic (dominant, differential, indicator, or character) overstory and understory species.	Additional dominant/ diagnostic species from any strata (e.g., Populus deltoides - [Salix amygdaloides] / Salix exigua Woodland).	A recurring plant community with a characteristic range in species composition, specific diagnostic species, and a defined range in habitat conditions and physiognomy.

Brohman, R. J.; Bryant, L. D. 2003. Existing Vegetation Classification and Mapping Technical Guide - REVIEW DRAFT. USDA Forest Service, Washington Office, Ecosystem Management Coordination Staff. p.

FGDC, ed. [Online]. Available: http://www.fgdc.gov/standards/documents/standards/vegetation/vegclass.pdf. accessed 1997.

Grossman, D. H.; Faber-Langendoen, D.; Weakley, A. S.; Anderson, M.; Bourgeron, P.; Crawford, R.; Goodin, K.; Landaal, S.; Metzler, K.; Patterson, K.; Pyne, M.; Reid, M.; Sneddon, L. 1998. International classification of ecological communities: Terrestrial vegetation of the United States Volume I. The National Vegetation Classification System: development, status, and applications. Arlington VA, USA: The Nature Conservancy. 126 p.

Table 3—Zone 19 cover type legend. The taxonomic groups are not listed because, where an individual group was continuous and had a distinct distribution across the landscape, it was made into a unique cover type and listed under the cover type column.

	Cover type				
CT#	**Forest**	**Subclass**	**Group**		
1201	Cedar	Evergreen	Needleleaf		
1202	Douglas-fir	Evergreen	Needleleaf		
1203	Grand Fir	Evergreen	Needleleaf		
1204	Hemlock	Evergreen	Needleleaf		
1205	Lodgepole Pine	Evergreen	Needleleaf		
1206	Juniper	Evergreen	Needleleaf		
1207	Ponderosa Pine	Evergreen	Needleleaf		
1208	Spruce – Fir	Evergreen	Needleleaf		
1209	Limber Pine	Evergreen	Needleleaf		
1212	White Pine	Evergreen	Needleleaf		
1401	Aspen – Birch	Deciduous	Broadleaf		
1402	Riparian Hardwood	Deciduous	Broadleaf		
1403	Western Larch	Deciduous	Needleleaf		
1801	Timberline Forest	Mixed	Needleleaf		
	Shrub	**Nativity**	**Site modifier**	**Leaf type**	**Height**
2101	Upland Broadleaf Dwarf Shrubland	Native	Upland	Broadleaf	Dwarf
2102	Upland Broadleaf Medium Shrubland	Native	Upland	Broadleaf	Medium
2103	Upland Broadleaf Tall Shrubland	Native	Upland	Broadleaf	Tall
2202	Upland Microphyllous Medium Shrubland	Native	Upland	Microphyllous	Medium
2211	Dwarf Sage	Native	Upland	Microphyllous	Dwarf
2212	Shrubby Cinquefoil	Native	Upland	Microphyllous	Medium
2213	Threetip Sage	Native	Upland	Microphyllous	Medium
2218	Mountain Big Sage	Native	Upland	Microphyllous	Medium
2219	Wyoming – Basin Big Sage	Native	Upland	Microphyllous	Medium
2220	Rabbitbrush	Native	Upland	Microphyllous	Medium
2222	Greasewood	Native	Upland	Microphyllous	Medium
2223	Mountain Mahogany	Native	Upland	Microphyllous	Tall
2300	Upland Needleleaf				
	Shrubland	**Native**	**Upland**	**Needleleaf**	**Medium**
2400	Upland Sclerophyllous Shrubland	Native	Upland	Sclerophyllous	Dwarf
2600	Riparian Broadleaf Shrubland	Native	Riparian	Broadleaf	Tall
	Herbaceous	**Site Modifier**	**Lifeform**	**Growth Form**	**Nativity**
3110	Annual Forb	Upland	Annual Forb	Na	Native
3120	Annual Graminoid	Upland	Annual Gram.	Bunch	Exotic
3130	Perennial Forb	Upland	Perennial Forb		
3141	Perennial Exotic Bunch Graminoid	Upland	Perennial Graminoid	Bunch	
3142	Perennial Native Bunch Graminoid	Upland	Perennial Graminoid	Bunch	
3151	Perennial Exotic Fhizomatous Graminoid	Upland	Perennial Graminoid	Rhizomatous	
3152	Perennial Native Rhizomatous Graminoid	Upland	Perennial Graminoid	Rhizomatous	
3200	Wetland Herbaceous	Riparian	Perennial Gram.	Rhizomatous	Native

plots in Zone 19, had so few species listed that it did not contain sufficient information to classify plots using more than one plant taxa. Usually, the dominant species on the plot was named at the species level, but other taxonomic levels were sometimes used. A generic level (for example, *Purshia*) was used when it was specific enough to identify a CT, and a sub-species level was used sometimes when a species level was not detailed enough to classify the CT, for example, mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*). Most often, however, generic level dominant species were not distinctive enough for LANDFIRE CTs in Zone 19. For example, when *Acer* or *Abies* were described as the dominant species on a plot, they were considered too taxonomically coarse for LANDFIRE map unit purposes and were not used in the classification process.

Many forested plots in Zone 19 were dominated typically by one or two taxa, and the classification of these species into CTs was relatively simple, as was the arrangement of the CTs into a hierarchy. Forest CTs were easily identified from plot data as only two plots of 6,532 forested plots were not classified to a CT. These two plots listed "*Pinus*" as the dominant tree species, which was not sufficient for classification. However, most of the forest plot data listed the full species name, and the dominant species (or group of dominant species) determined the CT. For example, ponderosa pine, Douglas-fir, and lodgepole pine typically form single species-dominated stands that occupy vast areas of the West. In such instances, the CT was simply the dominant species. In other instances, a few dominant species were grouped into a single CT, such as in the case of the Timberline Pine CT. These CTs were grouped into coarser hierarchical levels by leaf type and then leaf phenology. Species mixtures in other areas, such as the Sierra Nevada or the eastern U.S., where many species could potentially define the dominant species on a plot, may require different approaches to classification. The Zone 19 CT hierarchy can be found in table 4.

Shrubs presented unique challenges to the development of the LANDFIRE mapping classification due to the number of taxa, mixes in species composition, and the generally broad ecological amplitude of shrub species. The process of assigning dominant species to shrub plot data was the same as for forested plots; they were assigned according to the single taxa with the highest cover on the plot. Fifty-two of 3,352 plots (1.5%) remained unclassified because the plot data did not describe the species sufficiently. As with forest types, the dominant types were then grouped into taxonomic and physiognomic categories. However, the criteria for assigning the categories to shrub types were different from the criteria used to assign categories to forest types, and the resulting hierarchy had five levels above the dominant species because these different life forms have different criteria by which to group them (table 5).

We considered using the NVCS classification criteria (Grossman and others 1998) for the shrub classification but discovered that certain criteria did not meet LANDFIRE design criteria and guidelines. For example, we chose to exclude the xeromorphic leaf type (adapted to drought) since it is not always distinguishable (from a remote sensing or mapping standpoint) from the microphyllous (small) or sclerophyllous (small and leathery,

Table 4—Zone 19 forest cover type hierarchy structure and definitions.

Levels	Descriptions	Categories/examples
Subclass	Coarse classes based on leaf phenology.	Evergreen, Deciduous, Mixed Evergreen-Deciduous
Group	Classes based general leaf type.	Broadleaf, Needleleaf
Site modifier	Classes based primarily on similar physiognomy, successional ecology, and site characteristics. We also considered the "mappability" of similar vegetation types from other projects and advice given by remote sensing experts.	Ponderosa Pine, Timberline Pine,
Dominant species	A species in the uppermost vegetation layer that indicates a recurring plant community as determined from the plot data.	Douglas-fir

Table 5—Zone 19 shrub cover type hierarchy structure and definitions.

Level	Descriptions	Categories
Nativity	Categories refer to whether the dominant species occurred in North America prior to western settlement or was introduced to North America and is growing naturally in wild areas without cultivation.	Native, Exotic
Site modifier	Cover type level based on site characteristics. Specifically, dominant species may occur in upland and riparian-wetland areas or are obligate riparian-wetland.	Facultative Upland, Riparian
Leaf type	Map units based on leaf type.	Broadleaf, Microphyllous, Needleleaf (scale-leaf), Sclerophyllous, Succulents
Height	Broad, mature height categories of the dominance types.	Dwarf (<1 ft), Medium (1-8 ft) Tall (>8 ft)
Taxonomic group	Grouping of dominant species based on shared taxonomic and morphologic characteristics. The taxonomic level on which the grouping is based may occur at the specific, generic, or family level depending on the taxonomic level of the dominance type. We also considered the “mappability” of similar vegetation types from other projects and advice given by remote sensing experts.	
Dominant species	A species in the uppermost vegetation layer that indicates a recurring plant community as determined from the plot data.	Big sagebrush

drought adapted) leaf types. The terms *evergreen* and *deciduous* were also discarded due to confusion in applying the terms to specific taxa and the fact that two taxa that are similar morphologically may be different in leaf phenology. Distinguishing among drought deciduous shrubs that typically occur in arid environments, cold deciduous shrubs, and evergreen shrubs was problematic because it is difficult to know, based simply on leaf morphology, the phenology of a plant, whether a plant is evergreen or deciduous, and what causes it to drop its leaves.

Herbaceous CTs differed from forest and shrub CTs in the vast number of species within a zone and across the U.S. and because of the introduction and dominance of many exotic species – which made it difficult to use a single species to determine a unique CT. Only 30 of the 731 (4%) herbaceous plots were not classified to a CT. Unlike the forested plots, most of the dominant species were grouped in order to result in a reasonable number of CTs for LANDFIRE mapping purposes. Herbaceous-dominated plots were grouped into CTs based on a small number of criteria that can be consistently applied across the country. The hierarchical categories include site characteristics, growth characteristics, and nativity of the dominant taxa (table 6). The classification does not identify systems such as desert grassland, mixed grass prairie, tall grass prairie, and short grass prairie; however, these types can be delineated using geographic and ecological criteria, if necessary. Descriptions of all the Zone 19 CTs are found in appendix 6-E.

For the prototype effort, we required that any CT generated for Zone 19 must describe a western community at the landscape level; that is, it had to cover at least one percent of the western landscape. The amount of cover defining a landscape-level community may differ in other regions of the U.S. This criterion applied mainly to CTs

Table 6—Zone 19 herbaceous cover type hierarchy structure and definitions.

Levels	Descriptions	Categories
Site modifier	Map unit level based on site characteristics. Specifically, dominant species may occur in upland and riparian-wetland areas or are obligate riparian-wetland.	Upland
Life form	Map unit based on leaf type and periodicity of herbaceous plants	Annual Forb, Perennial Forb, Annual Graminoid, Perennial Graminoid
Growth form	Map unit based on the growing habits of graminiods (not applicable to forbs).	Bunch-forming, Rhizomatous
Nativity	Categories refer to whether the dominant species occurred in North America prior to western settlement or was introduced to North America and is growing naturally in wild areas without cultivation.	Native, Exotic
Dominant species	A species in the uppermost vegetation layer that indicates a recurring plant community as determined from the plot data.	Cheatgrass

that were also dominant species. For example, we could have grouped mountain big sage, rabbitbrush, shrubby cinquefoil, threetip sage, or Wyoming big sagebrush under the Upland Microphyllous Medium Shrublands CT. Instead, we considered these dominant species individually as CTs because of their abundance across the western U.S., their ecological importance, and/or the large total number of plots available within each type in the Zone 19 reference data. However, we grouped bitterbrush, horsebrush, shrubby chenopods, silver sage, and snakeweed into the Upland Microphyllous Medium Shrublands CT because the number of plots classified to the individual dominant species was few, ranging from 10 to 16 plots each.

If a CT was assigned to less than 20 to 30 plots, the CT was either unused or grouped with a similar type, if one existed. For example, only one plot (dominated by *Yucca glauca*) fell within the succulent leaf type. Due to its minor importance and single plot number, succulent was not used as a CT.

The data-driven nature of the bottom-up classification approach was the main strength of the LANDFIRE classification approach used for Zone 19. This approach enabled us to classify all plot data that had detailed species lists. However, there are drawbacks to this data-driven approach. The bottom-up approach is completely dependent upon reference plot data quality and quantity. Cover types that are represented by too few plots within a zone were not mapped because the Landsat-based mapping process requires a minimum number of plots from which to develop training sites (Zhu and others, Ch. 8). Moreover, it was difficult to build a hierarchy with data from a single zone that would encompass all of the CTs that would be encountered across the entire United States and allow for incorporation of new classes as they were identified. Finally, the data driven approach requires that the plot data be available before the classification can begin, which may or may not be realistic.

Modelers (Long and others, Ch. 9) found the 15 shrub types identified in Zone 19 too numerous; as a result, even though they were “model-able,” the number of succession classes found in some of the pathways became inflated. It was our intention that LANDFIRE vegetation modelers would have more choice in determining what scale of CT to use; they could collapse or expand the definition of the CT depending upon their needs. It was a “scalable” system. However, the modelers did not take advantage of the scalability of the CTs primarily because of a misunderstanding surrounding this design. In general, vegetation modelers (Long and others, Ch. 9) found it confusing to use CTs from different hierarchical levels throughout the succession pathway creation.

In addition, the LANDFIRE vegetation mapping team did not want flexibility in regards to which CTs they would map. They requested that we simply give them a

CT legend for Zone 19 and they would attempt to map those types. They determined that a flexible legend would complicate the process greatly. The legend provided was considered "mappable."

As with Zone 16 CTs, the LANDFIRE fuel mapping team found the Zone 19 CTs useful. Use of the bottom-up classification approach, in addition to the fact that many of the classification criteria were based on vegetation characteristics (such as leaf type or growth from), facilitated a clear description of the wildland fuel characteristics for many of the CTs. Some of the graminoid CTs, however, did not adequately distinguish between fine and coarse grass sites, which posed the same problem encountered in Zone 16 with grass fuel models (Keane and others, Ch. 12).

Potential Vegetation Type

We established four hierarchical levels to define the potential vegetation types (PVTs) and assigned indicator species to each PVT. Species within the PVTs in each level share similar site characteristics. Level 1, the top level, designates the life form of the PVT as forest, shrubland, or herbaceous. The CTs that would potentially dominate the site in the absence of disturbance form the next two lower levels of the PVT classification. We named level 2 according to either the CT or the species that was the most shade-tolerant, such as a "Spruce-Fir cover type," or the species or CT with the narrowest ecological amplitude that could occur on a shrub or herbaceous site, such as a "Riparian Shrub cover type." Level 3 was named according to the indicator species on that site or the geographical setting that differentiates fire regimes of the potential dominant vegetation type, an example being "montane." A fourth level was added to discriminate between major seral vegetation types of the PVTs because they represented an even finer resolution with which to identify unique site conditions. Level 4 was named according to the secondary indicator species, CT, or a geographical term such as "north." We identified a PVT by a linking the names in levels 2 through 4 with forward slashes (/). PVTs could also be collapsed back to coarser levels. Finally, a classifier key or sequence table was developed to automate the linkage of plots in the LFRDB to PVT classes using the indicator species (Caratti, Ch. 4).

We calculated the proportions of CTs occurring in each PVT using plot data from the LFRDB. The LANDFIRE vegetation mapping team used this information to limit the number of specific CTs that could possibly occur in each PVT. The probabilities generated from reference plot data form the foundation for evaluating the probability of CTs existing on sites with specific biophysical characteristics. This, in turn, allows a measure of certainty with regard to whether certain CTs can occur in specific areas on the map. Incorporating these probabilities into the LANDFIRE vegetation mapping process distinguishes the LANDFIRE mapping process from other broad-scale vegetation mapping efforts. A hierarchically organized list of the PVTs developed for zones 16 and 19 can be found in tables 7 and 8, respectively. Appendices 6-F and 6-G provide descriptions of the PVTs created for zones 16 and 19, respectively. Additional information on how the PVT classification formed the basis for vegetation modeling may be found in Long and others (Ch. 9).

The LANDFIRE fuel mapping team found that the number of PVT map classes was adequate to represent different site conditions that may influence surface and canopy fuel. The scale of the fire behavior fuel models and fuel loading models was much coarser than that of the PVT classification. To map surface fire behavior fuel models and fuel loading models, the LANDFIRE fuel mapping team used the upper levels of the PVT classification as a stratification to identify unique environmental site conditions. A general description of environmental site conditions was adequate for creating fire behavior fuel maps because few fuel classes exist for the entire United States. However, when mapping the Fuel Characteristic Classification System (FCCS) national fuelbeds, the LANDFIRE fuel mapping team found the levels 2 and 3 PVT classes helpful in determining the crosswalks between PVTs and fuelbeds (Keane and others, Ch. 12; Sandberg and others 2001).

Structural Stage

The structural stages (SS) for Zone 16 were composed of 16 classes based on a matrix of canopy density classes and height classes by life form (table 9). However, as the LANDFIRE vegetation modelers combined the SS units developed for Zone 16 with CT classes to represent seral stages in the succession pathways, they found the two height classes per life form insufficient. This insufficiency became especially evident when the modelers needed to use a mixed CT to represent a broad category of vegetation and had to use multiple seral stages in multiple pathways; however, the modelers had the use of only two height classes with which to describe distinctive seral stages within a CT. To allow more flexibility with regard to illustrating the age and structure of a CT, we needed a better way to describe situations in which the CT was general but potential seral stages were more floristically narrow . In response, for

Table 7—Zone 16 potential vegetation type partitioned by hierarchical level.

PVT#	Level 1	Level 2	Level 3	Level 4
1601	Forest	Spruce – Fir	Blue Spruce	
1602	Forest	Spruce – Fir	Blue Spruce	Lodgepole Pine
1603	Forest	Spruce – Fir	Spruce – Fir	
1604	Forest	Spruce – Fir	Spruce – Fir	Lodgepole Pine
1611	Forest	Grand Fir	White Fir	
1612	Forest	Grand Fir	White Fir	Maple
1621	Forest	Douglas-fir	Timberline Pine	
1622	Forest	Douglas-fir	Douglas-fir	
1623	Forest	Douglas-fir	Lodgepole Pine	
1631	Forest	Timberline Pine		
1632	Forest	Ponderosa Pine		
1633	Forest	Lodgepole Pine		
1634	Forest	Aspen		
1641	Forest	Pinyon – Juniper	Mountain Big Sagebrush	North
1642	Forest	Pinyon – Juniper	Mountain Big Sagebrush	South
1643	Forest	Pinyon – Juniper	Wyoming – Basin Big Sagebrush	North
1644	Forest	Pinyon – Juniper	Wyoming – Basin Big Sagebrush	South
1645	Forest	Pinyon – Juniper	Mountain Mahogany	
1646	Forest	Pinyon – Juniper	Gambel Oak	
1651	Shrubland	Blackbrush		
1652	Shrubland	Salt Desert Shrub		
1653	Herbaceous	Warm Herbaceous		
1661	Shrubland	Dwarf Sagebrush		
1662	Shrubland	Wyoming – Basin Big Sagebrush		
1663	Shrubland	Mountain Big Sagebrush		
1671	Forest	Riparian Hardwood		
1672	Shrubland	Riparian Shrub		
1673	Herbaceous	Wetland Herbaceous		
1680	Herbaceous	Alpine		

Zone 19, the vegetation modelers were consulted and a third height map unit was incorporated for both tree and shrub vegetation types (table 10). As a result, the LANDFIRE vegetation modelers had more groups with which to characterize seral stage, and fewer changes had to be made to rectify the SS map with the PVT and CT maps. For example, a tree SS would be valid for a forest or woodland CT.

The SS threshold breaks deemed adequate for vegetation modeling did not suffice for describing diverse wildland fuel characteristics when applied to fuel maps in zones 16 and 19. Two classes for vegetation cover, while perhaps increasing map accuracy (Vogelman and others, Ch. 13), were not sufficient for the derivation of fuel characteristics. In addition, the height classes were insufficient for portraying surface and canopy fuel. Many fire behavior fuel models require specific structural thresholds that are often different from those used by the LANDFIRE vegetation modelers. For example, whereas a five-meter class was sufficient to represent early seral forest in the succession models (Long and others, Ch. 9), this map unit was not fine enough for use in surface fuel descriptions where surface fuel height ranges only from 0 to 1.8 meters (Keane, Ch. 12).

Recommendations for National Implementation

To apply the LANDFIRE mapping approach across the United States, we recommend that a vegetation working group (VWG) be formed to ensure that the LANDFIRE classification systems meet national classification and mapping standards. The VWG should consist of members of the LANDFIRE technical teams

Table 8—Zone 19 potential vegetation types partitioned by hierarchical levels.

PVT#	Level 1	Level 2	Level 3	Level 4
1902	Forest	Western Redcedar		
1914	Forest	Grand Fir – White Fir		
1920	Forest	Spruce – Fir	Montane	Western Larch
1921	Forest	Spruce – Fir	Montane	Douglas-fir
1922	Forest	Spruce – Fir	Timberline	
1924	Forest	Spruce – Fir	Subalpine	
1930	Forest	Douglas-fir	Ponderosa Pine	Western Larch
1931	Forest	Douglas-fir	Ponderosa Pine	Douglas-fir
1932	Forest	Douglas-fir	Lodgepole Pine	
1934	Forest	Douglas-fir	Timberline Pine	
1936	Forest	Douglas-fir	Douglas-fir	
1940	Forest	Lodgepole Pine		
1942	Forest	Ponderosa Pine		
1944	Forest	Timberline Pine	Limber Pine	
1946	Forest	Timberline Pine	Whitebark Pine	
1950	Forest	Rocky Mountain Juniper		
1952	Forest	Riparian Hardwood		
1960	Shrubland	Riparian Shrub		
1962	Shrubland	Mountain Mahogany		
1964	Shrubland	Dry Shrub		
1965	Shrubland	Dry Shrub	Conifer	
1970	Shrubland	Dwarf Sagebrush Complex		
1971	Shrubland	Dwarf Sagebrush Complex	Conifer	
1972	Shrubland	Mountain Big Sagebrush Complex		
1973	Shrubland	Mountain Big Sagebrush Complex	Conifer	
1974	Shrubland	Threetip Sagebrush		
1975	Shrubland	Threetip Sagebrush	Conifer	
1976	Shrubland	Wyoming – Basin Big Sagebrush Complex		
1977	Shrubland	Wyoming – Basin Big Sagebrush Complex	Conifer	
1980	Herbaceous	Wetland Herbaceous		
1982	Herbaceous	Alpine		
1984	Herbaceous	Fescue Grasslands		
1985	Herbaceous	Fescue Grasslands	Conifer	
1986	Herbaceous	Bluebunch Wheatgrass		
1987	Herbaceous	Bluebunch Wheatgrass	Conifer	

Table 9—Zone 16 structural stage list and descriptions.

SS#	Structural stage name	Structural stage description
11	Low Cover, Low Height Forest	Cover ≤ 40% and Height ≤ 10M
12	High Cover, Low Height Forest	Cover > 40% and Height ≤ 10M
13	High Cover, High Height Forest	Cover > 40% and Height > 10M
14	Low Cover, High Height Forest	Cover ≤ 40% and Height > 10M
21	Low Cover, Low Height Woodland	Cover ≤ 40% and Height ≤ 10M
22	High Cover, Low Height Woodland	Cover > 40% and Height ≤ 10M
23	High Cover, High Height Woodland	Cover > 40% and Height > 10M
24	Low Cover, High Height Woodland	Cover ≤ 40% and Height > 10M
31	Low Cover, Low Height Shrubland	Cover ≤ 40% and Height ≤ 1M
32	High Cover, Low Height Shrubland	Cover > 40% and Height ≤ 1M
33	High Cover, High Height Shrubland	Cover > 40% and Height > 1M
34	Low Cover, High Height Shrubland	Cover ≤ 40% and Height > 1M
51	Low Cover, Low Height Herbaceous	Cover ≤ 40% and Height ≤ 0.24M
52	High Cover, Low Height Herbaceous	Cover > 40% and Height ≤ 0.24M
53	High Cover, High Height Herbaceous	Cover > 40% and Height > 0.24M
54	Low Cover, High Height Herbaceous	Cover ≤ 40% and Height > 0.24M

Table 10—Zone 19 structural stage list and descriptions.

SS#	Structural stage name	Structural stage description
10	Low Cover, Low Height Trees	Trees - Cover ≤ 40% and Height ≤ 5M
11	Low Cover, Low - Mod Height Trees	Trees - Cover ≤ 40% and Height ≤ 10M
12	High Cover, Low - Mod Height Trees	Trees - Cover > 40% and Height ≤ 10M
13	Low Cover, Mod Height Trees	Trees - Cover ≤ 40% and 5M < Height ≤ 10M
14	High Cover, Mod Height Trees	Trees - Cover > 40% and 5M < Height ≤ 10M
15	Low Cover, High Height Trees	Trees - Cover ≤ 40% and Height > 10M
16	High Cover, High Height Trees	Trees - Cover > 40% and Height > 10M
21	Low Cover, Low Height Shrubs	Shrubs - Cover ≤ 40% and Height ≤ 0.24M
22	High Cover, Low Height Shrubs	Shrubs - Cover > 40% and Height ≤ 0.24M
23	Low Cover, Mod Height Shrubs	Shrubs - Cover ≤ 40% and 0.24M < Height ≤ 1M
24	High Cover, Mod Height Shrubs	Shrubs - Cover > 40% and 0.24M < Height ≤ 1M
25	Low Cover, High Height Shrubs	Shrubs - Cover ≤ 40% and Height > 1M
26	High Cover, High Height Shrubs	Shrubs - Cover > 40% and Height > 1M
31	Low Cover, Low Height Herbs	Herbs - Cover ≤ 40% and Height ≤ 0.24M
32	High Cover, Low Height Herbs	Herbs - Cover > 40% and Height ≤ 0.24M
35	Low Cover, High Height Herbs	Herbs - Cover ≤ 40% and Height > 0.24M
36	High Cover, High Height Herbs	Herbs - Cover > 40% and Height > 0.24M

as well as national vegetation classification and mapping experts. An informed and involved VWG could have addressed and alleviated problems encountered during the LANDFIRE Prototype Project. This group should oversee all aspects of the biophysical and vegetation map classification development and work closely with modeling, vegetation mapping, and wildland fuel mapping teams to develop LANDFIRE map legends (ensuring standards are followed) for the nation, descriptions of the classes in these legends, classification keys linking the classes to LFRDB plot data, and cross-walks to existing national vegetation classification systems.

We recommend considering the use of an available national classification system as a starting point for the classification and legend development. New systems have been published since the LANDFIRE Prototype Project map classification effort, such as the vegetation classification developed by NatureServe called “Ecological Systems” (Comer and others 2003), which is an existing vegetation classification that uses biophysical information to classify types.

While the above recommendation seems to be more in concert with the Zone 16 CT classification development approach (a top-down approach initially based on other national classifications), plot data should not be discounted. Its value was illustrated specifically in the Zone 19 CT methodology. Zone 16 CT classes were refined from plot data, whereas Zone 19 CT classes were *developed* using plot data. Although existing reference data do not support Zone 19’s bottom-up approach for the national implementation of LANDFIRE, plot information from the reference database should play a significant role in the creation, improvement, and refinement of the LANDFIRE National’s biophysical and vegetation map units. Map units should be assigned to the plot data, and an analysis of the results should lead to refinements of the classification. In addition, these national CT, PVT, and SS map legends should be completed at the start of the national effort and should then be refined as the national effort moves to individual zones in different regions.

Cover types that have been assigned to plot data (via either approach) form the foundation for the training database that is critical to most of the LANDFIRE products. It is imperative that an adequate amount of reliable reference data be acquired in a timely fashion for CT refinement before the mapping of each new zone is initiated. Cooperative arrangements should be in place at the beginning of the national effort so that the data are available for use within a practical time frame. A plan should also exist for the collection of new data in areas lacking sufficient amounts.

In addition, as CTs are defined for each zone, it is important to ensure that the criteria for distinguishing CTs are applicable across the United States and that the developers of the CT classification apply these criteria in all zones. This will minimize artificial boundaries in the maps resulting from inconsistent classification efforts.

The CT classification should be developed in concert with the PVT and SS classifications. Developers should work together to ensure that all classes are ecologically consistent between classification systems. We recommend that the developers be the same group for all the biophysical and vegetation map classifications. A vegetation working group should be the arbitrator of all LANDFIRE classification systems to ensure consistency. In the LANDFIRE Prototype, the PVT and CT map legends had to be adjusted even after the maps were created because multiple versions of each classification were available and used, resulting in inconsistency between legends. For example, at one point, there was an "Herbaceous" PVT, but there was not an "Herbaceous" CT. These classifications must be consistent from the beginning so that the maps made from them correspond ecologically. In addition, LANDSUMv4 (Pratt and others, Ch. 10) requires that the maps be consistent with the succession pathway models described in Long and others, Ch. 9.

Throughout the development of the LANDFIRE vegetation classifications, we received feedback regarding our use of certain terminology and definitions. We found that the *potential vegetation* concept is not uniformly accepted among vegetation ecologists, especially range scientists. Alternative terminology, such as *potential natural vegetation group* (PNVG), is also not well received by some specialists. For national implementation, we recommend that the term *biophysical setting* (BpS) be used instead of PVT because this term applies to a wide range of environmental conditions in which vegetation occurs and does not imply an assumption of linear succession processes or the integration (or not) of disturbance into the classification system. We also recommend that the term *cover type* (CT) be changed to *existing vegetation* (EV) to more clearly indicate what is being represented.

Another problem that affected the PVT development particularly was the numerous personnel changes throughout the development process. The instability of the personnel resource available to the LANDFIRE Prototype Project resulted in inconsistent and sometimes conflicting approaches and insufficient documentation. For example, some ecologists tended to split biophysical characteristics, whereas others tended to lump them; the PVT classification therefore went through many phases of adjustment and revision. A clearly documented and detailed explanation of the purpose of the PVT classification would help developers understand their objectives, and documented procedures would help developers avoid conflicts in methodologies. Again, the VWG should oversee this effort throughout the implementation of LANDFIRE National to ensure standards are followed as PVTs are classified within and across mapping zones.

As mentioned above, the scalable nature of the PVT classification allowed flexibility in representing PVTs, but this characteristic was not utilized in the prototype effort. By choosing not to employ the scalable nature of the classification (not grouping to broader and thus fewer classes), the LANDFIRE vegetation modelers ended up with succession models that were too numerous and complicated, with over 40 CTs in the succession pathway for many PVTs in both prototype mapping zones (Long and others, Ch. 9). We do not recommend this level of complexity in vegetation modeling for LANDFIRE National. Various levels of the PVT classes could be used to represent different scales and interpretations of potential vegetation. For example, level 1 could be used to represent major environmental settings, as indicated by life form. In another example, level 3 – which differentiates between the historical fire regimes of PVTs – could be used as a link to potential natural vegetation types, which include natural disturbance in their definitions and descriptions. We recommend that vegetation modelers use coarser scale PVTs (and CTs) to simplify the models.

Conclusion

To meet the needs of vegetation and fuel mappers, we developed three ecologically consistent vegetation and biophysical map unit classifications that were identifiable, scaleable, mappable, and model-able. We found that successful implementation of such an endeavor requires detailed knowledge of many vegetation systems and their succession, fuel, and fire dynamics; awareness of differing scientific approaches to vegetation classification; recognition and understanding of the varying user needs; and recognition and understanding of the varying needs relating to different areas of the country. We emphasize the importance of creating a vegetation working group for the implementation of LANDFIRE National or any similar large scale effort. Lastly, centralized coordination and oversight of the development of these map unit classifications is crucial to promote the efficiency, consistency, and high scientific standards required for this type of project.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Appendix 6-A—Biophysical and vegetation map classification coding protocol

The purpose of the biophysical and vegetation map classification coding protocol was to create cover type (CT), potential vegetation type (PVT), and structural stage (SS) codes that allowed for informed interpretation of the vegetation map units. In other words, users of the classification would have access to information about the specific CT, PVT, or SS simply by referencing the code definition tables included below.

Cover Type

Zone 16: Central Utah Highlands

The cover type code for Zone 16 is a four-digit, two-level code representing the life form and life form subclass of the cover type. The life form is the first digit (app. 6-A: table 1). Note: Here, life form represents the *existing* vegetation life form, not the potential.

App. 6-A: Table 1—Zone 16 life form (1-digit)

Code	Life form
1	Forest (trees dominate)
2	Woodland (trees dominate)
3	Shrubland (shrubs dominate)
4	Herbaceous (herbs dominate)

The second digit (app. 6-A: tables 2 and 3) is the life form subclass (a delineation of leaf phenology and morphology). The herbaceous life form subclass is different from the shrub and forest subclass because leaf phenology and morphology in woody species (shrubs and trees) are described with different terms than those used for herbaceous or non-woody species. The final two digits represent the dominant species or group of species that indicates that type and are found in table 1 of Long and others, Ch. 6. For example, a cover type code of “3101” indicates that it is a shrub life form, broadleaf evergreen life form subclass, and the dominant species is mountain big sagebrush. A cover type of Warm Season Perennial Grasslands with code 4101 has an herbaceous life form, perennial graminoid life form subclass, and the dominant species group is warm season grasses.

App. 6-A: Table 2—Zone 16 life form subclass (1-digit) (excluding herbaceous)

Code	Life form subclass
1	Broadleaf evergreen
2	Needleleaf evergreen
3	Mixed broadleaf-needleleaf evergreen
4	Broadleaf deciduous
5	Needleleaf deciduous
6	Mixed broadleaf-needleleaf deciduous
7	Broadleaf mixed evergreen-deciduous
8	Needleleaf mixed evergreen-deciduous
9	Mixed broadleaf-needleleaf mixed evergreen-deciduous

App. 6-A: Table 3—Zone 16 herbaceous life form subclass (1-digit)

Code	Life form subclass
1	Perennial graminoids
2	Perennial forbs
3	Perennial mixed graminoids-forbs
4	Annual graminoid
5	Annual forb
6	Annual mixed graminoids-forbs
7	Mixed perennial-annual graminoid
8	Mixed perennial-annual forb
9	Mixed perennial-annual mixed graminoids-forbs

Zone 19: Northern Rockies

In Zone 19, the cover type code is a 4-digit code representing the life form and the hierarchical mapping level of the cover type, which are differentiated by criteria based on this life form. However, in all life forms, the first digit (app. 6-A: table 4) represents the life form of the current or existing vegetation. Note that these life form categories are different from those used in Zone 16.

App. 6-A: Table 4—Zone 19 life form (1-digit)

Code	Life form
1	Forest (trees dominate)
2	Shrubland (shrubs dominate)
3	Herbaceous (herbs dominate)

In the forest life form, the second digit represents the life form subclass (app. 6-A: table 5) and the third and fourth digits represent the dominant species or species groups found within the preceding life form and subclass (see table 3, Long and others, Ch. 6). For example, a forest cover type code of "1402" represents the Riparian Hardwood cover type, where the life form is forest, the life form subclass is broadleaf deciduous, and the dominant species group is riparian hardwoods.

App. 6-A: Table 5—Zone 16 forest life form subclass (1-digit)

Code	Life form subclass
1	Broadleaf evergreen
2	Needleleaf evergreen
3	Mixed broadleaf-needleleaf evergreen
4	Broadleaf deciduous
5	Needleleaf deciduous
6	Mixed broadleaf-needleleaf deciduous
7	Broadleaf mixed evergreen-deciduous
8	Needleleaf mixed evergreen-deciduous
9	Mixed broadleaf-needleleaf mixed evergreen-deciduous

In the shrub life form, the second digit represents the life form subclass (app. 6-A: table 6), which is categorized differently than the forest life form subclass. The third and fourth digits (app. 6-A: table 7) represent either the height class of the cover type (01-03) or the dominant species groups (beginning with 11). For example, a shrub cover type with code "2202" indicates that it is an Upland Microphyllous Medium [Height] Shrubland cover type and a cover type with code 2213 is the Threetip Sage cover type where the life form is shrub, the life form subclass is facultative-upland microphyllous, and the dominant species group is threetip sagebrush.

App. 6-A: Table 6—Zone 16 shrub life form subclass (1-digit)

Code	Life form-subclass
1	Facultative-upland broadleaf
2	Facultative-upland microphyllous
3	Facultative-upland needleleaf
4	Facultative-upland sclerophyllous
5	Facultative-upland succulent
6	Riparian broadleaf

App. 6-A: Table 7—Zone 16 shrub height class (1-digit)

Code	Height class
01	Dwarf
02	Medium
03	Tall

Herbaceous cover types have been coded differently from shrub and forest starting at the second digit, which represents the physiognomy (app. 6-A: table 8), not the life form subclass. The third digit (app. 6-A: table 9) represents the life history and growth form. The final and fourth digit (app. 6-A: table 10) represents the nativity of the cover type. For example, 3142 indicates that the cover type is herbaceous, facultative-upland, perennial bunch graminoid and native. It is called a Perennial Native Bunch Graminoid cover type.

App. 6-A: Table 8—Zone 16 herbaceous life form subclass (1-digit)

Code	Life form subclass
1	Facultative-upland
2	Riparian

App. 6-A: Table 9—Zone 16 life history and growth form (1-digit)

Code	Life history and growth form
1	Annual forb
2	Annual graminoid
3	Perennial forb
4	Perennial bunch gramminoid
5	Perennial rhizomatous gramminoid

App. 6-A: Table 10—Zone 16 herbaceous nativity class (1-digit)

Code	Nativity class
1	Exotic
2	Native

Potential Vegetation Type

The PVT code is a four-digit, two-level code which includes the zone number in the first and second digits and the potentially dominant species or species group in the last two digits (app. 6-A: tables 11 and 12). Exhaustive lists of the codes may be found in tables 7 and 8, Long and others, Ch. 6.

App. 6-A: Table 11—Zone 16 potentially dominant species (2-digit)

Code	Potential species
01-39	Forest-dominated life form
40-49	Woodland-dominated life form
50-69	Upland shrub- or herbaceous-dominated life form (non-alpine)
70-79	Riparian shrub- or herbaceous-dominated life form (non-alpine)
80-89	Alpine herbaceous-dominated life form

App. 6-A: Table 12—Zone 19 potentially dominant species (2-digit)

Code	Potential species
01-59	Tree-dominated life form
60-79	Shrub-dominated life form
80-89	Herbaceous-dominated life form

Structural Stage

The structural stage codes used in the LANDFIRE Prototype Project are quite simple because they are a two digit, two-level numeric code. The first digit is the life form (app. 6-A: tables 13 and 4). The second digit describes the cover and height for all life forms in Zone 16. Appendix 6-A: tables 14 and 15 describe the Zone 19 cover and height classes by life form.

App. 6-A: Table 13—Zone 16 structural stage life form (1-digit)

Code	Life form
1	Forest (trees dominate)
2	Woodland (trees dominate)
3	Shrubland (shrubs dominate)
5	Herbaceous (herbs dominate)

App. 6-A: Table 14—Zone 16 structural stage (1-digit)

Code	Structural stage
1	Low Cover, Low Height
2	High Cover Low Height
3	High Cover, High Height
4	Low Cover, High Height

App. 6-A: Table 15—Zone 19 structural stage (1-digit)

Code	Structural stage
0	Low Cover, Low Height Trees
1	Low Cover, Low Height Shrub and Herbaceous (Low, Moderate Trees)
2	High Cover, Low Height Shrub and Herbaceous (High, Low-Moderate Trees)
3	Low Cover, Moderate Height Trees and Shrubs
4	High Cover, Moderate Height Trees and Shrubs
5	Low Cover, High Height Trees, Shrubs, and Herbaceous
6	High Cover, High Height Trees, Shrubs, and Herbaceous

Appendix 6-B—Cover types for the western U.S.

CT#	Cover type	Description
1401	Riparian Hardwood[a]	Riparian hardwood forests in the western U.S. can be dominated by many species of deciduous trees, including cottonwoods (*Populus spp.*), which are the most wide ranging group. Other riparian hardwoods include green ash (*Fraxinus pennsylvanica*), and American elm (*Ulmus americana*) on the Great Plains; in California, California sycamore (*P. racemosa*), and California walnut (*Juglans californica*); Arizona sycamore (*Platanus wrightii*) in the southwest; netleaf hackberry (*Celtis laevigata* var. *reticulata*) in the southwest, intermountain west and Great Plains; and white alder (*Alnus rhombifolia*) and Oregon ash (*Fraxinus latifolia*) in the Pacific Northwest.
1405	Aspen -- Birch[a]	Extensive areas of upland forests that occur in the West and are dominated by trembling aspen (*Populus tremuloides*), the most widely distributed North American tree species (Burns and Honkala 1990).
1406	Pacific Deciduous Forest [Other Broadleaf]	Pure stands dominated by species such as red alder (*Alnus rubra*) and bigleaf maple (*Acer macrophyllum*) can occur in the Northwest, with red alder ranging from central California to southeast Alaska, and bigleaf maple extending only as far north as southwestern British Columbia. These species can co-occur and are often found in mixtures with other conifers and hardwoods (Minore 1979; Harrington 1990; Minore and Zasada 1990).
1101	Pacific Broadleaf Evergreen Forest [Other Broadleaf Evergreen]	Stands of California bay (*Umbellularia californica*) that are found in California and southwest Oregon (Stein 1990) or stands of tanoak (*Lithocarpus densiflorus*) (Tappeiner, McDonald et al. 1990). Both species commonly occur in mixes with other species.
1501	Larch	Stands dominated by western larch (*Larix occidentalis*) occur in the northern Rockies and east slopes of the Cascades. One of two species of deciduous conifers in the western U.S., western larch is most commonly associated with Douglas-fir, although it can grow with many other species of conifers (Schmidt and Shearer 1990).
1201	Ponderosa Pine[a]	Stands dominated by interior ponderosa pine (*Pinus ponderosa var. scopulorum*) are found in the interior West and Rocky Mountains, and Arizona pine (*Pinus ponderosa var. arizonica*) is found in the Southwestern U.S.
1218	Pacific Ponderosa Pine	Mixes of many coniferous species can dominate forests in middle to lower elevations in the Sierra Nevada Range, with Pacific ponderosa pine (*Pinus ponderosa var. pacifica*) being “the biological thread that holds the phases of this forest together” (Barbour and Minnich 2000). Other species that can dominate a site include sugar pine (*Pinus lambertiana*), incense–cedar (*Calocedrus decurrens*), Jeffrey pine (*Pinus jeffreyi*), white fir, and Douglas-fir (Barbour and Minnich 2000).
1202	Foothill Pines	The California endemics, Coulter pine (*Pinus coulteri*), and knobcone pine (*Pinus attenuata*) of California and Oregon have some or a high degree of cone serotiny in various populations. Where they occur in pure stands, these species occupy a transition zone between chaparral and coniferous forest or woodland at higher elevations (Howard 1992; Cope 1993).
1203	Western White Pine	Seral stands dominated by western white pine occur in the northern Rockies. It is a minor species in other forest communities in this area and occurs in mixed stands in the Pacific Northwest and Sierra Nevadas (Boyd 1980).
1204	Lodgepole Pine[a]	Lodgepole pine has four varieties, two of which are assigned to the lodgepole pine map type: Sierra lodgepole pine (*Pinus contorta var. murrayana*) and Rocky Mountain lodgepole pine (*P. contorta var. latifolia*). Extensive pure stands occur, as well as in association with many other species (Lotan and Critchfield 1990).

Appendix 6-B—(Continued)

CT#	Cover type	Description
1205	Douglas-fir[a]	Douglas-fir can be a dominant in large areas of forest in the West, occurring in pure stands, although frequently with a mix of many other species. Both coast Douglas-fir (*Pseudotsuga menziesii var. menziesii*) and Rocky Mountain Douglas-fir (*P. m. var. glauca*) are included in the Douglas-fir cover type.
1206	Grand Fir -- White Fir[a]	This type consists of stands dominated by grand fir (*Abies grandis*) or Rocky Mountain white-fir (*Abies concolor var. concolor*), a species and a variety of true fir that occur in somewhat similar habitats in the Interior West.
1207	Pacific Silver Fir -- Noble fir	Stands dominated by the conifers, Pacific silver fir (*Abies amabilis*) or noble fir (*Abies procera*), indicate a moist coastal site in the Pacific Northwest. These species often co-occur with other species of conifers, most consistently western hemlock (*Tsuga heterophylla*), and mountain hemlock (*Tsuga mertensiana*) (Franklin 1980).
1219	Red Fir	Red fir (*Abies magnifica and A. magnifica var. shastensis*) is a climax, high elevation species that can occur in pure stands in the Sierra Nevadas, southern Cascades, and Coast Ranges, although it also intergrades with other conifers (Laacke 1990a).
1220	California White Fir	Stands of this type are indicated by California white fir (*Abies concolor var. lowiana*) and occur in forested stands of California and Oregon. It commonly co-occurs in mixture with other conifer species typical of drier sites in the Sierra, Klamath, and Siskiyou Mountains, such as ponderosa pine, red fir, Jeffery pine, sugar pine and Douglas-fir. White fir is commonly a later seral species (Laacke 1990b).
1209	Western Hemlock	Pure or mixed stands dominated by western hemlock (*Tsuga heterophylla*) occur in mild, humid climatic zones of the Pacific Northwest, coastal Alaska, and the northern Rockies. It is a major or minor component of at least 20 different forest types (Packee 1990).
1210	Mountain Hemlock	In cold, snowy, high altitude forests of the Pacific Northwest, coastal Alaska, the Sierra Nevadas, and the northern Rocky Mountains, mountain hemlock (*Tsuga mertensiana*) can be the sole dominant or mixed with other high altitude conifers (Means 1990).
1211	Spruce -- Fir[a]	In the western U.S., the spruce-fir complex is a high elevation or montane forest community dominated by Engelmann spruce (*Picea engelmannii*) and/or subalpine fir (*Abies lasiocarpa*). Other species assigned to this complex include blue spruce (*Picea pungens*), and Brewer's spruce (*Picea breweriana*), a species of the mountains of northwest California and southwest Oregon (Thornburgh (1990b).
1212	Sitka Spruce	Pure stands of Sitka spruce (*Picea sitchensis*) occur in a narrow band along the Pacific coast, from central California to coastal Alaska (Harris 1980), although it is often associated with western hemlock (*Tsuga heterophlla*).
1213	Cedar	Western redcedar (*Thuja plicata*) is the most common western species in this Pacific Northwest type, commonly occurring in moist or wet locations, frequently in association with other moist site conifers (Minore 1990). Alaska cedar (*Chamaecyparis nootkatensis*) can dominate the canopy in Pacific Northwest forests, although it often occurs with many other tree species (Harris, 1990.). Port Orford cedar (*Chamaecyparis lawsoniana*) usually occurs in mixed stands in a small area of coastal southwest Oregon and adjacent northern California (Zobel 1990).

Appendix 6-B—(Continued)

CT#	Cover type	Description
1215	Redwood	Forested stands dominated by redwood (*Sequoia sempervirens*) are found in northern California and extreme southwestern Oregon, occurring in pure stands and in mixtures with other species.
1216	Sequoia	Giant sequoia (*Sequoiadendron giganteum*) occurs in a very limited distribution in the central and southern Sierra Nevada Mountains where it dominates stands where other coniferous species are commonly present.
1217	Cypress	The cypress cover type consists of stands dominated by one of three species of cypress, generally small trees with serotinous cones. Arizona cypress (*Cupressus arizonica*) (Sullivan 1993) sometimes occurs in pure stands or mixed with other species in riparian and some upland habitats of the southwest. MacNab's cypress (*Cupressus macnabiana*) (Esser 1994a) and Sargent's cypress (*Cupressus sargentii*) both occur in California (Esser 1994b), occurring in pure stands or mixed with at least one other conifer species.
1801	Timberline Pines[a]	This type consists of species of pines dominating forests and woodlands at upper and lower timberlines, including the high elevation species foxtail pine (*Pinus balfouriana*) of California, bristlecone pine (*Pinus aristata*), Great Basin bristlecone pine (*Pinus longaeva*), whitebark pine (*Pinus albicaulis*) and limber pine (*Pinus flexilis*), a species that can appear at both upper and lower timberline. Alpine larch (*Larix lyallii*), a deciduous conifer, is also included because it mixes with some of these species in the northern Rockies.
2401	Deciduous Oak	These woodlands are open stands dominated by a species of deciduous oak, including the California endemics, blue oak (*Quercus douglasii*) or California white oak (*Quercus lobata*) (Howard 1992b). These species co-occur at lower elevations (McDonald 1990b) Other species of deciduous oak that may each dominate forest or woodland stands include bur oak (*Quercus macrocarpa*) in the northern plains (Johnson 1990); California black oak (*Quercus kelloggii*), endemic to California (McDonald 1990a); and Oregon white oak (*Quercus garryana*), which ranges from southwestern British Columbia to central California (Stein 1990a).
2101	Evergreen Oak	Evergreen oak woodlands are open stands of generally small stature trees, occurring in the southwest and in California. Coast live oak (*Quercus agrifolia*), Engelmann's oak (*Quercus engelmannii*), and interior live oak (*Quercus wislizenii*) are common California woodland species (Finch and McCleery 1990; Tirmenstein 1989). Canyon live oak (*Quercus chrysolepis*) is a species of evergreen-leaved oak that dominates forest and woodland stands in Oregon, California, and Arizona (Thornburgh 1990a). In the Southwest, these woodlands may be dominated by Emory oak (*Quercus emoryi*) (Pavek 1994a), gray oak (*Quercus grisea*) (Pavek 1994b), Mexican blue oak (*Quercus olongifolia*) (Pavek 1993), or Arizona white oak (*Quercus arizonica*) (Pavek 1994c). Some of these southwestern woodland species can co-occur, as well as grow with conifers (Pavek 1994).
2201	Pinyon -- Juniper[a]	The pinyon-juniper type contains open stands dominated by a species of tree-like juniper and a species of pinyon pine, with the pinyon at least 20% of the total tree cover. Juniper species include alligator juniper (*Juniperus deppeana*), California juniper (*J. californica*), oneseed juniper (*J. monosperma*), Pinchot's juniper (*J. pinchottii*), redberry juniper (*J. coahuilensis*), Rocky Mountain juniper (*J. scopulorum*), Utah juniper (*J. osteosperma*), and western juniper (*J. occidentalis*). Pinyon species can include singleleaf pinyon (*Pinus monophylla*), two-needle pinyon (*Pinus edulis*), Mexican pinyon (*Pinus cembroides*), papershell pinyon (*Pinus remota/cembroides*), and Parry pinyon (*Pinus quadrifolia*).
2202	Juniper[a]	Open stands dominated by juniper, with pinyon less than 20% of the total tree cover, or absent. Juniper species are those listed for pinyon-juniper.

Appendix 6-B—(Continued)

CT#	Cover type	Description
3704	Mountain Deciduous Shrub[a]	These associations of medium to tall deciduous shrubs are usually in mesic upland sites, generally at lower elevations than continuous forest. In the eastern Great Basin, species can include serviceberry (*Amelanchier utahensis*), gambel oak (*Quercus gambelii*), chokecherry (*Prunus virginiana*), and snowberry (*Symphoricarpos oreophilus*).
3402	Riparian Shrub[a]	Riparian zones dominated by tall and medium sized shrubs, with one to several species of willows, occur throughout the West. In the Intermountain West, riparian willows include Bebb willow (*Salix bebbiana*), Booth willow (*S. boothii*), Drummond willow (*S. drummondiana*), coyote willow (*S. exigua*), Geyer willow (*S. geyeriana*), and yellow willow (*S. lutea*) (Welsh et. al. 1987). Thinleaf alder (*Alnus incana*), water birch (*Betula occidentalis*), and golden currant (*Ribes aureum*) are also common in riparian zones.
3403	Exotic Riparian Shrub[a]	Riparian communities can be dominated by pure or hybrid species of tamarisk (*Tamarix* spp.), a complex of hybridizing exotic species.
3101	Mountain Big Sagebrush Complex[a]	Common throughout the Intermountain West, this complex is usually dominated by mountain big sagebrush (*Artemisia tridentata ssp. vaseyana*). Other shrubs of similar ecological requirements that indicate this complex include mountain silver sagebrush (*Artemisia cana ssp. viscidula*), snowfield sagebrush (*Artemisia tridentata ssp. spiciformis*), *A. tridentata var. pauciflora*, Rothrocks's artemisia (*A. rothrockii*), and tall threetip sagebrush (*A. tripartita ssp. tripartita*)(Tart 2003). Occurring at higher elevations and more mesic conditions than the other big sagebrush subspecies, it is usually characterized by the presence of a moderately productive herbaceous understory of both grasses and forbs. No particular herbaceous species are consistently found in this complex.
3102	Wyoming -- Basin Big Sagebrush Complex[a]	Occurring at lower elevation and drier sites than mountain big sagebrush, this complex is usually identified by the pre ence of Wyoming big sagebrush (*Artemisia tridentata ssp. wyomingensis*), or basin big sagebrush (*A. tridentata ssp. tridentata*). Other shrubs that indicate this complex include plains silver sagebrush (*A. cana ssp. cana*), Bolander silver sagebrush (*A. cana ssp. bolanderi*), and *Artemisia tridentata ssp. xericensis* (Tart 2003). The herbaceous understory is less productive than on mountain big sagebrush sites. No herbaceous species is known consistently occur in this complex.
3103	Dwarf Sagebrush Complex[a]	Communities dominated by any of a group of small sagebrush species, usually with a sparse understory. Species can include black sagebrush (*Artemisia nova*), Rigid (stiff) sagebrush (*A. rigida*), Wyoming threetip sagebrush (A. *tripartita ssp. rupicola*), birdfoot sagebrush (*A.pedatifida*), and three subspecies of low sagebrush (*A. arbuscula ssp. longiloba, A. a. ssp. thermopopola and A. t. ssp. arbuscula*).
3104	Sand Sagebrush[a]	A shrub community common on the Great Plains is that dominated by sand sagebrush (*Artemisa filifolia*).
3105	Blackbrush[a]	This desert shrub community common in the arid Southwest is dominated by almost pure stands of blackbrush (*Coleogyne ramosissima*).
3106	Rabbitbrush[a]	Semi-arid to arid shrub communities are found in the Intermountain West that are dominated by any of several species of rabbitbrush, including rubber rabbitbrush (*Ericameria nauseosa*), Greene rabbitbrush (*Chrysothamnus greenei*), and stickyleaf rabbitbrush (*Chrysothamnus viscidiflorus*).

Appendix 6-B—(Continued)

CT#	Cover type	Description
3107	Chaparral[a]	Chaparral communities have moderate to dense cover of tall, stiffly branched evergreen-leaved shrubs, sometimes dominated by chamise (*Adenostoma fasciculatum*), and often composed of a mix of many shrub species. Other common chaparral species include: hoaryleaf ceanothus (*Ceanothus crassifolius*), buckbrush (*C. cuneatus*), cupleaf ceanothus (*C. greggii*), hairy ceanothus (*C. oliganthus*), whitethorn ceanothus (*Ceanothus cordulatus*), bigberry manzanita (*Arctostaphylos glauca*), Eastwood manzanita (*A. glandulosa*), pointleaf manzanita (*A. patula*), Nuttall's scrub oak (*Quercus dumosa*), and turbinella oak (*Q. turbinella*). This type occurs in occurs in California, Arizona, and southern Utah.
3108	Soft Chaparral	This is a coastal shrub community of central and southern California, occurring on dry, sometimes rocky slopes, dominated by a mix of species with soft, pliable leaves. Diagnostic species include black sage (*Salvia mellifera*), purple sage (*Salvia leucophylla*), white sage (*Salvia apiana*), and coastal sagebrush (*Artemisia californica*).
3301	Other Evergreen Shrubs[a]	These are characteristic, upland, mesic site shrub communities dominated by evergreen-leaved shrubs, such as curleaf mountain-mahogany (*Cercocarpus ledifolius*), littleleaf mountain-mahogany (*Cercocarpus intricatus*), or snowbrush (*Ceanothus velutinus*).
3701	Salt Desert Shrub[a]	This cover type consists of arid shrub communities that occur throughout the West and are dominated by mixes of halophytic (salt tolerant) shrub species, such as shadscale (*Atriplex confertifolia*), iodine bush (*Allenrolfea occidentalis*), black greasewood (*Sarcobatus vermiculatus*) and winterfat (*Krascheninnikovia lanata*) (West and Young 2000).
3702	Desert Shrub[a]	Desert shrub communities occur in arid lands of the Southwest, including the Sonoran and Mojave Deserts, often with a sparse herbaceous understory. Creosotebush (*Larrea tridentata*), and frequently bursage (*Ambrosia dumosa*), often dominate, although many other shrub species can be the dominant. Other species include tarbush (*Flourensia cernua*), paloverde (*Cercidium* spp.), catclaw acacia (*Acacia greggii*), and smoke tree (*Dalea spinosa*).
3703	Dry Deciduous Shrub[a]	Dry sites in the Intermountain West that can support a plant community dominated by deciduous leaved shrubs, including bitterbrush (*Purshia tridentata*), Utah serviceberry (*Amelanchier utahensis*), and true mountain mahogany (*Cercocarpus montanus*).
4101	Warm Season Grasses [a]	These are communities of grasses that grow during late spring and summer in climates where moisture is not limiting at that time of the year and remain green during the hottest part of the summer (C-4 grasses).
4102	Cool Season Grasses [a]	These plant communities are dominated by species of grasses that grow best during cool and moist periods of the year. They green up early in the growing season, cure during the heat of the summer, and can green up in the fall, depending on species characteristics and weather (C-3 grasses).
4201	Native Forbs[a]	These plant communities can be dominated by a high diversity of perennial forb species, usually occurring on mesic to moist sites in the mountains. Many different forb species can indicate this type including mountain bluebell (*Mertensiana ciliata*), northern mule's-ear (*Wyethia amplexicaulis*), nettleleaf giant-hyssop (*Agastache urticifolia*), fernleaf wild lovage (*Ligusticum filicinum*), Sitka valerian (*Valeriana sitchensis*), and Arctic lupine (*Lupinus arcticus ssp. subalpinus*) (Natureserve 2004).
4202	Exotic Forbs[a]	Communities of exotic forbs that can be dominated by weedy species such as spotted knapweed (*Centaurea maculosa*), leafy spurge (*Euphorbia esula*), or St. John's wort (*Hypericum perforatum*).

Appendix 6-B—(Continued)

CT#	Cover type	Description
4301	Wetland Herbaceous[a]	Riparian, wet meadows, and seep communities are dominated by graminoids and forbs and usually have soils that are saturated for at least part of the growing season. Common species of these communities include sedges (e.g. *Carex aquatilis*, *C. nebrascensis* and *C. rostrata*), alkali cordgrass (*Spartina gracilis*), marsh spikerush (*Eleocharis palustris*), and forbs such as primrose monkey-flower (*Mimulus primuloides*) and white marsh-marigold (*Caltha leptosepala*) (Natureserve 2004). Whether a community is considered riparian, wet meadow, or seep depends on the source of its water.
4302	Alpine[a]	These plant communities occur above upper treeline and are dominated by herbaceous species, usually mixes of sedges, grasses, and perennial forbs. Indicator forbs include Ross' avens (*Geum rossii*), white coil-beak lousewort (*Pedicularis contorta*), spreading phlox (*Phlox diffusa*), Colorado blue columbine (*Aquilegia caerulea*), and graminoids include shorthair reedgrass (*Calamagrostis breweri*), and Drummond's rush (*Juncus drummondii*) (Natureserve 2004).
4401	Annual Grasslandsa	Any extensive area of annual grasslands in the western U.S. that are dominated by exotic species, including cheatgrass (Bromus tectorum), and medusahead (Taeniaetherum caput-medusae).

[a] Indicates type was refined with Zone 16 plot data.

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Appendix 6-C—Crosswalk of western LANDFIRE cover types to Gap Analysis Program (GAP), Society of American Foresters (SAF), and Society for Range Management (SRM) cover types (Eyre 1980, Merchant and others 1998, Shiflet 1994)

CT#	(Western U.S.) LANDFIRE cover type	GAP cover type	SRM#	SRM cover type	SAF#	SAF cover type
1401	Riparian Hardwood	Maple	203	Riparian Woodland	222	Black Cottonwood-Willow
					235	Cottonwood-Willow
1405	Aspen -- Birch	Aspen			217	Aspen
		Aspen - Conifer			18	Paper Birch
1406	Pacific Deciduous Forest [Other Broadleaf]				221	Red Alder
1101	Pacific Broadleaf Evergreen Forest [Other Broadleaf Evergreen]	California Bay				
1501	Larch	Western Larch - Douglas-fir	109	Ponderosa Pine-Shrubland	212	Western Larch
1201	Ponderosa Pine	Ponderosa Pine			237	Interior Ponderosa Pine
		Ponderosa Pine/Shrub				
		Ponderosa Pine/Oak - Juniper-Pinyon				
		Ponderosa Pine - Lodgepole Pine				
		Interior Ponderosa Pine				
	Pacific Ponderosa Pine	Jeffrey Pine			247	Jeffrey Pine
		California Foothill Pine			245	Pacific Ponderosa Pine
		Mixed Sugar Pine			244	Pacific Ponderosa Pine-Douglas-fir
					243	Sierra Mixed Conifer
1202	Foothill Pine	California Foothill Pine			248	Knobcone Pine
		Knobcone Pine				
		Monterey Pine				
1203	Western White Pine	Western White Pine			215	Western White Pine
1204	Lodgepole Pine	Lodgepole Pine			218	Lodgepole Pine
		Lodgepole Pine - Douglas-fir				
		Coastal Lodgepole Pine				
		Sierra Lodgepole Pine				
1205	Douglas-fir	Inland Douglas-fir			210	Interior Douglas-fir
		Inland Douglas-fir - Western Red Cedar			230	Douglas-fir-Western Hemlock
		Douglas-fir - Ponderosa Pine - Incense Cedar			229	Pacific Douglas-fir
		Westside Douglas-fir - Western Hemlock			234	Douglas-fir-Tanoak-Pacific Madrone
		Westside Douglas-fir				
		Douglas-fir - Tanoak - Pacific Madrone				
		Douglas-fir - Sugar Pine - Ponderosa Pine				
		Douglas-fir - White Fir - Blue Spruce				
1206	Grand Fir -- White Fir	Grand Fir - Douglas-fir			213	Grand Fir
		White Fir - Douglas-fir			210	Interior Douglas-fir
		White Fir				
		White Fir - Douglas-fir/Shrub				

Appendix 6-C—(Continued)

CT#	LANDFIRE cover type	(Western U.S.) GAP cover type	SRM#	SRM cover type	SAF#	SAF cover type
1207	Pacific Silver Fir – Noble Fir	Pacific Silver Fir			226	Coastal True Fir-Hemlock
1219	Red Fir	Red Fir			207	Red Fir
1220	California White Fir				211	White Fir
1209	Western Hemlock	Westside Western Hemlock - Western Red Cedar Inland Western Red Hemlock			224 225	Western Hemlock Western Hemlock-Sitka Spruce
1210	Mountain Hemlock	Subalpine Spruce - Fir - Mountain Hemlock			205	Mountain Hemlock
1211	Spruce – Fir	Subalpine Spruce Fir - Mountain Hemlock			216 206	Blue Spruce Engelmann Spruce-Subalpine Fir
1212	Sitka Spruce	Sitka Spruce			223	Sitka Spruce
1213	Cedar	Inland Western Red Cedar - Western Hemlock			231 228 227	Port-Orford-Cedar Western Redcedar Western Redcedar-Western Hemlock
1215	Redwood	Coastal Redwood			232	Redwood
1216	Sequoia	Giant Sequoia			243	Sierra Mixed Conifer
1217	Cypress	Cypress			240	Arizona Cypress
1801	Timberline Pines	Subalpine Pine Limber Pine			209 256 219 208	Bristlecone Pine California Mixed Subalpine Limber Pine Whitebark Pine
2401	Deciduous Oak	California Oak California Oak - Conifer Mixed Oak Oregon White Oak Oregon White Oak - Conifer	201	Blue Oak Woodland	250 246 233	Blue Oak-Foothills Pine California Black Oak Oregon White Oak
2101	Evergreen Oak	Madrean Oak California Oak	202 509	Coast Live Oak Woodland Oak–Juniper Woodland and Mahogany-Oak	241 249 255	Western Live Oak Canyon Live Oak California Coast Live Oak
2201	Pinyon – Juniper	Pinyon - Juniper Pinyon Juniper Madrean Pinyon-Juniper	412 504 509	Juniper–Pinyon Woodland Juniper-Pinyon Pine Woodland Transition Oak – Juniper Woodland and Mahogany Oak Association	239	Pinyon-Juniper
2202	Juniper		504 412 107	Juniper-Pinyon Pine Woodland Juniper–Pinyon Woodland Western Juniper-Big Sagebrush–Bluebunch Wheatgrass	239 220 238 66	Pinyon-Juniper Rocky Mountain Juniper Western Juniper Ashe-Redberry (Pinchot) Juniper

Appendix 6-C—(Continued)

CT#	LANDFIRE cover type	(Western U.S.) GAP cover type	SRM#	SRM cover type	SAF#	SAF cover type
			509	Oak–Juniper Woodland and Mahogany-Oak		
3704	Mountain Deciduous Shrub	Mixed oak	421	Chokecherry-Serviceberry-Rose		
			413	Gambel Oak		
3402	Riparian Shrub	Riparian/Wetland	422	Riparian		
3403	Exotic Riparian Shrub					
3101	Mountain Big Sagebrush Complex	Sagebrush	612	Sagebrush–Grass		
		Sagebrush/Perennial Grass	404	Threetip Sagebrush		
			314	Big Sagebrush–Bluebunch Wheatgrass		
			315	Big Sagebrush–Idaho Fescue		
			316	Big Sagebrush–Rough Fescue		
			402	Mountain Big Sagebrush		
			408	Other Sagebrush Types		
			324	Threetip Sagebrush-Idaho Fescue		
3102	Wyoming -- Basin Big Sagebrush Complex	Sagebrush	401	Basin Big Sagebrush		
		Sagebrush/Perennial Grass	403	Wyoming Big Sagebrush		
			612	Sagebrush–Grass		
			408	Other Sagebrush Types		
			314	Big Sagebrush–Bluebunch Wheatgrass		
3103	Dwarf Sagebrush Complex	Sagebrush	320	Black Sagebrush–Bluebunch Wheatgrass		
		Sagebrush/Perennial Grass	321	Black Sagebrush–Idaho Fescue		
			404	Threetip Sagebrush		
			405	Black Sagebrush		
			406	Low Sagebrush		
			407	Stiff Sagebrush		
3104	Sand Sagebrush		722	Sand Sagebrush-Mixed Prairie		
3105	Blackbrush	Blackbrush	212	Blackbrush		
3106	Rabbitbrush					
3107	Chaparral	California Chaparral	206	Chamise Chaparral		
		Coastal Scrub	208	Ceanothus Mixed Chaparral		
		Coastal Dune Scrub	209	Montane Shrubland		
		Interior Chaparral	207	Scrub Oak Mixed Chaparral		
		Southern Rockies Oak - Manzanita Scrub	503	Arizona Chaparral		
	Soft Chaparral	Coastal sage	205	Coastal Sage Shrub		
3301	Montane Evergreen Shrubs	Mountain Mahogany	415	Curlleaf Mountain Mahogany		
			417	Littleleaf Mountain Mahogany		
			420	Snowbush		
3701	Salt Desert Shrub	Salt Desert Shrub	414	Salt Desert Shrub		
		Shadscale- Mixed Grass - Mixed Scrub	501	Saltbush-Greasewood		
		Hopsage				

Appendix 6-C—(Continued)

CT#	LANDFIRE cover type	(Western U.S.) GAP cover type	SRM#	SRM cover type	SAF#	SAF cover type
		Greasewood				
		Great Basin Saltbush Scrub				
3702	Desert Shrub	Creosote-Bursage	506	Creosotebush-Bursage		
		Mojave Creosotebrush - Yucca	211	Creosotebush Scrub		
		Paloverde - Mixed Cacti - Scrub	508	Creosotebush-Tarbush		
		Catclaw Acacia	507	Palo Verde-Cactus		
		Smoketree				
		Chihuahuan Creosotebush Scrub				
3703	Dry Deciduous Shrub	Bitterbrush	210	Bitterbrush		
		Mixed Oak	317	Bitterbrush-Bluebunch Wheatgrass		
		Mountain Mahogany	318	Bitterbrush-Idaho Fescue		
			319	Bitterbrush-Rough Fescue		
			416	True Mountain Mahogany		
			730	Sand Shinnery Oak		
4101	Warm Season Grasses	Chihuahuan Grassland	502	Grama-Galetta		
		Great Basin Grassland	702	Black Grama-Alkali Sacaton		
		Semidesert Mixed Grass	703	Black Grama-Sideoats Grama		
		Semidesert Tobosa Grass - Scrub	705	Blue Grama-Galetta		
			708	Bluestem-Dropseeed		
4102	Cool Season Grasses	California Native Perennial Grassland	302	Bluebunch Wheatgrass-Sandberg Bluegrass		
			303	Bluebunch Wheatgrass-Western Wheatgrass		
		Great Basin Grassland	304	Idaho Fescue-Bluebunch Wheatgrass		
			305	Idaho Fescue-Richardson Needlegrass		
			306	Idaho Fescue-Slender Wheatgrass		
			307	Idaho Fescue-Threadleaf Sedge		
			309	Idaho Wheatgrass-Western Wheatgrass		
			614	Crested Wheatgrass		
4201	Native Forbs		409	Tall forb		
4202	Exotic Forbs					
4301	Wetland Herbaceous	Riparian/Wetland	422	Riparian		
		Forest Meadow	216	Montane Wetlands		
		Meadow	217	Wetlands		
4302	Alpine	Alpine/Subalpine Meadows	410	Alpine Rangeland		
			213	Alpine Grassland		
4401	Annual Grasslands		215	Valley Grassland		

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Appendix 6-D—Crosswalk of LANDFIRE cover types to the National Vegetation Classification System (NVCS) hierarchy (Grossman and others 1998)

CT#	Cover type	NVCS class	NVCS subclass	NVCS group
1401	Riparian Hardwood[a]	Forest	Deciduous	Cold-deciduous
1405	Aspen -- Birch[a]	Forest	Deciduous	Cold-deciduous
1406	Pacific Deciduous Forest [Other Broadleaf]	Forest, Woodland	Deciduous	Cold-deciduous woodland
1101	Pacific Broadleaf Evergreen Forest [Other Broadleaf Evergreen]	Forest	Evergreen	Winter-rain broad-leaved evergreen sclerophyllous forest
1501	Larch	Forest	Deciduous	Cold-deciduous
1201	Ponderosa Pine[a]	Forest, Woodland, Herbaceous	Evergreen, Mixed evergreen-deciduous forest, Evergreen woodland, Perennial graminoid	Temperate or subpolar needle-leaved evergreen forest, Temperate or subpolar needle-leaved evergreen woodland, Mixed needle-leaved- evergreen - cold-deciduous forest, Mixed needle-leaved- evergreen - cold-deciduous woodland, Temperate or subpolar grassland with sparse tree layer
1218	Pacific Ponderosa Pine	Forest, Woodland	Evergreen	Temperate or subpolar needle-leaved evergreen forest; Temperate or subpolar needle-leaved evergreen woodland
1202	Foothill Pines	Forest, Woodland	Evergreen	Needle-leaved, Temperate or subpolar needle-leaved-evergreen woodland
1203	Western White Pine	Forest	Evergreen	Temperate or subpolar needle-leaved-evergreen forest
1204	Lodgepole Pine[a]	Forest, Woodland	Evergreen, Mixed evergreen-deciduous	Temperate or subpolar needle-leaved evergreen forest, Temperate or subpolar needle-leaved evergreen woodland, Mixed needle-leaved evergreen - cold-deciduous forest
1205	Douglas-fir[a]	Forest	Evergreen, Mixed evergreen-deciduous	Temperate or subpolar needle-leaved evergreen forest, Mixed needle-leaved evergreen - cold-deciduous forest

Appendix 6-D—(Continued)

CT#	Cover type	NVCS class	NVCS subclass	NVCS group
1206	Grand Fir -- White Fir[a]	Forest	Evergreen, Mixed evergreen-deciduous	Temperate or subpolar needle-leaved evergreen forest, Mixed needle-leaved evergreen - cold-deciduous forest
1207	Pacific Silver Fir -- Noble fir	Forest	Evergreen	Temperate or subpolar needle-leaved evergreen forest
1219	Red Fir	Forest	Evergreen	Temperate or subpolar needle-leaved evergreen forest
1220	California White Fir	Forest	Evergreen	Temperate or subpolar needle-leaved evergreen forest
1209	Western Hemlock	Forest	Evergreen	Temperate or subpolar needle-leaved evergreen forest
1210	Mountain Hemlock	Forest	Evergreen	
1211	Spruce -- Fir[a]	Forest, Woodland	Evergreen, Mixed evergreen-deciduous	Needle-leaved, Temperate or subpolar needle-leaved evergreen forest, Mixed needle-leaved evergreen - cold-deciduous forest
1212	Sitka Spruce	Forest	Evergreen	Temperate or subpolar needle-leaved evergreen forest
1213	Cedar	Forest	Evergreen	Temperate or subpolar needle-leaved evergreen forest
1215	Redwood	Forest	Evergreen	Temperate or subpolar needle-leaved evergreen forest
1216	Sequoia	Forest	Evergreen	Temperate or subpolar needle-leaved evergreen forest
1217	Cypress	Forest, Woodland	Evergreen	Temperate or subpolar needle-leaved evergreen forest, Temperate or subpolar needle-leaved evergreen woodland
1801	Timberline Pine[a]	Forest, Woodland	Evergreen, Mixed evergreen-deciduous forest	Temperate or subpolar needle-leaved evergreen forest, Temperate or subpolar needle-leaved evergreen woodland, Mixed needle-leaved evergreen - cold-deciduous forest

Appendix 6-D—(Continued)

CT#	Cover type	NVCS class	NVCS subclass	NVCS group
2101	Evergreen Oak	Forest, Woodland, Shrubland	Evergreen, Evergreen-deciduous	Broad-leaved evergreen forest,Temperate broadleaf evergreen forest, Temperate broadleaf evergreen woodland, Extremely xeromorphic evergreen woodland, Mixed broad-leaved evergreen cold-deciduous forest, Temperate broad-leaved evergreen shrubland
2401	Deciduous Oak	Forest, Woodland, Shrubland, Herbaceous, Shrubland	Deciduous, Mixed evergreen-deciduous	Cold-deciduous, Mixed needle-leaved-evergreen-cold-deciduous woodland, Temperate or subpolar grassland with a sparse tree layer
2201	Pinyon -- Juniper[a]	Woodland	Evergreen	Temperate or subpolar needle-leaved evergreen
2202	Juniper[a]	Woodland	Evergreen	Temperate or subpolar needle-leaved evergreen
3704	Mountain Deciduous Shrub[a]	Shrubland	Deciduous	Cold-deciduous
3402	Riparian Shrub[a]	Shrubland	Deciduous	Cold-deciduous
3403	Exotic Riparian Shrub[a]	Shrubland	Deciduous	Cold-deciduous
3101	Mountain Big Sagebrush Complex[a]	Shrubland, Dwarf-shrubland, Herbaceous	Evergreen, Perennial graminoid	Microphyllous evergreen, Extremely xeromorphic evergreen, Temperate or subpolar grassland with sparse shrub layer
3102	Wyoming -- Basin Big Sagebrush Complex[a]	Shrubland	Evergreen	Microphyllous evergreen
3103	Dwarf Sagebrush Complex[a]	Shrubland, Herbaceous	Evergreen, Perennial graminoid, Deciduous	Microphyllous evergreen, Temperate or subpolar grassland with a sparse shrub layer, Extremely xeromorphic deciduous shrubland
3104	Sand Sagebrush	Shrubland	Evergreen	Microphyllous Evergreen
3105	Blackbrush[a]	Shrubland	Evergreen	Extremely xeromorphic evergreen shrubland
3106	Rabbitbrush[a]	Shrubland, Herbaceous	Evergreen, Perennial graminoid	Microphyllous evergreen, Temperate or subpolar grassland with a sparse shrub layer
3107	Chaparral[a]	Shrubland	Evergreen	Temperate broadleaf evergreen

Appendix 6-D—(Continued)

CT#	Cover type	NVCS class	NVCS subclass	NVCS group
3108	Soft Chaparral	Shrubland	Evergreen	Temperate broad-leaved evergreen shrubland; Microphyllous evergreen shrubland
3301	Montane Evergreen Shrubs[a]	Shrubland	Evergreen	Microphyllous evergreen, Temperate broadleaf evergreen
3701	Salt Desert Shrub[a]	Shrubland, Dwarf shrubland	Deciduous shrubland, Evergreen dwarf shrubland, Evergreen	Extremely xeromorphic evergreen shrubland, Extremely xeromorphic deciduous shrubland
3702	Desert Shrub[a]	Shrubland	Evergreen shrubland, Deciduous shrubland	Extremely xeromorphic evergreen shrubland, Extremely xeromorphic deciduous shrubland, Drought deciduous shrubland
3703	Dry Deciduous Shrub[a]	Shrubland	Evergreen shrubland, Deciduous	Microphyllous evergreen shrubland, Temperate broadleaf evergreen, Cold-deciduous shrubland
4101	Warm Season Grasses [a]	Herbaceous	Perennial graminoid	Temperate or subpolar grassland
4102	Cool Season Grasses [a]	Herbaceous	Perennial graminoid	Temperate or subpolar grassland
4201	Native Forbs[a]	Herbaceous	Perennial forbs	Forbs
4202	Exotic Forbs[a]	Herbaceous		
4301	Wetland Herbaceous[a]	Herbaceous	Mixed perennial graminoid/forb, Hydromorphic herbs	Mixed Grass/Forbs
4302	Alpine[a]	Herbaceous	Mixed perennial graminoid/forbs	Mixed Grass/Forbs
4401	Annual Grasslands[a]	Herbaceous	Annual herbs	

[a] Refined with Zone 16 plot data.

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Appendix 6-E—Zone 19 cover type legend and descriptions

CT#	Cover type	Description
1201	Cedar	Western redcedar (*Thuja plicata*) is limited to the northwest corner of Zone 19 where it reaches the eastern limit of its distribution. It is the second most shade-tolerant coniferous species in the zone after western hemlock. Cedar commonly occurs in stands with many other conifer species including *Abies grandis, Larix occidentalis, Tsuga heterophylla, Pinus contorta, Pseudotsuga menziesii, Pinus monticola* and *Picea engelmannii*. Understory species may be abundant, and common species include *Oploplanax horridus, Gymnocarpium dryopteris, Tiarella trifoliata* and *Taxus brevifolia.* This is a minor type in the zone and is represented by less than 1 percent of the forested plots in the LFRDB.
1202	Douglas-fir	This is a major type within Zone 19 and across the western U.S., dominated by Douglas-fir (*Pseudotsuga menziezii*) and typically occurring at mid- elevation on a variety of aspects and slopes. This cover type mixes with or may be adjacent to many other cover types across the zone depending on location and local site factors. Common overstory associates include *Pinus contorta, Pinus ponderosa, Larix occidentalis* and *Abies lasiocarpa*. Common understory species vary widely depending on local site factors and stand history but may include *Xerophyllum tenax, Calamagrostis rubescens, Vaccinium membranaceum* and *Symphoricarpos albus*. Cover of Douglas-fir averages 32 percent and ranges from 3 to 90 percent. Thirty-three percent of all forested plots fall into this category and 20 percent of all plots.
1203	Grand Fir	Grand fir (*Abies grandis*) occurs only in the northern half of the zone and west of the continental divide. It commonly occurs in stands with other conifer species including *Pseudotsuga menziesii, Abies lasiocarpa, Thuja plicata, Larix occidentalis* and *Picea engelmannii*. Understory species may be abundant and include *Taxus brevifolia, Acer glabrum, Arnica spp., Linnaea borealis* and *Amelanchier alnifolia*. Cover of grand fir averages 40 percent with a range of 10 to 90 percent. This is a minor type in the zone and is represented by less than 1 percent of the plots in the database.
1204	Hemlock	This cover type, dominated by western hemlock (*Tsuga heterophylla*), is restricted to the northwest corner of the zone and is the most shade-tolerant conifer in the zone. Western hemlock cover averages 51 percent with a range of 30 to 90 percent. Common overstory associates include *Thuja plicata, Abies lasiocarpa, Larix occidentalis, Picea engelmannii, Pseudotsuga menziesii* and *Pinus contorta*. Understory vegetation may be abundant to non-existent depending on the overstory canopy and includes *Xerophyllum tenax, Taxus brevifolia, Amelanchier alnifolia, Acer glabrum,* and *Arnica latifolia*. Western hemlock reaches its eastern range limit within the northwestern portion of the zone and thus is a minor type with only 0.3 percent of forested plots occurring here.
1205	Lodgepole Pine	Lodgepole Pine is a major type within Zone 19, across the middle and northern Rockies and in portions of the Cascades and Sierra Nevadas. It typically occurs in the montane and lower subalpine zones on a variety of aspects and slopes. This cover type commonly mixes with or is adjacent to Douglas-fir and Spruce-fir types and is typically seral to those types. Dominated by lodgepole pine (*Pinus contorta*), common overstory associates include *Pinus ponderosa, Larix occidentalis* and *Abies lasiocarpa*. Common understory species vary widely depending on local site factors and stand history, but may include *Xerophyllum tenax, Calamagrostis rubescens, Vaccinium membranaceum* and *Symphoricarpos albus*. Cover of lodgepole pine averages 35 percent and ranges from 3 to 98 percent. Sixteen percent of all forested plots fall into this category and 20 percent of all plots.
1206	Juniper	Juniper species are wide-ranging though, as cover types, are found primarily east of the divide in Montana or in the very southern part of Zone 19. Communities are usually open and dominated by species including *Juniperus scopulorum* and *Juniperus osteosperma,* with cover averaging 22 percent with a range from 3 to 50 percent. Common associated species include *Artemisia nova, Artemisia tridentata* ssp. *vaseyana, Pseudoroegneria spicata, Festuca idahoensis* and *Koeleria macrantha*. This is a minor woodland type in the zone and only 0.5 percent of forest and woodland plots occur in this type.

Appendix 6-E—(Continued)

CT#	Cover type	Description
1207	Ponderosa Pine	Ponderosa pine (*Pinus ponderosa*) is distributed across large areas of the zone, though it is absent from several areas including the area south of Salmon, ID. As a cover type, it is limited to some of the lowest elevations and driest sites that are occupied by forest and woodland communities in the zone. At higher elevations or on more mesic sites, *Pseudotsuga menziesii* quickly replaces ponderosa pine. *Larix occidentalis* and *Pinus contorta* are other common overstory associates. Understory vegetation may be abundant and common species include *Mahonia repens, Calamagrostis rubescens, Symphoricarpos albus, Arctostaphylos uva-ursi, Spiraea betulifolia, Amelanchier alnifolia* and *Carex geyeri*. Cover of ponderosa pine averages 32 percent and ranges from 5 to 70 percent. Only 2 percent of the forested plots are classified to the cover type.
1208	Spruce -- Fir	Spruce-fir is a widespread cover type throughout Zone 19, dominating at high elevations and often mixing with the Lodgepole Pine, Douglas-fir, and Timberline Pine types. Stands are usually dominated by *Abies lasiocarpa* (subalpine fir) and *Picea engelmannii* (Engelmann spruce). Common overstory associates include *Pinus albicaulis, Pseudotsuga menziesii* and *Pinus contorta.* Understory species commonly occurring in this type include *Vaccinium membranaceum, Xerophyllum tenax, Menziesia ferruginea, Arnica latifolia, Vaccinium scoparium* and *Luzula glabrata.* Approximately 25 percent of forested plots occur in this cover type.
1209	Limber Pine	The distribution of this type, dominated by *Pinus flexilis,* is primarily east of the divide in Montana and in several mountain ranges in the southern portion of the zone. The Limber Pine type occurs at lower elevations where it may co-occur with juniper species and at high elevation timberline sites where it may mix with *Pinus albicaulis*. Common overstory associates are *Pseudotsuga menziesii* and *Juniperus scopulorum*. Common understory species include *Arctostaphylos uva-ursi, Dasiphora floribunda, Pseudoroegneria spicata, Festuca idahoensis, Shepherdia canadensis, Juniperus horizontalis* and *Juniperus communis*. Cover of limber pine averages 13 percent with a range of 3 to 50 percent. Approximately 1 percent of all forested plots occur in this type.
1212	White Pine	This cover type's distribution is primarily to the west of Zone 19, just reaching into the northwest corner of Zone 19 and, as such, is only represented by 3 plots in the LFRDB. It is dominated by *Pinus monticola*, western white pine.
1401	Aspen -- Birch	The Aspen-Birch type is most common east of the Continental Divide, where it ranges from low elevation riparian areas to the montane and lower subalpine zones and is usually dominated by *Populus tremuloides* (trembling aspen). In the northwest portion of Zone 19, however, *Betula papyrifera* (paper birch) as the dominant overstory species is more common than aspen. Understory diversity is high and includes many shrub and herbaceous species, including *Osmorhiza occidentalis, Prunus virginiana, Acer glabrum, Amelanchier alnifolia, Symphoricarpus albus, Calamagrostis rubescens, Angelica arguta* and *Thalictrum occidentale*. Cover of *Populus tremuloides* averages 42 percent with a range of 3 to 90 percent. Aspen-birch is much more common in other zones and in Zone 19 is represented by only 1.5 percent of the forest plots in the LFRDB.
1402	Riparian Hardwood	The widespread Riparian Hardwood cover type has limited coverage because of its restricted habitat requirements. It occupies low elevation riparian areas along major drainages where it often intermingles with the Riparian Broadleaf Shrubland cover type. Stands of riparian hardwoods at higher elevations are usually small and isolated. Only two cottonwood species occur in riparian hardwoods forests in the zone, *Populus angustfolia* (narrowleaf cottonwood), which largely occurs east of the Continental Divide in the eastern and northeastern part of the zone, and *Populus balsamifera* ssp. *trichocarpa* (black cottonwood), which occurs throughout the zone. Other deciduous trees such as *Acer negundo*, and *Salix amygdaloides* also occur in riparian hardwood communities as well as *Pinus ponderosa*, *Picea engelmannii,* and *Populus tremuloides*. Some common understory associated species include *Symphoricarpos albus, Salix spp., Poa pratensis, Acer glabrum* and *Amelanchier alnifolia*. Cover of cottonwood in these communities averages 30 percent with a range of 10 to 60 percent. This is a minor forest type and is represented in the LFRDB by less than 1 percent of the forest plots.

Appendix 6-E—(Continued)

CT#	Cover type	Description
1403	Western Larch	This type occurs in the northern half of the zone, predominantly west of the continental divide. Stands dominated by *Larix occidentalis* typically occur at mid-elevations and frequently mix with Douglas-fir and lodgepole pine types. Larch forests are usually seral to Douglas-fir, grand fir and spruce-fir types. Typical overstory associates are *Pseudotsuga menziesii* and *Pinus contorta*. Understory species are numerous with some of the most commonly occurring species being *Vaccinium membranaceum, Paxistima myrsinites, Rubus parviflorus, Xerophyllum tenax* and *Acer glabrum*. Approximately 4 percent of forested plots occur in this cover type.
1801	Timberline Forest	The Timberline Forest type occurs across the zone and occupies the highest elevations of any of the forested communities. It is generally dominated by *Pinus albicaulis* (whitebark pine) and can include *Larix lyallii* (alpine larch). At lower elevations, Timberline Forests typically mix with the Spruce-Fir cover type, and *Picea engelmannii* and *Abies lasiocarpa* are both common overstory associates. Common understory associated species include *Vaccinium scoparium, Xerophyllum tenax, Luzula glabrata* and *Carex geyeri*. Cover of *Pinus albicaulis* and *Larix lyallii* averages 19 percent and ranges from 3 to 50 percent. Approximately 4 percent of forested plots occur in this cover type.
2101	Upland Broadleaf Dwarf Shrubland	This cover type consists of three main dwarf shrub species, *Vaccinium scoparium*, *Salix artica,* and *Vaccinium caespitosum*. It is found from the upper montane region to the alpine region. In 77 percent of the plots, the dominant species is *Vaccinium scoparium*. The remaining plots are dominated by either *Vaccinium caespitosum* or *Salix arctica*. Both *Vaccinium* species resprout following fire. *Salix arctica* occurs in communities that rarely experience fire. Common associates in Vaccinium communities include *Xerophyllum tenax, Carex geyeri, Vaccinium membranaceum* and *Luzula glabrata*. This is a minor shrub type with approximately 0.5 percent of the total plots falling into this cover type and 1.5 percent of all shrub dominated plots occurring here.
2102	Upland Broadleaf Medium Shrubland	This cover type is dominated by numerous species characterized by medium stature (generally 1 to 8 feet in height) broadleaf shrubs including *Symphocarpus* spp., *Vaccinium membranaceum*, *Menziesia ferruginea*, *Physocarpus malvaceus*, *Spirea betufolia*, *Rubus parviflorus,* and various *Rosa*, *Ribes,* and *Lonicera* species. Common associated species outside of those indicated by the dominant species very widely depending on the dominant species and local site factors. Approximately 8 percent of shrub dominated plots occur in this type.
2103	Upland Broadleaf Tall Shrubland	This cover type consists of several dominant species characterized as tall stature (generally greater than 8 feet in height) broadleaf shrubs. These include *Alnus viridus* ssp. *sinuate*, *Acer glabrum*, *Amelanchier alnifolia*, *Sorbus scopulina,* and several *Prunus* species. Common associated species outside of those indicated by the dominant species include lower stature broadleaf shrubs and a variety of herbaceous species. Approximately 7 percent of shrub dominated plots occur in this type.
2202	Upland Microphyllous Medium Shrubland	This physiognomic grouping is composed of several dominant species characterized as medium stature microphyllous shrubs. These communities are generally on lower elevation arid sites and restricted to the southern portion of the zone. Dominant species include *Atriplex confertifolia*, *Purshia tridentata*, *Artemisia cana*, *Tetradymia canescens*, *Gutierrezia sarothrae,* and *Atriplex canescens*. Common associated species include *Artemisia frigida, Hesperostipa comata and Pseudoroegneria spicata*. These communities become much more common south of Zone 19. This cover type is of minor importance in the zone with approximately 1 percent of shrub dominated plots occurring in this type.
2211	Dwarf Sage	This cover type is dominated by two morphologically similar species, *Artemisia arbuscula* and *Artemisia nova*. Vegetative cover is generally low with only a few commonly occurring shrub and grass species. Common associates include *Pseudoroegneria spicata*, *Artemisia tridentata* ssp. *wyomingensis, Artemisia frigida* and *Heterostipa comata*. Cover of sagebrush average 17 percent with a range of 3 to 50 percent. Occurrence of this cover type in Zone 19 is minor though it is much more abundant in other parts of the western U.S. Very little plot data exists for dwarf sage communities in the zone with 0.1 percent of the total plots falling into this cover type and 0.4 percent of all shrub dominated plots occurring here.

Appendix 6-E—(Continued)

CT#	Cover type	Description
2212	Shrubby Cinquefoil	This cover type occurs at mid to upper elevations between 4,500 ft and 8,500 ft. *Dasiphora floribunda* (shrubby cinquefoil), the dominant species in this type, possesses the ability to resprout following fire depending on fire severity; it is usually killed by high severity fire. Common associated species include *Festuca idahoensis, Koeleria macrantha, Fragaria virginiana, Danthonia intermedia* and *Potentilla gracilis*. Cover of shrubby cinquefoil averages 15 percent with a range of 3 to 40 percent. This is a minor type in the zone with less than 1 percent of shrub dominated plots occurring in this cover type.
2213	Threetip Sage	This is a minor type in southwest Montana and becomes more abundant in the Idaho portion of the zone. *Artemisia tripartita* (threetip sage) is different from other sagebrush types in the zone because of its ability to resprout after fire, though the ability varies among populations. Common associated species include *Chrysothamnus viscidiflorus*, *Gutierrezia sarothrae*, *Pseudoroegneria spicata*. Cover of threetip sage averages 28 percent with a range of 10 to 45 percent. This type is represented by 23 percent of the shrub dominated plots in the zone. An abundance of plot data exists for this type, but it is clustered in a relatively small area of the zone so the amount of plot data over-represents its actual occurrence in the zone.
2218	Mountain Big Sage	Mountain Big Sage cover type (dominated by *Artemisia tridentata* ssp. *vaseyana*) generally occurs at higher elevations than the Wyoming-Basin Big Sage cover type and ranges to the subalpine region. Though present throughout Zone 19, it is most abundant in Idaho and in Montana generally south and east of Missoula. Common associated species include *Festuca idahoensis, Pseudoroegneria spicata, Geranium viscosissimum* and *Lupinus* species. Cover of *Artemisia tridentata* ssp. *vaseyana* averages 29 percent with a range of 3 to 70 percent. This is a major shrub type across the zone with 18 percent of shrub-dominated plots occurring here.
2219	Wyoming -- Basin Big Sage	This is a major shrub type in the southern half of the zone and a landscape dominant across vast areas of the West. Dominant species for this type are *Artemisia tridentata* ssp. *tridentate,* and *Artemisia tridentata* ssp. *wyomingensis*. Other common species include *Agropyron cristatum, Pseudoroegneria spicata, Poa fendleriana, Artemisia frigida, Achnatherum hymenoides, Heterostipa comata, Chrysothamnus viscidiflorus* and *Koeleria macrantha*. This type is represented by 31 percent of the shrub dominated plots in the zone. An abundance of plot data exists for this type but it is clustered in a relatively small area of the zone so the amount of plot data over-represents its actual occurrence in the zone.
2220	Rabbitbrush	This cover type is composed of two species of rabbitbrush within the zone, including *Chrysothamnus viscidiflorus* (yellow rabbitbrush) and *Ericameria nauseosa* (rubber rabbitbrush). It is a minor type in the zone and is usually adjacent to Wyoming-Basin Big Sage, Mountain Big Sage or herbaceous dominated cover types. Rabbitbrush may quickly recolonize a site following fire from sprouts and from seed. Common associated species include *Artemisia frigida, Pseudoroegneria spicata, Festuca idahoensis, Hesperostipa comata, Artemisia tridentata* ssp. *wyomingensis, Artemisia tridentata* ssp. *vaseyana, Poa fendleriana* and *Agropyron cristatum*. Cover of rabbitbrush species averages 8 percent with a range of 3 to 30 percent. Less than 2 percent of shrub-dominated plots occur in this cover type.
2222	Greasewood	*Sarcobatus vermiculatus* is the sole dominant species in this cover type. Though a minor type in Zone 19, it is a common species in other areas of the west with a distribution centered on the Great Basin Floristic Division. Black greasewood communities generally occur below the more moist sagebrush or shadscale zones and in Zone 19 are typically found on old alluvial terraces (Roundy and others 1978). Greasewood commonly grows in pure stands in high saline areas with little or no understory vegetation, but in less saline areas, other shrubs may be common as well as a grass component (McArthur and Plummer 1978). Generally, greasewood communities suffer little damage from fire and fire occurrence is minimal due to a lack of fine fuels. However, greasewood communities invaded by cheatgrass may have an increase in fire occurance. Species diversity is low, but common associates include *Agropyron cristatum, Artemisia frigida* and *Pseudoroegneria spicata*. Cover of greasewood averages 45 percent with a range of 10 to 70 percent. Plot data is almost nonexistent for greasewood communities in the zone and less than 0.1 percent of the total plots fall into this cover type and 0.2 percent of all shrub dominated plots occur here.

Appendix 6-E—(Continued)

CT#	Cover type	Description
2223	Mountain Mahogany	This cover type is restricted to the south half of the zone where it reaches its northerly range limit. Stands of this type typically occur at mid elevations on dry, southerly slopes. *Cercocarpus ledifolius* (mountain mahogany), the dominant species in this type, is usually killed by fire and relies on seed to reoccupy a site though regeneration may be slow (Scheldt and Tisdale 1970). Common associated species include *Festuca idahoensis, Pseudoroegneria spicata, Artemisia tridentata* ssp*. vaseyana* and *Artemisia tridentata* ssp*. wyomingensis*. Mountain mahogany cover averages 40 percent with a range of 4 to 70 percent. This type is relatively minor across the zone though locally abundant in Idaho. Less than 1 percent of shrub dominated plots are classified to this type.
2300	Upland Needleleaf	This physiognomic grouping is composed of dwarf to medium height needle-leaved shrub that typically form small patches in a variety of sites. On lower elevation dry sites, the dominant Shrubland species are *Juniperus communis* and *Juniperus horizontalis*, which account for 85 percent of the plots. These sites typically have sparse fuel. The remaining plots are dominated by *Phyllodoce empetriformis,* which occupies sites within the subalpine to lower alpine zones and are adjacent to or intermingled with subalpine forest types, herbaceous dominated alpine communities, or barren, rocky slopes. This is a very minor shrub type with approximately 0.2 percent of the total plots falling into this cover type and 0.8 percent of all shrub dominated plots occurring here.
2400	Upland Sclerophyllous Shrubland	This physiognomic grouping is composed of dwarf to medium height sclerophyllous-leaved shrubs that typically form small patches mainly within the montane zone. It is comprised of three dwarf shrubs, *Arctostaphylos uva-ursi*, *Paxistima myrsinites,* and *Mahonia repens,* which dominate 72 percent of the plots in this type, and one medium-height shrub species, *Ceanothus velutinus*, on 28 percent of the plots. All species possess the ability to resprout following fire and *Ceanothus velutinus* in particular may recolonize a site after fire from on-site seed sources. This is a minor shrub type with approximately 0.4 percent of the total plots falling into this cover type and 1 percent of all shrub dominated plots occurring here.
2600	Riparian Broadleaf Shrubland	This cover type is composed of native shrub communities dominated mainly by *Alnus incana* or by one of several *Salix* species. This type occupies riparian areas along major drainages. Where it is intermingled with the Riparian Hardwood cover type, the shrubs are usually quite tall and some species may be single-stemmed and tree-like. At lower elevations, these communities usually have a patchy distribution due to flood dynamics and more recently, human disturbances. At higher elevations, communities may occur as narrow stringers along low gradient streams or as broader patches that extend away from streams and into adjacent wet meadows where they often form mosaics with herbaceous-dominated communities. Overall, this is a minor though important landscape component with approximately 0.6 percent of the total plots falling into this cover type and 2 percent of all shrub dominated plots occurring here.
3110	Annual Forb	The Annual Forb cover type includes forbs that are annual or biennial species. This type usually occurs at lower elevation xeric sites across the zone and is composed of mostly naturalized species but also includes species that may be the result of seeding for restoration or forage in the cases of *Melilotus officianalis* or *Triticum aestivum*. Species composition varies widely and includes numerous forbs, natives and exotics, and annual and perennials in various mixtures. Approximately 0.2 percent of the total plots fall into this cover type and 3 percent of all herbaceous dominated plots occur in this cover type when combined with annual graminoid.
3120	Annual Graminoid	*Bromus tectorum* is the dominant species on the zone 19 plots classified to this cover type. This type usually occurs at lower elevation xeric sites across the zone and is composed of mostly naturalized species. Species composition varies widely and includes numerous graminoids, natives, and exotics, and annuals, biennals and perennials in various mixtures. Approximately 0.2 percent of the total plots fall into this cover type.

Appendix 6-E—(Continued)

CT#	Cover type	Description
3130	Perennial Forb	The Perennial Forb cover type consists of communities dominated mainly by native and occasionally exotic forbs. Occurring on xeric to mesic sites and ranging from the lowest elevations in the zone to the alpine region, species composition may vary widely. *Artemisia frigida* is the dominant species on almost 30 percent of the plots, and no other species dominant on more than 5 percent. The vertical structure of this type ranges from tall forbs such as *Chamerion angustifolium* to cushion plants such as *Phlox hoodii*. Approximately 2 percent of the total plots fall into this cover type and 24 percent of all herbaceous dominated plots.
3141	Perennial Exotic Bunch Gramminoid	Fifty-eight percent of the plots in this type are dominated by *Phleum pratense* (timothy). Plots occur on a variety of sites, ranging from low elevation xeric to mesic montane sites. Areas dominated by these grasses may be the result of seeding for restoration or pasture or at least have been subject to moderate to heavy disturbance in the past. Approximately 0.2 percent of the total plots fall into this cover type and 3 percent of all herbaceous dominated plots are classified to this type.
3142	Perennial Native Bunch Gramminoid	This cover type is mainly composed of low to moderate elevation communities dominated by *Festuca idahoensis*, *Festuca altaica,* and *Pseudoroegneria spicata*. These dominant species account for 82 percent of the plot data in this type and are the dominant grassland communities in Zone 19. These plots may occur at any elevation and on xeric to mesic sites. These species usually have a clumped or bunched growth form but may possess short rhizomes in some cases. Approximately 4 percent of the total plots fall into this cover type and 49 percent of all herbaceous dominated plots are classified to this cover type.
3151	Perennial Exotic Rhizomatous Gramminoid	Fifty percent of the plots in this cover type are dominated by *Poa pratensis.* The plots typically occur on low elevation xeric to mesic montane sites. Areas dominated by these grasses may be the result of seeding for restoration or pasture or at least have been subject to moderate to heavy disturbance in the past. Approximately 0.2 percent of the total plots fall into this cover type and 3 percent of all herbaceous dominated plots are classified to this type.
3152	Perennial Native Rhizomatous Gramminoid	*Calamagrostis rubescens* and *Carex geyeri* dominate 80 percent of the plots in this cover type. The remaining plots are dominated by a variety of species. Plots are found in areas ranging from low elevation xeric sites to mesic montane or subalpine sites. This cover type is composed of species that typically have a rhizomatous, stoloniferous, or sod-forming growth form, but may be clumped or bunched in some cases. Approximately 0.4 percent of the total plots fall into this cover type and 5 percent of all herbaceous dominated plots are classified to this cover type.
3200	Wetland Herbaceous	This cover type is dominated by perennial native rhizomatous gramminoids, including *Carex* and *Juncus* species, and several native perennial forb dominated communities would also be classified here. This minor type is scattered across the zone from low to high elevations. Approximately 0.4 percent of the total plots fall into this cover type and 5 percent of all herbaceous dominated plots are classified to this cover type.

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Appendix 6-F—Zone 16 potential vegetation type legend and descriptions

PVT#	Potential vegetation type	Description
1601	Spruce -- Fir / Blue Spruce	This type is dominated by *Picea pungens* along with *Abies lasiocarpa* as the climax species. *Picea engelmannii* may be a co-climax species in some areas. Common associates include *Pseudotsuga menziesii, Abies lasiocarpa, Pinus contorta,* and *Populus tremuloides.* Elevational ranges are generally between 7,600 and 9,000 feet. Sites tend to be relatively dry and generally occur on the warmer portion of the area where Spruce-Fir types are found. Understories are varied with *Juniperus communis* common on many sites. *Berberis repens* and *Carex geyeri* are common along with a wide variety of lesser shrubs and forbs.
1602	Spruce -- Fir / Blue Spruce / Lodgepole Pine	This type is dominated by *Picea pungens* along with *Abies lasiocarpa* as the climax species. *Picea engelmannii* may be a co-climax species in some areas. Common associates include *Pseudotsuga menziesii, Abies lasiocarpa, Pinus contorta,* and *Populus tremuloides.* Elevational ranges are generally between 7,600 and 9,000 feet. Sites tend to be relatively dry and generally occur on the warmer portion of the area where Spruce-Fir types are found. Understories are varied with *Juniperus communis* common on many sites. *Berberis repens* and *Carex geyeri* are common along with a wide variety of lesser shrubs and forbs. This PVT occurs in the northern portion of the zone where *Pinus contorta* occurs as a common seral species.
1603	Spruce -- Fir / Spruce -- Fir	This is a major type found throughout the zone. The major indicators for this type are *Abies lasiocarpa* and/or *Picea engelmannii.* Common associates include *Pseudotsuga menziesii* and *Populus tremuloides. Abies concolor* is locally present. Elevations range from 8,000 feet to above 11,000 feet and sites are cool to cold and moist to moderately dry. Understories are highly variable, ranging from shrub dominated to grasses to forbs. Common species include *Berberis repens, Juniperus communis, Ribes montigenum, Symphoricarpos oreophilus, Pachistima myrsinites, Vaccinium scoparium, Carex geyeri,* and *Arnica spp.*
1604	Spruce -- Fir / Spruce -- Fir / Lodgepole Pine	This is a major type found throughout the zone. The major indicators for this type are *Abies lasiocarpa* and/or *Picea engelmannii.* Common associates include *Pseudotsuga menziesii* and *Populus tremuloides.* This PVT occurs in the northern portion of the zone where *Pinus contorta* occurs as a common seral species. *Abies concolor* is locally present. Elevations range from 8,000 feet to above 11,000 feet and sites are cool to cold and moist to moderately dry. Understories are highly variable ranging from shrub dominated to grasses to forbs. Common species include *Berberis repens, Juniperus communis, Ribes montigenum, Symphoricarpos oreophilus, Pachistima myrsinites, Vaccinium scoparium, Carex geyeri,* and *Arnica spp.*
1611	Grand Fir -- White Fir	This type is represented by *Abies concolor* within the zone. Common associates include *Pseudotsuga menziesii* and *Populus tremuloides. Pinus ponderosa* and lesser amounts of *Pinus flexilis* may be found on the southern portion of the type. Sites range from about 6,200 feet up to 9,600 feet and are usually cool and dry, northerly aspects. Major understory associates include *Symphoricarpos oreophilus, Berberis repens, Juniperus communis,* and *Carex geyeri.*

Appendix 6-F—(Continued)

PVT#	Potential vegetation type	Description
1612	Grand Fir -- White Fir / Maple	This PVT is indiciated by *Acer grandidentatum* and generally occurs in relatively pure stands or interspersed with *Quercus, Artemisia, Pseudotsuge menziezii,* and *Abies concolor* communities and is usually found in canyon bottoms and on portions of side slopes with deep, well developed modal soils. In settings where it is at the edge of its ecological range, it normally occurs more shrublike.
1621	Douglas-fir / Timberline Pine	*Pseudotsuga menziesii,* in conjunction with either *Pinus flexilis* or *Pinus longaeva,* are indicators for this PVT. Other species commonly found include *Pinus ponderosa, Juniperus scopulorum* and *Populus tremuloides.* Minor amounts of *Pinus edulis* may also be encountered. The PVT is generally found on steep southerly aspects where windy conditions are common resulting in very dry sites. Elevations range from 6,500 to 9,000 feet and the site represents the very dry end of *Pseudotsuga menziesii* sites. Understories are usually sparse, shrubby and composed of various mixtures of *Symphoricarpos oreophilus, Juniperus communis, Cercocarpus ledifolius, Pachistima myrsinites, Artemisia spp.,* and *Amelanchier alnifolia*. The type occurs sporadically throughout the zone.
1622	Douglas-fir / Douglas-fir	*Pseudotsuga menziesii* is the sole indicator of this type. *Pinus ponderosa* and *Populus tremuloides* are common associates. *Juniperus scopulorum* may be a minor associate. The type is found on a variety of site conditions ranging in elevation from 5,000 to 9,500 feet. Sites range from warm and dry to cool, moderately moist conditions. Understories are a mixture of shrubs and grasses including *Physocarpus malvaceus, Acer glabrum, Amelanchier alnifolia, Berberis repens, Arnica cordifolia,* and *Carex geyeri.*
1623	Douglas-fir / Lodgepole Pine	This type is indicated by the combination of *Pseudotsuga menziesii* and *Pinus contorta*. While sites may be relatively warm, they represent the cooler portion of the *Pseudotsuga menziesii* environment and vary from moist to dry. Other common species include *Pinus ponderosa* and Populus *tremuloides.* Elevations range from about 5,500 to 7,500 feet. The type is found only in the northern half of the zone. Understories tend to be shrubby and include *Symphoricarpos oreophilus, Berberis repens,* and *Juniperus communis* along with some taller shrubs such as *Amelanchier alnifolia.*
1631	Timberline Pine	*Pinus flexilis* and/or *Pinus longaeva* are the indicators of this type. *Juniperus scopulorum* and minor amounts of *Pseudotsuga menziesii* or *Populus tremuloides* may be present on some sites. Stands are frequently found on very steep south or southwest aspects. Conditions are generally the most adverse for tree growth and the type often represents the lower timberline. Elevations range from 7,000 to 10,200 feet. Understories are shrubby and composed of various mixtures of *Artemisia tridentata, Symphoricarpos oreophilus, Berberis repens, Cercocarpus ledifolius, Pachistima myrsinites,* and *Juniperus communis.*
1632	Ponderosa Pine	*Pinus ponderosa* is the only indicator species for this type. Other trees commonly found are *Juniperus scopulorum* and *Populus tremuloides.* Occasionally *Pinus edulis* and *Juniperus osteosperma* may be found. Sites range in elevation from 6,800 to 9,000 feet. Sites are typically gentle to moderate usually on southerly exposures. Understories are varied and vary from shrubby to grass dominated. Common species include *Amelanchier alnifolia, Artemisia tridentata, Quercus gambelii, Symphoricarpos oreophilus, Carex geyeri, Festuca idahoensis,* and *Sitanion hystrix.*

Appendix 6-F—(Continued)

PVT#	Potential vegetation type	Description
1633	Lodgepole Pine	*Pinus contort,a* in the absence of other shade tolerant conifers, is the sole indicator of this type. *Populus tremuloides* may occupy some sites. The type is found on a variety of landforms, which are mostly warm and droughty although it is also found on seasonally moist sites. Elevations range from about 7,600 to 10,000 feet. Understories are commonly sparse and variable. The most commonly found species include *Juniperus communis, Vaccinium scoparium, Vaccinium caespitosum, Arctostaphylos uva-ursi, Berberis repens,* and *Calamagrostis canadensis.* The type is confined to the northern half of the zone.
1634	Aspen	The PVT is characterized by *Populus tremuloides* that frequently makes up pure stands. The type spans a broad range of environments ranging from high-elevation cool, moist spruce-fir forests to the relatively dry, low-elevation sagebrush steppes. As a result of this wide environmental span, the understory vegetation is highly variable. *Symphoricarpos oreophilus* is a common shrub along with varying amounts of *Berberis repens, Juniperus communis, Rosa woodsii,* and *Amelanchier alnifolia. Bromus carinatus* and E*lymus glaucus* are common grasses and *Geranium viscosissimum, Rudbeckia occidentalis, Lathyrus leucanthus,* and *Lathyrus lanszwertii* are common forbs.
1641	Pinyon -- Juniper / Mountain Big Sagebrush / North	This type is indicated by the presence of *Pinus edulis* and/or *Juniperus osteosperma* in conjuction with *Artemisia tridentata* var. *vaseyana*. Sites are at moderate elevations and occupy the upper reaches of the Pinyon-Juniper PVTs. Slopes may be gradual to steep. This type occurs mostly in the northern part of the zone where pinyon pine is less prevalent.
1642	Pinyon -- Juniper / Mountain Big Sagebrush / South	This type is indicated by the presence of *Pinus edulis* and/or *Juniperus osteosperma* in conjuction with *Artemisia tridentata* var. *vaseyana*. Sites are at moderate elevations and occupy the upper reaches of the Pinyon-Juniper PVTs. Slopes may be gradual to steep. This type occurs mostly in the southern part of the zone where pinyon pine is more prevalent..
1643	Pinyon -- Juniper / Wyoming -- Basin Big Sagebrush / North	This type is indicated by the presence of *Pinus edulis* and/or *Juniperus osteosperma* in conjuction with *Artemisia tridentata* var. *wyomingensis* or var. *tridentata*. Sites are at low to moderate elevations and occupy the lower reaches of the Pinyon-Juniper PVTs. Slopes may be gradual to steep. This PVT commonly intermixes with the Wyoming-Basin Big Sagebrush PVT at the lower end. This type is very common in the northern part of the zone where pinyon pine is less prevalent.
1644	Pinyon -- Juniper / Wyoming -- Basin Big Sagebrush / South	This type is indicated by the presence of *Pinus edulis* and/or *Juniperus osteosperma* in conjuction with *Artemisia tridentata* var. *wyomingensis* or var. *tridentata*. Sites are at low to moderate elevations and occupy the lower reaches of the Pinyon-Juniper PVTs. Slopes may be gradual to steep. This PVT commonly intermixes with the Wyoming-Basin Big Sagebrush PVT at the lower end. This type is very common in the southern part of the zone where pinyon pine is more prevalent.
1645	Pinyon -- Juniper / Mountain Mahogany	*Cercocarpus ledifolius* is the indicator species for this PVT. Sites are typically on mid elevation, steep slopes and are usually interspersed with Pinyon-Juniper, Douglas-fir, or White Fir PVTs. This

Appendix 6-F—(Continued)

PVT#	Potential vegetation type	Description
		type may occur throughout most of the zone. However, it usually occurs in relatively small patches and is of minor importance since most sites that are dominated by *Cercocarpus ledifolius* are probably seral to other PVTs.
1646	Pinyon -- Juniper / Gambel Oak	The indicator for this PVT is *Quercus gambelii*. Sites are typically on mid elevation slopes (5,500 ft. to 7,800 ft.) and are frequently bordered by Pinyon-Juniper PVTs on lower slopes and Douglas-fir or White Fir PVTs on the upper end. This type may occur throughout most of the zone.
1651	Blackbrush	*Coleogyne ramosissima* is the sole indicator species in this PVT. Sites occur in a transition zone between the Mohave and Great Basin Deserts and in the Colorado River Drainage in the southern portion of the zone. The Salt Desert Shrub PVT commonly intermixes with Blackbrush at the lower end of the PVT.
1652	Salt Desert Shrub	These sites are indicated by the presence of various shrub species, mostly in the Chenopodiaceae family. Species representative of this PVT include *Atriplex confertifolia, Atriplex corrugata, Kochia americana, Sarcobatus vermiculatus, Sueda torreyana,* and/or *Artemisia spinescens*. Sites are low elevation and usually occupy basin bottoms that have accumulations of saline or alkaline deposits. Sites may also occur on slopes with fine textured soils derived from formations such as the Mancos Shale and Tropic Shale. Total vegetation cover is usually relatively sparse though may be dense in some communities such as black greasewood.
1653	Warm Herbaceous	This PVT is represented by mid to low elevation grassland types, generally intermixed with Wyoming-Basin Big Sagebrush PVT and the Salt Desert Shrub PVT.
1654	Cool Herbaceous	This PVT is represented by mid to high elevation grassland types, generally intermixed with the Mountain Big Sagebrush PVT and the Alpine PVT.
1661	Dwarf Sagebrush	This PVT includes sites occupied by either *Artemisia nova* or *Artemisia arbuscula*. Sites are harsher than adjacent *Artemisia tridentata* PVT's and typically have shallow soil development. These communities are mostly at low elevations but may occur much higher in limited areas.
1662	Wyoming -- Basin Big Sagebrush	*Artemisia tridentata* var. *wyomingensis* or var. *tridentata* are the indicators of this type. Sites are low elevation and are commonly on flat to gradual slopes. These sites commonly intermix with the Pinyon-Juniper/Wyoming-Basin Big Sagebrush and Mountain Big Sagebrush PVTs on the upper end of the type. On lower elevations, it commonly intermixes with the Dwarf Sagebrush and the Salt Desert Shrub PVTs. This is a dominant PVT thoughout the zone in valley locations.
1663	Mountain Big Sagebrush	*Artemisia tridentata* var. *vaseyana* is the indicator of this type. Sites are at moderate to high elevations and are common on unforested areas on the central plateaus. Slopes may be almost flat to relatively steep. Many other PVTs may border this one depending on elevation, soils and local topographic features.

Appendix 6-F—(Continued)

PVT#	Potential vegetation type	Description
1671	Riparian Hardwood	This PVT is indicated by the presence of broadleaf trees such as *Populus angustifolia* and *Acer negundo.* Varying amounts of *Acer grandidentatum, Betula occidentalis, Populus acuminate,* and *Populus fremontii* are also present. *Juniperus scopulorum* may be present in limited amounts. Sites are usually low elevations along major drainages though they may extend into the mountains as narrow stringers along streams. Understories are highly variable. *Rosa spp.* is the most common shrub along with *Cornus serice. Smilacina stellata* is a common forb and *Poa pratensis* is the major grass.
1672	Riparian Shrub	This type is found adjacent to major drainages throughout the zone. A number of species of *Salix* plus *Alnus incana, Betula occidentalis, Lonicera involucrate, Cornus stolonifera, Ribes lacustre,* and *Rhus aromatica* var. *trilobata* are the major types found in the community.
1673	Wetland Herbaceous	This community is composed of mixtures of wetland forbs and grasses usually found in high mountain basins. Soils are seasonally saturated. Common species include *Calamagrostis canadensis, Streptopus amplexifolius, Senecio triangularis,* and *Equisetum arvense.*
1680	Alpine	These sites include all vegetated areas above treeline. Sites are generally above 11,000 ft. in elevation and occur in the Tushar, Uinta, and Wasatch Mtn Ranges. Grasses, sedges, forbs, and/or dwarf willows may dominate areas.

Appendix 6-G – Zone 19 potential vegetation type legend and descriptions

PVT#	Potential vegetation type	Description
1902	Western Redcedar	This is a small PVT found only in the northwest corner of the zone. Along with *Thuja plicata,* other common tree associates are *Pseudotsuga menziesii, Picea engelmannii, Larix occidentalis, and Tsuga heterophylla* plus lesser amounts of *Pinus monticola, Pinus contorta,* and *Abies grandis.* Sites are typically very moist and warm bottomland or northerly exposures and range in elevation from 2,000 to 5,000 feet. Understories are dominated by a variety of forbs including *Clintonia uniflora* with the shrubs *Menziesia ferruginea* and *Oplopanax horridum* found on some sites. Under dense stand conditions, understories may be very limited.
1914	Grand Fir -- White Fir	This type is represented by *Abies grandis* within the zone. Common associates are *Pseudotsuga menziesii, Picea engelmannii,* and *Pinus contorta*. Minor amounts of *Populus tremuloides* and *Pinus ponderosa* may also be present. In the northwestern portion of the zone, *Larix occidentalis* is a major component and *Pinus monticola* can be found in the extreme northwest corner in minor amounts. It is found on warm, moist sites between 2,500 and 5,500 feet elevation. *Vaccinium spp., Calamagrostis rubescens,* and *Xerophyllum tenax,* along with a wide variety of forbs and shrubs, may be found in a relatively dense understory.
1920	Spruce -- Fir / Montane / Western Larch	This PVT is represented by *Picea engelmannii* and *Abies lasiocarpa. Pseudotsuga menziesii* is a major component along with *Pinus contorta* and in the northwest corner. *Larix occidentalis* may be common. This type represents the lower elevations where *Abies lasiocarpa* is found. Sites are generally moist and cool however they are warm enough to support *Pseudotsuga menziesii*. Elevations range from 4,500 to 6,500 feet. Understories are dominated by *Vaccinium globulare, Xerophyllum tenax,* and *Arnica latifolia* with *Menziesia ferruginea* common on some sites.
1921	Spruce -- Fir / Montane / Douglas-fir	This PVT is represented by *Picea engelmannii* and *Abies lasiocarpa. Pseudotsuga menziesii* is a major component along with *Pinus contorta.* This type represents the lower elevations where *Abies lasiocarpa* is found. Sites are generally moist and cool however they are warm enough to support *Pseudotsuga menziesii*. Elevations range from 4,500 to 6,500 feet. Understories are dominated by *Vaccinium globulare, Xerophyllum tenax,* and *Arnica latifolia,* with *Menziesia ferruginea* common on some sites.
1922	Spruce -- Fir / Timberline	These areas represent the highest elevations of the subalpine area where a closed forest can develop. *Picea engelmannii, Abies lasiocarpa,* and *Pinus albicaulis* are all major species in the PVT, along with lesser amounts of *Pinus contorta.* The PVT is found along the major ridges above 7,000 feet throughout the zone. Understories are dominated by *Vaccinium scoparium* along with *Luzula hitchcockii* and lesser amounts of *Xerophyllum tenax* with *Menziesia ferruginea* on some sites. On some sites, this understory may be very sparse.
1924	Spruce -- Fir / Subalpine	This PVT is found on wet sites above the limits of *Pseudotsuga menziesii. Picea engelmannii* is the major tree species along with *Abies lasiocarpa* and *Pinus contorta.* Minor amounts of *Pinus albicaulis* may also be present. Elevations range from 6,000 to 8,000 feet and stands commonly are adjacent to wet meadows. Understories are mixtures of *Calamagrostis canadensis* and *Vaccinium scoparium* along with *Arnica latifolia* and a variety of other forbs and shrubs.
1930	Douglas-fir / Ponderosa Pine / Western Larch	This type is found on warm, dry sites where *Pseudotsuga menziesii* is the indicated climax; however, while *Pseudotsuga menziesii* may be present, the stand is dominated by fire maintained *Pinus ponderosa*. With the lack of disturbance, *Pseudotsuga menziesii* may eventually dominate the site. Minor amounts of *Larix occidentalis* may be found in the northwestern portion of the zone and pockets of *Pinus contorta* on the cooler, moister sites. Elevations range from about 2,700 to 6,400 feet. Understories are about equally divided between forb or grassy sites and shrub communities with *Calamagrostis rubescens, Pseudoroegneria spicata, Carex geyeri, Balsamorhiza sagittata, Arctostaphylos uva-ursi,* and *Symphoricarpos albus* as major species.

Appendix 6-G—(Continued)

PVT#	Potential vegetation type	Description
1931	Douglas-fir / Ponderosa Pine / Douglas-fir	This type is found on warm, dry sites where *Pseudotsuga menziesii* is the indicated climax; however, while *Pseudotsuga menziesii* may be present, the stand is dominated by fire maintained *Pinus ponderosa*. With the lack of disturbance, *Pseudotsuga menziesii* may eventually dominate the site. Minor amounts of *Pinus contorta* are found on the cooler, moister sites. Elevations range from about 2,700 to 6,400 feet. Understories are about equally divided between forb or grassy sites and shrub communities with *Calamagrostis rubescens, Pseudoroegneria spicata, Carex geyeri, Balsamorhiza sagittata, Arctostaphylos uva-ursi,* and *Symphoricarpos albus* as major species.
1932	Douglas-fir / Lodgepole Pine	This type is indicated by the combination of *Pseudotsuga menziesii* and *Pinus contorta*. Minor amounts of *Larix occidentalis* may be found in the northwestern portion of the zone. The type is found on relatively cold sites at the upper elevations of *Pseudotsuga menziesii* occurrence (4,800 to 7,000 feet). *Calamagrostis rubescens* and *Arnica spp.,* along with some *Linnaea borealis, Vaccinium globulare,* and *Xerophyllum tenax* typically dominate understories.
1934	Douglas-fir / Timberline Pine	This PVT is found on dry sites that are to cold for *Pinus ponderosa. Pseudotsuga menziesii* dominates most sites. East of the Continental Divide it may share dominance with *Pinus flexilis* on dry, wind-exposed slopes. *Juniperus scopulorum* is a minor component in some stands. Sites are typically cool and dry and range from 4,800 to 8,200 feet in elevation. Understory vegetation may be sparse and frequently dominated by bunchgrasses including *Pseudoroegneria spicata* and *Festuca idahoensis* or scattered forbs. Shrubs such as *Artemisia spp.* and *Juniperus communis* may be common on some sites.
1936	Douglas-fir / Douglas-fir	*Pseudotsuga menziesii* is the sole indicator of this type. Minor amounts of *Pinus contorta* may be present and occasionally *Larix occidentalis* or *Pinus ponderosa*. Sites are normally at the moist, cool end for *Pseudotsuga menziesii* and located on benches or north slopes ranging from 2,500 feet to about 6,000 feet. A minor amount may be found at elevations up to 6,700 ft. on southerly aspects. Shrubby understories composed of *Physocarpus malvaceus, Symphoricarpos albus,* and *Linnaea borealis* are common along with *Calamagrostis rubescens, Carex geyeri* ,and *Arnica cordifolia*.
1940	Lodgepole Pine	*Pinus contorta* is the only indicator of this fire maintained type. During long fire free periods, *Picea engelmannii* and *Abies lasiocarpa* will generally become abundant. Minor amounts of *Pseudotsuga menziesii* may also be present. Stands are typically found between 6,000 to 7,200 feet on cool to cold sites with moderate moisture. Understories composed of the low shrubs *Vaccinium scoparium; Vaccinium caespitosum,* and *Linnaea borealis* are common along with *Calamagrostis rubescens* and *Carex geyeri.*
1942	Ponderosa Pine	*Pinus ponderosa* is the only indicator species for this type. The only other conifer commonly represented is *Juniperus scopulorum. Pinus flexilis* may be found on some sites as an accidental. Sites range in elevation from the lower timberline, which is from about 2,600 feet, up to 5,000 feet in warm, dry environments associated with the larger valleys in the zone. Isolated stands may be found at higher elevations on steep southerly slopes. Understories are usually open and dominated by bunchgrasses including *Pseudoroegneria spicata, Festuca idahoensis,* and *Festuca scabrella.* Shrubs such as *Symphoricarpos albus, Amelanchier alnifolia, and Purshia tridentata* are common on some sites.
1944	Timberline Pine / Limber Pine	This PVT represents the lower elevation timberline where conditions become too dry to support tree growth. *Pinus flexilis* is the major overstory species along with some *Juniperus scopulorum* and scattered *Pseudotsuga menziesii*. Sites are generally marginal for tree growth and trees are short and open-grown. The type is generally confined to the east side of the Continental Divide between 4,000 and 8,000 feet. Lower elevation sites are dominated by *Pseudoroegneria spicata* while the higher elevations tend to be dominated by *Juniperus communis*. *Artemisia spp.* may be common on some sites.

Appendix 6-G—(Continued)

PVT#	Potential vegetation type	Description
1946	Timberline Pine / Whitebark Pine	This PVT is characterized by stands that are open and wind stunted. *Pinus albicaulis* is the principle species along with varying amounts of *Picea engelmannii*. *Abies lasiocarpa* may be present but normally very stunted and growing in the protection of the other two species. Site conditions are cold and dry and stands are usually found above about 7,800 feet. Understories may be depauperate and composed of a mixture of *Vaccinium scoparium, Juniperus communis, Phyllodoce glanduliflora* or *empetriformis, Festuca idahoensis,* and *Luzula hitchcockii.*
1950	Rocky Mountain Juniper	*Juniperus scopulorum* is the main indicator species in this PVT, although *Juniperus osteosperma* may also indicate this type. The Rocky Mountain Juniper PVT may be wide-ranging found on both sides of the divide in Montana. Communities are usually open with *Juniperus* cover averaging around 25 percent. Common associated species include: *Artemisia nova, Artemisia tridentata* ssp. *vaseyana, Pseudoroegneria spicata, Festuca idahoensis ,*and *Koeleria macrantha*. This is a minor woodland type in the zone.
1952	Riparian Hardwood	This is the only PVT where broadleaf trees are the major component. It is limited to the riparian area along the major rivers in the zone and dominated by *Populus trichocarpa* and some *Populus tremuloides.* Minor amounts of *Pinus ponderosa, Pseudotsuga menziesii,* and *Pinus contorta* may also be present. This type generally represents the lowest elevations in the zone and is rarely found outside of the major river valleys. Understories appear to be highly variable with *Cornus stolonifera, Rosa spp., Salix spp.,* and *Juniperus spp.* common with a wide variety of forbs and grasses also present.
1960	Riparian Shrub	This type is found adjacent to major drainages throughout the zone. A number of species of *Salix* plus *Alnus incana, Betula occidentalis, Lonicera involucrate, Cornus stolonifera, Ribes lacustre,* and *Rhus aromatica var trilobata* are the major types found in the community.
1962	Mountain Mahogany	*Cercocarpus ledifolius* is the indicator species for this PVT. Sites are typically on mid elevation, steep slopes and are usually interspersed with Rocky Mountain Juniper and Douglas-fir PVTs. This type may occur throughout most of the zone. However, it usually occurs in relatively small patches.
1964	Dry Shrub	*Dasiphora floribunda* is an indicator of this PVT on moderately moist Montana grassland and shrub foothill communities east of the Continental Divide. This is a productive mountain shrub type found under relatively mesic to dry site conditions with limited occurrence in the zone. It occurs at mid to upper elevations between 4,500 ft and 8,500 ft.
1965	Dry Shrub / Conifer	*Dasiphora floribunda* is an indicator of this PVT on moderately moist Montana grassland and shrub foothill communities east of the Continental Divide usually along with *Pseudotsuga menziesii,* which indicate conifer encroachment in this PVT. This is a productive mountain shrub type found under relatively mesic to dry site conditions with limited occurrence in the zone. It occurs at mid to upper elevations between 4,500 ft and 8,500 ft. This PVT has a conifer encroachment succession pathway.
1970	Dwarf Sagebrush Complex	This PVT is associated with nearly pure stands or mixtures of “low sagebrush” species. The indicator species are *Artemisia arbuscula* and *A. nova* and are usually associated with areas having little soil profile development in desert valleys and on west and south exposures along the lower slopes of the high desert foothills. It occurs most abundantly at elevations between 4,900 to 7,000 feet where annual precipitation ranges between 7 and 18 inches.

Appendix 6-G—(Continued)

PVT#	Potential vegetation type	Description
1971	Dwarf Sage Complex / Conifer	This PVT is associated with nearly pure stands or mixtures of “low sagebrush” species and possible conifer encroachment. The indicator of this type are *Artemisia arbuscula* and *A. nova* and are usually associated with areas having little soil profile development in desert valleys and on west and south exposures along the lower slopes of the high desert foothills. It occurs most abundantly at elevations between 4,900 to 7,000 feet where annual precipitation ranges between 7 and 18 inches. This PVT has a conifer encroachment succession pathway.
1972	Mountain Big Sagebrush Complex	*Artemisia tridentata* ssp*. vaseyana* is a major indicator species of this PVT in the zone. It is one of the more productive grassland sites. Mountain Big Sagebrush PVT extends from generally above Wyoming Big Sagebrush to forest edges and at times borders the subalpine area. Though present throughout the zone, it is most abundant in Idaho and in Montana generally south and east of Missoula.
1973	Mountain Big Sagebrush Complex / Conifer	*Artemisia tridentata* ssp*. vaseyana* is a major indicator species of this PVT in the zone along with conifer encroachment. It is one of the more productive grassland sites. Mountain Big Sagebrush PVT extends from generally above Wyoming Big Sagebrush to forest edges and at times borders the subalpine area. Though present throughout the zone, it is most abundant in Idaho and in Montana generally south and east of Missoula. This PVT has a conifer encroachment succession pathway.
1974	Threetip Sagebrush	*Artemisia tripartita* is the indicator of this PVT. It is a minor type in southwest Montana but becomes more abundant in the Idaho portion of the zone. It generally occurs on gentle, alluvial slopes or benches with moderately deep soils. This species is set apart by other sagebrush types in the zone by its ability to resprout after fire.
1975	Threetip Sagebrush / Conifer	The Threetip Sagebrush is the indicator of this PVT. It is a minor type in southwest Montana, but becomes more abundant in the Idaho portion of the zone. It generally occurs on gentle, alluvial slopes or benches with moderately deep soils. This species is set apart by other sagebrush types in the zone by its ability to resprout after fire. . This PVT has a conifer encroachment succession pathway.
1976	Wyoming -- Basin Big Sagebrush	The Wyoming-Basin Big Sagebrush PVT is a major type in the southern half of the zone. Both *Artemisia tridentata* ssp*. tridentata* and *Artemisia tridentata* ssp*. wyomingensis* are represented in this PVT.
1977	Wyoming -- Basin Big Sagebrush / Conifer	The Wyoming-Basin Big Sagebrush PVT is a major shrub type in the southern half of the zone. Both *Artemisia tridentata* ssp*. tridentata* and *Artemisia tridentata* ssp*. wyomingensis* are represented in this PVT. This PVT has a conifer encroachment succession pathway.
1980	Wetland Herbaceous	This type is confined to riparian stream areas and high mountain basins. Soils are seasonally saturated. Common species include *Calamagrostis canadensis, Streptopus amplexifolius, Senecio triangularis,* and *Equisetum arvense.*
1982	Alpine	These sites include all vegetated areas above treeline. Sites are generally above 9000 ft. in elevation and occur in small patches in various mountain ranges throughout the zone. Grasses, sedges, forbs, and/or dwarf willows may dominate areas.
1984	Fescue Grasslands	The Fescue Grassland PVT is indicated by *Festuca idahoensis* and *Festuca altaica*. *Pseudoroegneria spicata* is another major component as are a number of other cool season grasses depending on soil and moisture conditions. In general, this PVT occurs at low to moderate elevations.
1985	Fescue Grasslands / Conifer	The Fescue Grassland PVT is indicated by *Festuca idahoensis* and *Festuca altaica*. *Pseudoroegneria spicata* is another major component as are a number of other cool season grasses depending on soil and moisture conditions. In general, this PVT occurs at low to moderate elevations. This PVT has a conifer encroachment succession pathway.

Appendix 6-G—(Continued)

PVT#	Potential vegetation type	Description
1986	Bluebunch Wheatgrass	The Bluebuch Wheatgrass PVT is represented by grassland communities including *Pseudoroegneria spicata*/*Bouteloua gracilis*, *Pseudoroegneria spicata*/*Pascopyrum smithii,* and *Pseudoroegneria spicata*/*Poa secunda* along with *Festuca altaica*/*Pseudoroegneria spicata*. It is generally found east of the continental divide on toe-slopes of the foothills and steeper slopes and primarily occurs on southern slopes.
1987	Bluebunch Wheatgrass / Conifer	The Bluebuch Wheatgrass PVT is represented by grassland communities including *Pseudoroegneria spicata*/*Bouteloua gracilis*, *Pseudoroegneria spicata*/*Pascopyrum smithii,* and *Pseudoroegneria spicata*/*Poa secunda* along with *Festuca altaica*/*Pseudoroegneria spicata*. It is generally found east of the continental divide on toe-slopes of the foothills and steeper slopes and primarily occurs on southern slopes. This PVT has a conifer encroachment succession pathway.

Chapter
7

Mapping Potential Vegetation Type for the LANDFIRE Prototype Project

Tracey S. Frescino and Matthew G. Rollins

Introduction

Mapped potential vegetation functioned as a key component in the Landscape Fire and Resource Management Planning Tools Prototype Project (LANDFIRE Prototype Project). Disturbance regimes, vegetation response and succession, and wildland fuel dynamics across landscapes are controlled by patterns of the environmental factors (biophysical settings) that entrain the physiology and distribution of vegetation. These biophysical characteristics of landscapes are linked to stable vegetation communities that occur in the absence of disturbance (Arno and others 1985; Cooper and others 1991; Ferguson 1989; Pfister and Arno 1980; Pfister and others 1977). In the LANDFIRE Prototype Project, these stable vegetation community types were referred to as potential vegetation types (PVTs). Further, the concept of potential vegetation was used as a basis for developing biophysical map units that were critical for developing the LANDFIRE wildland fuel and fire regime products. In the LANDFIRE Prototype Project, maps of potential vegetation facilitated linkage of the ecological process of succession to simulation landscapes used as input the LANDSUMv4 landscape fire succession model for modeling historical vegetation reference conditions and historical fire regimes (Long and others, Ch. 9). In addition, maps of PVT were used to guide the parameterization and calibration of the landscape fire succession model LANDSUMv4 (Pratt and others, Ch. 10) and to stratify vegetation communities for mapping current vegetation and wildland fuel mapping (Zhu and others, Ch, 8; Keane and others, Ch. 12).

Analysis of the biophysical characteristics of landscapes is commonly used to quantify distributions of vegetation along biophysical gradients (Bray and Curtis 1957; Gleason 1926; Whittaker 1967). Previous research has employed cluster analysis and ordination techniques to delineate biophysical gradients and link them to corresponding potential vegetation (Galiván and others 1998). Other research has used supervised classification methods or predictive vegetation mapping techniques (Franklin 1995) to link potential natural vegetation with biophysical gradients (Keane and others 2000; Keane and others 2001; Lenihan and Neilson 1993; Rollins and others 2004) and gradients of climate, topography, and soils (Brzeziecki and others 1993; Jensen and others 2000).

We developed PVT map unit classifications based on species' shade tolerance and moisture tolerance to link LANDFIRE reference plot data to unique environmental conditions or biophysical settings. Here, we define biophysical setting as the suite of biotic and abiotic factors that affect the composition, structure, and function of vegetation. Our main assumption was that the shade tolerant species would serve as unique indicators of biophysical conditions (Daubenmire 1967). Because of dynamic climate and ecosystem complexities, we did not assume that a stable climax community would exist without the influence of disturbance (Keane and Rollins, Chapter 3).

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Initially, we investigated an unsupervised clustering approach to stratify the landscape using a series of indirect biophysical gradients (Hargrove and Luxmore 1998; Hessburg and others 2000a, Hessburg and others 2000b). This approach successfully delineated unique biophysical settings, but the categories were not significantly correlated to patterns of vegetation. Alternatively, we used a supervised predictive modeling approach based on ground-referenced data to explicitly link biophysical gradients to potential vegetation. This approach provided an objective and repeatable method that could be linked directly to vegetation patterns identifiable in the field. This chapter describes the process used for mapping potential vegetation for the LANDFIRE Prototype Project and provides recommendations for generating maps of potential vegetation for the national implementation of LANDFIRE.

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on the procedure followed in developing the potential vegetation maps, which served as spatial templates for nearly all mapping tasks in the LANDFIRE Prototype Project.

Field-referenced Data

Comprehensive field-based reference data are critical for implementing a supervised mapping application, and these "training data" must be a statistically robust sample of the population. The LANDFIRE reference database (LFRDB) was designed to meet these criteria and provided an excellent source of consistent, comprehensive reference data from which to develop training sites for our predictive landscape models (Caratti, Chapter 4). Georeferenced field locations were obtained from the LFRDB and assigned PVTs based on hierarchical, floristic keys organized along gradients of shade tolerance and moisture tolerance developed a priori (Long and others, Chapter 6). The development of the keys began with existing national classifications (Kuchler 1975) and was then revised by regional (Quigley and others 1996) and local (Pfister and others 1977) classifications. The keys were further revised using the LFRDB, an extensive literature review, and review by regional ecological experts. To qualify as a separate class, individual PVTs had to fit the criteria of being identifiable in the field, scalable, mappable, and model-able (See Keane and Rollins, Ch. 3 and Long and others, Ch. 6).

The keys divided PVTs into three physiological life forms, forest, shrub, and herbaceous, with forest PVTs following a shade tolerance gradient and shrub and herbaceous PVTs following moisture gradients. Initially, Zone 16 had 13 classes of forest PVTs, 10 classes of shrub PVTs, and 3 classes of herbaceous PVTs. Distinguishing between classes requires a sufficient number of training plots for each class. We grouped classes having fewer than 20 training plots with other classes, resulting in 10 forest classes, 8 shrub classes, and 3 herbaceous classes (table 1). To minimize the number of classes in Zone 19 and in an effort to increase overall map accuracy, we implemented the classification key for this zone under the criterion that a minimum of 30 training plots were necessary for a PVT to form a unique class. Table 2 shows Zone 19 PVT classes and the number of training plots from the database assigned to each class.

Spatial Data

The biophysical gradient layers included variables created using WXFIRE, an ecosystem simulation model developed by R.E. Keane at the USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory in Missoula, Montana (Keane and others 2006; Keane and Rollins, Ch. 3) and variables from the National Elevation Database (http://ned.usgs.gov). The WXFIRE model integrates DAYMET climate data (Running and Thornton 1996; Thornton and others 1997; Thornton and others 2000) with landscape data and site specific parameters (for example, soils and topography) and generates spatially explicit maps of climate and ecosystem variables that integrate landscape-weather interactions (See Holsinger and others, Ch. 5 for details about these variables and how they were derived). For topographic gradients, we used variables from the National Elevation Database, including elevation, derivatives of slope, aspect, a classified landform variable, and a topographic position index. This process resulted in a total of 38 biophysical gradients available for use as independent variables in our predictive landscape models of PVT. We reviewed correlation matrices and principle component analyses to reduce (winnow) this list of variables used in the modeling process. For Zone 16, we used 21 variables (table 3) and for Zone 19, 22 variables (table 4).

Table 1—Zone 16 codes, life forms, names, and the number of training sites and test sites by PVT. Life form categories include F (forest), S (shrub), and H (herbaceous).

Code	Life form	Name	Number of training sites	Number of test sites
1	F	Spruce - Fir / Blue Spruce	157	13
2	F	Spruce - Fir / Spruce - Fir	1188	92
3	F	Grand fir - White Fir	439	40
4	F	Douglas-fir / Lodgepole Pine - Timberline Pine	65	3
5	F	Douglas-fir / Douglas-fir	263	19
6	F	Lodgepole Pine - Timberline Pine	104	10
7	F	Ponderosa Pine	205	16
8	F	Pinyon - Juniper / Mountain Big Sagebrush	433	31
9	F	Pinyon - Juniper / Wyoming - Basin Big Sagebrush	1052	95
10	F	Riparian Hardwood	126	11
11	S	Riparian Shrub	33	4
12	S	Blackbrush - Chaparral - Dry Deciduous Shrub	22	3
13	S	Dwarf Sagebrush	99	14
14	S	Salt Desert Shrub	35	2
15	S	Mountain Mahogany	66	4
16	S	Gambel Oak	172	14
17	S	Wyoming - Basin Big Sagebrush	118	12
18	S	Mountain Big Sagebrush	171	17
19	H	Wetland Herbaceous	57	6
20	H	Alpine	47	6
21	H	Herbaceous	109	9

Table 2—Zone 19 codes, life forms, names, and the number of training sites and test sites by PVT. Life form categories include F (forest), S (shrub), and H (herbaceous).

Code	Life form	Name	Number of training sites	Number of test sites
1	F	Western Redcedar	176	23
2	F	Grand Fir - White Fir	194	33
3	F	Spruce - Fir / Montane	1418	235
4	F	Spruce - Fir / Timberline	951	133
5	F	Spruce - Fir / Subalpine	1165	171
6	F	Douglas-fir / Ponderosa Pine	363	56
7	F	Douglas-fir / Lodgepole Pine	546	88
8	F	Douglas-fir / Timberline Pine	161	26
9	F	Douglas-fir / Douglas-fir	947	125
10	F	Lodgepole Pine	460	55
11	F	Ponderosa Pine	76	8
12	F	Timberline Pine / Limber Pine	51	7
13	F	Timberline Pine / Whitebark Pine	40	6
14	F	Rocky Mountain Juniper	33	3
15	F	Riparian Hardwood	28	2
16	S	Riparian Shrub	94	5
17	S	Mountain Mahogany	32	3
18	S	Dry Shrub	51	4
19	S	Dwarf Sagebrush Complex	68	10
20	S	Mountain Big Sagebrush Complex	249	43
21	S	Threetip Sagebrush	187	26
22	S	Wyoming - Basin Big Sagebrush Complex	514	75
23	H	Wetland Herbaceous	112	9
24	H	Alpine	30	3
25	H	Fescue Grasslands	174	22
26	H	Bluebunch Wheatgrass	144	23

Table 3—Zone 16 PVT predictor layers. See Holsinger and others, Ch. 5, table 6 for biological significance of each layer.

Code	Units	Description
aet	kg H_20 yr^{-1}	Actual evapotranspiration
dsr	days	Days since last rain
dss	days	Days since last snow
gsws	-MPa	Growing season water stress
mc1	%	NFDRS – 1-hr wood moisture content
outflow	kg H_20 m^{-2} day^{-1}	Soil water lost to runoff and ground
pet	kg H_20 yr^{-1}	Potential evapotranspiration
ppt	cm	Precipitation
psi	-MPa	Water potential of soil and leaves
psi.max	-MPa	Maximum annual leaf water potential
rh	%	Relative humidity
srad.tg	kJ m^{-2} day^{-1}	Total solar radiation
tmin	°C	Minimum daily temperature
vmc	Scalar	Volumetric water content
sdepth	cm	Soil depth
elev	m	Elevation
aspect	8 classes	Aspect class*
slope	%	Slope
lndfrm	10 classes	Landform**
trmi	Index (0-1)	Topographic relative moisture index
posidx	Index (0-1)	Topographic position index

*Aspect classes – 0:Level; 1:North; 2:North-East; 3:East; 4:South-East; 5:South; 6: South-West; 7:West; 8:North-West

**Landform classes – 1:Vally flats; 2:Toe slopes; 3:Gently sloping ridges and hills; 4: Nearly level plateaus and hills; 5:Very moist steep slopes; 6:Moderately moist steep slopes; 7:Moderately dry slopes; 8:Very dry steep slopes; 9:Cool aspect cliffs, canyons; 10:Hot aspect cliffs, canyons.

Table 4—Zone 19 PVT predictor layers. See Holsinger and others, Ch. 5, table 6 for biological significance of each layer.

Code	Units	Description
aet	kg H_20 yr^{-1}	Actual evapotranspiration
dday	°C	Degree-days
dss	days	Days since last snow
evap	kg H_20 m^{-2} day^{-1}	Evaporation
g.sh	M sec^{-1}	Leaf-scale stomatal conductance
gsws	-MPa	Growing season water stress
outflow	kg H_20 m^{-2} day^{-1}	Soil water lost to runoff and ground
pet	kg H_20 yr^{-1}	Potential evapotranspiration
ppfd	Umol m^{-2}	Photon flux density
ppt	cm	Precipitation
psi	-MPa	Water potential of soil and leaves
snowfall	kg H_20 m^{-2} day^{-1}	Snowfall
srad.fg	KW m^{-2} day^{-1}	Solar radiation flux to the ground
tmax	°C	Maximum daily temperature
tmin	°C	Minimum daily temperature
tnight	°C	Nighttime daily temperature
trans	kg H_20 m^{-2} day^{-1}	Soil water transpired by canopy
vmc	Scalar	Volumetric water content
sdepth	cm	Soil depth
elev	m	Elevation
posidx	index (0-1)	Topographic position index
slope	%	Slope

*Aspect classes – 0:Level; 1:North; 2:North-East; 3:East; 4:South-East; 5:South; 6:South-West; 7:West; 8:North-West

Modeling and Mapping Process

Classification trees, also known as decision trees, have been widely applied in landscape mapping applications (Brown de Colstoun and others 2003; Friedl and Brodley 1997; Hansen and others 2000; Joy and others 2003; Moisen and others 2003, Moore and others 1991; Rollins and others 2004). Classification trees were originally developed for artificial intelligence research to identify patterns and recognize these patterns in similar situations using a hierarchical structure of rules (Quinlan 1986). The rules are constructed from available training data where observations are delineated into smaller subsets of more homogenous classes. Specifically, the classification tree algorithm considers each predictor variable and examines all *n*-1 ways to split the data into two clusters. For every possible split of each predictor variable, the within-cluster impurity is calculated. The first split in the tree is that which yields the smallest overall within-cluster impurity. This process is repeated for each branch defined by the previous split (Breiman and others 1984).

Classification trees are well-suited to vegetation mapping because they accommodate common conceptions that vegetation has a nonlinear, non-normal response to environmental gradients (Austin and others 1984). In addition, they are nonparametric models, meaning they make no underlying assumptions about the distribution of the data, and they are adaptable for nonlinear relationships between the predictors and the response (Friedl and Brodley 1997). Classification trees are also valuable because they are robust, are able to incorporate both categorical and continuous variables, and are relatively insensitive to outliers (Breiman and others 1984). Furthermore, for a large project such as LANDFIRE, classification trees offer the advantage that models are generated and executed quickly.

The classification trees for modeling PVTs were generated using the commercially available See5 machine-learning algorithm (Quinlan 1986, 1993; Rulequest Research 2004) and were applied within an ERDAS Imagine (ERDAS, Inc. 2001) interface. See5 uses a classification and regression tree (CART) approach for constructing a tree, generating a tree with high complexity, and pruning it back to a more simple tree by merging classes (Breiman and others 1984). This pruning process was found to improve the efficiency of the model and minimize the classification error (Breiman and others 1984). We used the boosting feature of See5 to improve the accuracy of the model (Friedl and others 1999; Quinlan 1986). In the boosting procedure, multiple trees are built in an iterative process and, each tree "learns" from the misclassification errors of the previously built tree (Bauer and Kohavi 1999). The final tree is selected from all the trees based on a weighted vote of the predictions. We also employed other features of See5 including winnowing, which excludes variables that are not relevant in the model, and differential misclassification cost weighting, which assigns more weight to classes with more costly classification errors.

Although not fully automated, the process for mapping PVTs was simplified using a suite of tools developed by Earth Satellite Corporation (2003) in support of the National Land Cover Database (NLCD 2000). These tools were developed to integrate the Rulequest See5/C5.0 software package with the ERDAS Imagine image-processing software. For mapping PVTs, we used the sampling tool to set up See5 input files and the classifier tool to generate the final map and a coinciding map of error or confidence. The sampling tool allows a user to input a spatially explicit layer of field-referenced training data as the dependent variable and multiple spatially explicit gradient layers as the independent variables and then outputs the input files needed to run See5. The classifier tool applies the output tree model from See5 over the specified spatial extent or a specified masked extent.

To meet the input requirements of See5 and to improve the efficiency of the model-making process, we followed three pre-processing rules: (1) all layers must be ERDAS Imagine images, (2) all layers must have the same number of rows and columns, and (3) all layers must be size 16-bit or smaller, with positive values. A few data preparation steps were necessary to follow these rules. The biophysical gradient layers are output from WX-FIRE as Arc/Info grids with float data values. We ran an Arc/Info AML (Arc Macro Language) to translate and dilate or "stretch" the grids to an unsigned, 16-bit integer format; converted the grids to ERDAS Imagine images using a batch setup in ArcGis 8.0 (ESRI Inc. 2001), and masked the images in Imagine using a buffered mask of the zone region (the zone boundaries). Through the entire LANDFIRE process, we used a 3-km buffer around the zone boundary. This buffer facilitated edge matching and reduced the edge effects in modeling historical fire regimes (Pratt and others, Ch. 10) The topographic and soil gradient layers were also converted to images and masked with the buffered zone region. We generated the spatially explicit dependent layer within ArcGis 8.0 using the spatial analyst tool to convert a data table to an image and set the extent to match the gradient images. Prior to creating this layer, we performed exploratory data analyses, both spatial and non-spatial, to look for and remove any major outliers or unusual patterns in the data. The output from the sampling tool includes a "data file," which contains values from the model response and the corresponding value of the model predictor layers for each georeferenced training site, and a "names file" identifying the model input names and data types.

For each prototype mapping zone, we built three different See5 classification trees and generated three different maps. The first classification tree was generated using a binary response variable describing forest and non-forest PVTs. The resulting map was used to stratify the zones to improve the performance of the PVT models. The other two classification trees were generated and applied to forest PVTs within the predicted forested areas and non-forest PVTs within the predicted non-forested areas. The final map was a combined product of the forest PVT predictions and the non-forest PVT predictions from each zone. For Zone 16, classes of agriculture, barren, open water, and urban/developed were masked from the Zone 16 cover type map and were considered non-forest types. For Zone 19, we masked only classes of barren, open water, and snow/ice following the assumption there is a potential for vegetation to grow on agricultural and urban lands. These classes had not been mapped for Zone 19 at this stage of the mapping process and were masked after the final PVT map was generated.

For the forested and non-forested stratification map, all training plots classified as forest PVTs were grouped into one class and the training plots classified as shrub or herbaceous PVTs into another class. There were a total of 4,032 training sites for Zone 16 with 4,032 forested plots and 929 non-forested plots (table 1). For Zone 19, there were a total of 8,264 training sites, 6,609 forested plots and 1,655 non-forested plots (table 2). Multiple models were executed exploring the different features of See5, including winnowing, boosting, and analyzing differential misclassification costs. We selected the model having the lowest error. The final PVT maps for each zone were created using the classifier tool and represented an integration of the forest/non-forest models defined by the masking strategy described above.

Accuracy Assessment

We used a 10-fold cross-validation routine performed by See5 to assess the accuracy of the binary forested and non-forested stratification map and used an independent test set to assess the accuracy of the forest and non-forest PVT predictions. We determined that a 10-fold cross-validation measure would be sufficient for assessing the accuracy of the stratification map and would maximize the number of plots used for developing the model. The independent test set would, in turn, assess the accuracy of the final map product. To perform the 10-fold cross-validation routine, the training data set was divided into 10 blocks of approximately the same size and class distribution. A classification tree was built ten times, and each time, one block was withheld for testing purposes. The error rate was averaged from the total number of errors and the total number of training sites. See5 output an error matrix generated from the sum of all errors and calculated the percent of the predictions that were correctly classified.

From the LANDFIRE reference database, we randomly reserved ten percent of the training sites. These sites were withheld from the modeling process and were used to independently evaluate the accuracy of the final map. There were a total of 421 test sites for Zone 16 and 1194 test sites for Zone 19 (tables 1 and 2). See5 automatically tested the model predictions at these sites and output an error matrix and a percentage measure of PVTs that were correctly classified. We brought the error matrix results into R statistical software (Ihaka and Gentleman 1996) and calculated user and producer accuracy measures and a kappa statistic to see if the model could achieve above-random accuracy (Cohen 1960; Congalton and Green 1999).

Error matrices provide a global summary of the accuracy of the map but do not show the range and variability of the accuracies across the map (Congalton 1988). The classifier tool provides the ability to generate a coinciding map of confidence. This map displays the prediction errors and thereby presents a spatial, visual representation of map accuracy. We generated a map of confidence for Zone 19 to examine this feature.

Results

The forest and non-forest stratification maps for zones 16 and 19 are displayed in figure 1. The classification model selected for Zone 16 used 12 boosting trials and a misclassification cost of 2, meaning the cost of misclassifying a non-forested plot as forested was doubled. This weighting compensated for the potential inaccuracies resulting from the fewer non-forested shrub and herbaceous training sites relative to the forested training sites. No variables were excluded from the model using the winnowing feature. The percent of plots correctly classified, according to the 10-fold cross-validation routine performed by See5, was 82.5 percent. For Zone 19, we also selected a classification tree using 12 boosting routines with a misclassification cost of 2. The 10-fold validation procedure identified the accuracy at 91.6 percent.

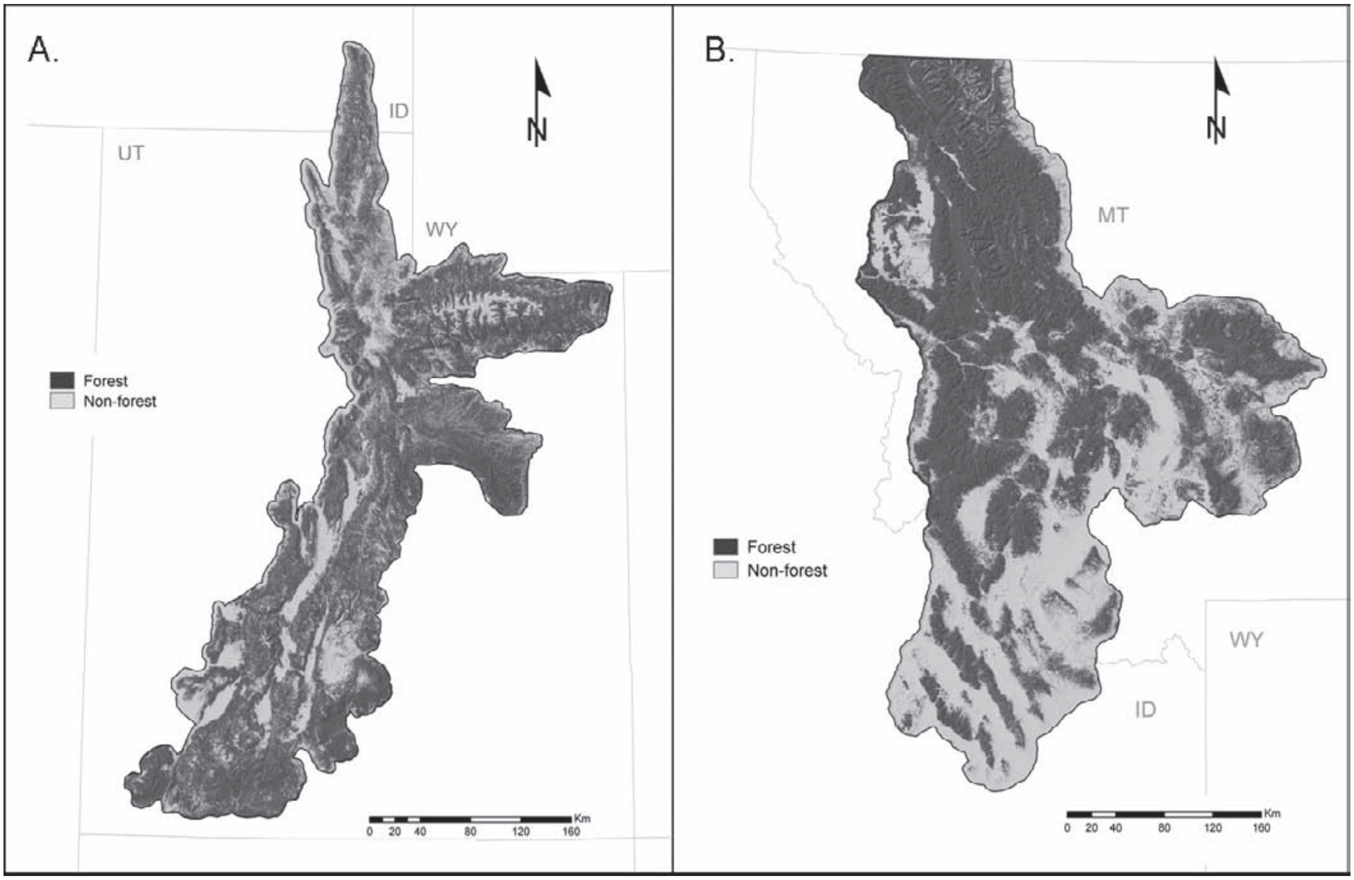

Figure 1—Forest and non-forest stratification maps. A, Zone 16; B, Zone 19.

The classification tree selected for Zone 16 forest PVTs used 10 boosting trials, and ten variables (gsws, outflow, pet, psi, psi.max, vmc, sdepth, aspect, slope, posidx) were winnowed from the model (table 3). The non-forest PVT classification tree for Zone 16 also used 10 boosting trials, and eleven variables (dsr, dss, gsws, mc1, outflow, posidx, psi.max, vmc, sdepth, aspect, lndfrm) were winnowed (table 3). The classification tree we selected for Zone 19 forest PVTs used 14 boosting trials and used all the variables in the model. The non-forest PVT classification tree for Zone 19 used 16 boosting trials with two variables (tnight, srad.fg) winnowed (table 4). The variables that explain the most variance in the models are usually at the top of the classification tree, defining the initial breaks. For the Zone 19 forest classification tree, no variables were winnowed, and the variables that most often appeared at the top of the trees were snowfall, gl.sh, dday, dss, evap, pet, and tmin (table 4). For the Zone 19 nonforest classification tree, tnight and srad.fg were winnowed, and the prominent variables were gl.sh, ppt, pet, aspect, and dday (table 4).

The total percent of plots correctly classified for Zone 16 was 61 percent, with a kappa coefficient of 0.55 (table 7). For Zone 19, the total percent of plots correctly classified was 58 percent with a kappa coefficient of 0.54 (table 7). The error matrices for forest and non-forest PVTs in Zone 16 are shown in tables 5 and 6, respectively. The number of plots correctly classified is represented by the diagonal values in bold font. The total percent of plots correctly classified for the forested lands was 65 percent with a kappa coefficient of 0.55 (table 7). The percent of plots correctly classified for shrub and herbaceous lands was 48 percent, with a kappa coefficient of 4.0 (table 7). The user and producer accuracies for each class in Zone 16 is provided in table 8. User accuracies range from 0 percent for the Douglas-fir / Lodgepole Pine - Timberline Pine type to 89 percent for the Spruce – Fir / Spruce – Fir type. Producer accuracies range from 0 percent for the Douglas-fir / Timberline Pine type to 100 percent for the Blackbrush and Salt Desert Shrub types. Zero percent values are the result of having no test sites occurring within a particular class. Most of the lower user accuracies are within PVT subgroups. The Spruce – Fir / Blue – Spruce PVT has a user accuracy of only 15 percent (table 8). From the error matrix, we can see that 54 percent of

Table 5—Error matrix for Zone 16 forest PVTs. PVT codes are listed in table 1. The number of test sites correctly classified is shown in bold.

PVT	**PVT Code**									
Code	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	**2**	7	1	0	2	0	1	0	0	0
2	1	**82**	2	0	2	1	2	0	0	2
3	1	7	**23**	0	3	0	2	1	1	2
4	0	1	1	**0**	0	1	0	0	0	0
5	0	8	3	0	**3**	0	2	0	2	1
6	0	4	3	0	0	**1**	0	1	0	1
7	0	1	1	0	1	0	**5**	1	7	0
8	0	0	4	0	0	0	1	**6**	19	1
9	0	2	1	0	0	2	2	3	**84**	1
10	0	1	2	0	2	0	0	0	0	**6**

Table 6—Error matrix for Zone 16 non-forest PVTs. PVT codes are listed in table 1. The number of test sites correctly classified is shown in bold.

PVT	**PVT Code**										
Code	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
11	**2**	0	0	0	0	0	0	0	0	0	2
12	0	**2**	0	0	0	0	0	1	0	0	0
13	0	0	**8**	0	0	0	3	3	0	0	0
14	0	0	0	**1**	0	1	0	0	0	0	0
15	0	0	0	0	**3**	1	0	0	0	0	0
16	0	0	0	0	1	**8**	1	2	0	1	1
17	0	0	0	0	0	2	**5**	5	0	0	0
18	0	0	1	0	0	3	2	**9**	0	1	1
19	1	0	0	0	0	0	0	2	**1**	0	2
20	0	0	0	0	0	0	0	1	2	**1**	2
21	1	0	0	0	0	2	0	3	0	0	**3**

Table 7—Overall accuracies and kappa coefficients for Zone 16 a nd Zone 19.

Zone	**Category**	**Overall accuracy**	**Kappa**
16	Total	61.2	0.55
	Forest	64.8	0.55
	Shrub and herbaceous	47.8	0.40
19	Total	58.4	0.54
	Forest	56.5	0.49
	Shrub and herbaceous	66.4	0.58

Table 8—Zone 16 user and producer accuracy measures.

PVT code	PVT name	User accuracy	Producer accuracy
1	Spruce – Fir / Blue Spruce	15.4	50.0
2	Spruce – Fir / Spruce - Fir	89.1	72.6
3	Grand Fir - White Fir	57.5	60.5
4	Douglas-fir / Lodgepole Pine - Timberline Pine	0.0	0.0
5	Douglas-fir / Douglas-fir	15.8	23.1
6	Lodgepole Pine - Timberline Pine	14.3	20.0
7	Ponderosa Pine	31.3	33.3
8	Pinyon - Juniper / Mountain Big Sagebrush	19.4	50.0
9	Pinyon - Juniper / Wyoming - Basin Big Sagebrush	88.4	74.3
10	Riparian Hardwood	54.6	42.9
11	Riparian Shrub	50.0	50.0
12	Blackbrush - Chaparral - Dry Deciduous Shrub	66.7	100.0
13	Dwarf Sagebrush	57.1	88.9
14	Salt Desert Shrub	50.0	100.0
15	Mountain Mahogany	75.0	75.0
16	Gambel Oak	61.5	47.1
17	Wyoming - Basin Big Sagebrush	41.7	45.5
18	Mountain Big Sagebrush	52.9	34.6
19	Wetland Herbaceous	16.7	33.3
20	Alpine	16.7	50.0
21	Herbaceous	33.3	27.3

the test sites classified as Spruce – Fir / Blue Spruce were predicted as Spruce – Fir / Spruce – Fir (table 5). The Pinyon – Juniper / Mountain Big Sagebrush type had similar results. The user accuracy was 19 percent, but 61 percent of the Pinyon – Juniper / Mountain Big Sagebrush test sites were predicted as Pinyon – Juniper / Wyoming – Basin Big Sagebrush (table 6).

Error matrices for Zone 19 forest and non-forest PVTs are presented in tables 9 and 10, respectively. The total percent of plots correctly classified for forest PVTs was 57 percent, with a kappa coefficient of 0.49 and 66 percent for shrub and herbaceous PVTs, with a kappa coefficient of 0.58 (table 7). Table 11 shows the user and producer accuracies for each class in Zone 19. For Zone 19, the

Table 9—Error matrix for Zone 19 forest PVTs. PVT codes are listed in table 2. The number of test sites correctly classified is shown in bold.

PVT	PVT Code														
Code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	**17**	2	3	0	1	0	0	0	0	0	0	0	0	0	0
2	3	**19**	7	0	2	2	0	0	0	0	0	0	0	0	0
3	7	3	**147**	17	41	5	6	1	6	1	0	1	0	0	0
4	0	0	7	**107**	16	0	0	0	0	1	0	0	2	0	0
5	1	3	42	35	**75**	4	6	0	0	5	0	0	0	0	0
6	1	3	5	0	1	**27**	3	1	12	0	2	1	0	0	0
7	0	0	20	4	3	2	**29**	1	22	7	0	0	0	0	0
8	0	0	1	3	2	0	1	**8**	10	1	0	0	0	0	0
9	0	2	11	1	4	10	13	3	**74**	5	0	1	0	0	1
10	0	0	2	3	6	0	4	0	6	**33**	1	0	0	0	0
11	0	0	0	0	0	2	0	0	1	0	**5**	0	0	0	0
12	0	0	1	0	0	0	0	0	3	0	0	**3**	0	0	0
13	0	0	0	2	0	0	0	0	0	2	0	0	**2**	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**	0
15	0	0	0	0	2	0	0	0	0	0	0	0	0	0	**0**

Table 10—Error matrix for Zone 19 non-forest PVTs. PVT codes are listed in table 2. The number of test sites correctly classified is shown in bold.

PVT	PVT Code										
Code	16	17	18	19	20	21	22	23	24	25	26
16	**2**	0	0	0	2	0	0	1	0	0	0
17	0	**1**	0	0	0	0	2	0	0	0	0
18	0	0	**3**	0	0	0	0	0	0	1	0
19	0	0	0	**1**	1	0	8	0	0	0	0
20	0	1	0	0	**28**	5	3	1	0	3	2
21	0	0	0	0	1	**18**	6	0	0	1	0
22	0	0	0	2	7	5	**61**	0	0	0	0
23	1	0	0	0	1	0	0	**6**	0	1	0
24	0	0	0	0	0	0	0	0	**1**	2	0
25	0	1	0	0	1	2	1	1	1	**15**	0
26	0	0	2	0	1	1	6	0	0	1	**12**

Table 11—Zone 19 user and producer accuracy measures.

PVT Code	PVT name	User accuracy	Producer accuracy
1	Western Redcedar	73.9	58.6
2	Grand Fir / White Fir	57.6	59.4
3	Spruce - Fir / Montane	62.6	59.8
4	Spruce - fir / Timberline	80.5	62.2
5	Spruce - Fir / Subalpine	43.9	49.0
6	Douglas-fir / Ponderosa Pine	48.2	51.9
7	Douglas-fir / Lodgepole Pine	33.0	46.8
8	Douglas-fir / Timberline Pine	30.8	57.1
9	Douglas-fir / Douglas-fir	59.2	55.2
10	Lodgepole Pine	60.0	60.0
11	Ponderosa Pine	62.5	62.5
12	Timberline Pine / Limber Pine	42.9	50.0
13	Timberline Pine / Whitebark Pine	33.3	50.0
14	Rocky Mountain Juniper	100.0	100.0
15	Riparian Hardwood	0.0	0.0
16	Riparian Shrub	40.0	66.7
17	Mountain Mahogany	33.3	33.3
18	Dry Shrub	75.0	60.0
19	Dwarf Sagebrush Complex	10.0	33.3
20	Mountain Big Sagebrush Complex	65.1	66.7
21	Threetip Sagebrush	69.2	58.1
22	Wyoming - Basin Big Sagebrush Complex	81.3	70.1
23	Wetland Herbaceous	66.7	66.7
24	Alpine	33.3	50.0
25	Fescue Grasslands	68.2	62.5
26	Bluebunch Wheatgrass	52.2	85.7

user accuracies range from 0 percent for the Riparian Hardwood type to 100 percent for the Rocky Mountain Juniper type. Again, we see similar patterns in the error matrices of within-subgroup inaccuracies. Forty-five percent of the Spruce – Fir / Subalpine test sites were misclassified as Spruce – Fir / Montane (Western Larch or Douglas-fir) or Spruce – Fir / Timberline, and 25 percent of the Spruce – Fir / Montane (Western Larch or Douglas-fir) test sites were misclassified as Spruce – Fir / Timberline or Spruce – Fir / Subalpine (table 9). Similarly, 19 percent of the Mountain Big Sagebrush test sites were misclassified as Threetip Sagebrush or Wyoming – Basin Big Sagebrush Complex, and 16 percent of the Wyoming – Basin Big Sagebrush Complex test sites were misclassified as Mountain Big Sagebrush or Threetip Sagebrush types (table 10). Thirty-six Douglas-fir sites were misclassified as Spruce – Fir / Montane (Western Larch or Douglas-fir) (table 10). The final PVT maps for zones 16 and 19 are presented in figure 2. The spatial estimate confidence for Zone 19 is shown in figure 3.

Discussion

The LANDFIRE PVT Mapping Approach

The LANDFIRE PVT mapping process represents an innovative framework for linking vegetation dynamics, such as post-disturbance recovery and succession, to landscape patterns represented by the biophysical variables compiled from the National Elevation Database and modeled using the WXFIRE model. The variables that were most important (defined by the first few splits of the tree) for the successful mapping of forest PVTs included: actual and potential evapotranspiration, days since snow, degree days, evaporation, relative humidity, leaf resistance to sensible heat, and minimum temperature. For the non-forest PVTs, the most important variables included: actual and potential evapotranspiration, precipitation, degree days, relative humidity, and minimum temperature. These gradients are associated with plant-water interactions and explain the influence of water and temperature derivatives in determining the distribution of vegetation across landscapes.

Classification and Regression Trees

Classification tree modeling proved an efficient means for identifying relationships between PVTs and biophysical variables across broad landscapes. With a comprehensive set of training data, classification trees can serve as strong predictors of these relationships. This predictive power extends across scales and is fully repeatable in time and space. Classification trees have proven successful in modeling and mapping vegetation at regional (Moisen and others 2003), national (Vogelmann and others 2001; Zhu and others, Chapter 8), and global scales (Hansen and others 2000). Although some research has found the predictive accuracy of classification trees to be inferior to other predictive modeling tools (Moisen and Frescino 2002; Pal and Mather 2003), the statistical flexibility, speed, and objectivity of the trees justify their use for large-scale mapping efforts such as LANDFIRE. See5 software adds efficiency to classification tree modeling by providing automated procedures, flexibility in terms of changing modeling functions, and by built-in accuracy measures.

Accuracy Assessment

There are several possible sources of the generally low accuracies found in the PVT maps created during the LANDFIRE Prototype Project. First, the performance of mapping models depends greatly on the quality of input data. The training databases for PVT mapping were collected and compiled from the LANDFIRE reference database (LFRDB), a database that comprised existing agency and non-agency field-referenced data sets and contained inventory, monitoring, and analysis data that originate from a variety of sampling objectives, sizes, and designs. (see Caratti, Ch. 4 for details). Data inaccuracies, major outliers, and unbalanced or insufficient numbers of training sites can have significant negative effects on the quality of mapping models (Friedman 2001). While the LFRDB was a large, comprehensive database that was compiled quickly and economically, the disparate sampling objectives, designs, and procedures certainly affected the final accuracies of the PVT maps.

A second possible explanation for the low accuracies is related to the model building characteristics of classification trees. As See5 builds classification trees, map units are divided using hard breaks, making it difficult to discriminate between vegetation types that have similar responses to the biophysical predictor variables. Most of the lower accuracies found during the LANDFIRE Prototype Project were within groups of similar PVTs, suggesting that these PVTs occur on overlapping biophysical settings, as represented by the predictor variables. The distributions of the three spruce-fir PVTs and the four Douglas-fir PVTs over a gradient of potential evapotranspiration are quite similar in Zone 19 (fig. 4). The error matrices reflect these similarities as well, indicating that the See5 classification tree algorithms had difficulty in discriminating these PVT subgroups. In any mapping application, this overlap between classes

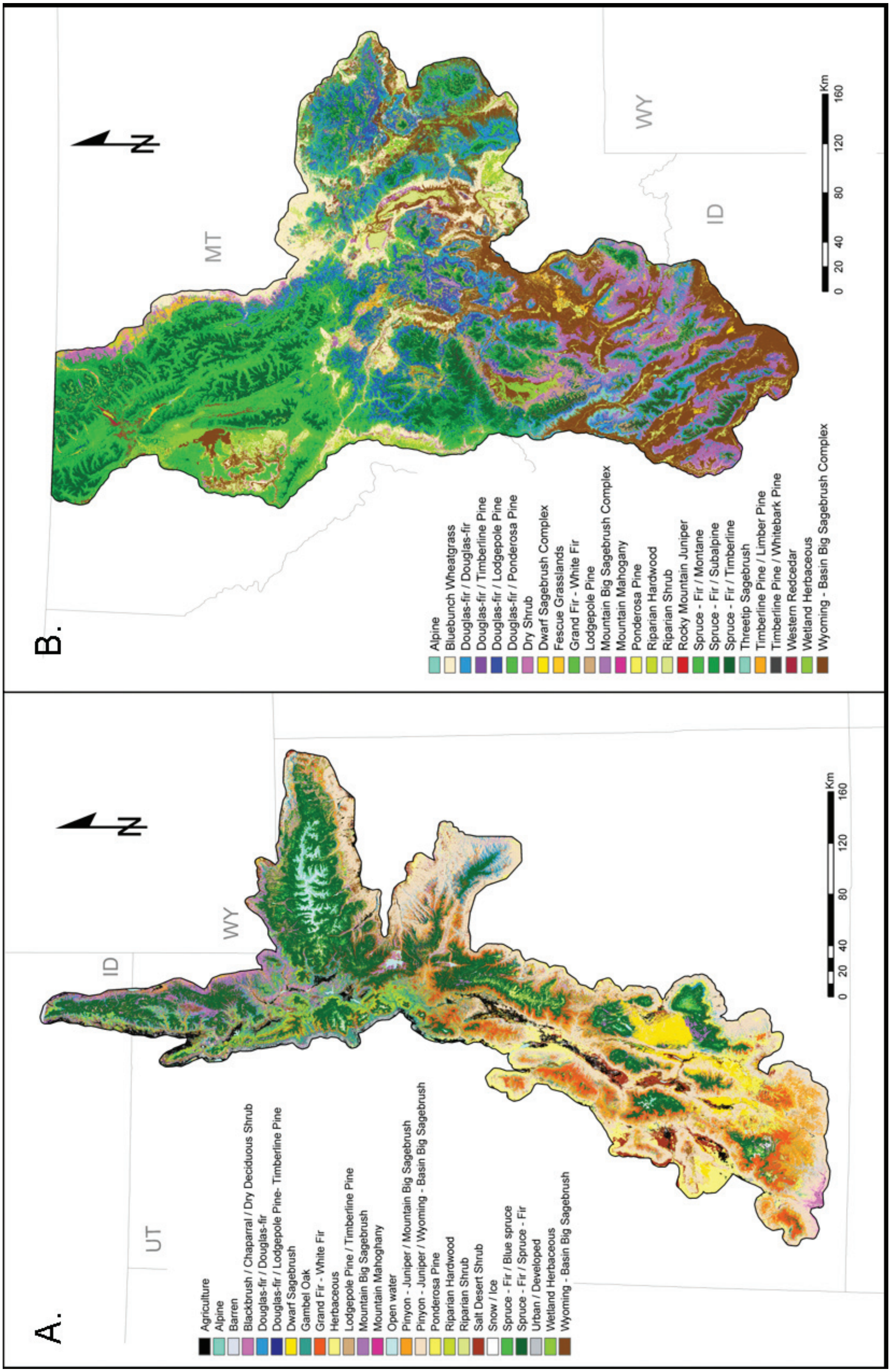

Figure 2—Final potential vegetation type (PVT) maps. A, Zone 16; B, Zone 19.

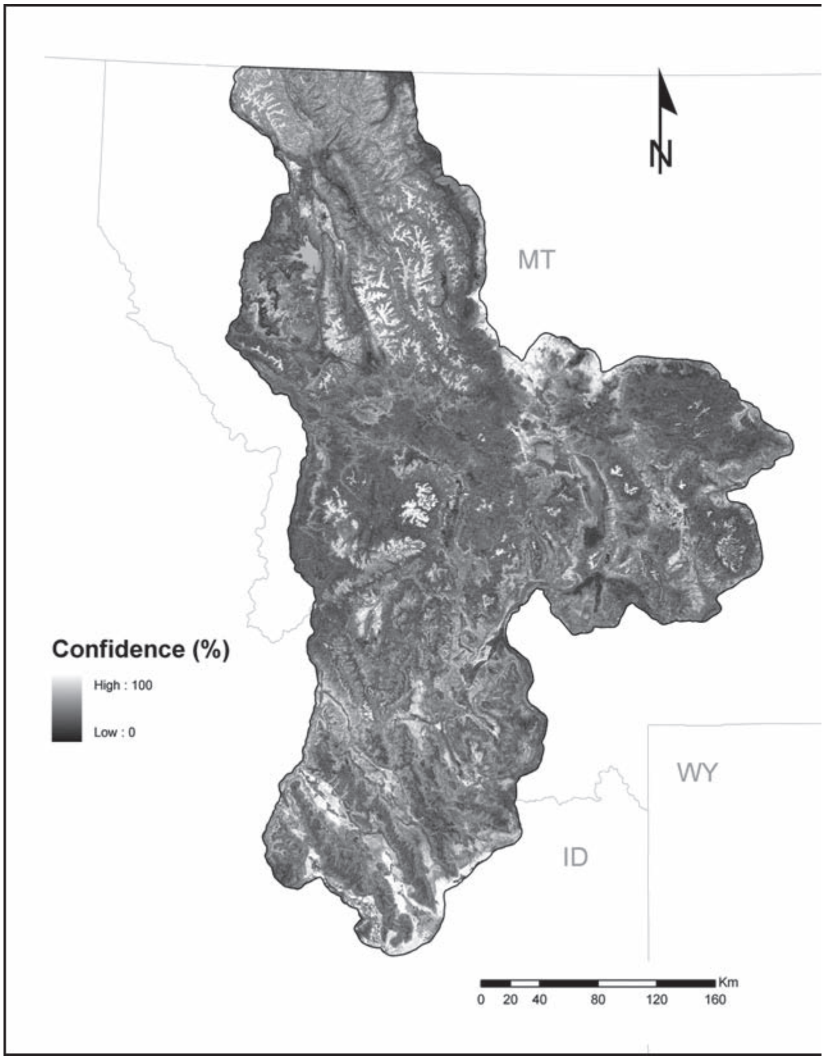

Figure 3—Potential Vegetation Type (PVT) Confidence map for Zone 19.

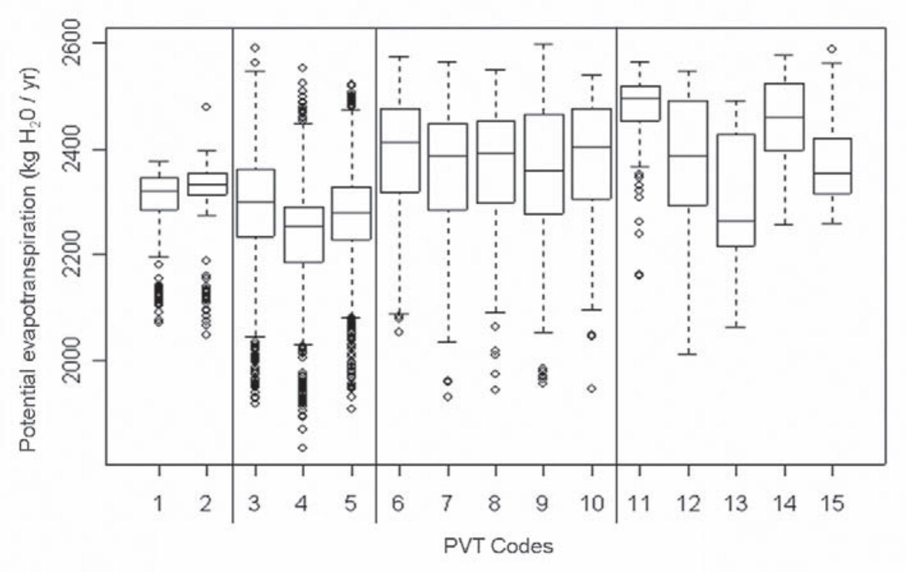

Figure 4—Boxplot distributions of potential vegetation types (PVTs) by potential evapotranspiration gradient. See table 1 for code descriptions. Codes 3 to 5 are Douglas-fir PVT variants and codes 6 to 10 are spruce – fir PVT variants.

negatively affects overall accuracy. Although accuracies may have been higher if we had grouped these PVT subgroups into single map units, we determined that the resulting loss in resolution in fire regime modeling would limit the utility of the final LANDFIRE fuel and fire regime products.

A third possible reason for overall low PVT map accuracies relates to the limited set of predictor variables used in PVT mapping. We did not include Landsat imagery in the mapping process because we did not want current land patterns influencing the final PVT maps; we relied completely on the affinity of individual PVT map units to specific distributions and combinations of biophysical variables. Further, because of technical difficulties, output from the LANDFIRE Biogeochemical Cycles model (LFBGC) (Holsinger and others, Ch. 5), which spatially represents the rates of the hydrologic, carbon, and nitrogen cycles, was not available in time to be used in the LANDFIRE Prototype Project and was therefore not included in the final mapping models. These ecophysiological gradients have proven to be highly useful in discriminating between potential vegetation types in other research (Keane and others 2001; Rollins and others 2004).

A fourth potential reason for low accuracies in the PVT maps lies in the possibility that the validation procedure we used did not represent true accuracy. The validation procedure used in the LANDFIRE Prototype Project included a cross-validation routine and a test set comparison using a randomly selected set of data withheld from classification tree building. Although, in both cases, the test sites were randomly selected from a probability sample, sampling was conducted at different intensities within different sub-populations. Therefore, more test sites are drawn from heavily sampled areas and fewer from less intensively sampled areas. Other possible sources of error include positional inaccuracies in the LANDFIRE reference database and errors imbedded in the biophysical predictor variables. It should be noted that quality control and assurance measures and methods for generating the biophysical gradient layers have been refined for national implementation (See Holsinger, Ch. 5 for details).

Recommendations for National Implementation

For mapping PVT at the national scale, we recommend employing the approach and methods described in this chapter. The efficiency and nonparametric flexibility of classification trees make them the optimal method for implementing LANDFIRE nationally, and the ease of implementation of the mapping models created using See5 software in ERDAS Imagine facilitate the broad-scale implementation of classification trees. We suggest conducting more structured quality control and assurance in the LANDFIRE reference database. In addition, we recommend detailed exploration of the relationships between response and predictors in the mapping database using correlation matrices and principle component analyses to reduce the number of gradient predictors and to remove major outliers or unusual patterns in the training data.

In addition, alternative validation sampling schemes should be considered for national implementation to ensure that the test sites are independent and representative of the population. For example, accuracy assessment sites developed solely from the systematically sampled Forest Inventory and Analysis data would ensure independent and representative test sites and therefore be a possible alternative as an equal probability sampling design. A similar procedure would be needed for shrub and herbaceous lands.

To compensate for positional errors in the training data set, we suggest employing alternative methods for calculating map accuracy when implementing LANDFIRE nationally. The agreement between each test site and its neighborhood of pixels (for example, 3 by 3) should be assessed. If the test site class matches any of the pixels, it correctly classifies the prediction. This kind of assessment is appropriate for plots in the LANDFIRE reference database that were not measured specifically for 30-meter pixel accuracy assessments.

Conclusion

In conclusion, maps of potential vegetation were valuable for supporting the broad-scale mapping of wildland fuel and also as a foundation for modeling fire regimes. The LANDFIRE process of generating biophysical gradients from topographic information and from the WXFIRE model served as an innovative framework for linking vegetation dynamics, such as post-disturbance recovery and succession, to landscape patterns represented by maps of potential vegetation. Although we found that the quality of field data for use as training data and of input spatial data layers can be limiting to the process of potential vegetation mapping, the LANDFIRE Prototype Project illustrated that the added effort involved in developing maps of potential vegetation results in higher quality data products representing fuel and fire regime characteristics.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Chapter
8

Mapping Existing Vegetation Composition and Structure for the LANDFIRE Prototype Project

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Introduction

Overview

The Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, required the mapping of existing vegetation composition (cover type) and structural stages at a 30-m spatial resolution to provide baseline vegetation data for the development of wildland fuel maps and for comparison to simulated historical vegetation reference conditions to develop indices of ecological departure. For the LANDFIRE Prototype Project, research was conducted to develop a vegetation mapping methodology that could meet the following general requirements:

- Cover types (species composition) must be characterized at a scale suitable for subsequent mapping of wildland fuel and fire regime condition class (FRCC). The vegetation map unit classification used for mapping cover types must be based on existing national systems, such as the United States National Vegetation Classification System (NVCS; Grossman and others 1998). The alliance (a community with multiple dominant species) or association (a community with a single dominant species) levels of this standard must provide a clearly defined list of map units that can be used as a basis for mapping vegetation classes that are both scaleable and representative of suitable units for modeling historical fire regimes (see Long and others, Ch. 6 for details on the LANDFIRE vegetation map units).
- The mapping of existing vegetation structure must be based on the relative composition of forest, shrub, and herbaceous canopy cover and average forest, shrub, and herbaceous canopy height. Although structural stages are discrete map units describing unique combinations of canopy cover and canopy height by life form, mapping individual canopy cover and height variables as continuous variables is desired to provide additional information for mapping and modeling vegetation and flexibility for setting threshold values.

The task of mapping existing vegetation is interconnected with several major tasks performed in the LANDFIRE Prototype Project. The mapping of existing vegetation requires attribute tables developed from the LANDFIRE reference database (LFRDB) (Caratti, Ch. 4), satellite imagery acquisition and processing, the development of a vegetation map unit classification system (see Long and others, Ch. 6), the development of a biophysical settings stratification (Frescino and Rollins, Ch. 7), and the modeling of environmental gradient layers (Holsinger and others, Ch. 5). The design and testing of the vegetation mapping methodology have substantial influences on the outcome of the overall project because accuracies of subsequent products (such as maps of wildland fuel) are a function of the accuracy of mapped vegetation types and structure. In this chapter, we discuss the design features of the existing vegetation mapping component of LANDFIRE and present

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In: Rollins, M.G.; Frame, C.K., tech. eds. 2006. The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. Gen. Tech. Rep. RMRS-GTR-175. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

results of the prototype. We conclude the chapter with recommendations for the national implementation of a consistent vegetation mapping effort.

Technical Problems

Significant technical limitations exist regarding achieving desired accuracies in the mapping of vegetation types and structure variables over broad areas. In the LANDFIRE Prototype, accuracies were affected by the spatial resolution, geographic extent, and information content defined by the project's objectives. The U.S. Geological Survey (USGS) Gap Analysis Program demonstrated the feasibility of mapping many existing vegetation cover types at the regional scale; however, methodologies have been inconsistent between regions (Eve and Merchant 1998). In addition, the mapping of forest canopy cover using imagery and regression techniques has been routinely performed for the operational mapping of vegetation structure variables (Huang and others 2001). Beyond that, however, literature reporting success stories regarding the mapping of vegetation structure using imagery is scant.

We conducted a prototype study to test a methodology for mapping vegetation cover types and structure variables. The three central objectives of the study were to:

- test an adaptable approach for mapping existing vegetation types and canopy structure at a 30-m resolution for the entire prototype area;
- develop digital maps of existing vegetation types and structural stages and conduct an accuracy assessment for the vegetation deliverables; and
- document research findings and limitations to the consistent mapping of existing vegetation composition and structure.

Specifically, this study tested a vegetation mapping protocol that met the design criteria and guidelines of the LANDFIRE Project (Keane and Rollins, Ch. 3). Further, this study investigated the limitations of using data contained within the LANDFIRE reference database (Carrati, Ch. 4) as training data and the applicability of satellite and ancillary data in meeting LANDFIRE's objectives. For vegetation modeling and wildland fuel mapping, the LANDFIRE Prototype Project required a structural stage map classified on the basis of mapped canopy cover (closed and open) and canopy height (high and low) by forest, shrub, and herbaceous life forms. We attempted to generate continuous maps of vegetation height and cover to maximize the utility of these products in a variety of applications.

As described in Rollins and others (Ch. 2), the LANDFIRE Prototype Project was conducted in two mapping zones: Zone 16, located in the central highlands of Utah and covering approximately 4 million ha of forest ecosystems (57 percent of the total land cover) and 2.5 million ha of shrub and herbaceous ecosystems (35 percent of the total land cover); and Zone 19, located in the northern Rocky Mountains of western Montana and northern Idaho and covering approximately 5.4 million ha of forest ecosystems (47 percent of the total land cover) and 5 million ha of shrub and herbaceous ecosystems (44 percent of the total land cover).

Literature Review of Vegetation Mapping

Similar to other natural science problems, the regional-scale mapping of vegetation types and structure variables carries unique technical and organizational challenges (Gemmell 1995). Spatial variations of vegetation types and structure are generally not characterized by unique spectral signatures, as captured by conventional broadband optical sensors (Kalliola and Syrjanen 1991; Keane and others 2001). Although significant improvements can be made by using specialized sensors, such as hyperspectral spectrometer or canopy lidar, data from such sensors having desired spatial resolutions are not available at national or regional scales. The associated enormous data volumes and high costs (in time and labor) make these technologies impractical for large-area applications at the present time.

Various techniques exist for modeling and estimating vegetation type and canopy structure (particularly percent forest cover); these include physics-based canopy reflectance models, empirical models linking ground-referenced data to satellite imagery, spectral mixture analysis, neural networks, and direct measurement using lidar and interferometric synthetic aperture radar. Each of these approaches has limitations in large-area applications, such as those related to cost and consistency. However, recent applications using the classification and regression tree (CART) approach (Breiman and others 1984) have been found to overcome many such limitations, provided sufficient amounts of field and geospatial data are available. Recent studies (Friedl and others 2002; Huang and Townshend 2003; Mahesh and Mather 2003; Yang and others 2003) have demonstrated the utility of CART techniques in mapping land cover, estimating species distribution, modeling percent forest canopy cover, and computing imperviousness at a 30-m grid resolution for large areas and even for the United States. Although CART techniques require relatively little human decision-making during algorithm executions, it is important to note that, ultimately, the knowledge scientists have acquired through studying vegetation patterns and attributes enhances the development mapping models to produce the most accurate results possible. Computer classifiers, regardless of their sophistication, are no substitute for scientists' understanding of the patterns, attributes, and conditions of existing vegetation and associated ecological processes.

Environmental data layers (such as elevation) are important predictor variables for characterizing vegetation patterns and attributes and for stratifying the distribution of vegetation along environmental gradient lines (Balice and others 2000). The use of spectral bands in combination with topographic data (for example, digital elevation models (DEM), slope, and aspect) is common in many land cover and vegetation mapping applications. However, topographic data capture only a part of the overall environmental factors that determine the establishment, growth, distribution, and succession of plant species and associations. The incorporation of a more complete set of environmental gradient layers into the mapping of existing vegetation should lead to increased predictive power and thematic accuracy (Keane and others 2002; Rollins and others 2004). Keane and others (2002) discuss techniques for deriving an entire set of climate, soil, and ecological gradient layers using interpolated weather observations in conjunction with topographic and soil databases and also describe the advantages of using such biophysical gradients in combination with remote sensing and field data to map vegetation, wildland fuel, and general ecosystem conditions.

In addition to the development and use of gradient variables, Keane and others (2001, 2002), Keane and Rollins, Ch. 3, and Rollins and others (2004) also suggest an approach for developing site-specific biophysical settings maps by mapping stable, late-seral communities as a function of certain climate, topographic, soil, and ecological gradients. This mapped "potential" vegetation can be used as a stratification tool in mapping actual vegetation distribution by constraining the distribution of cover types to those geographic strata where growth of the cover types' dominant species is ecologically possible.

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on maps of vegetation composition and structure, which served as important precursors to maps of wildland fuel and ecological departure in the LANDFIRE Prototype Project. Figure 1 outlines the technical approach used in LANDFIRE Prototype vegetation mapping and illustrates the data flow between several technically challenging tasks. Details of these tasks are described below.

Satellite Data Acquisition and Processing

The LANDFIRE Project partnered with the Multi-Resolution Land Characterization (MRLC) Consortium (Homer and others 2004) to facilitate the acquisition and processing of Landsat imagery. The consortium has completed the acquisition and processing of a full set of Landsat imagery for the United States with a minimum of three cloud-cover dates (circa 2001) for each pixel corresponding to phenological cycles of leaf-on, leaf-off, and spring green-up. Huang and others (2002) describe the steps involved in processing the MRLC satellite imagery, including terrain-corrected geometric registration and radiometric calibration using at-satellite reflectance models, calculations of normalized difference of vegetation index (NDVI), and tasseled cap transformations. The MRLC Consortium-sponsored development of the National Land Cover Dataset (NLCD) includes general land cover map units such as forest, agriculture, water, and urban areas mapped at a 30-m resolution (Homer and others 2004). The acquisition and processing of satellite imagery and the mapping of NLCD land cover map units were conducted for mapping zones, which were loosely delineated along major ecological regions. The LANDFIRE central Utah highlands and northern Rockies prototype areas were examples of these MRLC map zones.

The LANDFIRE Prototype Project had access to the following data layers from the MRLC catalogue for the Utah and northern Rockies prototype areas: 10 spectral bands for each of the 3 Landsat seasonal acquisitions (6 original spectral bands excluding the thermal band, 3 tasseled cap transformation bands, and 1 NDVI band) and land cover classes mapped to Anderson's Level 1 land cover classification (Anderson and others 1976). Using these data as a starting point, we mapped forest, shrub, and herbaceous cover types and structure attributes. These maps formed the foundation for mapping wildland fuel and fire regime characteristics (Holsinger and others, Ch. 11; Keane and others Ch. 12).

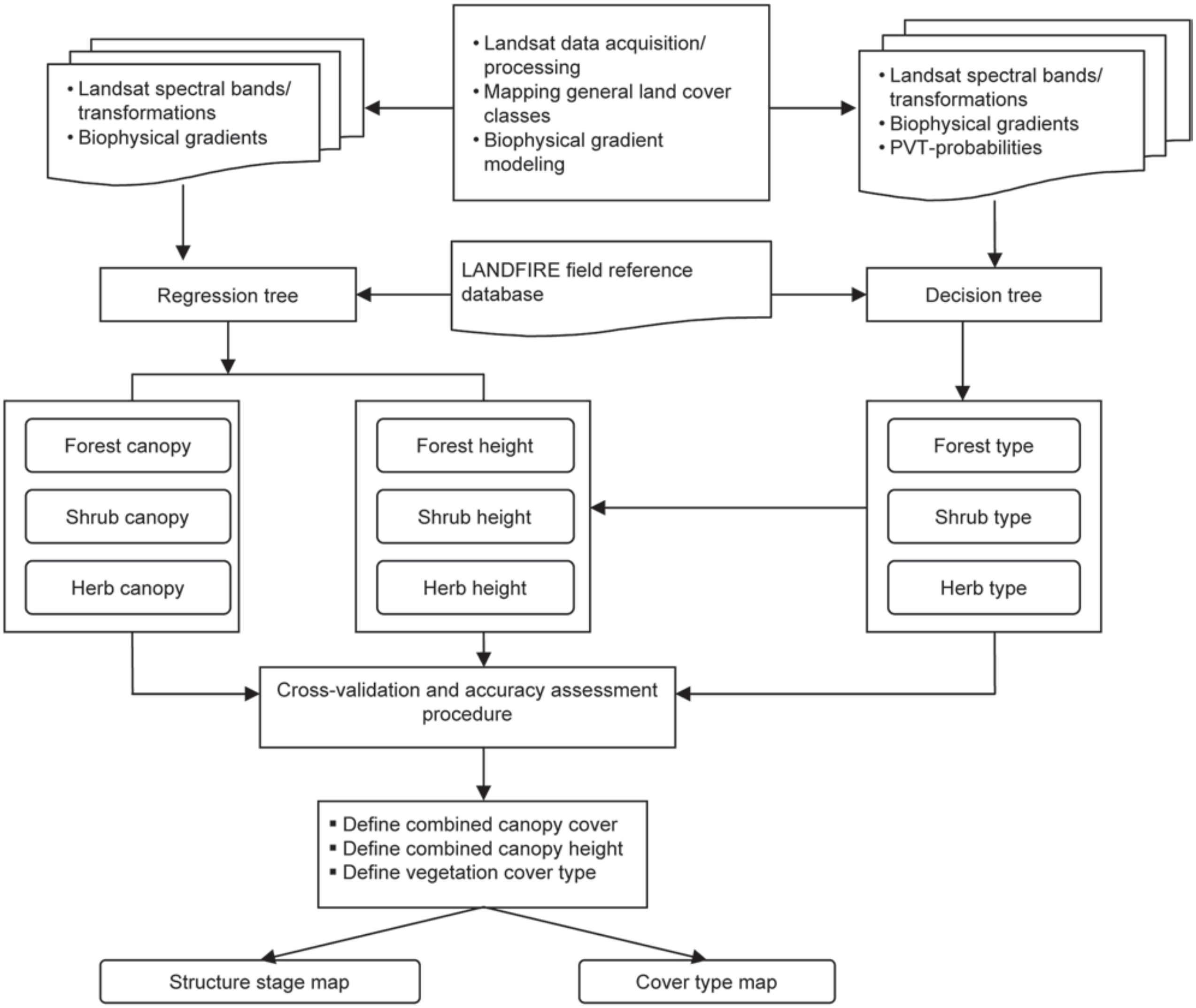


Figure 1—Flow diagram of the methodology used for mapping cover type and vegetation structure in the LANDFIRE Prototype Project.

Use of Biophysical Gradient Variables and Potential Vegetation Maps

In addition to the spectral predictor variables discussed above, the LANDFIRE existing vegetation mapping task incorporated two ancillary data sets that functioned differently in the mapping process. One was a suite of biophysical gradient layers developed as a set of intermediate LANDFIRE products with input from weather, topographic, and soil databases (Holsinger and others, Ch. 5: table 6). Table 1 lists the biophysical gradient variables used in the prototype for mapping existing vegetation; these represent a winnowed set of the entire suite of variables produced for the LANDFIRE Prototype. Biophysical gradients were used in the mapping process to provide a geographic context for the ecological processes that control establishment, growth, and distribution of vegetation communities.

The second data set was a potential vegetation type (PVT) map with attributes describing the probability of specific cover types existing in each PVT. This database was derived by calculating the distribution of cover types within individual PVTs by intersecting the plots contained in the LFRDB with the PVT map (Keane and Rollins, Ch. 3; Frescino and Rollins, Ch. 7). Conceptually, by using the PVT and cover type probability

Table 1—Biophysical and topographic layers used in the LANDFIRE vegetation mapping process.

Symbol	Description	Unit	Source data
SRAD	Daily solar radiation flux	$KW/m^2/Day$	Weather and topographic data
Tmin	Daily minimum temperature	C°	Weather and topographic data
Tmax	Daily maximum temperature	C°	Weather and topographic data
Tnight	Daily average nighttime temperature	C°	Weather and topographic data
Dday	Degree days	C°	Weather and topographic data
PPT	Daily precipitation	cm	Weather and topographic data
RH	Relative humidity	%	Weather and topographic data
PET	Potential evapotranspiration	kgH_2O/yr	Weather and topographic data
AET	Actual evapotranspiration	kgH_2O/yr	Weather, topographic, and soil data
GSWS	Growing season water stress	-Mpa	Weather, topographic, and soil data
PSI	Soil water potential	-Mpa	Weather, topographic, and soil data
KDBI	Keetch-Byram drought index	Index	Weather database
SWF	Soil water fraction	%	Weather, topographic, and soil data
Sdepth	Soil depth to bedrock	cm	Soil and topographic data
LAI	Potential leaf area index	Index	Landsat spectral data
DEM	Digital elevation model	m	National Elevation Database
Slope	Slope	%	National Elevation Database
Aspect	Aspect	Azimuth	National Elevation Database
POSIDX	Topographic position index	Index	National Elevation Database

information in the mapping of vegetation cover types, we implemented a stratification that constrained cover types to the geographic areas where cover types were ecologically possible. Sites (pixels) where certain cover types were not likely to occur would have low probabilities; therefore, these cover types were less likely to be predicted for these pixels. Each cover type was associated with a probability distribution map. The probability layers were implemented in the mapping process much in the same way as the biophysical gradient layers and satellite imagery.

Vegetation Map Unit Classification

Two different approaches were used in the development of the vegetation map unit classification systems for the prototype mapping zones. For the central Utah mapping zone, we formulated the map unit classificaton based on an overall understanding of the presence of vegetation alliances and associations (Long and others, Ch. 6). For the northern Rocky Mountains prototype area, we examined and summarized the LFRDB to form the basis for the vegetation map unit classification. Brohman and Bryant (2005) have described these approaches as the "top-down" and the "bottom-up" approaches, respectively. Long and others (Ch. 6) discuss the criteria and factors used in developing the LANDFIRE vegetation map unit classification systems, the lessons learned in applying them, and recommendations for a national approach to vegetation map unit development.

We were concerned with two technical issues when evaluating the map unit classifications of existing cover types for the prototype: 1) whether each cover type was sufficiently represented by an adequate number of field-referenced data from the LFRDB and, if not, how such "rare map units" should be treated and 2) whether some cover types (such as the Juniper cover type versus the Pinyon – Juniper cover type) would be floristically or ecologically difficult to separate in spectral, biophysical, and geographical domains. The technical issues were considered in the context of four guidelines defined at the beginning of the LANDFIRE Prototype Project: a map unit, whether it is a cover type or a fuel model, must be identifiable, scalable, mappable, and modelable (Keane and Rollins, Ch. 3). Because the prototype study areas were the first mapping zones to be mapped under the LANDFIRE design criteria and guidelines, we were unsure whether the map unit classification systems could perform consistently across different geographic areas.

Reference Data

Caratti (Ch. 4) describes in detail the compilation of the LFRDB for the prototype. The compilation of the LANDFIRE reference database relied on the coordination of three separate and independent efforts: 1) the cooperation and support from the U.S. Forest Service (USFS) Forest Inventory and Analysis (FIA) database collected nationwide on permanent inventory plots (Smith 2002); 2) the collection and processing of existing field data from all land management units such as Bureau of Land Management districts or national parks; and 3) the acquisition of new, supplementary field data from areas where there were no or not enough existing data (for example, various western rangelands in the United States do not currently have adequate field data collection programs).

Because the LFRDB was compiled from various sources collected for different purposes, information gleaned from the LFRDB was highly variable in terms of sampling design. The FIA data represented the most consistent information for forest cover types and canopy height. Rangeland field data usually contained cover type labels, but structure information was rare. In addition, reference data for mapping forest canopy cover were generated by calculating the number of forest cells within a 30-m cell using either high-resolution satellite data (spatial resolution of 1-m or better) or digital orthophotographs (Homer and others 2004).

Quality-control procedures were conducted as a part of the existing vegetation mapping process to detect problems and errors inherent in field-referenced data derived from disparate sources. We assumed that these procedures would identify most existing data problems but would not identify and eliminate all problems. These procedures were as follows:

Detecting outdated field data—Many field plots measured in years past were considered useful if the dominant species had not changed. A substantial number of plots, however, had undergone major disturbances such as fire or logging. We therefore computed the differences between the 1992 and 2001 Landsat NDVI values to flag field plots with conditions that had potentially changed during that 10-year period.

Detecting field data with erroneous geographic coordinates—We identified major geo-coding problems such as coordinates located on roads or located out of mapping areas. We visually examined plot locations overlaid with road networks and general land cover maps (such as NLCD maps).

Detecting field data with major coding errors—We detected such problems by overlaying field data on raw satellite imagery and by sorting variables according to major cover types. For example, if a field plot coded as *sagebrush* was located in the center of an otherwise intact *forest* polygon, or if a shrub plot had a height value taller than that of forest plots, such plots were flagged.

Reducing spatially clumped field plots—The LFRDB contains field data that come from different sources and are collected with different objectives, which occasionally results in spatially clumped plot information. In order to produce a spatially well-distributed and balanced data sample, we sub-sampled clumps of the available data to result in a more even distribution of field data.

The use of these quality-control procedures resulted in the exclusion of a number of available field plots from either the mapping or validation processes. This led to a total of 6,177 field plots (1,809 FIA forest plots and 4,368 non-FIA forest and rangeland plots) for Zone 16 and 7,735 field plots (1,993 FIA forest plots and 5,742 non-FIA forest and rangeland plots) for Zone 19 to be used for subsequent training or accuracy assessment. These numbers differ slightly from other applications of the LFRDB in LANDFRIE mapping because, based on objectives, each mapping effort implemented its own quality control procedure. Although all of the plots contained LANDFIRE cover type labels, only subsets of plots from the LFRDB had attributes of canopy height and canopy cover (table 2). In addition, ten percent of the field data points available for each of the cover type and structure mapping tasks were withheld from the mapping process for the purpose of accuracy assessment (Vogelmann and others, Ch. 13).

Mapping Algorithms

Classification and regression tree algorithms have demonstrated robust and consistent performance and advantages in integrating field data with geospatial data layers (Brown de Colstoun and others 2003; Friedl and Brodley 1997; Hansen and others 2000; Joy and others 2003; Moisen and others 2003, Moore and others 1991; Rollins and others 2004). Nonparametric CART approaches recursively divide feature space into many subsets in a hierarchical fashion to achieve the best overall model performance (lowest error and highest R^2, derived using a cross-validation technique). For this study, we adopted the classification tree algorithm to map vegetation types as discrete map units and the regression tree algorithm to map canopy cover and canopy height as continuous variables using two related

Table 2—Numbers of field reference plots in each mapping zone used in either mapping or accuracy assessment and corresponding to various map products. Forest canopy cover mapping relied on imagery of high spatial resolution instead of field reference plots.

	Mapping zone	Number of cover types	Cover type plots	Canopy cover plots	Canopy height plots
Forest	16	10	1,809	N/A	1,809
	19	14	1,993	N/A	1993
Shrub	16	14	1,595	2,120	1,698
	19	15	1,788	1,788	989
Herbaceous	16	7	300	2,263	1,311
	19	8	597	597	282

commercial applications: See5 (classification trees) and Cubist (regression trees) developed by Quinlan (1993). The mapping models were trained on the compiled data set of spectral bands and biophysical ancillary variables listed in table 1 and cover type and structure variables from the LFRDB.

Vegetation Database Development

Training vegetation mapping models—The creation of the CART-based algorithms for mapping existing vegetation involved several steps: 1) exploration of general data such as correlation analyses and plotting of cover types from the LFRDB against predictor layers, 2) iterations of CART algorithm runs to determine the adequacy of training data and other biophysical layers, 3) visual evaluation of classification and regression trees and final output maps, 4) generation of cross-validation statistics as an initial indicator of map accuracies, and 5) development of vegetation maps by applying the final mapping models. As mentioned above, we withheld data from 10 percent of available field reference plots for accuracy assessment and used the rest of the field plots for training the CART algorithms. We ran classification tree or regression tree classifiers, depending on whether the mapped theme was categorical or continuous, and generated 10-fold cross-validation statistics. Results of the cross-validation were used to determine the quality of training data and the performance of the predictor layers, but not to assess the final accuracy of resulting maps.

Determination of rare and similar map units—Although the LANDFIRE Prototype Project vegetation map unit classifications were developed to meet specific design criteria and guidelines (Keane and Rollins, Ch. 3; Long and others, Ch. 6), two technical questions arose during the mapping of existing vegetation: how to treat 1) rare cover types and 2) spectrally and biophysically similar cover types. We considered a cover type to be rare if it was supported with fewer than 30 reference plots, and those plots were not concentrated in one general location. We retained a rare map unit in the overall mapping process if the resulting spatial pattern made sense (such as when a riparian cover type followed river patterns) and if retaining the map unit did not result in a significant drop in accuracy. Otherwise, the rare map unit would be omitted. Additionally, we decided, based on differences in historical disturbance regimes, to keep cover types that were biophysically and spectrally similar (such as Pinyon – Juniper) separate, even though merging the cover types would significantly improve overall map accuracy.

Stratifications by life form—During the mapping of these vegetation attributes, the question arose as to whether the cover types and structural stages should be constrained by their respective forest, shrub, and herbaceous life forms; that is, we questioned whether a given pixel could be assigned more than one life form for cover type, height, and canopy designations. Multiple life form assignments provided flexibility for the characterization of wildland fuel. Such flexibility would also benefit other potential applications of LANDFIRE data, such as insect and disease or biomass studies. In the process of LANDFIRE vegetation mapping, we therefore modeled each pixel independently for each of the three life forms (forest, shrub, and herbaceous; fig. 1).

Product Validation Plan and Accuracy Assessment

The LANDFIRE accuracy assessment is described in detail in Vogelmann and others (Ch. 13). We tested the approach in which ten percent of the field data points available for cover type mapping were withheld from the mapping process for the purpose of accuracy assessment but found that the approach did not work well because of the uneven availability of field data in support of different cover types in the map unit classification. For several cover types in each of the mapping zones, the amount of data withheld in the 10 percent sample was too low to be statistically meaningful. As the result, we reported overall accuracies for cover types using the results of 10-fold cross-validations. For structure variables, we used a set of independent plots to assess statistical accuracy using regression techniques. This afforded us the opportunity to examine the behaviors of mapping structure variables versus those of categorical variables. Forest canopy cover, mapped with fine-resolution imagery as training data, would be assessed with both a sample of withheld reference points generated from the fine-resolution imagery as well as field estimates obtained from the use of digital cameras equipped with fisheye lenses.

Results

Maps of Cover Type and Structural Stage

We applied the vegetation mapping approach described above to the central Utah and northern Rockies prototype areas. Spectral imagery, biophysical gradients, PVTs, and probabilities were used together with field plot data to produce maps of forest, shrub, and herbaceous cover types, as well as canopy cover and canopy height by life form.

Accuracy of LANDFIRE Prototype Vegetation Mapping

We reported accuracy assessments using a cross-validation approach for cover types by life form (table 3) and by withholding field data for the structure variables by life form (table 4). For cover types, only overall accuracies were reported. For structural stages, R^2 values were variable and ranged from relatively consistent (for forest canopy cover and height) to relatively inconsistent (for shrub and herbaceous canopy cover and height). This variability indicates that forest structure may be mapped reasonably as a continuous variable, whereas consistency and accuracy would be questionable when mapping shrub and herbaceous structure as continuous variables. However, when evaluated as two-class variables (either as closed and open canopy cover or high and low canopy height), results showed that the same shrub and herbaceous structure can perform as consistently and accurately as categorical variables.

Discussion

Analysis of Mapping Consistency for Vegetation Types and Structure

In general, we found that the approach described above for mapping existing vegetation characteristics effectively met LANDFIRE requirements, which was a difficult objective to achieve due to the large number of vegetation map units, reliance on existing field-referenced data, the task of characterizing vegetation structure, and the requirement for a nationally consistent methodology. For the moderately detailed vegetation map unit classification, mapping accuracies of 60 percent or better were achieved at a 30-m spatial resolution.

We explored the mapping of more than two map units for structure variables. For example, we mapped herbaceous height to three map units (0 to 0.5 m, >0.5 to 1 m, and >1 m), shrub height to four map units (0 to 0.5 m, >0.5 to 1 m, >1 to 3 m, and >3 m), and forest height to four map units (0 to 5 m, >5 to 10 m, >10 to 25 m, and >25 m). The tests yielded independent overall accuracies of 73, 61, and 82 percent for herbaceous, shrub, and forest height, respectively. From these results, we concluded that grouping continuous values of the structure variables into several discrete map units would be an acceptable and rational alternative methodology for national implementation of the LANDFIRE methods. Use of this alternative methodology would require the development of a consistent national structural stage map unit classification.

Table 3—Cross validations (10 percent withheld, ten-fold repetitions) conducted separately by mapping zones and by forest, shrub, and herbaceous life forms.

Life form	Mapping zone	Number of classes	Cross validation
Forest	16	10	67
	19	14	64
Shrub	16	14	62
	19	15	68
Herbaceous	16	7	60
	19	8	56

Table 4—Accuracy assessments conducted separately for two structure variables by life forms and map zones. Overall accuracy (OA) was obtained by using holdout withheld field plots (n) that were set aside based on quality and distribution of the total available field plot data (N). Structure variables are treated as both continuous variables measured with the R2 statistic and two-class categorical variables for overall accuracy (OA). The Ttwo canopy cover classes of canopy cover are closed (≥40%) and open (<40%); for canopy height they classes are high (≥10m, 1m, 0.24m) and low (<10m, 1m, 0.24m) for forest, shrub, and herbaceous life forms, respectively.

	Map	Canopy cover			Canopy height		
Life form	zone	n/N	R^2	Overall accuracy	n/N	R^2	Overall accuracy
Forest	16	1,272/20,000	0.78	0.92	220/2204	0.58	0.88
	19	1,200/20,000	0.88	0.89	127/5,541	0.56	0.78
Shrub	16	125/1,253	0.41	0.74	107/1,073	0.36	0.85
	19	119/1,788	0.59	0.79	81/989	0.65	0.86
Herbaceous	16	18/182	0.37	0.71	15/280	0.04	0.86
	19	126/597	0.58	0.69	75/182	0.63	0.70

Consistency in field sampling and data collection affects the consistency of mapping vegetation characteristics. Of the three types of reference data used in mapping existing vegetation, cover type and canopy height values can generally be identified or measured consistently in the field. Canopy cover, on the other hand, can be difficult to measure in the field. This issue does not affect the measurement of forest canopy cover values because training data are derived from high-resolution (1 m or better) imagery by calculating numbers of high-resolution forest pixels within each 30-m Landsat pixel. The use of inconsistently estimated canopy cover values as training data, however, can potentially affect the mapping of shrub and herbaceous canopy percent cover (as happened during the prototype). Shrub and herbaceous canopy results from the two prototype mapping zones were reasonable (table 3), but difficulties in consistently estimating canopy cover in the field indicated that we needed to further research new or alternative methods for mapping shrub and herbaceous canopy cover.

The results of this study may be attributed, in part, to the use of ecologically significant ancillary data layers, which accounts for a moderate but nonetheless significant increase in accuracy (ranging from 1 to 9 percent). The development of biophysical gradient layers and PVT probabilities follows a standardized process for all mapping zones. However, for any given area, satellite reflectance can vary significantly for the same cover type with different canopy cover percentages (either due to land management practices or regeneration stages) or appear similar for different vegetation types or different structural stages during certain seasonal periods. Different cover types or structural stages, however, should respond consistently to the effects of biophysical gradient variables such as soil depth or potential evapotranspiration (PET); this addition of information from the biophysical gradient variables increases the likelihood that these map units will be discriminated by mapping algorithms. For example, one might expect Engelmann spruce (*picea engelmannii*) to grow in relatively deep soil on cool, north-facing sites with low PET, regardless of whether it is found in Zone 16 or Zone 19. Therefore, the incorporation of biophysical and PVT data in the mapping process should contribute to enhanced consistency and thematic accuracy in mapped existing vegetation across the United States.

Even though the existing vegetation maps shown in figures 2 and 3 characterize the vegetation composition of all life forms, it should be noted that each life form was mapped independently, by design, for cover type and structure. Modeling life forms independently preserves the possibility of more than one mapped life form per pixel (in other words, allows for probabilities of multiple canopy layers within a pixel) to improve fuel mapping and enhance the range of the data's ecological applications. However, mapping approaches should be carefully considered when comparing or merging these separate data sets. For example, a final map of cover types may look different depending on the order of precedence between forest, shrub, and herbaceous cover and the threshold values used in defining the life forms (for example, a pixel with 10 percent or greater forest canopy cover may be considered as forested land). It is important that precedence and thresholds be applied uniformly between mapping zones for consistency.

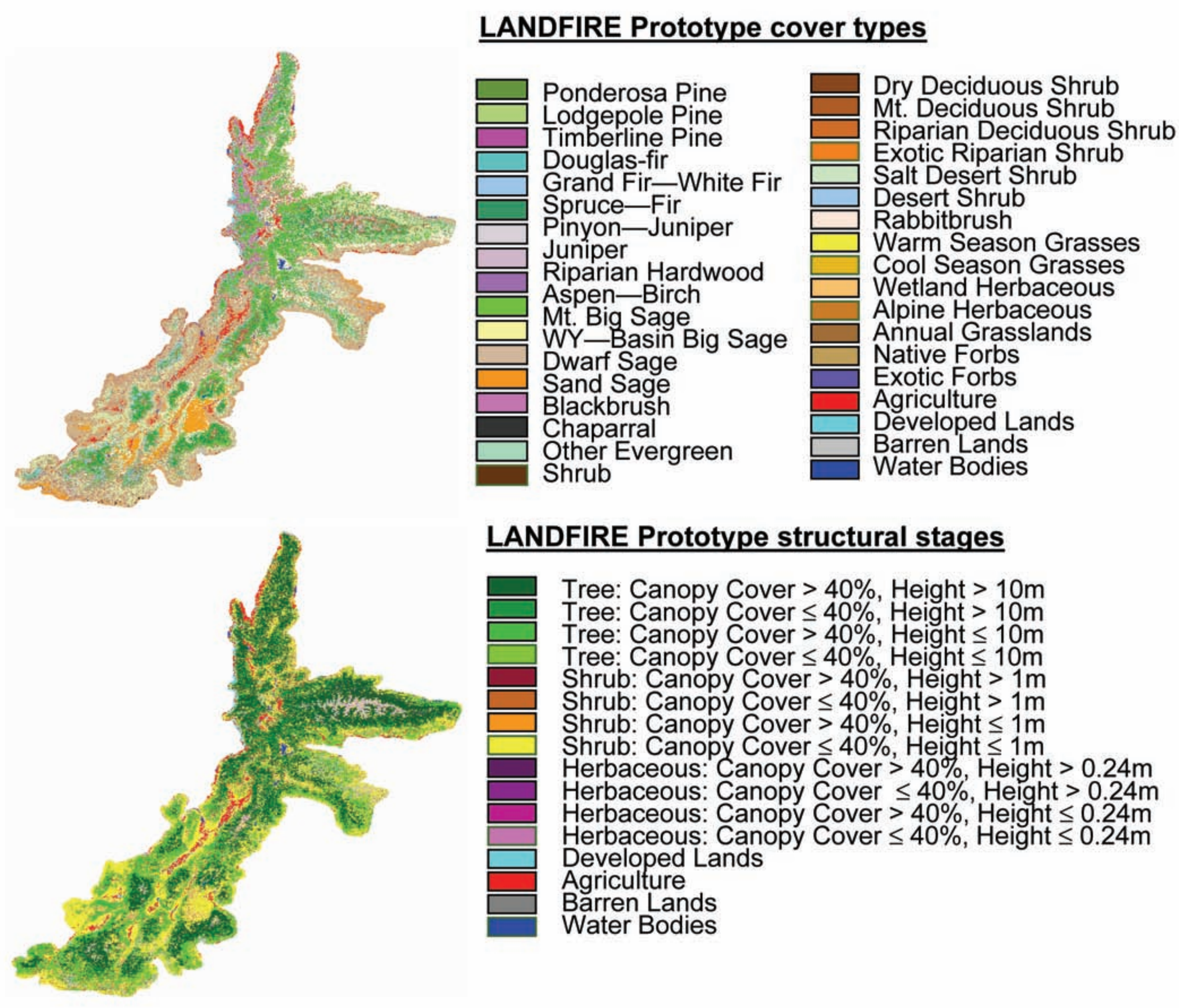


Figure 2—LANDFIRE Prototype cover type (top) and structural stage (bottom) maps for Zone 16. The cover type map is compiled from separate forest, shrub, and herbaceous cover type maps, whereas the structural stage map is grouped from continuous maps of height and cover for display purposes.

Factors that Affect Mapping Accuracies

Several factors should be considered when examining the accuracy estimates for maps of cover types and structure. First, the mapping and accuracy assessment of cover type and structure variables by life form were conducted based on field-referenced databases of different sizes and data collected throughout the study areas using a variety of sampling strategies. As would be expected, vegetation mapping was sensitive to the availability of field data. Test results showed that the number of field-referenced plots used for mapping and accuracy assessment affected not only the level but also the consistency of mapping accuracies, with fewer plots related to greater variability in accuracy estimates and more plots to more robust accuracy estimates (fig. 4). Data for herbaceous vegetation were limited in availability relative to the overall size of the field-referenced data set and hence affected herbaceous mapping accuracy. To improve uncertainties related to shrub and herbaceous cover and height, we determined that these variables should be mapped as categorical map units.

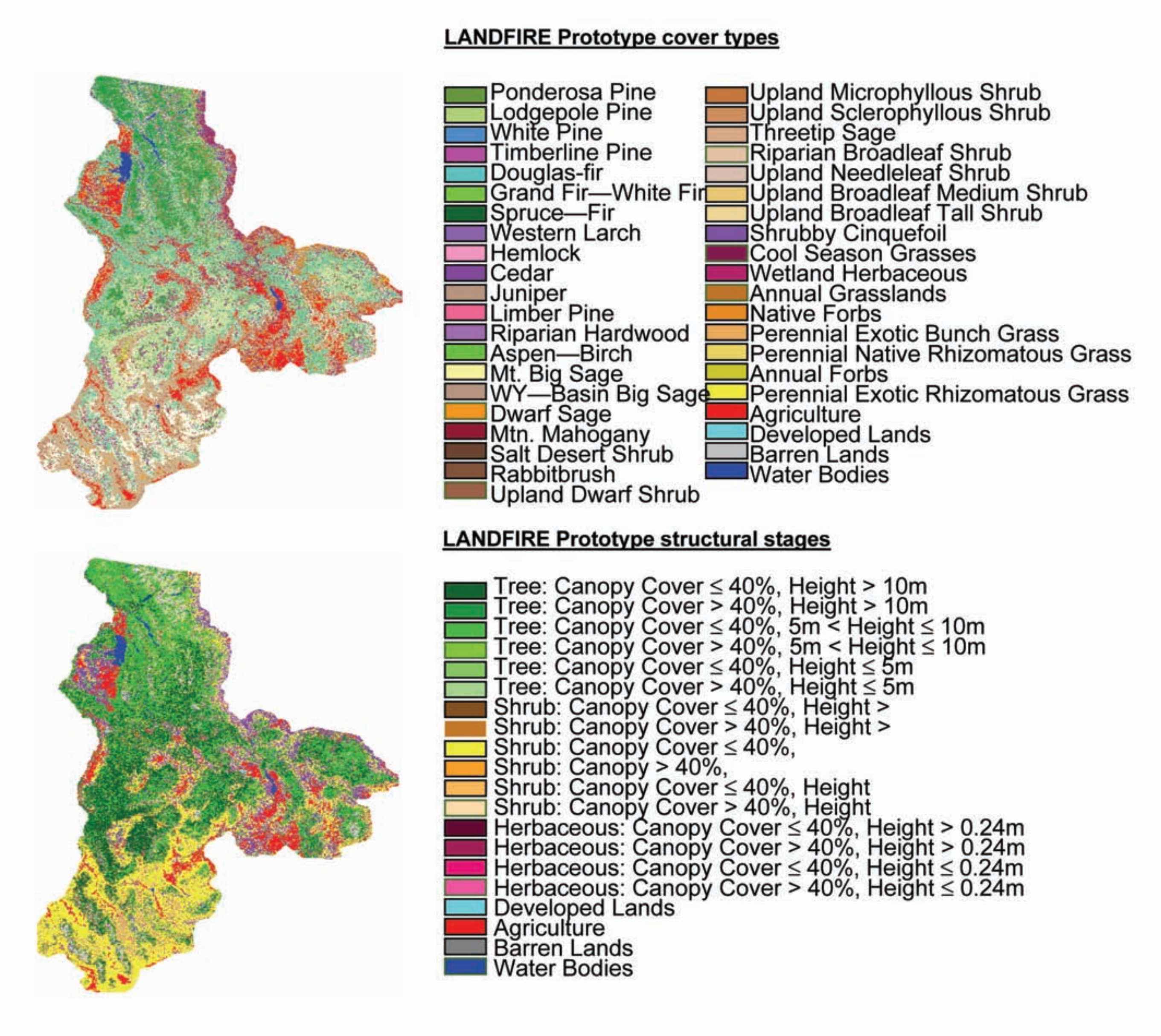


Figure 3—LANDFIRE Prototype cover type (top) and structural stage (bottom) maps for Zone 19. The cover type map is compiled from separate forest, shrub, and herbaceous cover type maps, whereas the structural stage map is grouped from continuous maps of height and cover for display purposes.

Second, field-referenced data, with which mapping models were trained and accuracy assessed, were collected from different sources, for different objectives, and with different techniques. Even though these plot data were quality-screened and standardized through an extensive effort (Caratti and others, Ch. 4), it was inevitable that the differences and errors in field data carried over into map quality and accuracy assessment. For example, certain reference data for forest canopy cover were derived using digital ortho-photographs, viewing forest cover synoptically from above the canopy. On the other hand, field estimates for shrub and herbaceous canopy cover were made using visual estimation from close-range, oblique positions that limited objectivity and consistency. We did not experience these problems when determining forest, shrub, and herbaceous *height*, which was usually directly measured and had a high degree of user-confidence.

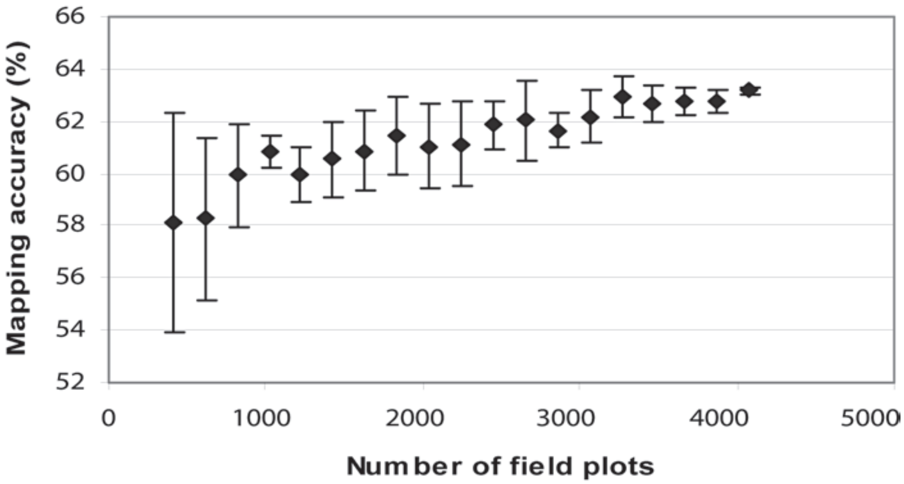


Figure 4—Cross-validation accuracy estimates obtained for the mapping of forest cover types as a function of the number of forest field plots. More plots contributed to better accuracy and consistency (smaller standard deviation) to a certain point, after which the relationship became flat.

Third, as discussed above, rare map units and ecologically and biophysically similar map units affected mapping accuracies. For example, if the Juniper cover type was merged with the combined Pinyon – Juniper cover type, forest cover type accuracy increased by more than 10 percent. The rationale for keeping such similar cover types separate is that, even though they occupy similar ecological niches and have similar site characteristics, separating them increases the utility of the LANDFIRE wildland fuel and fire regime products.

Utility of Biophysical Gradient Data for Vegetation Mapping

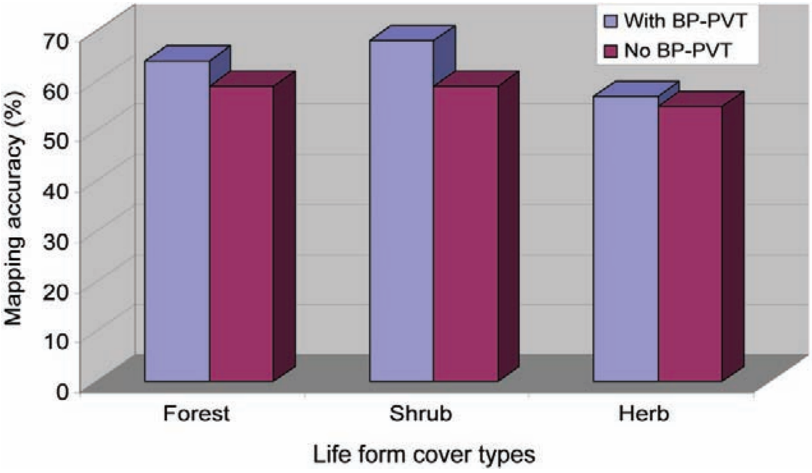
Although the use of DEM data for improving mapping results has been widely documented, the effects of a whole host of biophysical gradient layers and PVT-probability data layers is largely untested at the scale and scope of this study. These data layers provide information that supplements satellite imagery. Plant distribution patterns and conditions are strongly linked to a multitude of environmental factors (for example, temperature, soil, weather patterns, day length, soil properties, and rainfall), and the accurate characterization of these variables should, at least in theory, improve mapping results. In addition, spatial information that indicates where particular vegetation types can and cannot exist across a wide region (that is, PVT-probability data layers) should be similarly useful. Figure 5 compares cross-validation results using mapping models with and without the additional biophysical gradients listed in table 1 and using PVT-probabilities as predictor variables. Figure 6 displays mean and standard deviation values of a subset of the biophysical variables intersected with vegetation cover types from field plot data collected in the central Utah prototype area. These figures show that the incorporation of certain biophysical gradients and PVT-probabilities in mapping models contributes to increased mapping accuracy and consistency. These results are consistent with the findings of Keane and others (2002) and Rollins and others (2004).

Vegetation Patterns in Areas of Major Disturbances

Wildfires, insect and disease outbreaks, and forest clear cuts are some of the major disturbances to ecosystems captured by the satellite sensor in terms of their spectral properties. How well did our mapping capture and reflect these changes in vegetation conditions? We evaluated our mapping methods' effectiveness in this regard by looking at known areas of wildland fire, bark beetle infestation, and clear-cuts in the prototype mapping zones.

We evaluated two wildland fires areas that burned in Bryce (summer 2001) and Zion (fall 2001) national parks to determine what differences might exist between pre-fire and post-fire vegetation maps when mapped with the same pre-fire models. Pre- and post-fire map comparisons showed distinct differences between both

Figure 5—Cross-validation accuracy estimates obtained in the Zone 16 prototype area, by life form, with and without the 15 biophysical gradients and PVT-probabilities in the mapping models. An average of 8 percent increase in cross-validation accuracy was obtained by incorporating the selected biophysical gradients and PVT-probabilities that together describe the habitats of the cover types to be mapped.



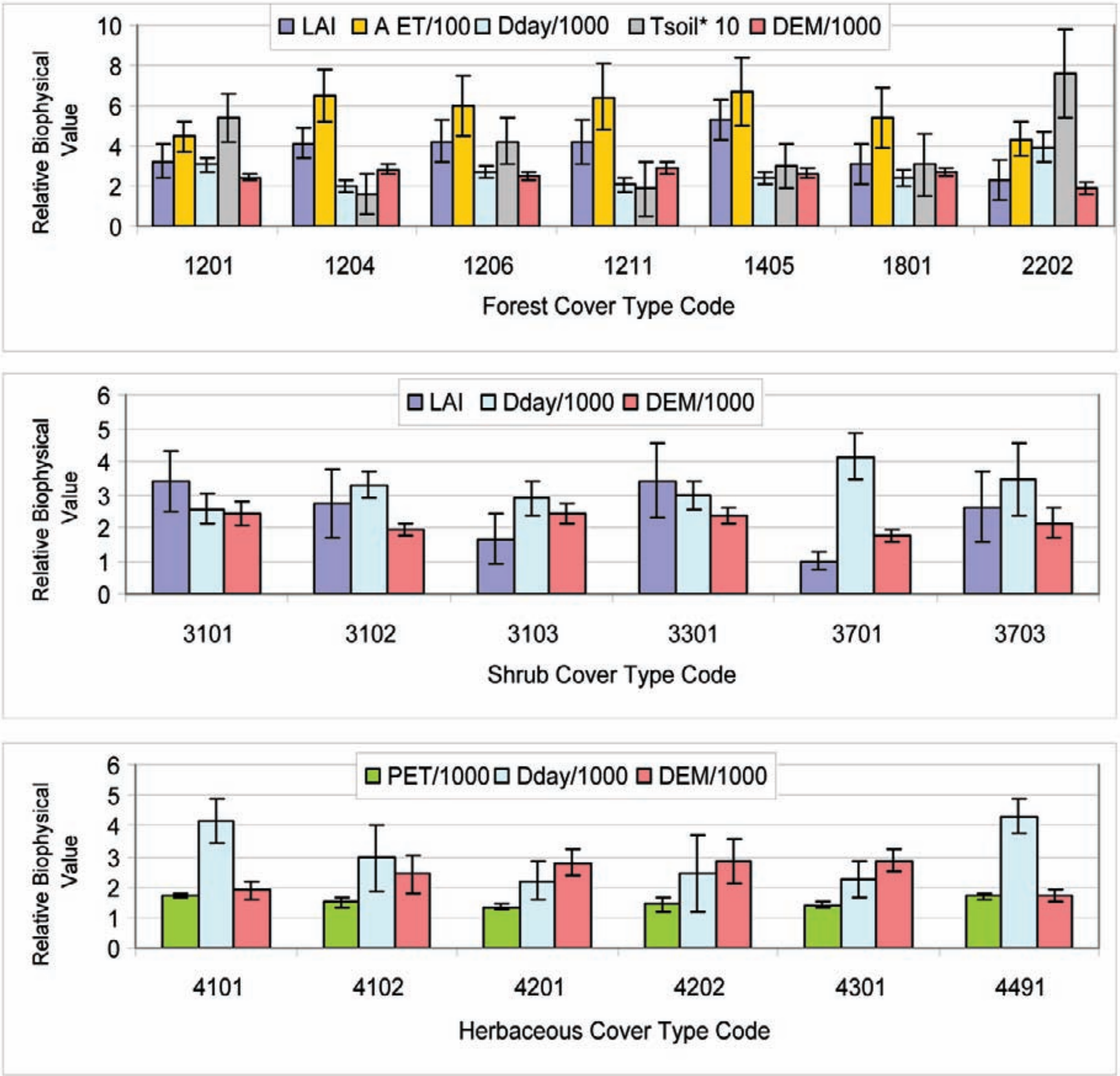


Figure 6—Mean and standard deviation values of selected biophysical variables found effective in mapping cover type against various forest (top), shrub (middle), and herbaceous (bottom) cover types of field-reference data. Most of the biophysical variables were divided or multiplied by a constant for display purposes. Refer to table 1 for definitions and descriptions of the biophysical variables. Refer to Long and others, Ch. 6 appendix 6-A for vegetation cover type coding protocol.

vegetation cover types and structural stages. The Bryce fire, a prescribed fire, showed general shifts from forest to shrub map units and, regarding structure, showed a shift toward increased low-height shrubs. The Zion fire, a wildfire, revealed a shift from predominately deciduous forest types to low shrubs.

Using bark beetle survey data obtained from the Dixie National Forest, we conducted simple zonal statistical analyses. Results indicated that the mapped species composition corresponded fairly well to that of those species identified in the survey data for the years 1998-2000. (Note that the level of actual disturbance varied within the survey data and was not differentiated in this study.) Structure information was not available in the survey data, but mapped structure data indicated that most bark beetle infestations occurred in areas identified as high forest cover (greater than 40 percent canopy cover) and height (greater than 10 m), indicating old-growth forest.

Similarly, we compared clear-cut areas, identified using modeling and masking methods, with mapped vegetation cover type and structure variables. Shrubs and a high percentage of grasses were dominant in clear-cut areas. Structural stages indicated a trend from forests with high canopy cover and canopy height to a high percentage of low cover (less than 40 percent), low height (less than 1 m) shrubs. Herbaceous cover was identified as being high cover (greater than 40 percent) with mixed heights.

Field Data Quality and Quantity Requirements

The acquisition of field-referenced data posed a significant challenge to the LANDFIRE Prototype effort, both logistically and technically. Caratti (Ch. 4) describes the logistical efforts and complications associated with conducting a national field data campaign. Specifically, technical challenges encountered during the mapping process, such as uneven amounts and disparate quality of field data used to meet various vegetation mapping objectives, were tied to the fact that the LFRDB was based on data from varying sources and collected with different objectives. As discussed above, such issues necessitated the careful implementation of a quality-control and quality-assurance (QA/QC) process prior to the training of the mapping algorithms for existing vegetation types and structure. “Lessons learned” from the QA/QC process follow:

- Accuracy and consistency are a function of the amount of available field-referenced data. Greater amounts of field-referenced data contribute to enhanced confidence in mapping accuracy (fig. 4), whereas limited field-referenced data are correlated to reduced confidence in mapping accuracies of affected cover types.
- The use of data from different sources requires that special attention be given to those cover type map units that are not supported with sufficient numbers of field plots. Both prototype mapping zones had map units with only a few field reference data points for training. As discussed above, the question of how to define and treat rare map units arose during the prototype, and we defined rare map units as those having less than 30 field reference plots scattered spatially within a mapping zone. Options for the treatment of these rare map units included keeping the map units in maps, omitting them, or omitting them and then “burning” the few field plots to the map in a post-process and merging them with floristically similar cover types. For the prototype, we chose to retain the rare map units in the models and resulting map products to inform the development of the LANDFIRE vegetation map unit classification system. For national implementation, rare map units that cannot be supported with a sufficient number of field plots will not attain target-level accuracies. We recommend omitting such map units from the mapping of existing vegetation cover types.
- Spatial distribution and a valid probability-based sampling design increase the consistency and accuracy of the map products. Compared with field-referenced data from various agency sources, the use of FIA forest inventory plots for mapping forest cover types and structure produced more consistent and accurate mapping results because the sampling design for FIA data produced training data that were spatially well-distributed across the landscape. Further, FIA data required very little additional processing time and were easy to use; in contrast, non-FIA field data required extensive processing time, related to QA/QC and re-selecting/re-sampling, to derive suitable data sets (in terms of spatial distribution and data quality) from available data points. For example, in Zone 19, a Bureau of Land Management study produced more than 4,800 field plots, mostly describing sagebrush, Douglas-fir, and lodgepole pine vegetation communities, in a relatively small area of approximately 1,152 km^2, near Salmon, ID. Spatially, this data set equated to approximately one plot for every 24 ha, versus a mapping zone average of one plot for every 835 ha. The inclusion of this data set in the

training process overwhelmed the mapping models and overrode areas with sparse plot coverage of different cover types. We therefore determined that the application of locally limited or concentrated data collected using various sampling designs to an entire mapping zone could have adverse effects on the accuracy of final products. For this reason, forest mapping in LANDFIRE National should employ FIA data exclusively. Rangeland mapping in LANDFIRE National, however, will require extensive QA/QC processing steps to transform available field-referenced data to a more suitable data set.

- As noted above, the following critical steps should be taken prior to the development of the mapping models: 1) examine field-referenced data, 2) conduct QA/QC procedures to detect spatial errors as well as information content-related errors, 3) correct these errors if necessary, and 4) derive a final, refined, error-free data set for training and accuracy assessment. This is a time-consuming yet necessary process that will contribute to increased consistency and confidence of map products.

Effects of the Vegetation Map Unit Classification System

Determining accuracy objectives and the appropriate extent of mapping areas are among the factors that need to be considered when defining a workable national vegetation map unit classification system. If floristically or ecologically overlapping cover types (such as Juniper and Pinyon -- Juniper or Upland Microphyllous and Upland Sclerophyllous) are to be mapped for LANDFIRE National, then guidelines must be developed for defining how the mapping accuracy of such overlapping map units is to be assessed.

Next, although our use of the NVCS was a reasonable starting point for vegetation map unit classification and the approach worked fine for each individual mapping zone, vegetation cover types were not always comparable between the two prototype mapping areas, however, as is evidenced by the legends in figures 2 and 3. As a result, accuracy estimates for the two prototype mapping zones could not be compared in a straightforward fashion, particularly for shrub cover types.

As discussed above, another challenge encountered during the application of the two vegetation map unit classification approaches (as discussed above in the *Vegetation Map Unit Classification* section) was answering the question of how to treat rare map units. There were no guidelines for consistently defining and treating rare map units. Moreover, there was no answer as to whether dropping rare map units, instead of using the alternative options discussed above, might affect the utility of LANDFIRE vegetation maps in other future natural resource management projects.

Recommendations for National Implementation

Because of the size and complexity of this research effort, many questions concerning LANDFIRE's national implementation are as of yet unanswered. The field data compilation effort will be an expensive and time consuming task, and a pressing need exists regarding the study of links between mapping performance, resource expenditure, and methods of field data collection. Ecological relationships between mapped potential vegetation and existing vegetation need to be investigated. Further research must be conducted to quantify the relative contributions of the different approaches and data sets used in the prototype. Performance consistency must be tested between adjacent western mapping zones, as well as in one or more prototype areas located in the eastern United States. Repeatability of the methods used in the prototype, both temporally and spatially, must also be evaluated. Furthermore, it is not clear whether the LANDFIRE Prototype methodology will suffice for other vegetation metrics, such as quantifying woody or non-woody biomass; a study in this area could yield information leading to enhanced applications of LANDFIRE vegetation maps. Nevertheless, the LANDFIRE Prototype Project provides sufficient information on which to base several recommendations regarding the national implementation of LANDFIRE.

Ways to Ensure Consistent National Vegetation Mapping

As noted above, several tasks related to existing vegetation mapping for the prototype effort may be standardized and potentially automated to facilitate LANDFIRE's national implementation. These tasks include: 1) the creation of a national vegetation map unit classification system that is mappable using spectral and biophysical/ecological data and is supported with adequate field-referenced data; 2) the consistent acquisition and processing of a multi-seasonal Landsat database; 3) the application of QA/QC procedures to the LFRDB to ensure a robust field-referenced database that can be used for a wide variety of applications; 4) the consistent modeling of biophysical data layers and probabilities of existing vegetation species or types associated with potential vegetation types; and 5) the continued application of CART as the primary mapping algorithms to ensure objectivity and flexibility when using high volumes of field data and predictor variables. We discuss these points in detail below.

Need for a Mappable Vegetation Map Unit Classification System

The vegetation map unit classification system used for the national implementation of LANDFIRE must meet a number of key criteria including the following: 1) the system must be nationally consistent, ecologically logical and hierarchical, acceptable to a wide array of users and groups, and must meet existing Federal Geographic Data Committee (FGDC) standards; 2) vegetation map units must be mappable using operational methodology to achieve reasonable accuracies; and 3) the map unit classification system must include vegetation map units that have high relevance with respect to the core LANDFIRE products. The Ecological Systems classification (Comer and others 2003) developed by NatureServe meets these objectives. This system represents the hierarchical merging of NVCS alliances into a nationally available suite of vegetation map units. Unlike alliances, which have proved exceedingly difficult to map accurately, most Ecological Systems classes are mappable, assuming an adequate number of field plots exist for training purposes. In addition, the Ecological Systems classification was developed by plant ecologists, lending credibility to the approach and resulting in a greater level of acceptance throughout the user community. We anticipate that a few additional "target alliance" map units will be added to the LANDFIRE National map unit classification legend on a case-by-case basis. These will be added only when it is determined that a particular map unit not specifically identified by the Ecological Systems classification has special relevance to LANDFIRE.

Need for National Field-referenced Data Collection and Processing

Many LANDFIRE tasks rely on a comprehensive, consistent, and extensive field-referenced database. The database serves as a reference for the development, testing, and accuracy assessment of all LANDFIRE vegetation, biophysical settings, and wildland fuel data layers and of all vegetation and fire regime simulation models. Field data from existing projects should be incorporated into this database whenever available and should include but not be limited to data sets such as FIREMON fire monitoring databases, USFS Landscape Ecosystem Inventory Systems databases, and the National Park Service fire monitoring databases. In addition, the USFS FIA Program's forest inventory plot database proved a useful source for the majority of forest data. Where data are lacking, supplemental field data collection is required to fill informational needs on rangeland map units. This assortment of field-referenced data should be collectively scrutinized for quality assurance, regularly updated, and maintained as a comprehensive LANDFIRE field-referenced database.

Need for Nationally Consistent Imagery Database

The availability of a quality Landsat imagery catalog is a key prerequisite for national implementation of the approaches developed for the LANDFIRE Prototype Project. Among all predictor variables, it is satellite imagery that usually captures the most current vegetation conditions, and, when used repeatedly over time, identifies changes in vegetation conditions and distributions. Thus, we recommend that LANDFIRE National continue to play an active role in the MRLC Consortium. This membership ensures the continued development of suitable multi-seasonal Landsat image catalogs, optimal levels of image processing (geometric, radiometric, and atmospheric rectification and calibration) for the rest of the country, and mapping zone-based image compilation for national vegetation mapping. In addition, LANDFIRE National should support studies that examine and compare the characteristics of other mid-resolution sensors with those of Landsat. Even though the LANDFIRE Project does not currently require any additional Landsat imagery, the potential benefits of using different satellite data for future updating should be considered.

Need for Nationally Consistent Set of Biophysical Gradient Layers

Biophysical gradients have effects similar to that of Landsat imagery on the spatial and information integrity of existing vegetation maps. Many of the biophysical layers are physiologically and ecologically related to the establishment, distribution, and conditions of plant species, and the incorporation of these gradient layers into the mapping process contributes to increased accuracies. For the national implementation of LANDFIRE, we recommend that a set of biophysical gradient layers similar to those listed in table 1 be used to map vegetation in all mapping zones. In addition, we recommend that further research be conducted to quantify the contribution of the individual biophysical variables to mapping accuracy. Furthermore, research should be conducted to minimize residual coarse-resolution imprints in 30-m biophysical data resulting from the coarser resolution weather and soil databases used to produce these data. The development of standard minimum mapping units in modeling simulations has shown promise in standardizing the process and eliminating coarse imprints.

The Need to Continue with Research and Improvements

Although results of the LANDFIRE Prototype Project indicate that the general approach should effectively meet target accuracy and consistency requirements for national implementation, there are areas where continued research and improvements are needed. One ongoing research effort involves the development of a new and more consistent approach to mapping shrub and herbaceous canopy cover. Current research is testing ways to effectively correlate calibrated Landsat-based NDVI to shrub and herbaceous canopy cover (Liu and others 2004). Other research areas include more efficient use of the individual biophysical gradient layers, more effective mapping of riparian vegetation, and a national accuracy assessment strategy.

Conclusion

The mapping of existing vegetation with complete national coverage at a 30-m spatial resolution is a core requirement of the LANDFIRE Project. National data at this 30-m resolution do not currently exist. As a result, the prototype research was needed to answer questions related to the mapping and characterizing of cover types and structure variables. LANDFIRE's existing vegetation products are expected to provide data not only for use in wildland fire management, but also for use in many other natural resource and environmental applications. Findings from the LANDFIRE Prototype effort are summarized as follows:

If supported with an adequate amount of field-referenced data, target accuracies of 60 percent or better are achievable for a mid-level vegetation map unit classification at the regional scale. The addition or subtraction of floristically or ecologically similar cover types has significant effects on resulting accuracies. Of the three major life forms, herbaceous cover types are the most difficult to map because these species adapt to many general biophysical characteristics and have few unique spectral signatures. Relationships between the floristic complexity of the vegetation map unit classification and mapping accuracies indicate that the national vegetation map unit classification will need to be designed carefully to include adequate flexibility.

For LANDIFRE, vegetation structure is defined by canopy cover and canopy height of forest, shrub, and herbaceous life forms. These structure attributes can be mapped consistently as categorical variables. Mapping these attributes as continuous variables, particularly for shrub and herbaceous height and cover, is inconsistent and, thus, is not recommended for national implementation of the LANDFIRE prototype methods.

Field data collection and processing are the most critical factors in ensuring that LANDFIRE maps of existing vegetation are objective and accurate. The detection and correction of errors existing in field-referenced data are time-consuming but absolutely necessary tasks, particularly for field data from sources other than FIA (as these other data sets tend to be locally limited and have various sampling designs). The objective of repeated field data processing and quality control is to derive a refined, high-quality field data set.

The incorporation of LANDFIRE biophysical gradient layers and cover-type probabilities associated with potential vegetation types into the mapping models contributes to a significant increase in mapping accuracy. In addition, the use of the biophysical and ecological stratifications that describe the environmental effects on species establishment and growth also contributes to enhanced mapping consistency.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Chapter
9

Vegetation Succession Modeling for the LANDFIRE Prototype Project

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Introduction

One of the main objectives of the Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, was to determine departure of current vegetation conditions from the range and variation of conditions that existed during the historical era identified in the LANDFIRE guidelines as 1600-1900 A.D. (Keane and Rollins, Ch. 3). In order to approximate this range and variation, we simulated a series of historical vegetation conditions using the landscape succession model LANDSUMv4, the fourth version of the LANDSUM model, developed specifically for the LANDFIRE Project (Keane and Rollins, Ch. 3).

LANDSUMv4 deterministically simulates vegetation dynamics based on successional communities called succession classes. Succession classes are characterized by cover types, which describe the species composition of the dominant vegetation, and structural stages, which describe the height and cover of the dominant vegetation. The combination of these two descriptors captures vegetation growth and development through time. These succession classes, linked by multiple pathways, transition between seral stages after a set number of years and eventually converge in an end-point community called a potential vegetation type or PVT. Disturbances occur probabilistically within the model and alter the successional status of vegetation communities, often setting succession back a number of time-steps (Pratt and others, Ch. 10).

At the end of a user-defined reporting period, LANDSUMv4 outputs a vegetation map. Synthesis of this chronosequence of vegetation maps over the simulation period reflects the net result of these successional transitions and disturbances. The modeling process results in an estimate of the distribution of succession classes through time for a particular PVT, which may be thought of as simulated historical reference conditions. (For a detailed description of the role played by LANDSUMv4 simulations in the LANDFIRE Prototype, see Pratt and others, Ch. 10 and Holsinger and others, Ch. 11)

To parameterize LANDSUMv4, we had to define all succession pathways and their associated transition times for each PVT. We estimated transition times between succession classes based on a number of factors, such as site productivity and species adaptations to disturbance. In addition, we had to define all disturbance pathways along with the probabilities of their occurrence, requiring that we convert knowledge of historical disturbance intervals into yearly probabilities. More importantly, we had to test these inputs before they could be used for modeling purposes. To test the inputs we created for the model, we used a computer model called the Vegetation Dynamics Development Tool (VDDT) (Beukema and others 2003).

The VDDT modeling framework is almost identical to that of LANDSUMv4 (Keane and others 2002), except that in VDDT, the modeling environment is "aspatial" and uses pixels to track succession classes. These pixels are independent of adjacent pixels because VDDT does not simulate the contagion of ecosystem processes (such as wildland fire) through space or over time (Beukema

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In: Rollins, M.G.; Frame, C.K., tech. eds. 2006. The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. Gen. Tech. Rep. RMRS-GTR-175. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

and others 2003). This simpler approach allows for near-instantaneous model execution as well as for rapid model building and rapid testing of the model's sensitivity to a wide range of inputs.

The objective of the LANDFIRE Prototype vegetation modeling was to provide the myriad of LANDSUMv4 inputs as well as to document both the processes used to derive these inputs and the assumptions involved in constructing the succession models. The following sections describe the general process we used to create the succession models in addition to all input parameters for LANDSUMv4. This process included the initial steps of deciding which PVTs to model, which cover types should be included in each PVT, and which structural stages should be used in combination with these cover types to represent the various succession classes within each PVT. We then defined pathways for each of the succession classes in each PVT. These pathways took two forms. One set described succession and the associated number of time-steps required to transition from one succession class to another without disturbance. The other set described disturbance, both in terms of the succession class that is the result of that disturbance and the associated probability of that disturbance occurring for that particular succession class. Also included are general descriptions of all of the models built as input into LANDSUMv4 along with recommendations for modifying this process in the context of national implementation.

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on the procedure followed in developing the models of vegetation dynamics (including disturbance probabilities and transition times) which were an important precursor to the modeling of historical vegetation conditions and fire regimes.

PVTs and Succession Classes

Succession classes for each PVT were represented by combinations of cover types and structural stages (Zhu and others, Ch. 8). An example of a succession class in the Spruce – Fir/Blue Spruce PVT would be "Douglas-fir, High Cover, High Height Forest," each succession class being described by a combination of one cover type and one structural stage. Thus, for each PVT, we first decided which cover types and which structural stages would be used to represent the various stages of succession for that PVT. The list of these PVTs developed for LANDFIRE mapping purposes, shown in tables 1 and 2, contains the PVTs used for succession modeling purposes. The cover type list (tables 3 and 4), which describes dominant species, and the structural stage list (table 5), which describes dominant vegetation cover and height, were used to limit the number of succession classes that could occur within a PVT. (For detailed information on the cover types, potential vegetation types, and structural stages mapped for the LANDFIRE Prototype, see Long and others, Ch. 6.) Tabular summaries from the LANDFIRE reference

Table 1—Potential vegetation types (PVTs) used for succession modeling in Zone 16.

PVT#	Potential vegetation type
1601	Spruce – Fir / Blue Spruce
1602	Spruce – Fir / Blue Spruce / Lodgepole Pine
1603	Spruce – Fir / Spruce – Fir
1604	Spruce – Fir / Spruce – Fir / Lodgepole Pine
1611	Grand Fir – White Fir
1612	Grand Fir – White Fir / Maple
1621	Douglas-fir / Timberline Pine
1622	Douglas-fir / Douglas-fir
1623	Douglas-fir / Lodgepole Pine
1631	Timberline Pine
1632	Ponderosa Pine
1633	Lodgepole Pine
1634	Aspen
1641	Pinyon – Juniper / Mountain Big Sagebrush / North
1642	Pinyon – Juniper / Mountain Big Sagebrush / South
1643	Pinyon – Juniper / Wyoming – Basin Big Sagebrush / North
1644	Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South
1645	Pinyon – Juniper / Mountain Mahogany
1646	Pinyon – Juniper / Gambel Oak
1651	Blackbrush
1652	Salt Desert Shrub
1653	Warm Herbaceous
1654	Cool Herbaceous
1661	Dwarf Sagebrush
1662	Wyoming – Basin Big Sagebrush
1663	Mountain Big Sagebrush
1671	Riparian Hardwood
1672	Riparian Shrub
1673	Wetland Herbaceous
1680	Alpine

database (Caratti and others, Ch. 4) provided a list of the cover types and structural stages that, based on plot data, occurred in each PVT. This list provided the building blocks for constructing the various succession models used to simulate historical reference conditions for the LANDFIRE Prototype.

Potential vegetation types represent specific biophysical environments and associated suites of successionally dominant species or species complexes (Keane and Rollins, Ch. 3; Long and others, Ch. 6) and, as such, are very similar in concept to "habitat types" (Daubenmire 1968). A number of habitat type classifications were available for the two prototype mapping zones, and we used data from these classifications to refine the lists of cover types that could exist in each PVT. For forest vegetation, habitat classifications for Zone 16 included those by Mauk and Henderson 1984; Muegler and Campbell 1986; Padgett and others 1989; Pfister 1972; Steele and others 1981; Youngblood and Mauk 1985; and Youngblood and others 1985. Habitat type classifications for Zone 19 included those by Hansen and others 1987; Hansen and others 1988; Pierce 1986; and Pfister and others 1977.

Table 2 — Potential vegetation types (PVTs) used for succession modeling in Zone 19.

PVT#	Potential vegetation type
1902	Western Redcedar
1914	Grand Fir – White Fir
1920	Spruce – Fir / Montane / Western Larch
1921	Spruce – Fir / Montane / Douglas-fir
1922	Spruce – Fir / Timberline
1924	Spruce – Fir / Subalpine
1930	Douglas-fir / Ponderosa Pine / Western Larch
1931	Douglas-fir / Ponderosa Pine / Douglas-fir
1932	Douglas-fir / Lodgepole Pine
1934	Douglas-fir / Timberline Pine
1936	Douglas-fir / Douglas-fir
1940	Lodgepole Pine
1942	Ponderosa Pine
1944	Timberline Pine / Limber Pine
1946	Timberline Pine / Whitebark Pine
1950	Rocky Mountain Juniper
1952	Riparian Hardwood
1960	Riparian Shrub
1962	Mountain Mahogany
1964	Dry Shrub
1965	Dry Shrub / Conifer
1970	Dwarf Sagebrush Complex
1971	Dwarf Sagebrush Complex / Conifer
1972	Mountain Big Sagebrush Complex
1973	Mountain Big Sagebrush Complex / Conifer
1974	Threetip Sagebrush
1975	Threetip Sagebrush / Conifer
1976	Wyoming – Basin Big Sagebrush Complex
1977	Wyoming – Basin Big Sagebrush Complex / Conifer
1980	Wetland Herbaceous
1982	Alpine
1984	Fescue Grasslands
1985	Fescue Grasslands / Conifer
1986	Bluebunch Wheatgrass
1987	Bluebunch Wheatgrass / Conifer

Table 3—Cover types (CTs) used for succession modeling in Zone 16.

CT#	Cover type
1401	Riparian Hardwood
1405	Aspen – Birch
1201	[Interior] Ponderosa Pine
1204	Lodgepole Pine
1205	Douglas-fir
1206	Grand Fir – White Fir
1211	Spruce – Fir
1801	Timberline Pines
2201	Pinyon – Juniper
2202	Juniper
3704	Mountain Deciduous Shrub
3402	Riparian Shrub
3403	Exotic Riparian Shrub
3101	Mountain Big Sagebrush Complex
3102	Wyoming – Basin Big Sagebrush Complex
3103	Dwarf Sagebrush Complex
3104	Sand Sagebrush
3105	Blackbrush
3106	Rabbitbrush
3107	Chaparral
3301	Montane Evergreen Shrubs
3701	Salt Desert Shrub
3702	Desert Shrub
3703	Dry Deciduous Shrub
4101	Warm Season Grasses
4102	Cool Season Grasses
4201	Native Forbs
4202	Exotic Forbs
4301	Wetland Herbaceous
4302	Alpine
4401	Annual Grasslands

Table 4—Cover types (CTs) used for succession modeling in Zone 19.

CT#	Cover type
1201	Cedar
1202	Douglas-fir
1203	Grand Fir
1204	Hemlock
1205	Lodgepole Pine
1206	Juniper
1207	Ponderosa Pine
1208	Spruce – Fir
1209	Limber Pine
1212	White Pine
1401	Aspen – Birch
1402	Riparian Hardwood
1403	Western Larch
1801	Timberline Forest
2101	Upland Broadleaf Dwarf Shrubland
2102	Upland Broadleaf Medium Shrubland
2103	Upland Broadleaf Tall Shrubland
2202	Upland Microphyllous Medium Shrubland
2211	Dwarf Sage
2212	Shrubby Cinquefoil
2213	Threetip Sage
2218	Mountain Big Sage
2219	Wyoming – Basin Big Sage
2220	Rabbitbrush
2222	Greasewood
2223	Mountain Mahogany
2300	Upland Needleleaf Shrubland
2400	Upland Sclerophyllous Shrubland
2600	Riparian Broadleaf Shrubland
3110	Annual Forb
3120	Annual Graminoid
3130	Perennial Forb
3141	Perennial Exotic Bunch Gramminoid
3142	Perennial Native Bunch Gramminoid
3151	Perennial Exotic Rhizomatous Gramminoid
3152	Perennial Native Rhizomatous Gramminoid
3200	Wetland Herbaceous

Table 5—Structural stages used for succession modeling in zones 16 and 19.

Structural stage #	Structural stage name	Structural stage abbreviation
Zone 16		
11	Low Cover, Low Height Forest	LLF
12	High Cover, Low Height Forest	HLF
13	High Cover, High Height Forest	HHF
14	Low Cover, High Height Forest	LHF
21	Low Cover, Low Height Woodland	LLW
22	High Cover, Low Height Woodland	HLW
23	High Cover, High Height Woodland	HHW
24	Low Cover, High Height Woodland	LHW
31	Low Cover, Low Height Shrubland	LLS
32	High Cover, Low Height Shrubland	HLS
33	High Cover, High Height Shrubland	HHS
34	Low Cover, High Height Shrubland	LHS
51	Low Cover, Low Height Herbaceous	LLH
52	High Cover, Low Height Herbaceous	HLH
53	High Cover, High Height Herbaceous	HHH
54	Low Cover, High Height Herbaceous	LHH
Zone 19		
10	Low Cover, Low Height Trees	LLT
11	Low Cover, Low -Mod Height Trees	LLMT
12	High Cover, Low - Mod Height Trees	HLMT
13	Low Cover, Mod Height Trees	LMT
14	High Cover, Mod Height Trees	HMT
15	Low Cover, High Height Trees	LHT
16	High Cover, High Height Trees	HHT
21	Low Cover, Low Height Shrubs	LLS
22	High Cover, Low Height Shrubs	HLS
23	Low Cover, Mod Height Shrubs	LMS
24	High Cover, Mod Height Shrubs	HMS
25	Low Cover, High Height Shrubs	LHS
26	High Cover, High Height Shrubs	HHS
31	Low Cover, Low Height Herbs	LLH
32	High Cover, Low Height Herbs	HLH
35	Low Cover, High Height Herbs	LHH
36	High Cover, High Height Herbs	HHH

In cases where several habitat types from a particular classification – each having different species compositions – were associated with one PVT, we used a weighting process to predict the average cover type composition. We assigned weights based on the number of plots recorded for each habitat type. If a cover type was listed as a major seral or climax species in a particular habitat type, we assumed that it could dominate the site and should therefore be included in the succession model. Using the weights assigned from data describing each habitat type within a PVT, we developed a list of cover types and associated expected percent composition for each PVT.

Regarding rangeland vegetation, we found no existing habitat type classifications for Zone 16. This lack of previously established rangeland habitat classifications led us to rely almost entirely on tabular summaries from the LANDFIRE reference database (Caratti and others, Ch. 4) for the assignment of cover types to rangeland PVTs. In Zone 16, the plot data were well distributed across PVTs and there were enough data to effectively describe the cover types within each PVT. Habitat types as defined by Mueggler and Stewart (1980) served as the source for nearly all the information used to describe cover types found in specific PVTs in Zone 19.

Once all possible cover types had been assigned to each PVT, we began defining structural stages for each cover type for each PVT. For forest PVTs, each cover type was represented by a standard set of structural stages (Long and others, Ch. 6). These structural stages consisted of one or more shrub or herbaceous cover types (used to describe early seral conditions), which generally result from a stand-replacing disturbance. Four structural stages, defined by two categories of tree height and two categories of crown cover, were used to describe each forest succession class. Modeled succession for each PVT began in the various early seral types and then flowed through the three structural stages for that particular cover type: "Low Cover, Low Height Forest," "High Cover, Low Height Forest," and "High Cover, High Height Forest." A fourth structural stage, "Low Cover, High Height Forest," was used to represent stands that resulted only from mixed-severity, non-stand-replacing disturbances (see Pratt and others, Ch. 10 for details on the fire regime classification used in the LANDFIRE Prototype).

The development of rangeland pathways was predicated on the theory that rangeland vegetation exhibits multiple states and transitions (Stringham and others 2003). The changes in structural stages generally represented transitions from a grass-dominated state (generally resulting from a stand-replacing disturbance, such as fire) to a shrub state or, depending on the PVT, a forest state. In addition, to capture more subtle transitions between these states, we included additional succession classes by incorporating two and sometimes three cover and height breaks for each cover type.

Succession and Disturbance Modeling

For forest PVTs, we estimated transition times between succession classes by forest cover type using site index data from a number of sources. Site index is a measure often used to describe the height of a free-growing tree after a certain number of years, generally between 50 to 100 years. We then interpolated these data to the height classes defined in the structural stages. Transition times for rangeland PVTs were gleaned from a wide variety of rangeland vegetation studies. Information from these studies often characterized the response of rangeland plant communities to fire and other stand-replacing disturbances and was applied on a case-by-case basis to the appropriate PVT.

For Zone 16, we obtained site index data from Alexander 1966; Brickell 1966; Mauk and Henderson 1984; Mueggler and Stewart 1980; Padgett and others 1989; Pfister 1972; Youngblood and Mauk 1985; Youngblood and others 1985; and, for adjacent areas, from studies by Pfister and others 1977 and Steele and others 1975. We based the expected longevity of various tree species on Alexander 1974; Burns and Honkala 1990; Jones 1974; and McCaughey and Schmidt 1982.

For Zone 19, we obtained site index data from Brickell 1966; Burns and Honkala 1990; Pfister and others 1977; and Seidel 1982. We based the expected longevity of various tree species on Burns and Honkala 1990 and Ferguson and others 1986. We then adjusted the life expectancy to reflect the environmental conditions found in the PVT.

We used an extensive literature search to define disturbance pathways for each PVT. Disturbance pathway parameters were based primarily on the way each succession class responds to disturbance. These parameters were generally based on vegetation studies that addressed an individual species' response to fire. We supplemented the results of the literature search with information provided by local scientists as well as with online sources of information on plant communities' responses to fire, including the Fire Effects Information System (FEIS) database (USDA Forest Service 2005) and the National Resource Conservation Service and its associated descriptions of rangeland ecological site data (USDA NRCS 2005).

For Zone 16, information pertinent to defining disturbance pathways was gleaned from studies by Bradley and others 1992; Brown and Debyle 1989; and Yanish 2002. For Zone 19, these data were taken from studies by Fisher and Bradley 1987; Zlatnik and others 1999; Arno and Gruell 1983, 1986; Fiedler (no date); Ferguson and others 1986; and Oliver 1979.

We obtained information on fire intervals from literature searches and from personal communication with local scientists, as well as from online sources of information on plant communities' responses to fire, including the FEIS database (USDA Forest Service 2005) and the National Resource Conservation Service and its associated descriptions of rangeland ecological site data (USDA NRCS 2005).

For Zone 19, historical fire intervals for each succession class were derived from Arno 1976; Arno and others 2000; Barrett 1988, 1995, 2002; Losensky 1989, 1992, 1993, and 1995; and Pierce 1982.

Model Evaluation

We ran each of our models for a 1000-year simulation period and examined the distribution of succession classes for each PVT. We assumed that the proportion of succession classes at the end of the simulation period would represent the natural conditions found on the landscape at the time of Euro-American settlement. These values were largely dependent on the assignment of pixels to various succession classes as they moved from initiation communities to tree-dominated communities. In addition, changes in succession class could result from wildland fire. Evaluation of the proportion of succession classes associated with each PVT is highly important in the parameterization of each model. We reviewed the models to determine if the proportion of succession classes within a PVT, the modeled fire intervals, and the modeled severities were similar to findings in the literature or as expected according to the known information about the plant communities.

Model Descriptions

The next two sections describe VDDT succession modeling results. These results relate to groups of PVTs with similar succession dynamics and similar fire return intervals. The objective of the discussion is to highlight the important succession and disturbance regimes of each PVT and connect them to the resulting succession class distributions. Detailed results from the simulations are presented in appendices 9-A through 9-P and include summaries of transition times between succession classes, fire return intervals, and succession class distributions -- by succession class for each PVT. (Note: PVT legends and descriptions can be found in Long and others, Ch. 6: appendices 6-F and 6-G.)

Zone 16 Models

Spruce – Fir Forests—Spruce – Fir forests in Zone 16 were represented by the Spruce – Fir/Blue Spruce and Spruce – Fir/Spruce Fir PVTs in Zone 16 (appendix 9-A). Two variants were modeled for both of these PVTs to reflect the distribution of the Lodgepole Pine cover type in the northern sections of Zone 16 and the lack of the Lodgepole Pine cover type in the southern part of Zone 16 (table 1). All PVTs had fairly long fire return intervals between stand-replacing fires and moderately long intervals between mixed-severity fires and non-lethal fires (appendix 9-A: table 2). Dominant cover types were Douglas-fir, Spruce – Fir, Lodgepole Pine (restricted to northern portions of the zone) and Aspen – Birch. Each cover type was consistently dominated by late seral structural stages, with a slightly higher proportion of the open cover class. Spruce – Fir was the successional endpoint in all of these models, but Douglas-fir is a long-lived seral dominant.

White Fir/Douglas-fir Forests—White Fir/Douglas-fir forests in Zone 16 were represented by one Grand Fir/White Fir PVT and three Douglas-fir PVTs (appendix 9-B). All of these PVTs support the Douglas-fir, Ponderosa Pine, and Aspen – Birch cover types but differ from each other in the unique combinations of other seral species they also support. Non-lethal fires with short return intervals characterize nearly all of this group's PVTs (appendix 9-B: table 2). Late seral Douglas-fir cover types dominate nearly all PVTs in this group, with the exception of late seral Ponderosa Pine cover types in the Grand Fir/White Fir PVT (appendix 9-B: table 3).

Pine Forests—Pine forests in Zone 16 were represented by three PVTs, each of which occupies a fairly distinct landscape setting that generally favored the dominance of a single cover type (appendix 9-C). The Lodgepole Pine PVT occurred primarily in an upper montane and subalpine setting, while the Ponderosa Pine PVT occupied a lower montane setting. The Timberline Pine PVT occupied unique sites where species composition was purely limber pine or bristlecone pine. Fire intervals were modeled to be moderately long or very long for stand-replacing and mixed-severity fires, but short to moderate for non-lethal fires (appendix 9-C: table 2). Modeling results under these fire intervals produced a mixture of all structural stages of the dominant cover type, except where the Aspen – Birch cover type co-dominates with the Lodgepole Pine cover type in the Lodgepole Pine PVT.

Broadleaf Forests—Broadleaf forest PVTs in Zone 16 were represented with the Riparian Hardwood PVT and the Aspen PVT (appendix 9-D). The Juniper cover type played a mid-seral role in the Riparian Hardwood PVT and eventually succeeded to the Riparian Hardwood cover type, which is dominated mostly by cottonwood, the endpoint of succession for this PVT (appendix 9-D: table 3). The fire regime of this PVT was stand-replacing fires with moderate to long return intervals (appendix 9-D: table 2). The Aspen PVT occurred on sites where the Aspen – Birch cover type, dominated by aspen, is the "stable" climax community. The fire regime of this PVT was stand-replacing fires with moderate to long return intervals as well (appendix 9-D: table 2).

Pinyon – Juniper Woodlands—Pinyon – Juniper woodlands in Zone 16 were composed of the Pinyon – Juniper/Mountain Big Sagebrush PVT and the Pinyon – Juniper/Wyoming – Basin Big Sagebrush PVT (appendix 9-E). The Pinyon – Juniper/Mountain Big Sagebrush PVT was divided into two succession models: a northern variant and a southern variant. Fires were always stand-replacing and had fairly short intervals (appendix 9-E: table 2). The major differences between the northern and southern succession models were associated with the amount of Juniper cover type on the landscape. The Juniper cover type is dominant in the northern model, whereas the Pinyon – Juniper cover type is dominant in the southern model.

The Pinyon – Juniper/Wyoming – Basin Big Sagebrush PVT was also divided geographically into two succession models (northern and southern). They are identical with the exception of the time spent in the Cool Season Grasses cover type, which reflects site productivity differences across the PVT. We varied the fire intervals in this PVT from 40 to 60 years, depending on the succession class (appendix 9-E: table 2). This range in fire frequency reflected the biophysical variation in this PVT, with dryer sites of the PVT having a longer fire return interval. The resulting distribution of succession classes varied between the northern and southern zones. The Pinyon – Juniper cover type dominates more in the south, while the Wyoming – Basin Big Sagebrush cover type has a much larger component in the north.

Mountain Shrublands—Mountain shrubland PVTs in Zone 16 consisted of the Pinyon – Juniper/Mountain Mahogany PVT, the Pinyon – Juniper/Gambel Oak PVT, and the Grand Fir – White Fir/Maple PVT (appendix 9-F). The Mountain Mahogany PVT has a moderate fire return interval, which allowed Mountain Mahogany to escape fires and form relatively mature stands of tree-like shrubs. The Pinyon – Juniper/Gambel Oak PVT was designed to have two successional endpoints: one in the Pinyon – Juniper cover type and one in the Mountain Deciduous Shrub cover type, which is dominated by Gambel oak. On somewhat drier sites in this PVT, the successional endpoint leads to the Pinyon – Juniper cover type; however, on more mesic sites, dominance of pure Gambel oak is more common, and the successional endpoint is the Mountain Deciduous Shrub cover type. Stand-replacing fires with fairly short return intervals were modeled in this PVT (appendix 9-F: table 2). We considered the Bigtooth Maple PVT to be a moister, northern variant of the Pinyon – Juniper/Gambel Oak PVT. This PVT was found in northern parts of Zone 16 where bigtooth maple, contained within the Riparian Hardwood cover type, occurred in relatively pure stands. The results of the VDDT modeling show a fairly significant component of white fir sharing dominance with bigtooth maple (appendix 9-F: table 3). Moderately short fire return intervals were modeled in the Bigtooth Maple PVT (appendix 9-F: table 2).

Sagebrush Shrublands—We modeled three individual sagebrush PVTs for Zone 16 (appendix 9-G). The Mountain Big Sagebrush PVT represented the upper elevation ranges that support big sagebrush. Fire intervals in the Mountain Big Sagebrush PVT were fairly short (appendix 9-G: table 2). This fire regime resulted in the dominance of Low Cover, Low Height Shrubland structural stages of the Mountain Big Sagebrush cover type. The Dwarf Sage PVT represented lower elevations with drier, warmer conditions and nearly pure stands of "low sagebrush" species or mixtures of low sagebrush and black sagebrush. This PVT was modeled with a moderately long fire return interval (appendix 9-G: table 2). High Cover, Low Height Shrubland structural stages of the Dwarf Sagebrush Complex cover type almost completely dominated the landscape (appendix 9-G: table 3). More mesic sites at lower elevations with deeper soils were represented by the Wyoming – Basin Big Sagebrush PVT. Moderately short fire return intervals were used in this PVT (appendix 9-G: table 2), resulting in a mixture of High Cover, Low Height and Low Cover, Low Height Shrubland structural stages of the Wyoming – Basin Big Sagebrush cover type and a substantial component of the Cool Season Grasses cover type (appendix 9-G: table 3).

Desert Shrublands—The Blackbrush PVT and the Salt Desert Shrub PVT were modeled to represent desert shrubland conditions in Zone 16 (appendix 9-H). The Blackbrush PVT had low productivity, and fire intervals were modeled to be fairly low (appendix 9-H: table 2). Much of the landscape in the Blackbrush PVT was dominated by the High Cover, High Height Shrublands structural stage of the Blackbrush cover type along with a significant component of both High Cover, Low Height Shrubland and Low Cover, Low Height Shrubland structural stages of the Desert Shrub cover type. (appendix 9-H: table 3). The Salt Desert Shrub PVT had a limited distribution in Zone 16. Moderately low fire return intervals were modeled for this PVT (appendix 9-H: table 2). The Wyoming – Basin Big Sagebrush cover type dominated much of this PVT -- both as a High Cover, Low Height Shrubland and Low Cover, Low Height Shrubland -- along with a significant proportion of the Salt Desert Shrub cover type.

Zone 19 Models

Western Redcedar and Grand Fir Forests—Cedar and Grand Fir forest PVTs in Zone 19 were comprised of the Western Redcedar PVT and the Grand Fir/White Fir PVT (appendix 9-I). We used a diverse array of succession classes for each of these two PVTs (appendix 9-I: table 1). We modeled very long fire intervals for most stand-replacing fires in the Western Redcedar PVT and moderate to long intervals for the Grand Fir/White Fir PVT (appendix 9-I: table 2). Intervals for mixed-severity fires were generally moderate for both types, and non-lethal fires were also modeled at moderate intervals. For both PVTs, the results of the modeling (appendix 9-I: table 3) featured the dominance of long-lived seral species including the Douglas-fir cover type and the Western Larch cover type, in addition to smaller amounts of the White Pine cover type. The main difference between the two PVTs is the substantial amounts of the Cedar, Hemlock, and Spruce – Fir cover types in the Western Redcedar PVT.

Spruce – Fir Forests—Spruce – Fir forests in Zone 19 (appendix 9-J) were divided into two groups: those that occurred in a montane or mid-elevation landscape setting and those occurring in a higher elevation, subalpine or timberline landscape setting. Montane settings were represented by the Spruce – Fir/Montane PVT, which had the most floristically diverse succession classes (appendix 9-J: table 1). The Spruce – Fir/Subalpine PVT and Spruce – Fir/Timberline PVT were less productive PVTs and were modeled with fewer cover types (appendix 9-J: table 1). Moderately long return interval, mixed-severity fires played a significant role in the Spruce – Fir/Subalpine PVT, whereas stand-replacing fires occurred in these systems infrequently (appendix 9-J: table 2). VDDT modeling results (appendix 9-J: table 3) show that, with the exception of the Douglas-fir cover type in the Spruce – Fir/Montane PVT, the Spruce – Fir cover type dominated these sites historically. Lodgepole Pine was the next most dominant cover type in the Spruce – Fir/Subalpine PVT, while Timberline Forest, which consisted of whitebark pine, was the next most dominant cover type in the Spruce – Fir/Timberline PVT.

Douglas-fir Forests—A wide array of Douglas-fir PVTs was modeled to represent the historical dynamics of Douglas-fir forests in Zone 19 (appendix 9-K). Succession classes for each PVT are shown in appendix 9-K: table 1. The Western larch cover type was modeled in the Douglas-fir/Ponderosa Pine PVT and played minor roles in the Douglas-fir/Douglas-fir PVT and in the higher, colder Douglas-fir/Lodgepole Pine PVT. In all cases, the cover type was restricted to the northwest corner of the zone. The Ponderosa pine cover type played a major role in the Douglas-fir/Ponderosa Pine PVT and a minor role in the Douglas-fir/Douglas-fir PVT. Both PVTs had the Lodgepole Pine cover type as well. The driest of the Douglas-fir forests was the Douglas-fir/Timberline PVT. This PVT had a distinctive array of cover types, including the Limber Pine and Juniper cover types, in addition to the Douglas-fir cover type. Many of the succession classes in these PVTs historically had short to moderately short fire intervals in mixed-severity and non-lethal regimes (appendix 9-K: table 2). Stand-replacing fires were rare, except in younger age classes for all of these PVTs. With the exception of the Douglas-fir/Ponderosa Pine PVT, which was dominated by the Ponderosa Pine cover type, cover types were dominated by Douglas-fir in nearly all of these PVTs (appendix 9-K: table 3).

Pine Forests—Pine forest PVTs represented areas generally out of the range of distribution of either the Spruce – Fir cover type or the Douglas-fir cover type. These PVTs included the Ponderosa Pine PVT, the Timberline Pine/Limber Pine PVT, the Lodgepole Pine PVT, and the Timberline Pine/Whitebark Pine PVT (appendix 9-L). The Ponderosa Pine PVT occurred at the lowest elevations and was characterized by very short fire return intervals (appendix 9-L: table 2). This regime maintained both High Cover, High Height and Low Cover, High Height Forest structural stages of the Ponderosa Pine cover type in high proportions (appendix 9-L: table 3). The remaining PVTs were characterized by fairly long fire return intervals, which maintained a variety of structural stages in each of the cover types that were modeled in the PVT.

Broadleaf Forests—Broadleaf forests were represented by the Riparian Hardwood PVT, which was the only PVT where broadleaf trees were the chief component (appendix 9-M). Appendix 9-M: table 1 shows the list of succession classes used for the VDDT modeling of the Riparian Hardwood PVT. This PVT had a mix of fire regimes but tended to be dominated by stand-replacing fire with a long return interval (although, unlike other PVTs, the influence of surrounding PVTs' fire regimes seemed to affect this PVT more than its own). The result of this PVT's fire regime was dominance of the Riparian Hardwood cover type, dominated by cottonwood, with small and dispersed amounts of the Aspen – Birch cover type (appendix 9-M: table 3).

Woodlands—Woodland vegetation in Zone 19 was represented by the Rocky Mountain Juniper PVT and the Mountain Mahogany PVT (appendix 9-N). The Rocky Mountain Juniper PVT featured the Juniper cover type – with Rocky Mountain juniper as the dominant species – in addition to a significant component of the Perennial Native Bunch Graminoids cover type (appendix 9-N: table 3). Fire intervals used in the VDDT modeling process were fairly long (appendix 9-N: table 2). The Mountain Mahogany PVT represented somewhat rare sites around the zone that were located adjacent to ridge tops and on rock outcrops that support the Mountain Mahogany cover type. Our succession model used fairly long fire return intervals (appendix 9-N: table 2), resulting in the dominance of the Mountain Mahogany cover type and a wide array of structural stages, along with lesser amounts of the Wyoming – Basin Big Sagebrush cover type.

Sagebrush and Other Dry Shrublands—Sagebrush and other shrub types in Zone 19 were represented by four different PVTs (appendix 9-O). All of these PVTs featured a model including conifer succession classes and a model excluding conifer succession. Models with conifer succession classes represented areas generally adjacent to conifer PVTs where conifer encroachment is most likely to occur due to proximity to seed source and site conditions. The Mountain Big Sagebrush PVT and the Threetip Sagebrush PVT were modeled with fairly short fire return intervals (appendix 9-O: table 2). In both cases, a substantial proportion of the PVT was maintained in the Perennial Native Bunch Graminoid cover type (appendix 9-O: table 3). The remainder of the PVT was dominated by each respective sagebrush species cover type. The Wyoming – Basin Big Sagebrush PVT had somewhat longer fire return intervals and was maintained historically in a higher proportion of the Wyoming – Basin Big Sagebrush cover type; however, this PVT also had a significant proportion of the Perennial Native Bunch Graminoid cover type (appendix 9-O: table 3). The Dwarf Sagebrush PVT was modeled to represent fairly dry and less productive sites. With an available seed source, conifer encroachment will occur without fire; however, the encroachment will be very slow as these sites have soils with high salinity, or a caliche layer exists. Fire return intervals were moderately long (appendix 9-O: table 2), and most of the PVT was dominated by various structural stages of the Dwarf Sagebrush cover type (appendix 9-O: table 3).

The Dry Shrub PVT was modeled to represent a wide variety of shrub cover types found across a number of landscape settings (appendix 9-O: table 4). These cover types were relatively common in Zone 19 but did not necessarily grow adjacent to each other. Similar to the sagebrushes, this PVT had two succession pathway models, one associated with conifer encroachment and one not. We assumed a long fire return interval for this PVT and, like the sagebrushes, results showed a substantial proportion of the PVT dominated by the Perennial Native Bunch Graminoid cover type (appendix 9-O: table 6). The dominant shrub cover was the Shrubby Cinquefoil cover type.

Grasslands—Grassland PVTs for Zone 19 consisted of the Fescue Grassland PVT and the Bluebunch Wheatgrass PVT (appendix 9-P). The Fescue Grassland PVT was represented by Idaho fescue and rough fescue. We modeled two fescue grasslands that differ only in inclusion of a conifer component. Conifers, predominantly Douglas-fir, are often adjacent to fescue grassland PVTs, and if a seed source is available, conifer encroachment will occur over time without fire. We modeled these types of sites with the Fescue Grassland/Conifer PVT. On sites where grasses are competitive, especially on finer-textured soils, large areas of the landscape presently show very little conifer encroachment. These types of sites were modeled with a moderately short fire return interval (appendix 9-P: table 2) which, over time, maintained the PVT with an even distribution of the Perennial Native Bunch Graminoid and shrub cover types (appendix 9-P: table 3).

The Bluebunch Wheatgrass PVT represents some of the drier grasslands in Zone 19, and conifer invasion occurred slowly. The potential and degree of conifer invasion depended on the soils, surrounding landscape, and past disturbances. In the southern portion of the zone, Utah juniper and Rocky Mountain juniper were the conifer species most likely to encroach into these grasslands. In the central and northern parts of Zone 19, Rocky Mountain juniper was common, as were Douglas-fir, limber pine and ponderosa pine. Fire intervals in this PVT were fairly short (appendix 9-P: table 2). A large proportion of the PVT was maintained in the Perennial Native Bunch Graminoid cover type, attesting to the drier nature of these sites.

Recommendations for National Implementation

PVT Classification

The PVT classification formed the foundation for all succession modeling in the two prototype areas (Long and others, Ch. 6). A number of existing western U.S. habitat type classifications, which could be linked directly to the LANDFIRE PVT classification, proved to be immensely helpful. The modeling of succession and the effects of disturbance would have been, at best, conjectural without these baseline, floristically detailed classifications embedded within the PVT classification. This classification provided the framework for understanding the interactions between the succession classes found within each PVT. As noted, much of the western U.S. has existing habitat classifications in place, at least for forest vegetation; however, in other portions of the country, such classifications do not exist. Furthermore, the development of a climax vegetation-based PVT classification and subsequent succession modeling become problematic due to the historical land use of these non-western areas and the more subtle and complicated species interactions therein. The modeling of vegetation response in the Midwest and East should therefore be based on concepts other than the climax vegetation theory to properly evaluate succession and disturbance processes.

Cover Type Classification

The vegetation models were generally designed to simulate vegetation dynamics at the mid-level, but small inclusions of other PVTs or cover types were often evident in the plot data. These inclusions resulted in a number of illogical cover type combinations for some PVTs. Unfortunately, there was no process in place to address this issue, and, in some cases, these combinations were carried forward into the succession modeling process. Similarly, we encountered situations where, within a zone, a cover type occurred in only a particular geographic region of the PVT. In these situations, it became necessary to develop rules by which to subdivide the mapping zone and apply different succession models to these geographic variants. We recommend developing succession classes based on a more generalized and robust characterization of cover types so these situations can be avoided.

In addition, because there is a wide diversity of understory vegetation that may dominate during the early seral stages of forest development, we had to use a number of cover types to represent these stages of many PVTs. We used four succession classes to describe the early seral stages of forest development in Zone 16 PVTs and, on average, over seven succession classes to describe the early seral stages of forest development in Zone 19. At any given time, these early stages represented l0 percent or less of the total amount of all succession classes. Consequently, at any point in time in the modeling, a particular succession class in these early seral stages may have represented less than one percent of the vegetation. For this reason, we recommend that the number of cover types used to describe early seral stages of forest development be kept to a minimum and represent broad categories of vegetation.

For Zone 19, we employed a cover type classification that relied more on physiognomic characteristics in an attempt to provide a more systematic methodology to the classification process (Long and others, Ch. 6). However, this classification resulted in a number of cover types that were difficult to use for succession modeling purposes. For example, the Upland Broadleaf Medium Shrubland cover type included both mountain snowberry and menziesia shrubs. In one case, the cover type occurs in very dry conditions while, in the other case, it occurs in a moist, cool environment. This resulted in two very different fire intervals for the same cover type. We recommend using a cover type classification more closely aligned with the classification employed for Zone 16, which categorizes the cover types based on their response to environmental conditions and fire intervals, rather than on a physiognomic classification (Long and others, Ch. 6). It should be noted that the development of such a classification requires the input of expert opinion.

Structural Stage Classification

Structural stages, as defined by the LANDFIRE structural stage classification, served as the main characteristic to describe forest development in the modeling process. It was assumed that as forests age, they become taller and denser. In addition, it was assumed that the height and cover classes would represent meaningful differences in seral stages and effectively describe early, mid, and late seral communities associated with the forest development process. The structural stage classification was built around four combinations of two height and two cover classes for each life form, and these classes were defined prior to the model building process. Thresholds used to define low height and high height as well as low cover and high cover had a great bearing on the modelers' ability to describe the forest development process.

For many of the cover types, the height thresholds used to define low height structural stages created succession classes that existed for too short of a time period and did not capture the entire age range of the mid-seral stage of forest development. This caused these classes to be insensitive to changes made in many of the model parameters, and they consequently had very little effect on the final results of the model. Conversely, height thresholds used define high height structural stages created succession classes that existed for too long of a time period and subsequently affected the model results greatly. We recommend defining structural stage categories that use height breaks that more concisely bracket age ranges within the succession classes and tier more to early, mid, and late seral stage concepts.

Disturbance Modeling

The overall disturbance modeling process became somewhat problematic because of the inherent differences between the ways VDDT and LANDSUMv4 model disturbance. The VDDT model is designed to treat each pixel independently of its neighbors, whereas LANDSUMv4 models fire spread across landscapes, incorporating landscape context into mapped model output. In other words, a simulated fire will spread to adjacent pixels in the LANDSUMv4 model, whereas pixels are modeled independently in the VDDT model. Thus fire intervals modeled in LANDSUMv4 for particular places on the landscape may not match those modeled in VDDT. We recommend use of LANDSUMv4 to test and verify the succession model input parameters. There may also be value in allowing the modelers to review the LANDSUMv4 output as a final assessment of the input parameters used in the modeling process and to evaluate the spatial aspects that LANDSUMv4 uses in the disturbance simulation process.

Another issue related to disturbance modeling encountered in the LANDFIRE Prototype Project involved species that followed stand-replacing disturbances. No preference was given to cover types that aggressively colonize following a fire event, such as Lodgepole Pine. Similarly, no advantage was given to cover types better-adapted to regeneration under the tree canopy conditions that usually develop after moderate disturbances, in types such as Grand Fir – White Fir. This approach may have underestimated the amount of Lodgepole Pine cover type resulting from stand-replacing fire as well as the amount of Grand Fir – White Fir cover type resulting from an insect outbreak. This situation should be evaluated in future modeling efforts. We recommend that, when estimating proportions of these outcomes, fire adapted species and their inherent survival strategies be considered in this process with less reliance on proportions from habitat type classifications.

One of the most difficult tasks in the vegetation modeling for the LANDFIRE Prototype was estimating the fire intervals and fire severities for the various succession classes within each PVT. Although estimates were available in the literature for the average fire return interval and fire severity of a particular cover type, little information was available regarding the ways return intervals or severities varied with the age of the cover type. In addition, there is very little information available regarding the return intervals of post-disturbance early seral stages of many cover types. We recommend that a wider array of experts, who specialize in a wide array of ecological conditions found around the country, develop such estimates for use in future modeling efforts.

Although we adjusted fire intervals by the structural stage of the cover type, no attempt was made to adjust fire intervals following events in the life of a stand that affect fuel loading or fuel conditions. One example of such an event would be an outbreak of mountain pine beetle in a lodgepole pine stand, which generally increases the risk of stand-replacing fire. We recommend that these types of interactions be explored in future modeling studies.

Model Evaluation

Historical vegetation studies may be used as guidelines to evaluate the results of each model; however, conclusive evaluation of the results from the various succession models is uncertain at best. Even in areas with good fire history studies, the model evaluation is subjective. In areas with limited data available on natural fire frequencies, the process will be even more difficult. We recommend developing guidelines, according to expert opinion, prior to model development to determine which criteria will be used to evaluate model results.

Conclusion

We executed each of our models for a 1000-year simulation period and assumed that the proportion of succession classes for each PVT at the end of the period would represent the historical conditions found on the landscape at the time of Euro-American settlement. In the succession model development process, we made every effort to simulate the historical succession and disturbance processes for each PVT. However, the variation and complexity of these processes is such that we should not imply that these results are the only representation of historical conditions for each PVT. The models reflect only our best understanding of these historical processes. The results of these models should be thought of as portraying a range of conditions, with a great deal of variation from one time period to the next.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Appendix 9-A—Spruce – Fir Forest PVTs

Appendix 9-A: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 16 Spruce – Fir PVTs.

Succession class	Spruce – Fir/Blue Spruce	Spruce – Fir/Spruce – Fir
Cool Season Grasses	15	15
Dry Deciduous Shrub	15	15
Montane Evergreen Shrubs	15	15
Mountain Deciduous Shrub		15
Native Forbs	10	10
Wetland Herbaceous	15	17
Aspen – Birch-HHF*	115	120
Aspen – Birch-HLF	25	22
Aspen – Birch-LHF	40	35
Aspen – Birch-LLF	10	8
Douglas-fir-HHF	255	260
Douglas-fir-HLF	30	27
Douglas-fir-LHF	45	45
Douglas-fir-LLF	15	13
Grand Fir – White Fir-HHF	250	
Grand Fir – White Fir-HLF	35	
Grand Fir – White Fir-LHF	50	
Grand Fir – White Fir-LLF	15	
Lodgepole Pine-HHF	170	175
Lodgepole Pine-HLF	15	13
Lodgepole Pine-LHF	35	30
Lodgepole Pine-LLF	15	12
Ponderosa Pine-HHF	470	
Ponderosa Pine-HLF	17	
Ponderosa Pine-LHF	35	
Ponderosa Pine-LLF	13	
Spruce – Fir-HHF	395	400
Spruce – Fir-HLF	30	30
Spruce – Fir-LHF	55	50
Spruce – Fir-LLF	25	20
Timberline Pine-HHF	225	
Timberline Pine-HLF	45	
Timberline Pine-LHF	45	
Timberline Pine-LLF	30	

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-A: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 16 Spruce – Fir PVTs.

Succession class	**Spruce – Fir/Blue Spruce**			**Spruce – Fir/Spruce – Fir**		
	SR*	MS	NL	SR	MS	NL
Cool Season Perennial Grass	200			200		
Native Forb	350			345		
Wetland Herbaceous	750			750		
Mountain Deciduous Shrub				600		
Dry Deciduous Shrub	300			400		
Montane Evergreen Shrub	250			300		
Aspen – Birch-LLF**	250			300		
Aspen – Birch-HLF	200			200		
Aspen – Birch-LHF	150		50	150		50
Aspen – Birch-HHF	125	85	60	125	100	60
Douglas-fir-LLF	75			100		
Douglas-fir-HLF	150		50	75		
Douglas-fir-LHF	300	100	40	400	100	40
Douglas-fir-HHF	200	100	50	300	100	50
Ponderosa Pine-LLF	75					
Ponderosa Pine-HLF	150		50			
Ponderosa Pine-LHF	250	150	30			
Ponderosa Pine-HHF	200	125	35			
Lodgepole Pine-LLF	300			300		
Lodgepole Pine-HLF	150			150		
Lodgepole Pine-LHF	200	125	80	200	150	80
Lodgepole Pine-HHF	175	100	75	175	125	80
Timberline Pine-LLF	300					
Timberline Pine-HLF	300					
Timberline Pine-LHF	300		100			
Timberline Pine-HHF	300	200	75			
Spruce – Fir-LLF	400			400		
Spruce – Fir-HLF	300			300		
Spruce – Fir-LHF	400	200	75	400	200	75
Spruce – Fir-HHF	300	200	75	300	200	100
Grand Fir – White Fir-LLF	100					
Grand Fir – White Fir-HLF	150		50			
Grand Fir – White Fir-LHF	300	125	40			
Grand Fir – White Fir-HHF	200	125	50			

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire

** For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-A: Table 3—Succession modeling results in percent composition of each of the Zone 16 Spruce – Fir PVTs.

Succession class	Spruce – Fir/ Blue Spruce	Spruce – Fir/ Spruce – Fir
Dry Deciduous Shrub	1.4	1.4
Mountain Deciduous Shrub		0.9
Montane Evergreen Shrub	1.5	0.1
Riparian Shrub		
Cool Season Perennial Grass	0.9	0.4
Native Forb	0.9	1.5
Wetland Herbaceous	0.1	0.4
Douglas-fir-LLF*	1	1.2
Douglas-fir-HLF	1	1.3
Douglas-fir-LHF	9.6	10.2
Douglas-fir-HHF	14.8	16.1
Ponderosa Pine-LLF	0.2	
Ponderosa Pine-HLF	0.3	
Ponderosa Pine-LHF	1	
Ponderosa Pine-HHF	2.1	
Grand Fir – White Fir-LLF	0.4	
Grand Fir – White Fir-HLF	0.6	
Grand Fir – White Fir-LHF	1.3	
Grand Fir – White Fir-HHF	1.3	
Lodgepole Pine-LLF	0.4	1
Lodgepole Pine-HLF	0.4	0.4
Lodgepole Pine-LHF	6.2	4.8
Lodgepole Pine-HHF	3.7	6.5
Spruce – Fir-LLF	1.1	2.8
Spruce – Fir-HLF	2	3.1
Spruce – Fir-LHF	9.6	11.3
Spruce – Fir-HHF	10.3	14.7
Aspen – Birch-LLF	2.1	1.6
Aspen – Birch-HLF	4.1	5.5
Aspen – Birch-LHF	7.7	5.3
Aspen – Birch-HHF	7.6	9.4
Timberline Pine-LLF	1.4	
Timberline Pine-HLF	0.5	
Timberline Pine-LHF	0.5	
Timberline Pine-HHF	3.9	

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-B—White Fir / Douglas-fir Forest PVTs

Appendix 9-B: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 16 White Fir / Douglas-fir PVTs.

Succession class	Grand Fir – White Fir	Douglas-fir/ Timberline Pine	Douglas-fir/ Douglas-fir	Douglas-fir/ Lodgepole Pine
Cool Season Grasses-HLH*			19	
Dry Deciduous Shrub-HLS	12		17	
Montane Evergreen Shrub-LLS	14			14
Mountain Deciduous Shrub-LHS	14	24	19	14
Native Forb-HLH				11
Aspen – Birch-HHF	110	125	110	110
Aspen – Birch-HLF	30	35	30	30
Aspen – Birch-LHF	45	50	45	45
Aspen – Birch-LLF	12	15	12	12
Douglas-fir-HHF	255	300	305	305
Douglas-fir-HLF	25	20	25	25
Douglas-fir-LHF	45	60	45	45
Douglas-fir-LLF	20	30	20	20
Grand Fir – White Fir-HHF	250			
Grand Fir – White Fir-HLF	30			
Grand Fir – White Fir-LHF	50			
Grand Fir – White Fir-LLF	20			
Juniper-HHF		310	310	
Juniper-HLF		150	150	
Juniper-LHF		75	75	
Juniper-LLF		40	40	
Lodgepole Pine-HHF				175
Lodgepole Pine-HLF				13
Lodgepole Pine-LHF				30
Lodgepole Pine-LLF				12
Pinyon – Juniper-HHF		225		
Pinyon – Juniper-HLF		35		
Pinyon – Juniper-LHF		75		
Pinyon – Juniper-LLF		40		
Ponderosa Pine-HHF	470	460	460	270
Ponderosa Pine-HLF	15	20	20	15
Ponderosa Pine-LHF	35	45	45	35
Ponderosa Pine-LLF	15	20	20	15
Timberline Pine-HHF	225	225		
Timberline Pine-HLF	45	35		
Timberline Pine-LHF	50	75		
Timberline Pine-LLF	30	40		

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-B: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 16 White Fir and Douglas-fir PVTs.

	Grand Fir – White Fir			Douglas-fi/Lodgepole Pine		
Succession class	**SR***	**MS**	**NL**	**SR**	**MS**	**NL**
Cool Season Grasses-HLH**						
Dry Deciduous Shrub-HLS	500			200		
Montane Evergreen Shrub-LLS	200			200		
Mountain Deciduous Shrub-LHS	150					
Native Forb-HLH				300		
Aspen – Birch-HHF	125	75	50	125	75	50
Aspen – Birch-HLF	150			150		
Aspen – Birch-LHF	200		50	175		50
Aspen – Birch-LLF	200			200		
Douglas-fir-HHF	200	125	40	150	125	75
Douglas-fir-HLF	150		40	100		60
Douglas-fir-LHF	300	100	40	300	75	50
Douglas-fir-LLF	50			75		
Grand Fir – White Fir-HHF	200	125	40			
Grand Fir – White Fir-HLF	150		40			
Grand Fir – White Fir-LHF	300	150	40			
Grand Fir – White Fir-LLF	75					
Lodgepole Pine-HHF				150	75	45
Lodgepole Pine-HLF				100		
Lodgepole Pine-LHF				200	150	50
Lodgepole Pine-LLF				300		
Ponderosa Pine-HHF	250	100	35	300	100	35
Ponderosa Pine-HLF	150		50	150		50
Ponderosa Pine-LHF	250	150	30	300	150	30
Ponderosa Pine-LLF	75			75		
Timberline Pine-HHF	300	200	75			
Timberline Pine-HLF	250					
Timberline Pine-LHF	300		100			
Timberline Pine-LLF	250					

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire
** For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-B: Table 3—Fire frequencies, in years and by severity type, used in succession modeling for Zone 16 White Fir and Douglas-fir PVTs.

	Douglas-fir/Timberline Pine			Douglas-fir/Douglas-fir		
Succession class	**SR***	**MS**	**NL**	**SR**	**MS**	**NL**
Cool Season Grasses-HLH**				100		
Dry Deciduous Shrub-HLS				400		
Montane Evergreen Shrub-LLS						
Mountain Deciduous Shrub-LHS	50			150		
Native Forb-HLH						
Aspen – Birch-HHF	125	85	59	125	85	50
Aspen – Birch-HLF	150			150		
Aspen – Birch-LHF	175		75	175		50
Aspen – Birch-LLF	200			200		
Douglas-fir-HHF	300	150	59	150	100	35
Douglas-fir-HLF	150		59	125		35
Douglas-fir-LHF	350		50	250	100	35
Douglas-fir-LLF	100			50		
Juniper-HHF	300	200		250	250	
Juniper-HLF	200			125		
Juniper-LHF	300	200		200	150	
Juniper-LLF	200			75		
Lodgepole Pine-HHF		75	45			
Lodgepole Pine-HLF						
Lodgepole Pine-LHF		150	50			
Lodgepole Pine-LLF						
Pinyon – Juniper-HHF	250	150	100			
Pinyon – Juniper-HLF	200		100			
Pinyon – Juniper-LHF	250	150	75			
Pinyon – Juniper-LLF	200			300	200	15
Ponderosa Pine-HHF	300		25	100		25
Ponderosa Pine-HLF	150		30	400	200	15
Ponderosa Pine-LHF	400	150	20	40		
Ponderosa Pine-LLF	50					
Timberline Pine-HHF	300	200	100			
Timberline Pine-HLF	100					
Timberline Pine-LHF	300		75			
Timberline Pine-LLF	200					

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire
** For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-B: Table 4—Succession modeling results in percent composition of each of the Zone 16 White Fir / Douglas-fir PVTs.

Succession class	**Grand Fir – White Fir**	**Douglas-fir/ Timberline Pine**	**Douglas-fir/ Douglas-fir**	**Douglas-fir/ Lodgepole Pine**
Cool Season Grasses-HLH*			0.2	
Dry Deciduous Shrub-HLS	5.1	10.3	1	3.4
Montane Evergreen Shrub-LLS	0.8			1.1
Mountain Deciduous Shrub-LHS	0.7		7.8	
Native Forb-HLH				2.8
Aspen – Birch-HHF	4.1	1.8	9.8	3.7
Aspen – Birch-HLF	4	1.3	5.6	2.8
Aspen – Birch-LHF	3.1	2.2	11.1	3.5
Aspen – Birch-LLF	1.8	1.1	2.7	1.2
Douglas-fir-HHF	19.3	30	21.5	38.7
Douglas-fir-HLF	1.3	1.8	3.2	2.3
Douglas-fir-LHF	11.3	15.6	15.6	17.7
Douglas-fir-LLF	2.1	2.9	4.7	4.2
Grand Fir – White Fir-HHF	4.4			
Grand Fir – White Fir-HLF	0.8			
Grand Fir – White Fir-LHF	4.7			
Grand Fir – White Fir-LLF	2.8			
Juniper-HHF		1.8	1.2	
Juniper-HLF		1.3	2.2	
Juniper-LHF		1.3	0.1	
Juniper-LLF		0.8	1.1	
Lodgepole Pine-HHF				3.2
Lodgepole Pine-HLF				0.5
Lodgepole Pine-LHF				2.8
Lodgepole Pine-LLF				1.3
Pinyon – Juniper-HHF		2		
Pinyon – Juniper-HLF		0.4		
Pinyon – Juniper-LHF		1.5		
Pinyon – Juniper-LLF		1		
Ponderosa Pine-HHF	14.1	7.6	7	7
Ponderosa Pine-HLF	1.1	0.4	0.9	0.7
Ponderosa Pine-LHF	6.8	4	3.7	2.4
Ponderosa Pine-LLF	1.3	0.5	0.5	0.6
Timberline Pine-HHF	4.8	5.5		
Timberline Pine-HLF	1.2	1.2		
Timberline Pine-LHF	0.9	1.9		
Timberline Pine-LLF	0.4	1.7		

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-C—Pine Forest PVTs

Appendix 9-C: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 16 Pine PVTs.

Succession class	Lodgepole Pine	Ponderosa Pine	Timberline Pine
Cool Season Grasses-HLH*	12	25	
Mountain Deciduous Shrub-LHS	12	30	50
Montane Evergreen Shrub-LLS	12	25	
Native Forb-HLH	10		
Wetland Herbaceous-LHH	15		
Aspen – Birch-HHF	110	100	
Aspen – Birch-HLF	30	35	
Aspen – Birch-LHF	45	50	
Aspen – Birch-LLF	12	15	
Juniper-HHF		310	
Juniper-HLF		150	
Juniper-LHF		75	
Juniper-LLF		40	
Lodgepole Pine-HHF	270		
Lodgepole Pine-HLF	18		
Lodgepole Pine-LHF	35		
Lodgepole Pine-LLF	12		
Pinyon – Juniper-HHF		225	
Pinyon – Juniper-HLF		35	
Pinyon – Juniper-LHF		75	
Pinyon – Juniper-LLF		40	
Ponderosa Pine-HHF		460	
Ponderosa Pine-HLF		20	
Ponderosa Pine-LHF		45	
Ponderosa Pine-LLF		20	
Timberline Pine-HHF			925
Timberline Pine-HLF			35
Timberline Pine-LHF			75
Timberline Pine-LLF			40

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-C: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 16 Pine PVTs.

	Lodgepole Pine			**Ponderosa Pine**			**Timberline Pine**		
Succession class	**SR***	**MS**	**NL**	**SR**	**MS**	**NL**	**SR**	**MS**	**NL**
Cool Season Grasses-HLH**	150								
Mountain Deciduous Shrub-LHS	200			50			200		
Montane Evergreen Shrub-LLS	200			75					
Native Forb-HLH	300								
Wetland Herbaceous-LHH	500								
Aspen – Birch-HHF	150	100	60	100	75	40			
Aspen – Birch-HLF	150			75					
Aspen – Birch-LHF	175		60	125		45			
Aspen – Birch-LLF	300			100					
Juniper-HHF				200	100	40			
Juniper-HLF				100		40			
Juniper-LHF				300	200	35			
Juniper-LLF				50					
Lodgepole Pine-HHF	150		45						
Lodgepole Pine-HLF	100								
Lodgepole Pine-LHF	200	100	60						
Lodgepole Pine-LLF	300								
Pinyon – Juniper-HHF				200	100	30			
Pinyon – Juniper-HLF				100		30			
Pinyon – Juniper-LHF				300	200	25			
Pinyon – Juniper-LLF				40					
Ponderosa Pine-HHF				300	100	15			
Ponderosa Pine-HLF				100		25			
Ponderosa Pine-LHF				400	200	10			
Ponderosa Pine-LLF				40					
Timberline Pine-HHF							300	200	100
Timberline Pine-HLF							100		
Timberline Pine-LHF							350		75
Timberline Pine-LLF							200		

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire
** For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-C: Table 3—Succession modeling results in percent composition of each of the Zone 16 Pine PVTs.

Succession class	Lodgepole Pine	Ponderosa Pine	Timberline Pine
Cool Season Grasses-HLH*	0.4	3.8	
Mountain Deciduous Shrub-LHS	1.7	6.8	17.1
Montane Evergreen Shrub-LLS	0.8	2.5	
Native Forb-HLH	0.2		
Wetland Herbaceous-LHH	0.6		
Aspen – Birch-HHF	17.7	2.7	
Aspen – Birch-HLF	9.5	3	
Aspen – Birch-LHF	16.6	2.8	
Aspen – Birch-LLF	4.5	1	
Juniper-HHF		0.5	
Juniper-HLF		1.3	
Juniper-LHF		0.1	
Juniper-LLF		0.9	
Lodgepole Pine-HHF	19.7		
Lodgepole Pine-HLF	5.7		
Lodgepole Pine-LHF	16.6		
Lodgepole Pine-LLF	5.9		
Pinyon – Juniper-HHF		0.8	
Pinyon – Juniper-HLF		0.5	
Pinyon – Juniper-LHF		0.2	
Pinyon – Juniper-LLF		0.5	
Ponderosa Pine-HHF		38.7	
Ponderosa Pine-HLF		1.8	
Ponderosa Pine-LHF		28	
Ponderosa Pine-LLF		4	
Timberline Pine-HHF			49.3
Timberline Pine-HLF			7.2
Timberline Pine-LHF			16
Timberline Pine-LLF			10.4

* For complete structural stage names, refer to table 5: *Structural stages used for succession modeling in zones 16 and 19.*

Appendix 9-D—Broadleaf Forest PVTs

Appendix 9-D: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 16 Broadleaf PVTs.

Succession class	Riparian Hardwood	Aspen
Cool Season Grasses-HLH*	10	10
Dry Deciduous Shrub-HLS	15	12
Montane Evergreen Shrub-LLS		12
Mountain Deciduous Shrub-LHS	15	
Native Forb-HLH		8
Wetland Herbaceous-LHH		10
Aspen – Birch-HHF		120
Aspen – Birch-HLF		22
Aspen – Birch-LHF		35
Aspen – Birch-LLF		8
Juniper-HHF	100	
Juniper-HLF	70	
Juniper-LHF	50	
Juniper-LLF	30	
Mountain Deciduous Shrub -HHF	80	
Mountain Deciduous Shrub -HLF	10	
Mountain Deciduous Shrub -LHF	25	
Mountain Deciduous Shrub -LLF	10	
Riparian Hardwood-HHF	200	
Riparian Hardwood-HLF	22	
Riparian Hardwood-LHF	50	
Riparian Hardwood-LLF	8	

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-D: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 16 Broadleaf PVTs.

Succession class	Riparian Hardwood SR*	Riparian Hardwood MS	Riparian Hardwood NL	Aspen SR	Aspen MS	Aspen NL
Cool Season Grasses-HLH**	250			200		
Dry Deciduous Shrub-HLS	300			300		
Montane Evergreen Shrub-LLS				300		
Mountain Deciduous Shrub-LHS	400					
Native Forb-HLH				350		
Wetland Herbaceous-LHH				750		
Aspen – Birch-HHF				100		75
Aspen – Birch-HLF				150		
Aspen – Birch-LHF				200		50
Aspen – Birch-LLF				200		
Juniper-HHF 150	100	75				
Juniper-HLF 150		75				
Juniper-LHF 150	100	75				
Juniper-LLF 200						
Mountain Deciduous Shrub-HHF	150		75			
Mountain Deciduous Shrub-HLF	200					
Mountain Deciduous Shrub-LHF	150		60			
Mountain Deciduous Shrub-LLF	200					
Riparian Hardwood-HHF	200		100			
Riparian Hardwood-HLF	200					
Riparian Hardwood-LHF	200		100			
Riparian Hardwood-LLF	200					

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire

* *For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-D: Table 3—Succession modeling results in percent composition of each of the Zone 16 Broadleaf PVTs.

Succession class	Riparian Hardwood	Aspen
Cool Season Grasses-HLH*	2.5	0.5
Dry Deciduous Shrub-HLS	2.3	2.5
Montane Evergreen Shrub-LLS		0.9
Mountain Deciduous Shrub-LHS	1.2	
Native Forb-HLH		0.8
Wetland Herbaceous-LHH		0
Aspen – Birch-HHF		55.4
Aspen – Birch-HLF		14.8
Aspen – Birch-LHF		17.7
Aspen – Birch-LLF		7.4
Juniper-HHF	2.3	
Juniper-HLF	2.4	
Juniper-LHF	3.9	
Juniper-LLF	2.9	
Mountain Deciduous Shrub -HHF	3.8	
Mountain Deciduous Shrub -HLF	0.8	
Mountain Deciduous Shrub -LHF	0.9	
Mountain Deciduous Shrub -LLF	0.6	
Riparian Hardwood-HHF	39.7	
Riparian Hardwood-HLF	8.7	
Riparian Hardwood-LHF	23.3	
Riparian Hardwood-LLF	3.8	

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-E—Pinyon – Juniper Woodland PVTs

Appendix 9-E: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 16 Pinyon – Juniper PVTs.

Succession class	Pinyon – Juniper/Wyoming – Basin Big Sagebrush		Pinyon – Juniper/ Mountain Big Sagebrush	
	Northern variant	Southern variant	Northern variant	Southern variant
Cool Season Grasses-LHH*	20		5	10
Cool Season Grasses-LLH	25	25		
Desert Shrub-LHS	25	25		
Desert Shrub-LLS	20	20		
Dry Deciduous Shrub-LHS	25		25	25
Dry Deciduous Shrub-LLS	20		20	20
Dwarf Sagebrush Complex-LHS	25	25		
Dwarf Sagebrush Complex-LLS	20	20		
Juniper-HHW	250	250	300	300
Juniper-LHW	100	100	100	100
Juniper-LLW	50	50	50	5
Mountain Big Sagebrush Complex-HLS			30	30
Mountain Big Sagebrush Complex-LLS			10	15
Mountain Deciduous Shrub-LHS			25	25
Mountain Deciduous Shrub-LLS			20	20
Pinyon – Juniper HHW	250	250	300	300
Pinyon – Juniper-LHW	100	100	100	100
Pinyon – Juniper-LLW	50	50	50	50
Wyoming – Basin Big Sagebrush Complex-HLS	50	50		
Wyoming – Basin Big Sagebrush Complex-LLS	25	25		

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-E: Table 2—Fire frequencies, in years, used in succession modeling for Zone 16 Pinyon – Juniper PVTs. All fires were modeled as stand-replacing.

	Pinyon – Juniper/Wyoming – Basin Big Sagebrush		Pinyon – Juniper/ Mountain Big Sagebrush	
Succession class	**Northern variant**	**Southern variant**	**Northern variant**	**Southern variant**
Cool Season Grasses-LHH*	50	50	30	30
Cool Sseason Grasses-LLH	50	50	30	30
Desert Shrub-HLS	60	60		
Desert Shrub-LLS	60	60		
Dry Deciduous Shrub-HLS	40	40		
Dry Deciduous Shrub-LLS	50	50		
Dwarf Sagebrush Complex-HLS	60	60		
Dwarf Sagebrush Complex-LLS	60	60		
Juniper-HHW	60	60	30	30
Juniper-HLW	50	50	30	30
Mountain Big Sagebrush Complex –LLS			30	30
Mountain Big Sagebrush Complex-HLS			30	30
Mountain Deciduous Shrub-HLS			30	30
Mountain Deciduous Shrub-LLS			30	30
Pinyon – Juniper-HHW	50	50	30	30
Pinyon – Juniper-HLW	60	60	30	30
Wyoming – Basin Big Sagebrush Complex-HLS	50	50		
Wyoming – Basin Big Sagebrush Complex–LLS	50	50		

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-E: Table 3—Succession modeling results in percent composition of each of the Zone 16 Pinyon – Juniper PVTs. PVTs. All fires were modeled as stand-replacing.

	Pinyon – Juniper/Wyoming – Basin Big Sagebrush		Pinyon – Juniper/ Mountain Big Sagebrush	
Succession class	**Northern variant**	**Southern variant**	**Northern variant**	**Southern variant**
Cool Season Grasses-LHH*			5	
Cool Season Grasses-LLH	2	1	4	3
Desert Shrub-LHS	2	2		
Desert Shrub-LLS	2	2		
Dry Deciduous Shrub-LHS	2			
Dry Deciduous Shrub-LLS	3		1	
Dwarf Sagebrush Complex-LHS		1		
Dwarf Sagebrush Complex-LLS		2		
Juniper-HHW			1	
Juniper-LHW			15	
Juniper-LLW			46	
Mountain Big Sagebrush Complex-HLS			8	7
Mountain Big Sagebrush Complex-LLS			19	18
Mountain Deciduous Shrub-LHS				9
Mountain Deciduous ShrubLLS				1
Pinyon – Juniper High-HHW	5	10		
Pinyon – Juniper-LHW	24	35		16
Pinyon – Juniper-LLW	33	32		44
Wyoming – Basin Big Sagebrush Complex-HLS	4	1		
Wyoming – Basin Big Sagebrush Complex-LLS	23	2		

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-F—Mountain Shrubland PVTs

Appendix 9-F: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 16 Mountain PVTs.

Succession class	Pinyon – Juniper/ Mountain Mahogany	Pinyon – Juniper/ Gambel Oak	Grand Fir – White Fir/Maple
Cool Season Grasses-HLH*			2
Cool Season Grasses-LLH	10	3	1
Dry Deciduous Shrub-LHS	25	15	
Dry Deciduous Shrub-LLS	25	12	
Grand Fir – White Fir-HHF			50
Grand Fir – White Fir-LHF			50
Mountain Deciduous Shrub-HLW	20	20	14
Mountain Deciduous Shrub-LHW		150	
Mountain Deciduous Shrub-LLW	16	27	14
Mountain Mahogany-HHW	35		
Mountain Mahogany-LHW	255		
Pinyon – Juniper -LHW	65	100	
Pinyon – Juniper-HHW	100	100	
Pinyon – Juniper-LLW	25	50	
Riparian Hardwood-HHF			100
Riparian Hardwood-LHF			65
Riparian Hardwood-LLF			30

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-F: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 16 Mountain PVTs.

Succession class	Pinyon – Juniper/ Mountain Mahogany	Pinyon – Juniper/ Gambel Oak	Grand Fir – White Fir/Maple
Cool season perennial grass-HLH*			35
Cool season perennial grass-LLH	60	50	100
Dry Deciduous Shrub-LHS	50	40	
Dry Deciduous Shrub_LLS	60	50	
Grand Fir – White Fir-HHF			35
Grand Fir – White Fir-LHF			50
Mountain Deciduous Shrub-HLW	50		35
Mountain Deciduous Shrub-LHW	50		50
Mountain Deciduous Shrub-LLW		40	
Mountain Deciduous Shrub-HHW		40	
Mountain Mahogany-HHW	60		
Mountain Mahogany-LHW	60		
Pinyon – Juniper-HHW	60	35	
Pinyon – Juniper-LLW	60	35	
Riparian Hardwood-HHF			
Riparian Hardwood-LHF			50
Riparian Hardwood-LLF			50

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-F: Table 3—Succession modeling results in percent composition of each of the Zone 16 Mountain PVTs.

Succession class	Pinyon – Juniper/ Mountain Mahogany	Pinyon – Juniper/ Gambel Oak	Grand Fir – White Fir/Maple
Cool season perennial grass-HLH*			3
Cool season perennial grass-LLH	2	4	1
Dry Deciduous Shrub-LHS	8	13	
Dry Deciduous Shrub-LLS	3	11	
Grand Fir – White Fir-HHF			49
Grand Fir – White Fir-LHF			19
Mountain Deciduous Shrub-HLW		23	13
Mountain Deciduous Shrub-LHW		0	
Mountain Deciduous Shrub-LLW		2	11
Mountain Mahogany-HHW	33		
Mountain Mahogany-LHW	54		
Pinyon – Juniper-HHW		2	
Pinyon – Juniper-HLW	1	14	
Pinyon – Juniper-LLW		31	
Riparian Hardwood-HHF			0
Riparian Hardwood-LHF			4
Riparian Hardwood-LLF			0

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-G—Sagebrush Shrubland PVTs

Appendix 9-G: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 16 Sagebrush PVTs.

Succession class	Dwarf Sagebrush Complex	Wyoming – Basin Big Sagebrush Complex	Mountain Big Sagebrush Complex
Cool Season Grasses-HLH*		42	15
Cool Season Grasses-LLH	20	3	
Dry Deciduous Shrub-HLS		30	30
Dry Deciduous Shrub-LLS		12	11
Dwarf Sagebrush Complex-HLS	150		
Dwarf Sagebrush Complex-LLS	30		
Mountain Deciduous Shrub-HHS		12	30
Mountain Deciduous Shrub-LHS		185	13
Mountain Big Sagebrush Complex-HLS			56
Mountain Big Sagebrush Complex-LLS			30
Rabbitbrush-HLS	30	12	13
Rabbitbrush-LLS	17	30	30
Salt Desert Shrub-HLS	180	175	
Salt Desert Shrub-LLS	17	22	
Wyoming – Basin Big Sagebrush-HLS	100	100	
Wyoming – Basin Big Sagebrush-LLS	50	55	

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-G: Table 2—Fire frequencies, in years, used in succession modeling for Zone 16 Sagebrush PVTs. All fires were modeled as stand-replacing.

Succession class	Dwarf Sagebrush Complex	Wyoming – Basin Big Sagebrush Complex	Mountain Big Sagebrush Complex
Cool Season Grasses-HLH*		80	20
Cool Season Grasses-LLH	80	100	20
Dry Deciduous Shrub-HLS		60	20
Dry Deciduous Shrub-LLS		80	20
Dwarf Sagebrush Complex-HLS	100		
Dwarf Sagebrush Complex-LLS	100		
Mountain Deciduous Shrub-HHS		60	20
Mountain Deciduous Shrub-LHS		80	20
Mountain Big Sagebrush Complex-HLS			20
Mountain Big Sagebrush Complex-LLS			20
Rabbitbrush-HLS	60	60	20
Rabbitbrush-LLS	80	80	20
Salt Desert Shrub-HLS	100	100	
Salt Desert Shrub-LLS	120	100	
Wyoming – Basin Big Sagebrush-HLS	80	80	
Wyoming – Basin Big Sagebrush-LLS	80	80	

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-G: Table 3—Succession modeling results in percent composition of each of the Zone 16 Sagebrush PVTs.

Succession class	Dwarf Sagebrush Complex	Wyoming – Basin Big Sagebrush Complex	Mountain Big Sagebrush Complex
Cool Season Grasses-HLH*		23	5
Cool Season Grasses-LLH	3	2	
Dry Deciduous Shrub-HLS		3	7
Dry Deciduous Shrub-LLS		3	6
Dwarf Sagebrush Complex-HLS	80		
Dwarf Sagebrush Complex-LLS			
Mountain Deciduous Shrub-HHS		1	6
Mountain Deciduous Shrub-LHS		7	8
Mountain Big Sagebrush Complex-HLS			22
Mountain Big Sagebrush Complex-LLS			47
Rabbitbrush-HLS		4	
Rabbitbrush-LLS	5	2	
Salt Desert Shrub-HLS	1		
Salt Desert Shrub-LLS	10		
Wyoming – Basin Big Sagebrush-HLS		27	
Wyoming – Basin Big Sagebrush-LLS	1	28	

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-H—Desert Shrubland PVTs

Appendix 9-H: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 16 Desert PVTs.

Succession class	Blackbrush	Salt Desert Shrub
Blackbrush-HLS* 100		
Cool Season Grasses-LLH		15
Warm Season Grasses-LLH	3	
Desert Shrub-HLS	27	185
Desert Shrub-LLS	71	12
Rabbitbrush-LLS		12
Salt Desert Shrub-HLS		150
Salt Desert Shrub-LLS		35
Wyoming – Basin Big Sagebrush Complex-HLS		100

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-H: Table 2—Fire frequencies, in years, used in succession modeling for Zone 16 Desert PVTs. All fires were modeled as stand-replacing.

Succession class	Blackbrush	Salt Desert Shrub
Blackbrush-HLS*	200	
Cool Season Grasses-LLH		150
Warm Season Grasses-LLH	200	
Desert Shrub-HLS	200	100
Desert Shrub-LLS	200	150
Rabbitbrush-LLS		100
Salt Desert Shrub-HLS		100
Salt Desert Shrub-LLS		150
Wyoming – Basin Big Sagebrush Complex-HLS		85

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-H: Table 3—Succession modeling results in percent composition of each of the Zone 16 Desert PVTs.

Succession class	Blackbrush	Salt Desert Shrub
Blackbrush-HLS*	61	
Cool Season Grasses-LLH		1
Warm Season Grasses-LLH	1	
Desert Shrub-HLS	13	0
Desert Shrub-LLS	25	0
Rabbitbrush-LLS		3
Salt Desert Shrub-HLS		32
Salt Desert Shrub-LLS		4
Wyoming – Basin Big Sagebrush Complex-HLS		29

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-I—Western Redcedar and Grand Fir Forest PVTs

Appendix 9-I: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 19 Western Redcedar and Grand Fir PVTs.

Succession class	Western Redcedar	Grand Fir
Aspen – Birch-HHT*		120
Aspen – Birch-HLMT		18
Aspen – Birch-LHT		35
Aspen – Birch-LLMT		12
Cedar-HHT	550	
Cedar-HLMT	20	
Cedar-LHT	55	
Cedar-LLMT	30	
Douglas-fir-HHT	375	375
Douglas-fir-HLMT	10	10
Douglas-fir-LHT	30	30
Douglas-fir-LLMT	15	15
Grand fir-HHT	265	945
Grand fir-HLMT	15	15
Grand fir-LHT	40	40
Grand fir-LLMT	20	20
Hemlock-HHT	460	
Hemlock-HLMT	15	
Hemlock-LHT	45	
Hemlock-LLMT	25	
Larch-HHT	330	480
Larch-HLMT	8	10
Larch-LHT	25	30
Larch-LLMT	12	12
Lodgepole Pine-HHT	125	175
Lodgepole Pine-HLMT	10	10
Lodgepole Pine-LHT	30	30
Lodgepole Pine-LLMT	15	15
Ponderosa Pine-HHT		420
Ponderosa Pine-HLMT		15
Ponderosa Pine-LHT		35
Ponderosa Pine-LLMT		15
Spruce – Fir-HHT	365	310
Spruce – Fir-HLMT	15	15
Spruce – Fir-LHT	40	45
Spruce – Fir-LLMT	20	25
White Pine-HHT	420	370
White Pine-HLMT	13	15
White Pine-LHT	35	35
White Pine-LLMT	15	15
Perennial Forb-HLHB	9	11
Perennial Native Bunch Gramminoid-HHHB	11	
Perennial Native Rhizomatous Gramminoid-HLHB	9	11
Riparian Broadleaf Shrubland-HHSH	14	
Upland Broadleaf Dwarf Shrubland-HLSH		14
Upland Broadleaf Medium Shrubland-HMSH	11	14
Upland Broadleaf Tall Shrubland-HHSH	14	17
Wetland Herbaceous-HHHB	11	14

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-I: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 19 Western Redcedar and Grand Fir PVTs.

	Western Redcedar			**Grand Fir**		
Succession class	**SR***	**MS**	**NF**	**SR**	**MS**	**NL**
Aspen – Birch-HHT**				200	95	
Aspen – Birch-HLMT				150		
Aspen – Birch-LHT				200		65
Aspen – Birch-LLMT				200		
Cedar-HHT	350	350				
Cedar-HLMT	350					
Cedar-LHT	400	300	200			
Cedar-LLMT	350					
Douglas-fir-HHT	350	250	200	300	125	90
Douglas-fir-HLMT	300			50		
Douglas-fir-LHT	400	200	170	350	150	65
Douglas-fir-LLMT	300			75		
Grand Fir-HHT	300	125		250	100	150
Grand Fir-HLMT	300			75		
Grand Fir-LHT	400	200	170	300	125	90
Grand Fir-LLMT	300			75		
Hemlock-HHT	350	350				
Hemlock-HLMT	350					
Hemlock-LHT	400	300	200			
Hemlock-LLMT	350					
Larch-HHT	200	100		150	75	
Larch-HLMT	250			75		
Larch-LHT	300	200	85	200	100	100
Larch-LLMT	350			200		
Lodgepole Pine-HHT				300	150	54
Lodgepole Pine-HLMT				100	100	
Lodgepole Pine-LHT				350	250	38
Lodgepole Pine-LLMT				75		
Ponderosa Pine-HHT	350	350		250	110	
Ponderosa Pine-HLMT	350			200		
Ponderosa Pine-LHT	400	300	250	300	150	100
Ponderosa Pine-LLMT	350			250		
Spruce – Fir-HHT	300	200	135	300	200	60
Spruce – Fir-HLMT	500	500		100	100	
Spruce – Fir-LHT	350	200	100	350	200	48
Spruce – Fir-LLMT	250			75		
White Pine-HHT	350	150	400	300	200	200
White Pine-HLMT	350			100		
White Pine-LHT	400	250	150	300	250	155
White Pine-LLMT	350			150		
Perennial Forb-HLHB	350					
Perennial Native Bunch Gramminoid-HHHB	200			150		
Perennial Native Rhizomatous Gramminoid-HLHB	225			400		
Riparian Broadleaf Shrubland-HHSH				150		
Upland Broadleaf Dwarf Shrubland-HLSH	250			150		
Upland Broadleaf Medium Shrubland-HMSH	250			150		
Upland Broadleaf Tall Shrubland-HHSH	450			150		
Wetland Herbaceous-HHHB	500					

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire
** For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-I: Table 3—Succession modeling results in percent composition of each of the Zone 19 Western Redcedar and Grand Fir PVTs.

Succession class	Western Redcedar	Grand Fir
Aspen – Birch-HHT*		0.9
Aspen – Birch-HLMT		0.7
Aspen – Birch-LHT		0.3
Aspen – Birch-LLMT		0.4
Cedar-HHT	15.8	
Cedar-HLMT	0.9	
Cedar-LHT	0.9	
Cedar-LLMT	1.2	
Douglas-fir-HHT	20.3	20.7
Douglas-fir-HLMT	0.5	0.4
Douglas-fir-LHT	4.5	9.8
Douglas-fir-LLMT	1.7	2.7
Grand Fir-HHT	0.7	5.8
Grand Fir-HLMT	0.2	0.5
Grand Fir-LHT	0.1	3.7
Grand Fir-LLMT	0.5	1.7
Hemlock-HHT	9.2	
Hemlock-HLMT	0.5	
Hemlock-LHT	0	
Hemlock-LLMT	1.2	
Larch-HHT	0.9	0.6
Larch-HLMT	0.1	0.5
Larch-LHT	0	0.6
Larch-LLMT	0.3	0.7
Lodgepole Pine-HHT		1.5
Lodgepole Pine-HLMT		0.1
Lodgepole Pine-LHT		1.1
Lodgepole Pine-LLMT		0.1
Ponderosa Pine-HHT	7.1	3.9
Ponderosa Pine-HLMT	0.4	0.5
Ponderosa Pine-LHT	0.9	1.2
Ponderosa Pine-LLMT	0.9	1.2
Spruce – Fir-HHT	16.6	21.6
Spruce – Fir-HLMT	0.5	0.4
Spruce – Fir-LHT	1.6	8.7
Spruce – Fir-LLMT	1	0.7
White Pine-HHT	5.5	2.5
White Pine-HLMT	0.1	0.1
White Pine-LHT	2.1	0.4
White Pine-LLMT	0	0.2
Perennial Forb-HLHB	1.5	1.4
Perennial Native Bunch Gramminoid-HHHB	0.3	
Perennial Native Rhizomatous Gramminoid-HLHB	0	0.4
Riparian Broadleaf Shrubland-HHSH		0.5
Upland Broadleaf Dwarf Shrubland-HLSH	0.7	2.5
Upland Broadleaf Medium Shrubland-HMSH	0.6	0.5
Upland Broadleaf Tall Shrubland-HHSH	0.6	
Wetland Herbaceous-HHHB	0	0.5

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-J—Spruce – Fir Forest PVTs

Appendix 9-J: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 19 Spruce – Fir PVTs.

Succession class	Spruce – Fir/ Montane	Spruce – Fir/ Subalpine	Spruce – Fir/ Timberline
Douglas-fir-HHTR*	370		
Douglas-fir-HLMT	15		
Douglas-fir-LHT	35		
Douglas-fir-LLMT	15		
Lodgepole Pine-HHT	175	220	300
Lodgepole Pine-HLMT	10	12	20
Lodgepole Pine-LHT	30	35	55
Lodgepole Pine-LLMT	15	16	30
Spruce – Fir-HHT	302	300	290
Spruce – Fir-HLMT	20	20	20
Spruce – Fir-LHT	55	55	65
Spruce – Fir-LLMT	28	30	40
Timberline Forest-HHT			310
Timberline Forest-HLMT			40
Timberline Forest-LHT			100
Timberline Forest-LLMT			50
Western Larch-HHT	325		
Western Larch-HLMT	10		
Western Larch-LHT	30		
Western Larch-LLMT	16		
Perennial Forb-HLHB	12	15	35
Perennial Native Bunch Gramminoid-HHHB	15	15	50
Perennial Native Rhizomatous Gramminoid-HLHB	12	15	45
Riparian Broadleaf Shrub-HHSH	18	20	
Shrubby Cinquefoil-HMSH			40
Upland Broadleaf Dwarf Shrub-HLSH	15	15	40
Upland Broadleaf Medium Shrub-HMSH	15	12	40
Upland Broadleaf Tall Shrub-HHSH	18	20	
Upland Needleleaf Shrub-LLSH	18		
Upland Sclerophyllous Shrub-HLSH	15	15	
Wetland Herbaceous-HHHB	15	15	

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-J: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 19 Spruce – Fir PVTs.

	Spruce – Fir/ Montane			**Spruce – Fir/ Subalpine**			**Spruce – Fir/ Timberline**		
Succession class	**SR***	**MS**	**NL**	**SR**	**MS**	**NL**	**SR**	**MS**	**NL**
Douglas-fir-HHTR**	300	200	100						
Douglas-fir-HLMT	200								
Douglas-fir-LHT	400	200	75						
Douglas-fir-LLMT	250								
Lodgepole Pine-HHT	250	100		300	200		300	300	
Lodgepole Pine-HLMT	100			300			250		
Lodgepole Pine-LHT	300	150	150	300		100	400		200
Lodgepole Pine-LLMT	300			350			300		
Spruce – Fir-HHT	250	270		350	350		300	400	
Spruce – Fir-HLMT	300			400			350		
Spruce – Fir-LHT	350	180	70	400	400		400	300	
Spruce – Fir-LLMT	300			400			350		
Timberline Forest-HHT							300	300	
Timberline Forest-HLMT							400		
Timberline Forest-LHT							400	400	
Timberline Forest-LLMT							400		
Western Larch-HHT	300	200	75						
Western Larch-HLMT	400	400							
Western Larch-LHT	500		45						
Western Larch-LLMT	250								
Perennial Forb-HLHB	300			350			400		
Perennial Native Bunch Gramminoid-HHHB	175			150			200		
Perennial Native Rhizomatous Gramminoid-HLHB	200			200			300		
Riparian Broadleaf Shrub-HHSH	400			400					
Shrubby Cinquefoil-HMSH							300		
Upland Broadleaf Dwarf Shrub-HLSH	200			175			300		
Upland Broadleaf Medium Shrub-HMSH	200			250			200		
Upland Broadleaf Tall Shrub-HHSH	150			300					
Upland Needleleaf Shrub-LLSH	150								
Upland Ssclerophyllous Shrub-HLSH	250			200					
Wetland Herbaceous-HHHB				500					

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire
**For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-J: Table 3—Succession modeling results in percent composition of each of the Zone 19 Spruce – Fir PVTs.

Succession class	Spruce – Fir/ Montane	Spruce – Fir/ Subalpine	Spruce – Fir/ Timberline
Douglas-fir-HHTR*	24.1		
Douglas-fir-HLMT	1.1		
Douglas-fir-LHT	7.7		
Douglas-fir-LLMT	1.9		
Lodgepole Pine-HHT	6.1	11.1	3.8
Lodgepole Pine-HLMT	0.7	0.8	0.8
Lodgepole Pine-LHT	3.2	6.1	0.7
Lodgepole Pine-LLMT	1.5	1.6	1.2
Spruce – Fir-HHT	21.3	50.2	38.3
Spruce – Fir-HLMT	2.2	4.6	2.8
Spruce – Fir-LHT	6.7	14.2	10.5
Spruce – Fir-LLMT	3.9	6.5	5.1
Timberline Forest-HHT			10.6
Timberline Forest-HLMT			3
Timberline Forest-LHT			7.2
Timberline Forest-LLMT			4.5
Western Larch-HHT	9.5		
Western Larch-HLMT	0.5		
Western Larch-LHT	4.3		
Western Larch-LLMT	0.6		
Perennial Forb-HLHB	1.3	1.4	3.6
Perennial Native Bunch Gramminoid-HHHB	0.1	0.3	1.2
Perennial Native Rhizomatous Gramminoid-HLHB	0.3	0.3	0.4
Riparian Broadleaf Shrub-HHSH	0.1	0.3	
Shrubby Cinquefoil-HMSH			0.4
Upland Broadleaf Dwarf Shrub-HLSH	0.5	0.6	4.7
Upland Broadleaf Medium Shrub-HMSH	1.6	0.1	1.2
Upland Broadleaf Tall Shrub-HHSH	0.2	0	
Upland Needleleaf Shrub-LLSH	0.1		
Upland Sclerophyllous Shrub-HLSH	0.2	0.8	
Wetland Herbaceous-HHHB	0.2	1	

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-K—Douglas-fir Forest PVTs

Appendix 9-K: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 19 Douglas-fir PVTs.

Succession class	Douglas-fir/ Timber-line Pine	Douglas-fir/ Ponderosa Pine	Douglas-fir/ Douglas-fir	Douglas-fir/ Lodge-pole Pine
Douglas-fir-HHT*	350	415	375	365
Douglas-fir-HLMT	20	15	10	15
Douglas-fir-LHT	60	40	30	40
Douglas-fir-LLMT	30	20	15	20
Juniper-HHT	250			
Juniper-HLMT	40			
Juniper-LHT	110			
Juniper-LLMT	60			
Limber Pine-HHT	620			
Limber Pine-HLMT	30			
Limber Pine-LHT	90			
Limber Pine-LLMT	50			
Lodgepole Pine-HHT		175	170	170
Lodgepole Pine-HLMT		12	12	12
Lodgepole Pine-LHT		35	35	35
Lodgepole Pine-LLMT		15	16	16
Ponderosa Pine-HHT		470	420	
Ponderosa Pine-HLMT		15	13	
Ponderosa Pine-LHT		35	35	
Ponderosa Pine-LLMT		17	16	
Western Larch-HHT		475	430	420
Western Larch-HLMT		12	10	13
Western Larch-LHT		35	30	35
Western Larch-LLMT		15	13	17
Mountain Big Sage-HMSH	45		35	
Perennial Forb-HLHB	35	20	15	15
Perennial Native Bunch Gramminoid-HHHB	50	25	20	20
Perennial Native Rhizomatous Gramminoid-HLHB		25	20	18
Upland Broadleaf Dwarf Shrub-HLSH			18	15
Upland Broadleaf Medium Shrub-HMSH	40	20	18	15
Upland Broadleaf Tall Shrub-HHSH			20	
Upland Needleleaf Shrub-LMSH	50			20
Upland Sclerophyllous Shrub-HLSH	40	20		15
Wyoming – Basin Big Sage-HMSH	45	30	35	25

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-K: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 19 Douglas-fir / Timberline Pine and Douglas-fir / Ponderosa Pine PVTs.

	Douglas-fir/Timberline Pine			**Douglas-fir/Ponderosa Pine**		
Succession class	**SR***	**MS**	**NL**	**SR**	**MS**	**NL**
Douglas-fir-HHT**	200	150	120	150	75	50
Douglas-fir-HLMT	75			40		
Douglas-fir-LHT	200		58	300	150	25
Douglas-fir-LLMT	75			45		
Juniper-HHT200	150					
Juniper-HLMT	200					
Juniper-LHT300		75				
Juniper-LLMT200						
Limber Pine-HHT	200	150				
Limber Pine-HLMT	200					
Limber Pine-LHT	300		75			
Limber Pine-LLMT	200					
Lodgepole Pine-HHT				150	75	115
Lodgepole Pine-HLMT				30		
Lodgepole Pine-LHT				200	125	50
Lodgepole Pine-LLMT				50		
Ponderosa Pine-HHT				400	150	25
Ponderosa Pine-HLMT				70	70	
Ponderosa Pine-LHT				400	400	16
Ponderosa Pine-LLMT				40		
Western Larch-HHT				450	150	32
Western Larch-HLMT				80	60	
Western Larch-LHT				500	250	23
Western Larch-LLMT				40		
Mountain Big Sage-HMSH	60					
Perennial Forb-HLHB	75			50		
Perennial Native Bunch Gramminoid-HHHB	30			20		
Perennial Native Rhizomatous Gramminoid-HLHB				30		
Upland Broadleaf Dwarf Shrub-HLSH						
Upland Broadleaf Medium Shrub-HMSH	150			60		
Upland Broadleaf Tall Shrub-HHSH						
Upland Needleleaf Shrub-LMSH	60					
Upland Sclerophyllous Shrub-HLSH	50			50		
Wyoming – Basin Big Sage-HMSH	60			25		

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire
**For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-K: Table 3—Fire frequencies, in years and by severity type, used in succession modeling for Zone 19 Douglas-fir / Lodgepole Pine and Douglas-fir / Douglas-fir PVTs.

	Douglas-fir/Lodgepole Pine			Douglas-fir/Douglas-fir		
Succession class	**SR***	**MS**	**NL**	**SR**	**MS**	**NL**
Douglas-fir-HHT**	250	125	93	300	100	120
Douglas-fir-HLMT	50			50		
Douglas-fir-LHT	300	200	55	350	100	60
Douglas-fir-LLMT	75			75		
Lodgepole Pine-HHT	150	65		150	125	125
Lodgepole Pine-HLMT	50			50		
Lodgepole Pine-LHT	200	150	75	200	150	75
Lodgepole Pine-LLMT	75			75		
Ponderosa Pine-HHT				300	150	50
Ponderosa Pine-HLMT				67	200	
Ponderosa Pine-LHT				350		32
Ponderosa Pine-LLMT				75		
Western Larch-HHT	400	175	75	300	200	50
Western Larch-HLMT	100	100		100	100	
Western Larch-LHT	500		38	350		35
Western Larch-LLMT	75			75		
Mountain Big Sage-HMSH				35		
Perennial Forb-HLHB	100			75		
Perennial Native Bunch Gramminoid-HHHB	50			40		
Perennial Native Rhizomatous Gramminoid-HLHB	75			75		
Upland Broadleaf Dwarf Shrub-HLSH	100			100		
Upland Broadleaf Medium Shrub-HMSH	75			75		
Upland Broadleaf Tall Shrub-HHSH				100		
Upland Needleleaf Shrub-LMSH	75					
Upland Sclerophyllous Shrub-HLSH	100					
Wyoming – Basin Big Sage-HMSH	40			35		

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire
**For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-K: Table 4—Succession modeling results in percent composition of each of the Zone 19 Douglas-fir PVTs.

Succession class	Douglas-fir/ Timber-line Pine	Douglas-fir/ Ponderosa Pine	Douglas-fir/ Douglas-fir	Douglas-fir/ Lodge-pole Pine
Douglas-fir-HHT*	25.2	8.6	43.7	32.9
Douglas-fir-HLMT	4	1.9	1.7	2.1
Douglas-fir-LHT	13.2	10.4	17.7	19.4
Douglas-fir-LLMT	9.2	3.3	6	5
Juniper-HHT	1			
Juniper-HLMT	0.4			
Juniper-LHT	0.7			
Juniper-LLMT	0.4			
Limber Pine-HHT	10.1			
Limber Pine-HLMT	2.5			
Limber Pine-LHT	4.9			
Limber Pine-LLMT	4.9			
Lodgepole Pine-HHT		0.5	1.9	10.1
Lodgepole Pine-HLMT		0.1	0.4	2.1
Lodgepole Pine-LHT		0.3	0.7	6.7
Lodgepole Pine-LLMT		0.1	0.2	4.4
Ponderosa Pine-HHT		24.7	2.7	
Ponderosa Pine-HLMT		1.4	0	
Ponderosa Pine-LHT		25.7	1.6	
Ponderosa Pine-LLMT		3	0.1	
Western Larch-HHT		4.7	11.2	5
Western Larch-HLMT		0	0.2	0.1
Western Larch-LHT		3	2.8	0.7
Western Larch-LLMT		0	0.1	0.6
Mountain Big Sage-HMSH	0.1		0.2	
Perennial Forb-HLHB	6.5	1.5	1	1.6
Perennial Native Bunch Gramminoid-HHHB	12.5	3.6	1.4	0.3
Perennial Native Rhizomatous Gramminoid-HLHB		3.8	1.9	4.4
Upland Broadleaf Dwarf Shrub-HLSH			0	1.8
Upland Broadleaf Medium Shrub-HMSH	1.6	1.4	3.7	1
Upland Broadleaf Tall Shrub-HHSH			0.2	
Upland Needleleaf Shrub-LMSH	1.6			1.1
Upland Sclerophyllous Shrub-HLSH	0.3	1.5		0.1
Wyoming – Basin Big Sage-HMSH	0.8	0.4	0.6	0.6

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-L—Pine Forest PVTs

Appendix 9-L: Table1—Transition times between succession classes, in years, used in succession modeling for Zone 19 Pine PVTs.

Succession class	Lodgepole Pine	Whitebark Pine	Limber Pine	Ponderosa Pine
Douglas-fir-HHT*	365		875	
Douglas-fir-HLMT	15		25	
Douglas-fir-LHT	40		70	
Douglas-fir-LLMT	20		40	
Juniper-HLT			45	35
Juniper-HMT			245	275
Juniper-LHT			115	80
Juniper-LLT			60	40
Juniper-LMT			100	50
Limber pine-HLT			40	
Limber pine-HMT			610	
Limber pine-LHT			100	
Limber pine-LLT			50	
Limber pine-LMT			50	
Lodgepole Pine-HHT	320			
Lodgepole Pine-HLMT	10			
Lodgepole Pine-LHT	35			
Lodgepole Pine-LLMT	20			
Ponderosa Pine-HHT				555
Ponderosa Pine-HLMT				25
Ponderosa Pine-LHT				50
Ponderosa Pine-LLMT				20
Spruce – Fir-HHT	930	850		
Spruce – Fir-HLMT	15	40		
Spruce – Fir-LHT	50	100		
Spruce – Fir-LLMT	30	50		
Timberline forest-HHT		540		
Timberline forest-HLMT		50		
Timberline forest-LHT		115		
Timberline forest-LLMT		60		
Mountain Big Sage-HMSH	24	54		
Upland Broadleaf Dwarf Shrubland-HLSH	11	44		
Upland Broadleaf Medium Shrubland-HMSH	11			29
Upland Broadleaf Tall Shrubland-LHSH				29
Upland Microphyllous Medium Shrubland-HMSH				34
Upland Needle-leaf Shrubland-LMSH		59	54	
Upland Sclerophyllous Shrubland-HLSH	14			
Upland Sclerophyllous Shrubland-LLSH			44	
Wyoming-Basin Big Sage-HMSH			59	39
Perennial Frb-HLHB	9	49		24
Perennial Forb-LLHB			39	
Perennial Native Bunch Gramminoid-HHHB	14	59	54	34
Perennial Native Rhizomatous Gramminoid-HLHB	11	54	49	
Wetland Herbaceous-HHHB	19			

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-L: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 19 Ponderosa Pine and Timberline Pine PVTs.

	Ponderosa Pine			Limber Pine		
Succession class	**SR***	**MS**	**NL**	**SR**	**MS**	**NL**
Douglas-fir-HHT**			278	244		
Douglas-fir-HLMT			150			
Douglas-fir-LHT			300		200	
Douglas-fir-LLMT			300			
Juniper-HLT	50			300	200	
Juniper-HLMT	400	100	40	300		
Juniper-LLT	50			400		135
Juniper-LLMT	300	150	25	300		
Limber Pine-HLT			350		350	
Limber Pine-HMT			300			
Limber Pine-LLT			400		240	
Limber Pine-LMT			300			
Lodgepole Pine-HHT						
Lodgepole Pine-HLMT						
Lodgepole Pine-LHT						
Lodgepole Pine-LLMT						
Ponderosa Pine-HHT	300	100	19			
Ponderosa Pine-HLMT	100	25				
Ponderosa Pine-LHT	400	200	10			
Ponderosa Pine-LLMT	30					
Mountain Big Sage-HMSH						
Upland Broadleaf Dwarf Shrub-HLSH						
Upland Broadleaf Medium Shrub-HMSH	30					
Upland Broadleaf Tall Shrub-LHSH	30					
Upland Microphyllous Medium Shrub-LMSH	30					
Upland Needleleaf Shrub-LMSH			300			
Upland Sclerophyllous Shrub-LLSH			400			
Wyoming – Basin Big Sage-HMSH	25			100		
Perennial Forb-HLHB	50			400		
Perennial Native Bunch Graminoid-HHHB	20			150		
Perennial Native Rhizomatous Graminoid-HLHB				200		
Wetland Herbaceous-HHHB						

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire
** For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-L: Table 3—Fire frequencies, in years and by severity type, used in succession modeling for Zone 19 Lodgepole Pine and Whitebark Pine PVTs.

	Lodgepole Pine			**Whitebark Pine**		
Succession class	**SR***	**MS**	**NL**	**SR**	**MS**	**NL**
Douglas-fir-HHT**	200	125	95			
Douglas-fir-HLMT	75					
Douglas-fir-LHT	300	200	60			
Douglas-fir-LLMT	200					
Lodgepole Pine-HHT	150	75				
Lodgepole Pine-HLMT	75					
Lodgepole Pine-LHT	200	150	100			
Lodgepole Pine-LLMT	200					
Spruce – Fir-HHT	150	150		150	350	
Spruce – Fir-HLMT	150			400		
Spruce – Fir-LHT	300	200	150	200	400	
Spruce – Fir-LLMT	300			400		
Timberline Forest-HHT				300	300	
Timberline Forest-HLMT				400		
Timberline Forest-LHT				400		400
Timberline Forest-LLMT				400		
Mountain Big Sage-HMSH	100			300		
Upland Broadleaf Dwarf Shrub-HLSH	150			300		
Upland Broadleaf Medium Shrub-HMSH	200					
Upland Needleleaf Shrub-HLSH				300		
Upland Sclerophyllous Shrub-HLSH	200					
Perennial Forb-HLHB	200			400		
Perennial Native Bunch Graminoid-HHHB	100			300		
Perennial Native Rhizomatous Graminoid-HLHB	200			300		
Wetland Herbaceous-HHHB	500					

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire
** For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-L: Table 4—Succession modeling results in percent composition of each of the Zone 19 Pine PVTs.

Succession class	Ponderosa Pine	Timberline Pine	Lodgepole Pine	Whitebark Pine
Douglas-fir-HHT*		0.9	0.7	
Douglas-fir-HLMT		0	0.3	
Douglas-fir-LHT		0.1	0.9	
Douglas-fir-LLMT		0.4	0.3	
Juniper-HHT	0.3	5.4		
Juniper-HLMT	0.4	1.3		
Juniper-LHT	0.2	2.1		
Juniper-LLMT	0.7	2.8		
Limber Pine-HHT		31.5		
Limber Pine-HLMT		8.6		
Limber Pine-LHT		19		
Limber Pine-LLMT		10.4		
Lodgepole Pine-HHT			30.8	
Lodgepole Pine-HLMT			6.9	
Lodgepole Pine-LHT			19	
Lodgepole Pine-LLMT			14.9	
Ponderosa Pine-HHT	40.6			
Ponderosa Pine-HLMT	3.3			
Ponderosa Pine-LHT	31.3			
Ponderosa Pine-LLMT	7			
Spruce – Fir-HHT			11.1	8
Spruce – Fir-HLMT			2.5	2.6
Spruce – Fir-LHT			1	7.2
Spruce – Fir-LLMT			4.5	2.7
Timberline Forest-HHT				25.2
Timberline Forest-HLMT				8.8
Timberline Forest-LHT				17.4
Timberline Forest-LLMT				13.1
Mountain Big Sage-HMSH			0	1.2
Upland Broadleaf Dwarf Shrub-HLSH			3.8	3.3
Upland Broadleaf Medium Shrub-HMSH	1.6		0.2	
Upland Broadleaf Tall Shrub-LHSH	1.2			
Upland Microphyllous Medium Shrub-HMSH	1.7			
Upland Needleleaf shrub-LMSH		5.7		3.6
Upland Sclerophyllous shrub-LMSH		0.9	0.5	
Wyoming – Basin Big Sage-HMSH	0.6	1.6		
Perennial Forb-HLHB	1.8	0.8	0.4	2.7
Perennial Native Bunch Graminoid-HHHB	9.3	7.5	0.9	3.7
Perennial Native Rhizomatous Graminoid-HLHB		1	0.8	0.5
Wetland Herbaceous-HHHB			0.5	

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-M—Broadleaf Forest PVTs

Appendix 9-M: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 19 Broadleaf PVTs.

Succession class	Riparian Hardwood
Aspen – Birch-HHT*	135
Aspen – Birch-HLMT	7
Aspen – Birch-LHT	20
Aspen – Birch-LLMT	8
Douglas-fir-HHT	365
Douglas-fir-HLMT	15
Douglas-fir-LHT	40
Douglas-fir-LLMT	20
Lodgepole Pine-HLMT	12
Lodgepole Pine-LHT	35
Lodgepole Pine-LHT	175
Lodgepole Pine-LLMT	15
Ponderosa Pine-HHT	420
Ponderosa Pine-HLMT	15
Ponderosa Pine-LHT	35
Ponderosa Pine-LLMT	15
Riparian Hardwood-HHT	190
Riparian Hardwood-HLMT	5
Riparian Hardwood-LHT	15
Riparian Hardwood-LLMT	5
Perennial Forb	10
Perennial Native Bunch Gramminoid	15
Perennial Native Rhizomatous Gramminoid	12
Riparian Broadleaf Shrub	15
Upland Broadleaf Medium Shrub	10
Upland Broadleaf Tall Shrub	15
Upland Needleleaf Shrub	15
Wetland Herbaceous	10

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-M: Table 2—Fire frequencies, in years and by severity, used in succession modeling for zone 19 Broadleaf PVTs.

	Riparian Hardwood		
Succession class	**SR***	**MS**	**NL**
Aspen – Birch-HHT**	250	150	
Aspen – Birch-HLMT	250		
Aspen – Birch-LHT	300		200
Aspen – Birch-LLMT	350		
Douglas-fir-HHT	300	175	60
Douglas-fir-HLMT	75		
Douglas-fir-LHT	300	250	50
Douglas-fir-LLMT	75		
Lodgepole Pine-HHT	250	140	
Lodgepole Pine-HLMT	150		
Lodgepole Pine-LHT	300		100
Lodgepole Pine-LLMT	250		
Ponderosa Pine-HHT	300	150	40
Ponderosa Pine-HLMT	67	200	
Ponderosa Pine-LHT	300	200	30
Ponderosa Pine-LLMT	75		
Riparian Hardwood-HHT	250	250	500
Riparian Hardwood-HLMT	250		
Riparian Hardwood-LHT	200		150
Riparian Hardwood-LLMT	300		
Perennial Forb	350		
Perennial Native Bunch Gramminoid	200		
Perennial Native Rhizomatous Gramminoid	225		
Riparian Broadleaf Shrub	450		
Upland Broadleaf Medium Shrub	250		
Upland Broadleaf Tall Shrub	250		
Upland Needleleaf Shrub	250		
Wetland Herbaceous	500		

*SR = stand-replacing fire
MS = mixed-severity fire
NL = non-lethal fire

**For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-M: Table 3—Succession modeling results in percent composition of each of the Zone 19 Broadleaf PVTs.

Succession class	Riparian Hardwood
Aspen – Birch-HHT*	12.3
Aspen – Birch-HLMT	0.9
Aspen – Birch-LHT	1.2
Aspen – Birch-LLMT	1.2
Douglas-fir-HHT	6
Douglas-fir-HLMT	0.1
Douglas-fir-LHT	4.4
Douglas-fir-LLMT	0.2
Lodgepole Pine-HHT	0.5
Lodgepole Pine-HLMT	0.1
Lodgepole Pine-LHT	0
Lodgepole Pine-LLMT	0.3
Ponderosa Pine-HHT	5
Ponderosa Pine-HLMT	0.4
Ponderosa Pine-LHT	5.5
Ponderosa Pine-LLMT	0.6
Riparian Hardwood-HHT	49.2
Riparian Hardwood-HLMT	1.9
Riparian Hardwood-LHT	3.8
Riparian Hardwood-LLMT	1.5
Perennial Forb	1.3
Perennial Native Bunch Gramminoid	0.1
Perennial Native Rhizomatous Gramminoid	0.2
Riparian Broadleaf Shrub	1.6
Upland Broadleaf Medium Shrub	0.2
Upland Broadleaf Tall Shrub	1
Upland Needleleaf Shrub	0.3
Wetland Herbaceous	0.1

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-N—Woodland PVTs

Appendix 9-N: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 19 Woodland PVTs.

Succession class	Rocky Mountain Juniper	Mountain Mahogany
Douglas-fir-HHT*		99
Douglas-fir-LHT		84
Douglas-fir-LLT		29
Douglas-fir-LMT		39
Mountain Mahogany-HHS		255
Mountain Mahogany-HMS		14
Mountain Mahogany-LHS		14
Mountain Mahogany-LLS		12
Mountain Mahogany-LMT		14
Mountain Big Sage-HMS	14	14
Mountain Big Sage-LLS	12	12
Mountain Big Sage-LMS	14	14
Perennial Native Bunch Graminoid-HHH	14	29
Perennial Native Bunch Graminoid-HLH	14	14
Perennial Native Bunch Graminoid-LHH	12	12
Perennial Native Bunch Graminoid-LLH	2	14
Perennial Forb-LHH	29	
Perennial Forb-LLH	12	12
Rabbitbrush-LLH	12	12
Rabbitbrush-LMH	29	29
Juniper-HHH	200	
Juniper-LHH	200	
Juniper-LLH	14	
Juniper-LMH	54	
Upland Microphyllous Medium Shrubland-HMS	14	14
Upland Microphyllous Medium Shrubland-LLS	12	12
Upland Microphyllous Medium Shrubland-LMS	14	14
Wyoming – Basin Big Sage-HMS	200	200
Wyoming – Basin Big Sage-LLS	14	14
Wyoming – Basin Big Sage-LMS	54	54

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-N: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 19 Woodland PVTs.

Succession class	Rocky Mountain Juniper	Mountain Mahogany
Douglas-fir-HHT*		
Douglas-fir-LHT		
Douglas-fir-LLT		
Douglas-fir- LMT		
Mountain Mahogany-HHS		33
Mountain Mahogany-HMS		40
Mountain Mahogany-LHS		50
Mountain Mahogany-LLS		50
Mountain Mahogany-LMT		40
Mountain Big Sage-HMS	22	22
Mountain Big Sage-LLS	29	29
Mountain Big Sage-LMS	25	25
Perennial Native Bunch Graminoid-HHH	25	25
Perennial Native Bunch Graminoid-HLH	50	50
Perennial Native Bunch Graminoid-LHH	40	40
Perennial Native Bunch Graminoid-LLH	50	50
Perennial Forb-LHH	29	
Perennial Forb-LLH	29	40
Rabbitbrush-LLH	33	33
Rabbitbrush-LMH	29	29
Juniper-HHH	25	
Juniper-LHH	33[1]	
Juniper-LLH	295	
Juniper-LMH	25	
Upland Microphyllous Medium Shrubland-HMS	25	29
Upland Microphyllous Medium Shrubland-LLS	33	40
Upland Microphyllous Medium Shrubland-LMS	29	34
Wyoming – Basin Big Sage-HMS	29	33
Wyoming – Basin Big Sage-LLS	40	40
Wyoming – Basin Big Sage-LMS	33	50

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

[1] In this class, approximately 20 percent of fires were estimated as mixed stand-replacing fires.

Appendix 9-N: Table 3—Succession modeling results in percent composition of each of the Zone 19 Woodland PVTs.

Succession class	Rocky Mountain Juniper	Mountain Mahogany
Douglas-fir-HHT*		0
Douglas-fir-LHT		0
Douglas-fir-LLT		0
Douglas-fir- LMT		0
Mountain Mahogany-HHS		3
Mountain Mahogany-HMS		4
Mountain Mahogany-LHS		14
Mountain Mahogany-LLS		12
Mountain Mahogany-LMT		9
Mountain Big Sage-HMS	4	0
Mountain Big Sage-LLS	3	7
Mountain Big Sage-LMS	1	0
Perennial Native Bunch Graminoid-HHH	13	2
Perennial Native Bunch Graminoid-HLH	1	9
Perennial Native Bunch Graminoid-LHH	18	5
Perennial Native Bunch Graminoid-LLH	4	2
Perennial Forb-LHH	2	
Perennial Forb-LLH	2	0
Rabbitbrush-LLH	3	0
Rabbitbrush-LMH	2	0
Juniper-HHH	0	
Juniper-LHH	3	
Juniper-LLH	10	
Juniper-LMH	20	
Upland Microphyllous Medium Shrubland-HMS	2	0
Upland Microphyllous Medium Shrubland-LLS	5	0
Upland Microphyllous Medium Shrubland-LMS	3	0
Wyoming – Basin Big Sage-HMS	2	6
Wyoming – Basin Big Sage-LLS	0	9
Wyoming – Basin Big Sage-LMS	2	18

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-O—Sagebrush and Other Dry Shrubland PVTs

Appendix 9-O: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 19 Sagebrush and Other Dry Shrubland PVTs.

Succession class	Dwarf Sage	Mountain Big Sage	Threetip Sage	Wyoming Sage
Douglas-fir-HHT*	200	200	200	200
Douglas-fir-LHT	69	84	84	79
Douglas-fir-LLT	34	29	29	29
Douglas-fir-LMT	49	39	39	39
Dwarf Sage-HMS	270			
Dwarf Sage-LLS	12			
Dwarf Sage-LMS	14			
Mountain Big Sage-HMS	19	19	19	24
Mountain Big Sage-LLS	12	8	8	12
Mountain Big Sage-LMS	14	14	14	9
Perennial Forb-HHH				9
Perennial Forb-LHH		34	34	12
Perennial Forb-LLH		8	8	
Perennial Native Bunch Graminoid-HHH		34	34	12
Perennial Native Bunch Graminoid-HLH		14	14	
Perennial Native Bunch Graminoid-LHH	27	8	8	12
Perennial Native Bunch Graminoid-LLH	1	1	1	1
Rabbitbrush-HMH	19		15	25
Rabbitbrush-LLH	12	8	8	12
Rabbitbrush-LMH	14	14	14	19
Three-tip Sage-HMS	19	19	275	
Three-tip Sage-LLS	12	8	8	
Three-tip Sage-LMS	14	14	14	
Upland Microphyllous Medium Shrubland-HMS		19	19	
Upland Microphyllous Medium Shrubland-LLS		8	8	18
Upland Microphyllous Medium Shrubland-LMS		14	14	19
Wyoming – Basin Big Sage-HHS				199
Wyoming – Basin Big Sage-HMS	125	200	200	250
Wyoming – Basin Big Sage-LHS				49
Wyoming – Basin Big Sage-LLS	19	19	19	9
Wyoming – Basin Big Sage-LMS	24	54	54	14

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-O: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 19 Sagebrush and Other Dry Shrubland PVTs. All fires are stand-replacing unless otherwise noted.

Succession class	Dwarf Sage	Mountain Big Sage	Threetip Sage	Wyoming Sage
Douglas-fir-HHT*	25	20	20	40
Douglas-fir-LHT	401	291	291	50[1]
Douglas-fir-LLT	40	25	25	40
Douglas-fir-LMT	33	22	22	40
Dwarf Sage-HMS	100			
Dwarf Sage-LLS	149			
Dwarf Sage-LMS	125			
Mountain Big Sage-HMS	25	20	20	25
Mountain Big Sage-LLS	33	29	29	40
Mountain Big Sage-LMS	29	25	25	29
Perennial Forb-HHH		40		50
Perennial Forb-LHH		40	40	60
Perennial Forb-LLH		50	50	
Perennial Native Bunch Graminoid-HHH		29	29	50
Perennial Native Bunch Graminoid-HLH		50	50	
Perennial Native Bunch Graminoid-LHH	75	40	40	60
Perennial Native Bunch Graminoid-LLH	149	50	50	100
Rabbitbrush-HMH	40			
Rabbitbrush-LLH	60	40	40	60
Rabbitbrush-LMH	50	34	34	40
Three-tip Sage-HMS	29	22	22	
Three-tip Sage-LLS	60	295	29	
Three-tip Sage-LMS	33	25	25	
Upland Microphyllous Medium Shrubland-HMS		33	50	
Upland Microphyllous Medium Shrubland-LLS		40	50	60
Upland Microphyllous Medium Shrubland-LMS		40	40	50
Wyoming – Basin Big Sage-HHS				40
Wyoming – Basin Big Sage-HMS	50	33	33	50
Wyoming – Basin Big Sage-LHS				50
Wyoming – Basin Big Sage-LLS	60	40	40	50
Wyoming – Basin Big Sage-LMS	50	40	40	50

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

[1] In this class, approximately 20 percent of fires were estimated as mixed stand-replacing fires.

Appendix 9-O: Table 3—Succession modeling results in percent composition of each of the Zone 19 Sagebrush and Other Dry Shrubland PVTs.

Succession class	Dwarf Sage	Mountain Big Sage	Threetip Sage	Wyoming Sage
Douglas-fir-HHT*	0	0	0	1
Douglas-fir-LHT	2	1	1	2
Douglas-fir-LLT	1	2	2	1
Douglas-fir-LMT	2	1	2	2
Dwarf Sage-HMS	34			
Dwarf Sage-LLS	7			
Dwarf Sage-LMS	18			
Mountain Big Sage-HMS	1	0		0
Mountain Big Sage-LLS	1	62		0
Mountain Big Sage-LMS	2	0		0
Perennial Forb-HHH		0	0	3
Perennial Forb-LHH		0	0	1
Perennial Forb-LLH		0	0	2
Perennial Native Bunch Graminoid-HHH		29	29	10
Perennial Native Bunch Graminoid-HLH	10	0	0	1
Perennial Native Bunch Graminoid-LHH		0	0	13
Perennial Native Bunch Graminoid-LLH	1	5	4	1
Rabbitbrush-HMH	1	0	0	2
Rabbitbrush-LLH	2	0	0	1
Rabbitbrush-LMH	1	0	0	1
Three-tip Sage-HMS	2	0	17	
Three-tip Sage-LLS	2	0	31	
Three-tip Sage-LMS	2	0	14	
Upland Microphyllous Medium Shrubland-HMS		0	0	2
Upland Microphyllous Medium Shrubland-LLS		0	0	2
Upland Microphyllous Medium Shrubland-LMS		0	0	1
Wyoming – Basin Big Sage-HHS				0
Wyoming – Basin Big Sage-HMS	4	0	0	34
Wyoming – Basin Big Sage-LHS				1
Wyoming – Basin Big Sage-LLS	4	0	0	8
Wyoming – Basin Big Sage-LMS	3	0	0	11

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-O: Table 4—Transition times between succession classes, in years, used in succession modeling for the Zone 19 Sagebrush and Other Dry Shrubland PVTs.

Succession class	Dry shrub
Douglas-fir-HHT*	299
Douglas-fir-LHT	84
Douglas-fir-LLT	29
Douglas-fir-LMT	39
Mountain Big Sage-HMS	14
Mountain Big Sage-LLS	14
Mountain Big Sage-LMS	14
Perennial Forb-LHH	14
Perennial Forb-LLH	12
Perennial Naive Bunch Graminoid-HHH	42
Perennial Native Bunch Graminoid-HLH	27
Perennial Native Bunch Graminoid-LLH	2
Shrubby cinquefoil-HMS	14
Shrubby cinquefoil-LLS	12
Shrubby cinquefoil-LMS	14
Upland Broadleaf Medium Shrubland-LLS	12
Upland Broadleaf Medium Shrubland-LMS	14
Upland Microphyllous Medium Shrubland-HMS	14
Upland Microphyllous Medium Shrubland-LLS	12
Upland Microphyllous Medium Shrubland-LMS	14
Upland Needleleaf Shrubland–LLS	12
Wyoming – Basin Big Sage-HMS	199
Wyoming – Basin Big Sage-LLS	14
Wyoming – Basin Big Sage-LMS	54

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-O: Table 5—Fire frequencies, in years and by severity type, used in succession modeling for Zone 19 Sagebrush and Other Dry Shrubland PVTs.

Succession class	Dry shrub
Douglas-fir-HHT*	20
Douglas-fir-LHT	25[1]
Douglas-fir-LLT	29
Douglas-fir-LMT	29
Mountain Big Sage-HMS	25
Mountain Big Sage-LLS	33
Mountain Big Sage-LMS	29
Perennial Forb-LHH	33
Perennial Forb-LLH	40
Perennial Naive Bunch Graminoid-HHH	25
Perennial Native Bunch Graminoid-HLH	29
Perennial Native Bunch Graminoid-LLH	40
Shrubby cinquefoil-HMS	25
Shrubby cinquefoil-LLS	25
Shrubby cinquefoil-LMS	29
Upland Broadleaf Medium Shrubland-LLS	33
Upland Broadleaf Medium Shrubland-LMS	29
Upland Microphyllous Medium Shrubland-HMS	25
Upland Microphyllous Medium Shrubland-LLS	33
Upland Microphyllous Medium Shrubland-LMS	29
Upland Needleleaf Shrubland–LLS	33
Wyoming – Basin Big Sage-HMS	50
Wyoming – Basin Big Sage-LLS	50
Wyoming – Basin Big Sage-LMS	40

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

[1] In this class, approximately 20 percent of fires were estimated as mixed stand-replacing fires.

Appendix 9-O: Table 6—Succession modeling results in percent composition of each of the Zone 19 Sagebrush and Other Dry Shrubland PVTs.

Succession class	Dry shrub
Douglas-fir-HHT*	0
Douglas-fir-LHT	0
Douglas-fir-LLT	0
Douglas-fir-LMT	0
Mountain Big Sage-HMS	1
Mountain Big Sage-LLS	2
Mountain Big Sage-LMS	2
Perennial Forb-LHH	2
Perennial Forb-LLH	2
Perennial Naive Bunch Graminoid-HHH	13
Perennial Native Bunch Graminoid-HLH	14
Perennial Native Bunch Graminoid-LLH	3
Shrubby cinquefoil-HMS	5
Shrubby cinquefoil-LLS	7
Shrubby cinquefoil-LMS	36
Upland Broadleaf Medium Shrubland-LLS	0
Upland Broadleaf Medium Shrubland-LMS	1
Upland Microphyllous Medium Shrubland-HMS	0
Upland Microphyllous Medium Shrubland-LLS	1
Upland Microphyllous Medium Shrubland-LMS	1
Upland Needleleaf Shrubland–LLS	1
Wyoming – Basin Big Sage-HMS	4
Wyoming – Basin Big Sage-LLS	2
Wyoming – Basin Big Sage-LMS	1

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-P—Grassland PVTs

Appendix 9-P: Table 1—Transition times between succession classes, in years, used in succession modeling for Zone 19 Grassland PVTs.

Succession class	Fescue Grassland	Bluebunch Wheatgrass
Douglas-fir-HHT*	300	400
Douglas-fir-LHT	84	59
Douglas-fir-LLT	29	14
Douglas-fir-LMT	39	14
Juniper-HHT		200
Juniper-LHT		220
Juniper-LLT		14
Juniper-LMT		49
Mountain Big Sage-HMS	14	64
Mountain Big Sage-LLS	12	13
Mountain Big Sage-LMS	14	20
Perennial Forb-LHH		9
Perennial Forb-LLH		8
Perennial Native Bunch Graminoid-HHH	43	8
Perennial Native Bunch Graminoid-LHH	28	8
Perennial Native Bunch Graminoid-LLH	1	1
Rabbitbrush-LLS		8
Rabbitbrush-LMS		9
Shrubby Cinquefoil-HMS	14	
Shrubby Cinquefoil-LLS	14	
Shrubby Cinquefoil-LMS	12	
Upland Broadleaf Medium Shrubland-HLS	12	8
Upland Broadleaf Medium Shrubland-HMS	14	59
Upland Broadleaf Medium Shrubland-LMS	14	9
Upland Microphyllous Medium Shrubland-LLS		8
Upland Microphyllous Medium Shrubland-LMS		9
Wyoming – Basin Big Sage-HMS	200	59
Wyoming – Basin Big Sage-LLS	14	14
Wyoming – Basin Big Sage-LMS	54	14

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Appendix 9-P: Table 2—Fire frequencies, in years and by severity type, used in succession modeling for Zone 19 Grassland PVTs.

Succession class	Fescue Grassland	Bluebunch Wheatgrass
Douglas-fir-HHT*	20	20
Douglas-fir-LHT	331	25[1]
Douglas-fir-LLT	20	29
Douglas-fir-LMT	20	29
Juniper-HHT		22
Juniper-LHT		25[1]
Juniper-LLT		29
Juniper-LMT		29
Mountain Big Sage-HMS	50	20
Mountain Big Sage-LLS	29	29
Mountain Big Sage-LMS	29	29
Perennial Forb-LHH		33
Perennial Forb-LLH		40
Perennial Native Bunch Graminoid-HHH	33	25
Perennial Native Bunch Graminoid-LHH	33	29
Perennial Native Bunch Graminoid-LLH	40	40
Rabbitbrush-LLS		25
Rabbitbrush-LMS		22
Shrubby Cinquefoil-HMS	25	
Shrubby Cinquefoil-LLS	22	
Shrubby Cinquefoil-LMS	25	
Upland Broadleaf Medium Shrubland-HLS	100	33
Upland Broadleaf Medium Shrubland-HMS	25	25
Upland Broadleaf Medium Shrubland-LMS	33	29
Upland Microphyllous Medium Shrubland-LLS		33
Upland Microphyllous Medium Shrubland-LMS		25
Wyoming – Basin Big Sage-HMS	50	50
Wyoming – Basin Big Sage-LLS	50	50
Wyoming – Basin Big Sage-LMS	40	40

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

[1] Frequency of mixed-severity fire.

Appendix 9-P: Table 3—Succession modeling results in percent composition of each of the Zone 19 Grassland PVTs.

Succession class	Fescue Grassland	Bluebunch Wheatgrass
Douglas-fir-HHT*	1	0
Douglas-fir-LHT	8	0
Douglas-fir-LLT	15	0
Douglas-fir-LMT	8	0
Juniper-HHT		0
Juniper-LHT		0
Juniper-LLT		0
Juniper-LMT		1
Mountain Big Sage-HMS	0	2
Mountain Big Sage-LLS	1	4
Mountain Big Sage-LMS	1	6
Perennial Forb-LHH		0
Perennial Forb-LLH		0
Perennial Native Bunch Graminoid-HHH	6	5
Perennial Native Bunch Graminoid-LHH	16	48
Perennial Native Bunch Graminoid-LLH	2	2
Rabbitbrush-LLS		0
Rabbitbrush-LMS		0
Shrubby Cinquefoil-HMS	3	
Shrubby Cinquefoil-LLS	17	
Shrubby Cinquefoil-LMS	19	
Upland Broadleaf Medium Shrubland-HLS	1	1
Upland Broadleaf Medium Shrubland-HMS	1	1
Upland Broadleaf Medium Shrubland-LMS	0	1
Upland Microphyllous Medium Shrubland-LLS		2
Upland Microphyllous Medium Shrubland-LMS		2
Wyoming – Basin Big Sage-HMS	1	14
Wyoming – Basin Big Sage-LLS	0	6
Wyoming – Basin Big Sage-LMS	0	5

* For complete structural stage names, refer to table 5: Structural stages used for succession modeling in zones 16 and 19.

Chapter
10

Using Simulation Modeling to Assess Historical Reference Conditions for Vegetation and Fire Regimes for the LANDFIRE Prototype Project

Sarah Pratt, Lisa Holsinger, and Robert E. Keane

Introduction

A critical component of the Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, was the development of a nationally consistent method for estimating historical reference conditions for vegetation composition and structure and wildland fire regimes. These estimates of past vegetation composition and condition are used as a baseline for evaluating current landscape conditions in terms of ecological departure from historical conditions (Landres and others 1999). Simulated historical fire regime characteristics provide managers with information for designing and evaluating hazardous fuel treatments in which the objective is to restore landscapes to near-historical reference conditions (Keane and Rollins, Ch. 3). In LANDFIRE, simulated historical conditions are used to characterize the departure of current landscapes using Fire Regime Condition Class (FRCC) calculations (Hann and Bunnell 2001) and other measures of ecological departure (Holsinger and others, Ch. 11). Previously, Schmidt and others (2002) produced fire regime and departure information on a nationwide basis at a 1-km resolution; this effort used existing broad-scale spatial data and a rule-based approach to assign fire regimes and FRCC to mapped biophysical settings across the United States. The LANDFIRE Prototype methods used the Landscape Succession Model version 4.0 (LANDSUMv4), a spatially explicit fire and vegetation dynamics simulation model, to simulate disturbance and succession dynamics over a simulation period of thousands of years (Keane and others 2006). The model uses pathways of successional transitions and disturbance effects stratified by unique biophysical settings, called potential vegetation types (PVTs), across the simulation landscape to produce estimates of historical reference conditions for fire frequency, fire severity, and vegetation conditions. This chapter describes the model and how it was used to generate historical reference conditions of vegetation and fire regimes for the LANDFIRE Prototype Project.

Background

Estimating reference conditions for vegetation and fire regimes—The non-equilibrium paradigm of disturbance ecology maintains that ecosystems are not static, and natural disturbance regimes create temporal and spatial variability in the structure and composition of most ecosystems (Picket and White 1985). Within this framework, therefore, reference conditions should be defined in terms of a range of conditions over space and time rather than in terms of a static set of conditions. For the LANDFIRE Prototype, we described reference conditions for vegetation by the quantification of the temporal fluctuations in vegetation characteristics (defined by dominant species and stand structure) prior to Euro-American settlement, specifically from 1600 to 1900 A.D. (Keane and Rollins, Ch. 3). Fire regimes

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In: Rollins, M.G.; Frame, C.K., tech. eds. 2006. The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. Gen. Tech. Rep. RMRS-GTR-175. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

describe fire characteristics over time (Baker 1992) and are often defined in terms of fire frequency, size, pattern, seasonality, intensity, and severity (Agee 1993; Heinselman 1981). In the LANDFIRE Prototype, we described fire regimes by their frequency and severity because these metrics influence vegetation composition and structure across landscapes and have been used in the majority of fire regime studies (Barrett and others 1991; Brown and others 1994; Keane and others 2003; Morgan and others 2001; Rollins and others 2004) and management planning activities. We used the point-based mean fire return interval (MFRI; in years) to quantify fire frequency. Fire severity is defined as the effect on overstory vegetation, and we use three categories to describe fire severity: 1) non-lethal surface fires, 2) mixed-severity fires, and 3) stand-replacing fires. A non-lethal surface fire kills few individuals (< 10 percent) in the overstory (Schimdt and others 2002), whereas stand-replacing fires kill the majority (> 90 percent) of the dominant vegetation (Brown 1995; Schmidt and others 2002). Mixed-severity fire regimes contain elements of both non-lethal surface and stand-replacing fires and may be used to describe an area of patchy burn patterns created during one fire event; however, mixed-severity fire regimes can also be used to describe a mix of fire severities occurring over time (Shinneman and Baker 1997). For the LANDFIRE Prototype simulation modeling effort, we used mixed-severity fires to describe single fire events that cause mixed mortality and have moderate effects on overstory vegetation (Schmidt and others 2002).

Since the turn of the twentieth century, human activities such as fire suppression, logging, and grazing of domestic livestock have altered fire regimes and vegetation structure and dynamics in ecosystems across the United States (Baker 1992; Ferry and others 1995; Heinselman 1973; Herron 2001; Keane and others 2002b). In recent years, there has been increasing recognition that information about ecosystem processes and characteristics prior to intensive Euro-American settlement may offer the best reference conditions for managing complex ecosystems to maintain diversity and sustainability (Kaufmann and others 1998; Landres and others 1999; Swanson and others 1994). Furthermore, the increasing occurrence of large, ecosystem-altering fires and escalating fire suppression costs in recent years have shown that managing ecosystems outside of their natural range can be difficult, costly, and devastating to important ecosystem elements. Although historical reference conditions of vegetation and fire dynamics can serve as effective tools for fire planning and management, fire managers in many areas of the country lack the necessary information to develop baseline historical information (Keane and others 2002b; Landres and others 1999; Schmidt and others 2002).

The importance and challenges of estimating historical reference conditions for vegetation have been widely recognized by the scientific and land management communities (Kaufmann and others 1998; Landres and others 1999; Moore and others 1999; Swanson and others 1994; Veblen 2003). There are several types of data that may be used to estimate historical fire regimes and vegetation conditions including 1) time series data, 2) spatial series data, and 3) simulated data. Time series data are based on actual data from one location over a long period of time. Time series data used in estimating historical vegetation characteristics may come from historical imagery, historical documents, or dendroecological data. Information about historical fire regimes, on the other hand, is often gathered from fire scars, charcoal sediments in lakes, bogs, or soils, or post-fire tree establishment dates from tree ring analysis (Kaufmann and others 1994, 1998; Keane and others 2004; Swanson and others 1994). Time series data have the benefit of being based on the evidence of actual fires, but are often difficult to obtain. Furthermore, the data generally describe fire regimes or vegetation over small spatial extents or short temporal spans and cannot be extrapolated consistently across broad areas. Historical vegetation conditions and fire regimes may also be estimated for a geographic region from spatial series of data (imagery or otherwise) collected on several similar landscapes within a geographic region (Hessburg and others 1999). Inferences about conditions for the larger region are predicated on the assumption that the sampled landscapes represent the range of possible conditions over time for the entire region. This assumption may be tenuous, however, as variations in disturbance histories between sites may obscure historical patterns when extrapolated over the entire region. Furthermore, an adequate amount of data to fully describe the range of possible conditions may be difficult to obtain, and data may not be equally available for all ecosystems and regions. Simulation modeling provides an alternative for estimating historical fire regimes and vegetation conditions. This approach substitutes data modeled over long simulation periods for actual historical data. Although the parameters used in the models are based on available data, simulation modeling is necessarily a simplification of the actual processes occurring in ecosystems. Simulated results represent only an estimate of actual historical conditions. Nevertheless, simulation modeling has several advantages: 1) models can integrate the limited data available and extrapolate over larger areas, 2) simulation modeling can be applied over large areas consistently and comprehensively, and 3) models can be used to simulate a broad range of potential conditions rather than merely the actual conditions experienced, which represent only one possible scenario.

Simulation modeling—Given the LANDFIRE objective of creating a robust methodology for estimating historical reference conditions consistently and comprehensively across the nation, simulation modeling, despite limitations, proves the best source for estimating historical fire regimes and vegetation conditions. A class of simulation models, called landscape fire succession models (LFSMs), simulate fire and vegetation dynamics in the spatial domain (Keane and others 2004), and several existing LFSMs have the potential to generate estimates of historical fire regimes and vegetation conditions over time (for reviews of existing models see Baker 1989, Gardner and others 1999, Keane and others 2004, and Mladenoff and Baker 1999). Keane and others (2004) identified four separate components essential for simulating fire and vegetation dynamics in LFSMs: 1) vegetation succession, 2) fire ignition, 3) fire spread, and 4) fire effects. For each of these components, the complexity of the approach and the scale of application may differ from model to model and must be considered when selecting a model for a particular use (Keane and others 2004).

LANDSUMv4—We selected LANDSUMv4 as the landscape fire succession model for LANDFIRE because of the minimal number of inputs required and its generalized structure, which allowed it to be portable, flexible, and robust with respect to geographic area, ecosystem, and disturbance regime (Keane and others 2002a; Keane and others 2006). More complex models, such as Fire-BGC (Keane and others 1996) and LANDIS (Mladenoff and others 1996), would likely have generated more realistic landscape simulations, but the required extensive parameterization would likely have been difficult to implement for every ecosystem and landscape in the United States. Also, to generate sufficient time series (especially for landscapes with infrequent fires), complex models such as these would have required prohibitively long execution times. Less complex models, such as TELSA (Kurz and others1999) or SIMPPLLE (Chew and others 2004), would have been easy to parameterize, but these models do not adequately simulate the spatial dynamics of fire spread and effects so that variation in landscape structure can be assessed. LANDSUMv4 provided a good balance between the realism of more complex models and the simplicity of less complex models.

LANDSUMv4 is a spatial state-and-transition patch-level succession model combined with a spatially explicit disturbance model that simulates fire growth using a cell-to-cell spread method (Keane and others 2002a). The model is based on vegetation pathways developed for each PVT on the simulation landscape with user-defined transition times for succession events and user-defined probabilities for disturbance events and their effects (see Long and others, Ch. 9 for details on pathway development). A PVT identifies a distinct biophysical setting that supports a unique and stable climax plant community under a constant climate regime (see Keane and Rollins, Ch. 3; Long and others, Ch. 6; and Frescino and Rollins, Ch. 7 for detailed information on the role of PVT in the LANDFIRE Prototype). Succession classes, which are defined by the combination of the dominant species, or cover type (CT), and the stand structure, or structural stage (SS) (see Long and others, Ch. 6; Zhu and others, Ch. 8; and Long and others, Ch. 9 for descriptions of the CTs and SSs used in the LANDFIRE Prototype), serve as discrete stages along the pathways. The pathways are applied across the landscape to mapped patches and their associated PVTs and succession classes. In the model, patches (also referred to as polygons or stands) are spatially contiguous areas having homogenous attributes of PVT, CT, SS, and age (Keane and others 2006).

LANDUSMv4 operates at an annual time–step, and, for each year, the model first simulates disturbance (fig. 1). The model iterates through all the patches in the landscape and, for each patch, cycles through all possible disturbances for the current PVT/succession class for that patch and stochastically determines if a disturbance occurs. Once a disturbance is modeled for a particular patch, the simulation year is over for that patch and no further disturbances or succession can occur.

There are two different disturbance categories in LANDSUMv4: non-fire, or aspatial, and fire, or spatial. Non-fire disturbances are simulated in two steps: initiation and effects. Initiation is based on probabilities defined in the vegetation pathways. Effects are then modeled as a change in succession class based on a second set of probabilities, also defined in the vegetation pathways, unique to the succession class/disturbance combination. A disturbance effect can have multiple pathways; in other words, a patch can transition to any one of several succession classes following a disturbance. The probabilities for all pathways from a particular succession class/disturbance combination must total one.

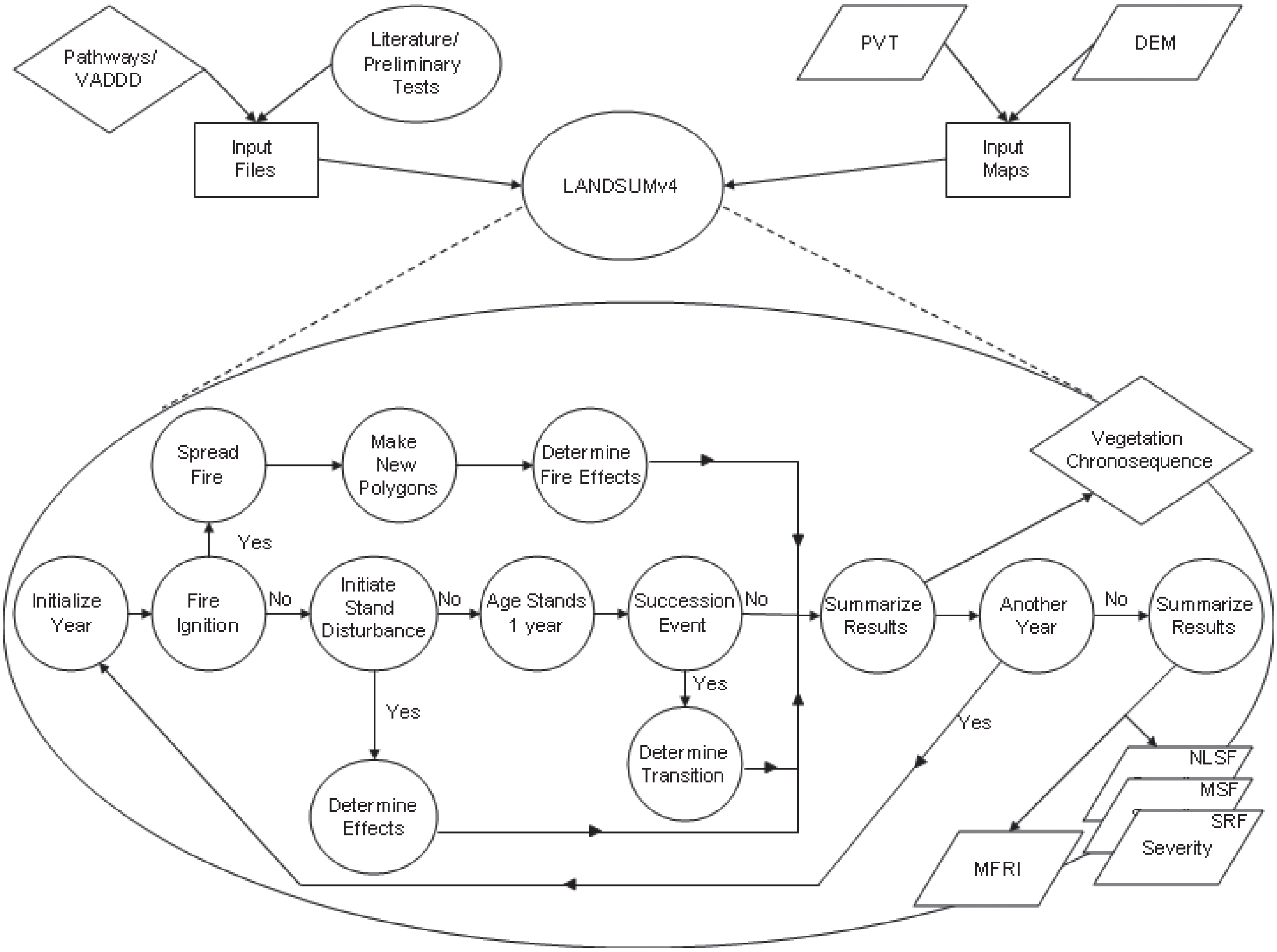

Figure 1—Flow diagram showing the LANDSUMv4 modeling process. Information from vegetation pathway models, parameters estimated from literature and preliminary testing, an elevation map, and a potential vegetation type (PVT) map are used to make the input files and input maps for the model. Each model year, LANDSUMv4 begins by simulating disturbances. Fire is simulated in three steps (ignition, spread, and effects) and results in the creation of new patches on the landscape. Other disturbances are simulated at the stand level and are simulated in two steps (initiation and effects). For stands where no disturbances are modeled, the stand ages one year and a succession event is modeled based on transition times. Summaries of the area occupied by each PVT/succession class combination are output to a tabular file every reporting year, and fire regime characteristics (mean fire return interval [MFRI], non-lethal surface fires [NLSF], mixed-severity fires [MSF], and stand-replacing fires [SRF]) are output to maps at the end of the simulation.

Fire disturbances are modeled in three steps: ignition, spread, and effects. Like non-fire disturbances, fire ignitions are based on probabilities in the pathways, but the probabilities are adjusted to account for fuel build-up (probability increases with increased time since last fire) and a no-burn period following a fire (Keane and others 2006). The probability is then further adjusted using a fire weather multiplier and a scaling factor based on patch size and average fire size (Keane and others 2006). Once a fire has ignited, the model calculates the size of the fire and then, based on wind and slope vectors, spreads this burned area over the landscape until it has reached the calculated fire size or reaches an unburnable boundary (Keane and others 2002a; Keane and others 2006). The model limits the fire size estimate using a minimum fire size of 1 ha and a maximum fire size equal to the size of the simulation landscape, which, for the LANDFIRE Prototype, was 20,000 ha (see the *Methods* section below for details on the LANDFIRE simulation landscape) (Keane and others 2006). The fire spread is independent of patch boundaries, thus fires can divide patches and create new patches. Fire effects are then simulated at the patch level for each of the new patches created by the fire. The model stochastically determines the fire severity based on the probabilities for each fire severity type (non-lethal surface, mixed-severity, and stand-replacing fire) in the vegetation pathways. Finally, the model determines the post-fire succession class based on probabilities assigned to the pre-fire succession class/severity combination.

For those patches where no disturbances occurred, the model simulates succession. LANDSUMv4 implements a multiple pathway succession approach using unique sets of succession pathways for each PVT. This approach assumes that all pathways of successional development will eventually converge to a stable or climax plant community (PVT) in the absence of disturbance (Arno and others 1985; Cattelino and others 1979; Davis and others 1980; Kessell and Fischer 1981; Noble and Slatyer 1977; Steele 1984). Each simulation year, all undisturbed patches advance one year in age, and when a patch reaches the final age for the current succession class (defined in the pathways), the patch transitions to a new succession class. A succession event can result in the patch transitioning to any one of several classes defined in the vegetation pathways (Long and others, Ch. 9), and the model stochastically determines which pathway succession follows.

The LANDFIRE Prototype was conducted for two broad study areas or mapping zones: one in the central Utah highlands and the other in the northern Rocky Mountains (referred to as Zone 16 and Zone 19, respectively; see Rollins and others, Ch. 2 for description of the two study areas). In this chapter, we describe the use of the LANDSUMV4 simulation model to generate estimates of historical reference conditions for vegetation composition and structure and wildland fire regimes for the LANDFIRE Prototype (for more information on the use of models in simulating historical fire regimes and vegetation and the LANDSUMv4 model, see Keane and others 2004 and Keane and others 2006). Whereas the fire regime data form a final LANDFIRE product (Rollins and others, Ch. 2), the data on reference condition vegetation served as an interim product used to determine ecological departure (this chapter describes only the LANDSUMv4 simulation process; for information on how departure was estimated using the LANDSUMv4 output, see Holsinger and others, Ch. 11). In this chapter, we outline the preliminary testing and analyses used to parameterize and initialize LANDSUMv4 in addition to the final methods used to simulate historical chronosequences (time series) and fire regimes for each mapping zone. We present the results from each mapping zone, a discussion of the benefits and limitations of our approach, and recommendations for estimating vegetation and fire regime reference conditions for LANDFIRE's national implementation.

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on the procedure for modeling historical vegetation and fire regimes in the LANDFIRE Prototype Project.

We prepared the inputs for LANDSUMv4 from several key pieces of data, including a PVT map, a digital elevation model (DEM), succession pathways containing probabilities for disturbance events and effects, and times and transitions for succession events (fig. 1). Frescino and Rollins (Ch. 7) developed the PVT map using a suite of biophysical gradient layers (Holsinger and others, Ch. 5) and predictive landscape modeling. We obtained the DEM from the National Elevation Database (NED; ned.usgs.gov). Local experts developed the succession pathways for each PVT based on extensive literature review and experience (Long and others, Ch. 9). They prepared and tested these pathways with the aid of a simple aspatial state-and-transition model, the Vegetation Dynamics Development Tool or VDDT (Beukema and others 2003; Kurz and others 1999), before converting them for use in LANDSUMv4. We determined the model parameters through a combination of literature review, expert opinion, and exploratory analysis. We partitioned each zone into a series of 20,000 ha simulation landscapes and divided the landscapes into discrete 81 ha reporting units for summarizing statistics (fig. 2). Succession and disturbance were then simulated for each landscape using LANDSUMv4. The total simulation time for Zone 16 was 4,500 years, but because of temporal autocorrelation in the vegetation output, the simulation time for Zone 19 was extended to 10,500 years. The model produced maps of fire severity and mean fire return interval, which were processed in a global information system (GIS) to create the final fire

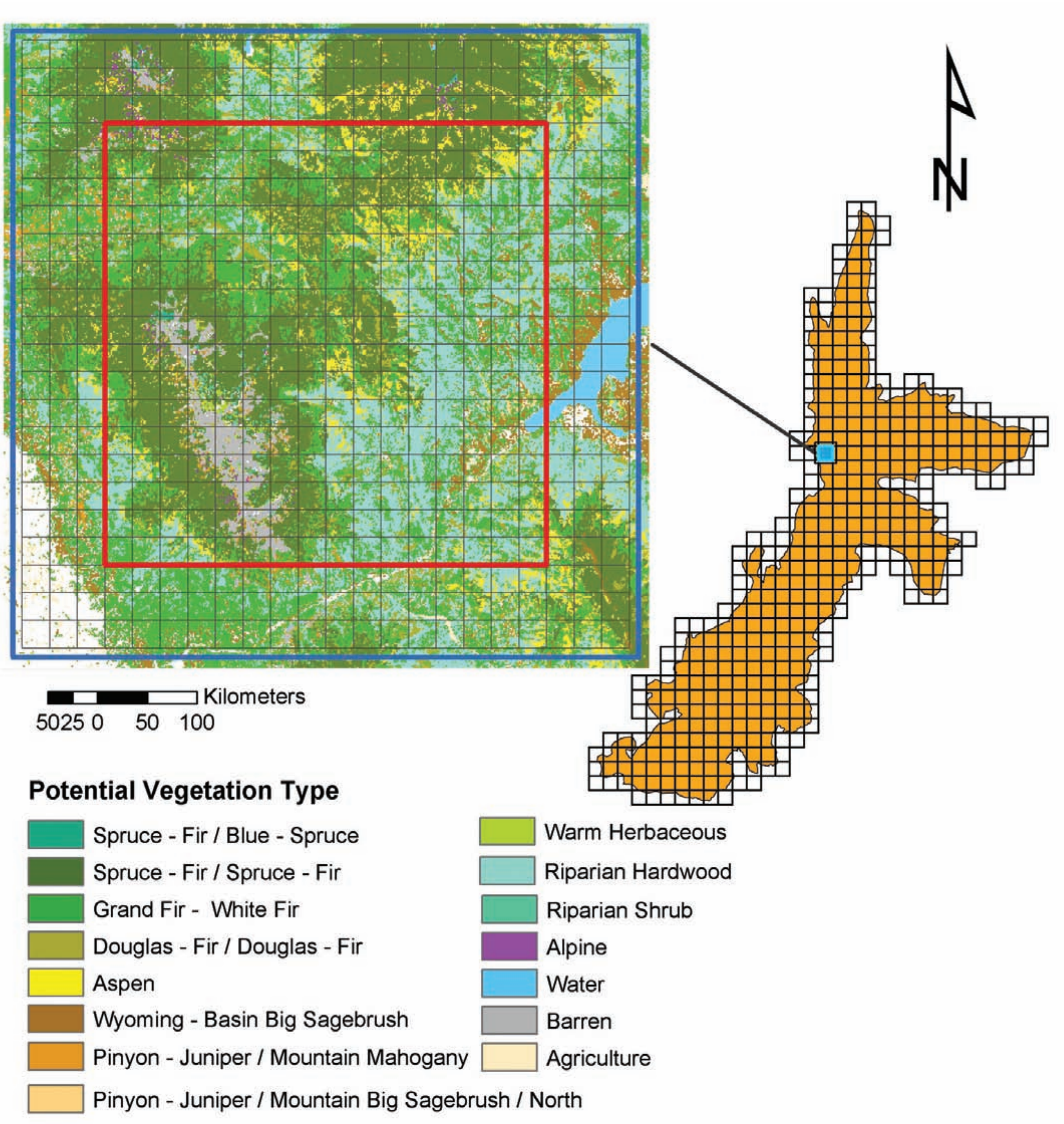

Figure 2—The simulation landscapes for LANDFIRE consisted of a 20,000-ha context area and a 3-km buffer. Each mapping zone was divided into a series of simulation landscapes, and each simulation landscape was further divided into reporting units. Here, Zone 16 is divided into 427 context landscapes. One context landscape (boundary shown in red) with buffer (boundary shown in blue) is displayed with a PVT background and the 900-m by 900-m reporting units. Stand boundaries for the initial map were determined by a spatial overlay of the PVT and reporting unit boundaries.

regime maps for each zone. Statistical summaries of vegetation composition by PVT were computed for each reporting unit for every reporting year. These summaries comprised the reference conditions that Holsinger and others (Ch. 11) then used in subsequent LANDFIRE processes to calculate ecological departure and FRCC. The following sections detail methods for 1) designing the simulation landscape, 2) preparing the input maps, 3) preparing the input files, 4) parameterizing the model, and 5) processing the output data.

Designing the Simulation Landscape

Before preparing the LANDSUMv4 input files, we had to determine the most appropriate size and shape of the simulation area and the landscape reporting units. In designing the simulation landscape, we aimed to balance the need for model efficiency with that of obtaining realistic simulation results. The main factor influencing simulation time is the number of patches on the simulation landscape, and the number of patches increases exponentially throughout the simulation period because fire creates new patches throughout the simulation. In general, use of smaller simulation landscapes increases model efficiency, whereas use of larger landscapes better represents fire's long-term effects on vegetation composition (Keane and others 2002a).

Size and shape of the simulation landscape–The simulation landscape for the LANDFIRE Prototype consisted of the area of interest — or context area — for which vegetation conditions were summarized and a simulation buffer surrounding this area, which was not included in the summaries. The LANDFIRE Prototype required a simulation landscape (context area surrounded by a simulation buffer) that allowed for realistic simulations of fire and vegetation while at the same time minimized 1) the edge effect, 2) the amount of simulation time, 3) the area of overlap between simulations (thus minimizing total computing time for the entire zone), and 4) the total number of simulations required to complete a mapping zone. Previous analysis of the model showed that the effect of both landscape shape and size on fire spread and patch dynamics (Keane and others 2002a) was significant. Circular or square landscapes resulted in the most realistic simulation of fire spread, while narrow, linear landscapes tended to underestimate fire spread. We selected square-shaped simulation landscapes over circular shapes for the LANDFIRE Prototype to simplify GIS processing and to decrease overlap between simulation landscapes.

Keane and others (2002a) also found that use of smaller landscapes led to the overestimation of mean fire return intervals. This overestimation results from the inability of fires to immigrate from outside the landscape into the edges of the simulation area; therefore, fewer fires than expected occur near the edges. With smaller landscapes, this "edge effect" impacts a greater proportion of the simulation landscape than with larger landscapes. The edge effect can also be decreased by adding a buffer zone around the context area to provide a place from which fires can spread into the context area. The ideal simulation area size may depend on both the size of the context area and the size of fires. Keane and others (2002a) recommend a total simulation area of 8 to 10 times the size of the context area for a 2,500-ha context landscape; however, the appropriate size is highly dependent on landscape complexity. Although larger landscapes and larger buffers minimized edge effects, they increased simulation times. We determined that a 20,000-ha context box with a 3-km buffer offered a reasonable compromise between minimal edge effects and manageable simulation times. In addition, all other LANDFIRE maps (such as DEM and PVT) were produced with a 3-km buffer around the zone boundary; therefore, the maximum buffer size that was available at the edges of the zone was only 3 km. We used a 14,400-m x 14,400-m (20,736 ha) context area to allow the 30-m pixels to nest within the landscape and simplify GIS processing. With the 3-km buffer on all sides, the simulation landscape was 20,400 m x 20,400 m (41,616 ha). We divided the entire mapping zone into a series of adjacent 20,000-ha boxes with 3-km buffers where buffer areas overlapped adjacent context areas (fig. 3).

Size and shape of the landscape reporting units– Landscape reporting units define the area on the ground into which the vegetation conditions are summarized and are used in subsequent modeling to calculate departure and FRCC (Holsinger and others, Ch. 11). For LANDSUMv4, the simulation landscape must be stratified into reporting units because ecological departure and FRCC are spatial and not point measurements. Although reporting units have no impact on the LANDSUMv4 simulations, the size and shape of these reporting units is important when summarizing the LANDSUMv4 output for use in departure calculations (see Holsinger and others, Ch.11 for a complete discussion of the considerations relevant to selecting landscape reporting units for departure calculations). For LANDFIRE, the selection of an appropriate landscape reporting unit must include

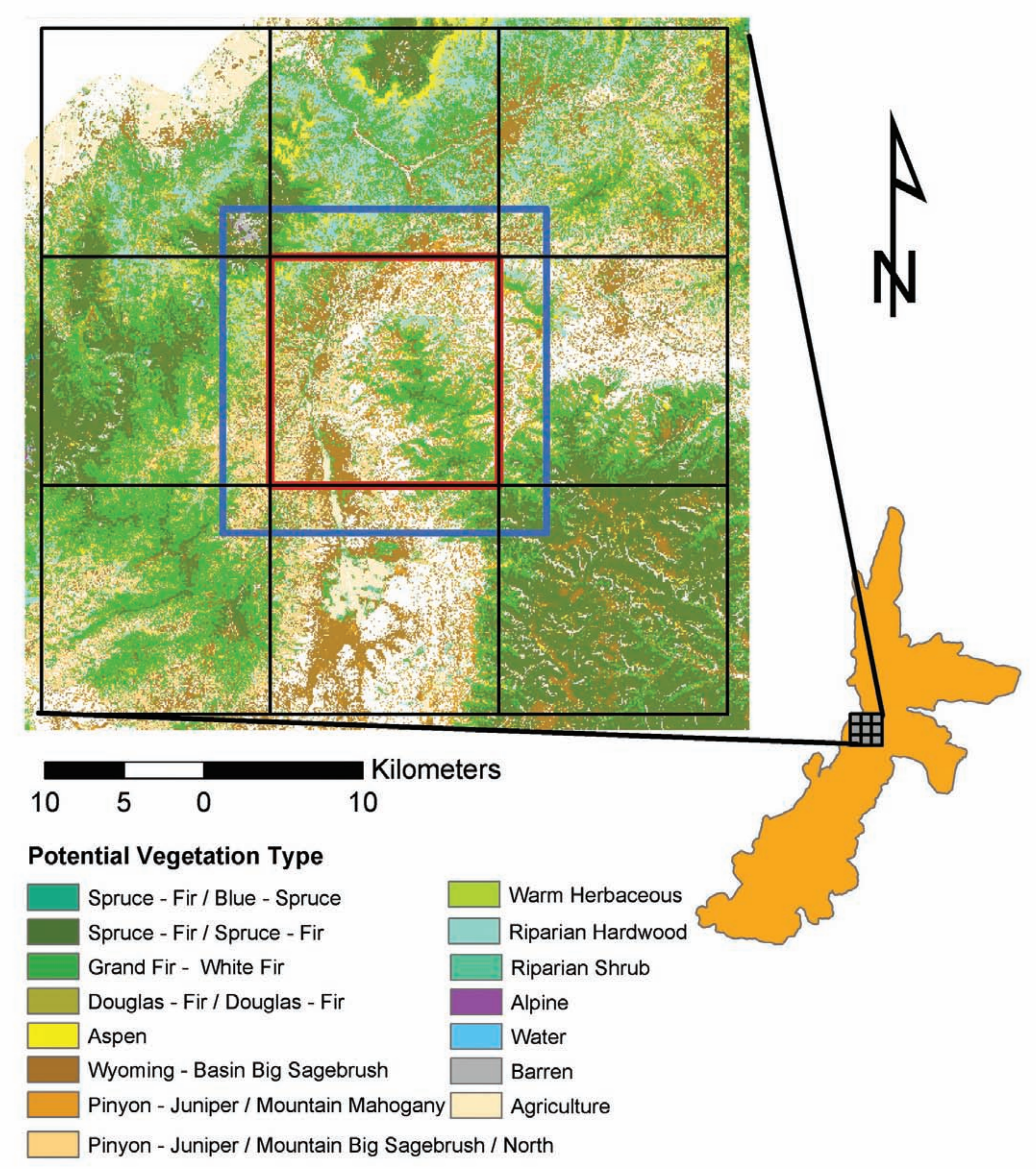

Figure 3—A series of nine 20,000-ha context areas in Zone 16 shown with potential vegetation type in the background. The 3-km buffer area (in blue) is shown for the center context area (in red). Notice that the 3-km buffer area overlaps adjacent context areas. The total simulation landscape (context area + buffer) is 40,000 ha.

consideration of scale from both an ecological standpoint and a management standpoint. The most desirable landscape extent is one that is small enough to detect subtle changes resulting from land management actions (such as fuel treatments) but large enough to capture important ecological patterns and processes (such as fire, migration, and climate) in the correct spatial context. Other studies have used watersheds or ownerships to delineate reporting units. These units are highly variable in size, however, which complicates the comparability of departure estimates across reporting units. Furthermore, 4th and 5th order Hydrologic Unit Codes (HUCs) were too large for our purposes, and the spatial data for 6th order HUCs were at that time incomplete for both prototype zones as well as for many areas across the nation. We chose reasonably small, uniform squares of 900 m by 900 m (or 81 ha) as reporting units (fig. 2) based on the need for ecological and managerial relevance, national consistency, and computational efficiency. Furthermore, we chose the 900-m box so that the 30-m pixels of the LANDFIRE vegetation layers would nest perfectly inside and reporting unit boundaries would therefore not split pixels.

Preparing Input Maps

A map of patch boundaries and a map of elevation are the only spatial inputs required for the model. The elevation map was derived directly from the DEM map obtained from NED and required no additional processing, whereas the map of patch boundaries had to be created. As mentioned above, patches in LANDSUMv4 are spatially contiguous areas that have identical PVT, CT, and structure. In addition, each patch can belong to only a single reporting unit. Succession and disturbance input parameters are stratified by PVT, and PVT distributions remain constant for any given landscape throughout the simulation.

In LANDSUMv4 simulations, overall processing time increases dramatically with the number of patches on the initial landscape. To minimize the number of patches on the initial landscape, we used only PVT and reporting units to determine our initial patch boundaries (fig. 2) and assigned a single value for each of the other patch attributes. Before the PVT map could be used to determine patch boundaries, however, we had to rectify the PVT, CT, and SS maps.

In the LANDFIRE Prototype, vegetation conditions, whether current or reference, were defined by PVT, CT, and SS. The reference conditions were generated by LANDSUMv4, and the current conditions were defined by mapped existing vegetation composition and structure (Frescino and Rollins, Ch. 7; Zhu and others, Ch. 8; Holsinger and others, Ch. 11). The succession pathways in LANDSUMv4 were based on the assumption that there is a unique set of succession classes (CT and SS combinations) that can occur naturally within a PVT. All of these succession classes were included as modeled states and thus had some probability of occurring in the historical reference conditions. When LANDSUMv4 output is compared to current conditions, succession classes that cannot occur in the reference conditions will tend to increase departure when calculating FRCC. These succession classes may appear in the current conditions because of exotic or invasive species or as a result of mapping errors in the independently created PVT, cover, or structure maps. Mismatches that are the result of mapping errors and not the result of exotic species must be corrected so that there is ecological consistency between a given PVT and the CTs and SSs that occur therein.

To ensure this ecological consistency, we performed a spatial overlay of the PVT, cover, and structure maps along with confidence layers to identify and correct such mismatches. The confidence layers (associated with each LANDFIRE vegetation layer) report a percentage of confidence in the predicted vegetation attribute for a pixel based on the rules that were used to classify it (Earth Satellite Corporation 2003; Frescino and Rollins, Ch. 7). A value of zero represents the lowest confidence whereas a value of 100 represents the highest confidence. For Zone 16, the only confidence layer available was that associated with the CT map (Zhu and others, Ch. 8). Succession classes that did not occur in the vegetation pathways and that included a CT not considered an exotic species were assumed to result from errors in the PVT or CT maps. The confidence layer information was then used to determine whether the PVT or CT should be changed. If the CT confidence was 50 percent or greater, the PVT was changed; otherwise, the CT was changed. For Zone 19, we had confidence layers for both the PVT and CT maps (Frescino and others, Ch. 7; Zhu and others, Ch. 8), so if the PVT confidence was greater than the CT confidence, the CT was changed; otherwise, the PVT was changed. Following all reassignments, the PVT, CT, and SS maps were recoded to reflect the changes. We then used the rectified PVT map as input for LANDSUMv4 and the rectified PVT, CT, and SS maps to define current conditions.

Non-vegetated areas (urban, barren, water, snow/ice, and agriculture) presented a special case regarding the rectification of the PVT and CT maps. For Zone 16, we used a mask of all non-vegetated types in making both the PVT and CT maps, ensuring that there was 100 percent agreement between the maps for all non-vegetated types. LANDSUMv4 will not simulate fire occurrence and spread through areas mapped as non-vegetated PVTs. In terms of historical reference conditions, however, some of these non-vegetated PVTs, particularly agriculture and urban, would have historically been vegetation CTs and thus would have experienced wildland fire. Agriculture and urban areas, therefore, serve as unnatural fire breaks and will lower the fire frequency of surrounding pixels, creating an effect similar to that on the edges of the simulation landscape where fire immigration is limited. To remedy this problem for Zone 19, Frescino and others (Ch. 7) predicted a PVT for every pixel on the map rather than masking non-vegetated types before predicting PVTs. In the rectification process described above, we reassigned the water, barren, and snow/ice land covers in the PVT layer to agree with the CT layer because these non-vegetated types occurred historically. The mapped PVTs in areas where the CT was agriculture or urban were not changed; thus, these areas did not act as fire breaks and LANDSUMv4 could simulate fire occurrence and spread according to the vegetation and topography.

Preparing Input Files from the Vegetation Pathways

Many of the key inputs into the LANDSUMv4 model come from the succession pathways developed by the vegetation modelers (Long and others, Ch 9). The modelers used the VDDT model to develop and test the vegetation pathways and stored the results of the VDDT modeling process in the Vegetation and Disturbance Dynamics Database (VADDD; Long and others, Ch. 9). This database was structured to store all vegetation and disturbance dynamics information used as input to LANDSUMv4 (see appendix 10-A for a description of VADDD, VADDD tables, and the fields within). The VADDD served as the primary reference for the codes and labels for all map unit classifications developed in LANDFIRE, including PVT, CT, and SS. In addition, this database was designed to efficiently check for errors in the succession and disturbance information prior to input into simulation modeling and to provide a standardized set of LANDSUMv4 parameters for subsequent applications of the model in different settings.

We converted the vegetation pathways developed in VDDT to the appropriate LANDSUMv4 files through the use of a custom software program, V2L. In addition to the spatial quality of LANDSUMV4, there are subtle differences between the way VDDT and LANDSUMv4 simulate succession and disturbance, including 1) partitioning disturbance and effects probabilities, 2) implementing multiple pathway succession, and 3) tracking patch age (Keane and others 2006; Kurz and others 1999). Most of these differences are rectified by the V2L program, but careful scrutiny was required to ensure that the pathways developed in VDDT functioned as intended in LANDSUMv4.

Parameterizing the Model

Many parameters must be set by the user prior to running LANDSUMv4. Previous research using the model has shown that simulation time, reporting interval, and fire spread parameters are important factors affecting simulation results (Keane and others 2002a; Keane and others 2003). In this section, we discuss the preliminary testing conducted to determine several key parameters, including simulation time parameters and fire ignition and spread parameters (for a list of all model parameters and associated values for the LANDFIRE Prototype, see appendix 10-B).

Simulation time parameters—Simulation time parameters for the model include 1) reporting interval, 2) total simulation time, and 3) initialization time. The reporting interval determines how often (in years) LANDSUMv4 reports vegetation conditions and fire characteristics across the landscape over the simulation period and the number of samples available for quantifying historical reference conditions. The selection of the reporting interval was largely driven by the need to reduce temporal autocorrelation in the LANDSUMv4 output so that each reporting interval represented an independent observation for calculating departure (Holsinger and others, Ch. 11; Steele and others, in preparation). After preliminary analysis, we selected a 20-year reporting interval for Zone 16. Following the Zone 16 runs, however, we determined that a 20-year reporting interval resulted in autocorrelation between observations, so we extended the reporting interval to 50 years for Zone 19 (see Holsinger and others, Ch. 11 for details on temporal autocorrelation in the reference conditions data).

The initialization period represents the number of years it takes the initial simulation landscape to reach equilibrium, and this initial simulation period is excluded from subsequent analysis. Keane and others (2002a) found that it took approximately 200 years for succession class distributions to reach equilibrium, whereas Keane and others (2003) found that the landscape MFRI stabilized after the first 200 – 400 years of simulation. In our exploratory analysis for Zone 16, we found that successional development had a distinct trend for the first 250 to 500 years and then stabilized around a mean with expected variations (Keane and others 2002a). As a result, we specified a 500-year initialization period for both Zone 16 and Zone 19.

The total simulation period needed to be long enough to adequately capture the full range of vegetation conditions and fire regime characteristics and produce an adequate chronosequence to quantify historical vegetation conditions for subsequent departure calculations. In addition, extreme fire events, though rare, have a disproportionately large impact on vegetation patterns across the landscape (Moritz 1997; Strauss and others 1989), so it is important that the simulation period is long enough to allow sufficient opportunity for these rare events to occur. The fire return interval influences the simulation length appropriate for capturing fire and vegetation characteristics, and thus the appropriate simulation length varies across landscapes. Our selection of the total simulation period was largely informed by the number of samples needed for departure analysis. Holsinger and others (Ch. 11) found that a minimum of 200 independent observations from LANDSUMv4 were required to develop a time series reasonable for quantifying historical landscape conditions for departure calculations. Based on this criterion, we calculated simulation periods of 4,500 years and 10,500 years (each including a 500-year initialization period) for Zone 16 and Zone 19, respectively.

Fire ignition and fire spread parameters—In LANDSUMv4, wildland fire is modeled in three steps: ignition, spread, and effects. Fire effects are determined stochastically by the probabilities defined in the vegetation pathways. Fire ignition uses a three-parameter Weibull hazard function (Johnson and Gutsell 1994; Johnson and Van Wagner 1985) based on the fire probabilities in the vegetation pathways, a shape parameter, and a years-until-reburn parameter to adjust the probability in the pathways to account for fuel build-up. The fire probabilities from the vegetation pathways reflect point estimates of fire return interval and describe the probability that a fire will burn a point on the landscape. The probability is adjusted using the relationship of average fire size (ignition average fire size parameter) to the pixel area (90 m^2) and patch size to pixel area to scale point-level fire probabilities to stand-level ignition probabilities. The ignition probability is also adjusted for yearly weather variations based on a fire weather parameter that establishes the number of dry, normal, and wet fire years in a decade (for a thorough discussion of the equations and parameters used LANDSUMv4 fire simulations, see Keane and others 2002a and Keane and others 2006). The fire spread algorithm calculates a fire size from a heavy-tailed exponential distribution that is defined by a shape and a scale parameter (Keane and others 2002a; Keane and others 2006). Fire is then spread cell-to-cell based on the modified equations of Rothermel (1991) and wind and slope vectors until it reaches the calculated fire size or an unburnable boundary. In this section, we will discuss the ignition average fire size parameter, the spread scale parameter, and the ignition fire weather parameter.

Both the ignition average fire size parameter and the spread scale parameter are related to average fire size. The spread scale parameter influences the average fire size simulated by LANDSUMv4 by controlling the distribution from which fire sizes are drawn. As the scale parameter increases, the simulated average fire size also increases (fig. 4). The ignition fire size parameter should approximate the estimated average fire size for the landscape and is used in scaling fire probabilities to ignition probabilities. As the ignition fire size parameter increases, the number of fires (number of ignitions) decreases (fig. 4). Estimating both of these parameters correctly requires information about historical fire sizes; however, reliable data on historical average fire sizes are difficult to obtain. We calculated an average fire size from the National Integrated Fire Management Interagency Database (NIFMID; USDA Forest Service 1993) for each mapping zone. Although this database records recent fires only and is therefore likely a poor representation of historical fire sizes, it was the only source available for estimating fire size across the entire United States. We used the NIFMID estimate as a starting point for the ignition average fire size and the spread scale parameter estimates. Together, ignition and spread will determine the mean fire return interval over the simulation. In an attempt to refine these parameters, we tried various combinations of the ignition average fire size and spread scale parameters within a test area and evaluated the mean fire return interval. The vegetation pathways define fire probabilities based on estimates of historical fire frequencies from literature review and fire history studies (Long and others, Ch. 9). We averaged these probabilities and treated these mean probabilities

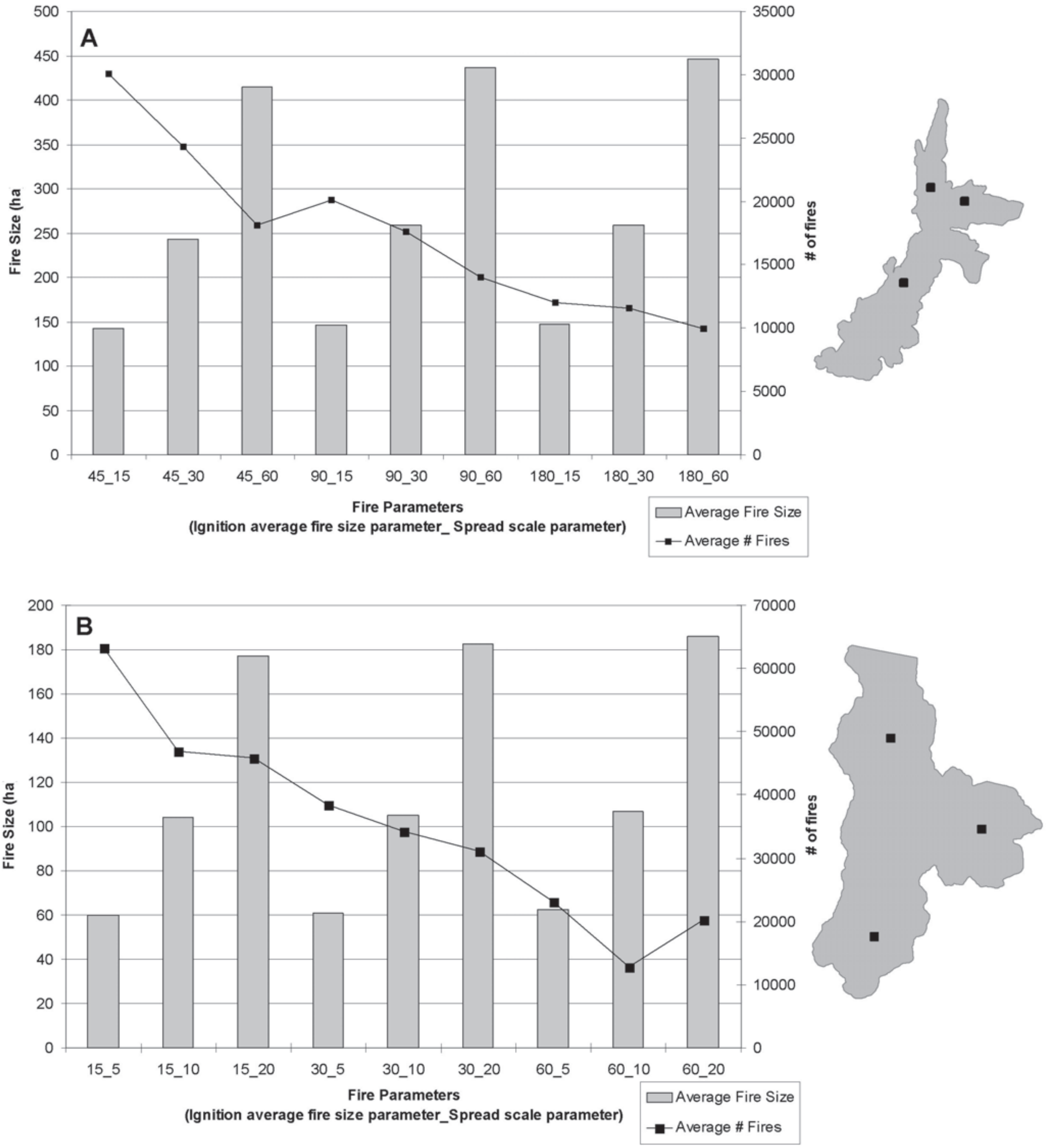

Figure 4—Average fire size and average number of fires as a function of fire size parameter pairs (ignition fire size parameter and spread scale parameter) for three test landscapes in a) Zone 16 and b) Zone 19. The average fire size and the number of fires were calculated for each landscape and then averaged for a single parameter pair.

as the expected fire occurrence and the inverse of these probabilities as the expected mean fire return interval. Fire occurrence in LANDSUMv4 is based, in part, on the probabilities of fire in the succession pathways, so we operated under the assumption that the MFRI modeled by LANDSUMv4 should be reasonably close (within 25 percent) to the expected MFRI calculated from the vegetation pathways. LANDSUMv4 calculates and reports a simulated MFRI and an expected MFRI (calculated from the pathway-defined fire probabilities) for the entire simulation landscape. For Zone 16, we found that an ignition average fire size parameter that was three times the spread scale parameter resulted in simulated MFRIs for the simulation landscape that were similar to the expected MFRI as calculated by LANDSUMv4. We set the spread scale parameter to the 30-ha NIFMID estimate and the ignition average fire size parameter to 90 ha for Zone 16.

After simulating the entire zone, the MFRI for many PVTs in Zone 16 were much longer than expected (see the *Results* section below for details). We therefore modified our methods for setting the ignition average fire size and spread scale parameters for Zone 19. We started with an average fire size estimate of 30 ha from the NIFMID database. We then varied the two fire size distribution parameters and ran simulations for each parameter pair on three test landscapes of varying topography and vegetation (fig. 5). We calculated the simulated mean fire return interval for each PVT and calculated a similarity value (expected MFRI divided by simulated MFRI) to compare the simulated MFRI and expected MFRI for each PVT (fig. 5b). For the Zone 19 simulations, we selected 30 ha for the ignition average fire size parameter based on the 30 ha NIFMID estimate and 15 ha for the spread scale parameter.

The ignition fire weather multiplier does not affect the long-term fire probabilities, but rather affects the year-to-year probability of fire occurrence. To estimate the weather parameter (the number of dry, normal, and wet years in a decade), we used reconstructions of the Palmer Drought Severity Index (PDSI; Palmer 1965) from various sources. PDSI is an index of soil moisture based on precipitation, temperature, and available water content (AWC) of the soil. The index varies roughly between -6.0 and +6.0, with positive numbers representing wetter conditions and negative numbers drier conditions. For Zone 16, we relied on the Northeastern Utah Palmer Drought Severity Index Reconstruction, which is based on tree ring chronologies in and around the Uinta Basin (Gray and others 2003), to estimate historical climate conditions from 1405 to 2000 A.D. We assumed that wet years were those with a PDSI greater than 1.0, normal years were those with a PDSI between –1.99 and 0.99, and severe drought years were those with a PDSI of less than –1.99. Accordingly, we estimated the number of dry, normal, and wet years over the course of a decade as 3, 5, and 2, respectively. For Zone 19, we extracted data from the Alternative Method USA Summer PDSI Reconstruction (Zhang and others 2004). This data set is based on tree ring chronologies from 1700 to 1894 and instrumental data from 1895 to 1978. Using the same breaks for wet, normal, and dry years as described above, we estimated the number of dry, normal, and wet years as 1, 6, and 3, respectively, for Zone 19.

Model Output

Although there are many maps and tabular files output from LANDSUM, we produced only two types of data for the LANDFIRE Prototype: (1) vegetation chronosequence data and 2) fire regime maps. The time series data that define reference conditions for vegetation are summarized in a tabular file that summarizes the area (m^2) within each reporting unit that is occupied by each PVT-succession class combination for each reporting year. Holsinger and others (Ch. 11) used these data to calculate FRCC and departure values for each reporting unit. While there are many important characteristics of fire regimes, we mapped and evaluated only fire frequency and fire severity values. Other characteristics such as fire size and pattern can be evaluated using output from LANDSUMv4 but, because of limited computer resources, we chose not to create these files for the entire mapping zone. The fire frequency and fire severity maps were processed to create the final LANDFIRE Prototype fire regime map products.

Fire regime maps—LANDSUMv4 outputs four different fire regime maps — three severity maps and one frequency map — which we then processed to create the final LANDFIRE Prototype fire regime maps. Fire effects in LANDSUMv4 are defined as one of three severity types: non-lethal surface, mixed-severity, and stand-replacing fires. LANDFIRE produces maps for each of these severity types that display the percentage of fires of the given severity type experienced by a particular pixel. Fire severity is calculated as the total number of fires of the given severity type divided by the total number of fires experienced by that cell times 100. Values for each map range from 0 - 100 and, for any cell, the sum of the three maps should equal 100. The fire frequency map simply reports the fire return

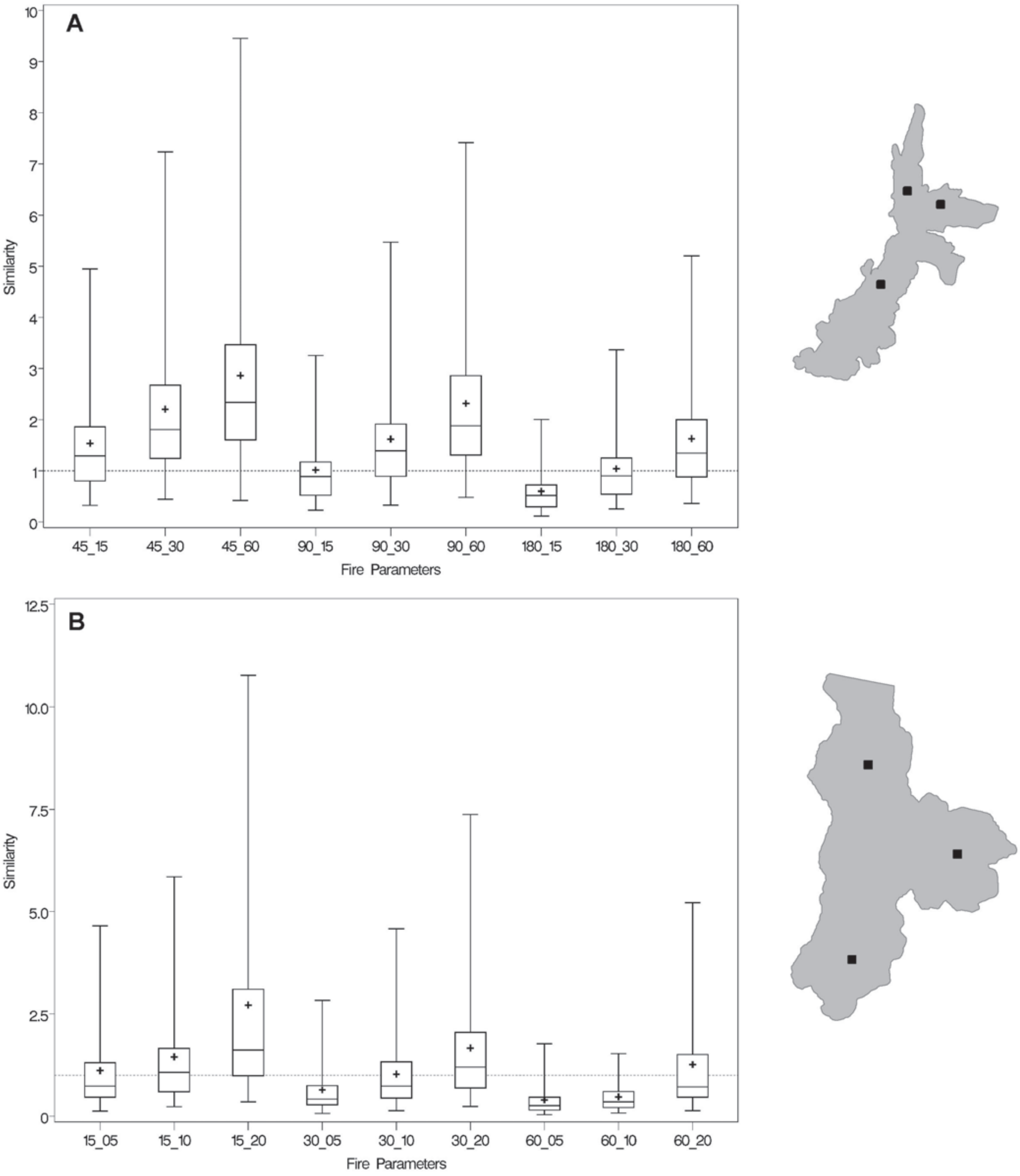

Figure 5—Box and whisker plots for the similarity index calculated for each of the nine fire parameter pairs (ignition fire size parameter and spread scale parameter) for three test landscapes in a) Zone 16 and b) Zone 19. The similarity index is a measure of the similarity between the simulated mean fire return intervals and the mean fire return intervals based on the fire probabilities set in the vegetation pathways. A similarity value of 1 indicates that the two MFRIs are the same. A similarity above 1 indicates that the simulated MFRI is shorter than the scenario MFRI, and a similarity less than 1 indicates that the simulated MFRI is longer than the scenario MFRI.

interval (in years) and is calculated as the total number of simulation years divided by the total number of fires occurring in that cell.

When the fire frequency maps from the individual simulations were tiled together to create a composite map for the entire zone, the resulting map contained a heavy imprint from the individual simulation landscapes (fig. 6a). We used the simulation buffer areas to smooth the edges between adjacent simulation landscapes and reduce the imprint to create a seamless map for the zone. The buffer area for one simulation landscape overlapped the context area of the adjacent simulation landscape (fig. 3). As noted above, these buffer regions tended to yield underestimations of fire frequencies. However, since fires tend to burn primarily in the direction of the prevailing winds (WSW in our simulation areas), buffer areas along the north and east edges still had many fires burning in from the context area; thus, fire was usually realistically simulated in these areas. We clipped the south and west buffer areas off of each context area and left the north and east buffer areas intact. We then used the *mosaic* command in ARC/INFO to overlay the individual simulation landscapes and smooth the overlapping areas (fig. 6b). Although this process led us to change some pixel values from their original simulated value, values were changed only in areas where fires tended to be underestimated by the model (along the western and southern borders of the context area). Following the smoothing process for Zone 16, 26 percent of the pixel values on the map changed from the simulated values and the mean change for all pixels was three fires.

Results

Fire Regime Maps

Fire frequency—Figure 7 shows the mean fire return interval (MFRI) in years for both mapping zones. The MFRIs for Zone 16 were relatively short: 58 percent of the zone had a fire return interval of 35 years or less, 94 percent of the zone had a fire return interval of 100 years or less, and fire return intervals of more than 100 years occurred in less than 0.5 percent of the zone. Six percent of the zone never burned during the 4,500-year simulation period. The MFRIs in Zone 19 tended to be longer: 31 percent of the zone had a fire return interval of 35 years or less, 93 percent had fire return intervals of 100 years or less, and nearly 5 percent of the zone had fire return intervals between 100 and 200 years. Less than 3 percent of the zone was unburned during the 10,500-year simulation period. In both zones, most of the pixels that did not burn (99 percent) belonged to PVTs that were defined as unburnable in the model (water, rock, snow/ice, agriculture, and urban for Zone 16 and water, rock, and snow/ice for Zone 19). There were a few vegetated areas with the potential to burn that never burned; these pixels were imbedded in a matrix of unburnable pixels, thereby preventing fires from spreading to those pixels.

To get a sense of how well the model simulated fire for different vegetation types, we compared the expected MFRI calculated from the fire probabilities in the vegetation pathways to the simulated MFRIs averaged for each PVT (tables 1 and 2). As noted previously, the simulation of fire in LANDSUMv4 is based in part on the fire probabilities in the vegetation pathways. Fire spread, however, operates independent of these probabilities. Furthermore, adjacency of PVTs with different fire probabilities may cause the simulated MFRI to be different from the expected MFRI in some PVTs. We determined, however, that when averaged by PVT across the zone, the simulated MFRI should be within 25 percent of the expected MFRI for most PVTs. Two-thirds of the PVTs in Zone 16 had more than a 30-percent difference between the simulated MFRI and the expected MFRI (table 1). Many of these PVTs represented only a small portion of the zone, but together, these 20 PVTs represented over 70 percent of Zone 16. In all but three of these PVTs, the simulated MFRI was shorter than the expected MFRI. For example, the Spruce Fir / Spruce Fir PVT had an MFRI in the pathways of 53 years, whereas the MFRI simulated by LANDSUMv4 for this PVT was 32 years. For some PVTs, however, the simulated MFRI was fairly close to the expected MFRI (see Pinyon Juniper / Mountain Big Sagebrush / South, Douglas-fir / Douglas-fir, and Grand Fir – White Fir in table 1). In Zone 19, the simulated MFRIs corresponded somewhat better to the expected MFRIs (table 2). Just over 50 percent of the PVTs in Zone 19 had more than a 30-percent difference between the simulated MFRI and the expected MFRI; however, these PVTs comprised only 38 percent of Zone 19. Again, the simulated MFRIs tended to be shorter than the expected MFRIs for these PVTs (see Spruce-Fir / Timberline in table 2, for example), yet six PVTs did have a simulated MFRI that was longer than the pathway MFRI (see Douglas-fir / Ponderosa Pine / Douglas-fir in table 2, for example).

Fire severity—The model produced three fire severity maps, one for each severity type (stand-replacing, mixed-severity, and non-lethal surface fires). Each map displayed the percentage of total fires that were of a particular severity (see *Model Output* in the *Methods* section for

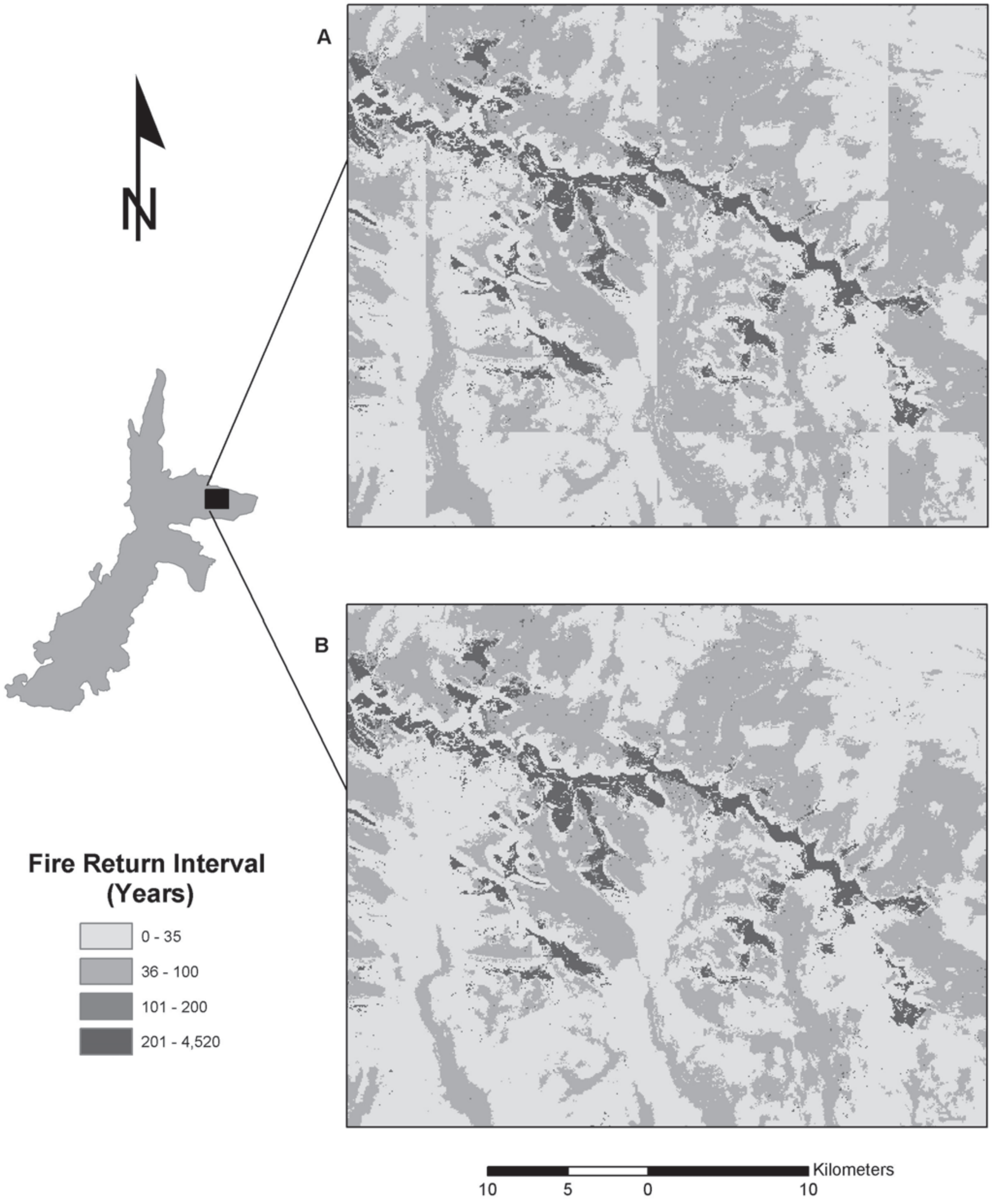

Figure 6—Fire frequency maps for two adjacent simulation landscapes in Zone 16 that were processed by a) removing all 3-km buffer areas and merging the context areas and b) removing only the south and west 3-km buffer areas and mosaicking the context areas and overlapping buffers.

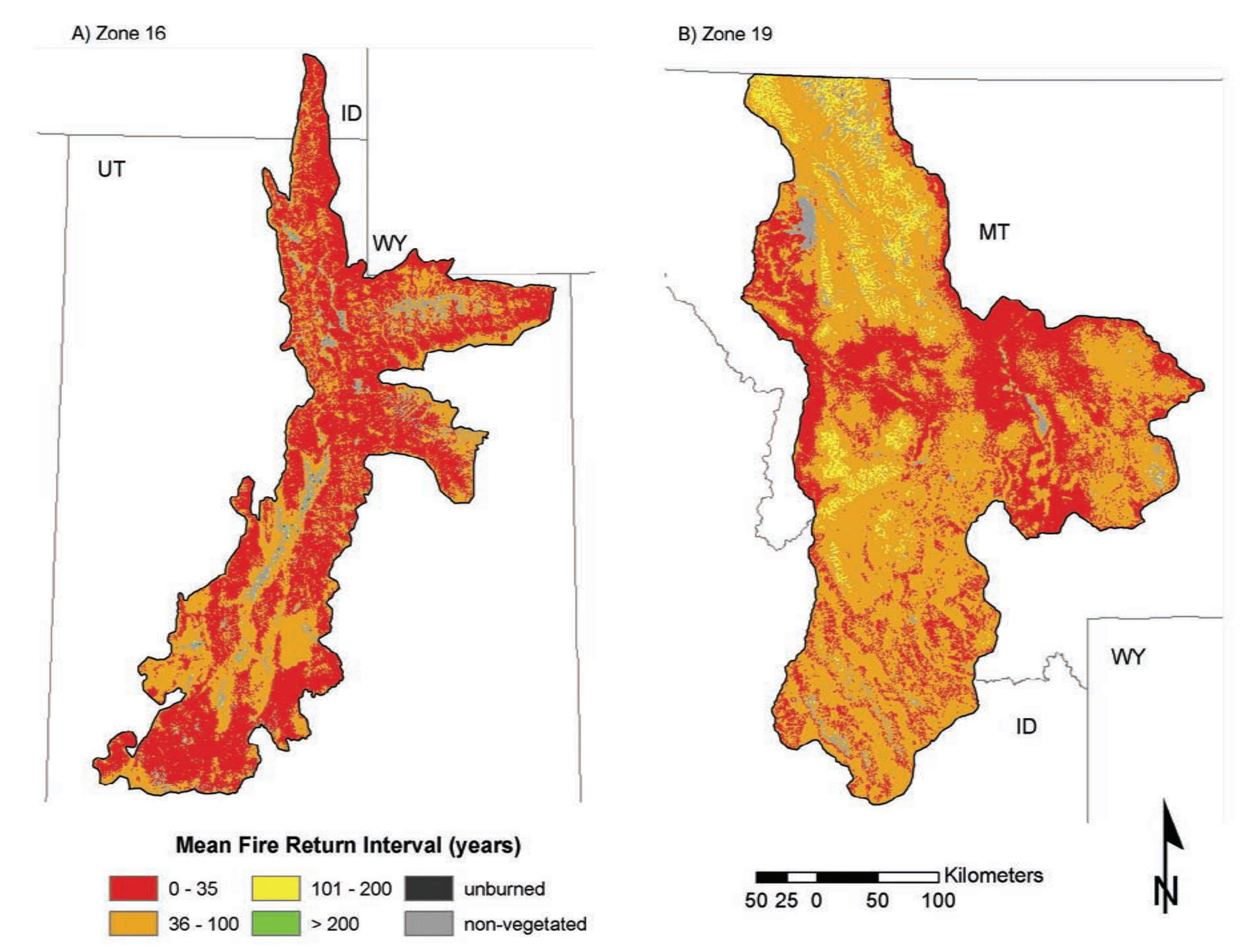

Figure 7—Mean fire return interval (MFRI) in years for a) Zone 16 and b) Zone 19. MFRI was calculated for each pixel as the total simulation time divided by the total number of fires that occurred within the pixel during the simulation period. Non-vegetated pixels are those areas with no natural vegetation, such as water or rock, and therefore cannot burn. Unburned pixels are vegetated pixels that never burned during the simulation period.

Table 1—Mean fire return interval (MFRI) values summarized for each PVT in Zone 16. MFRIs are reported as "Pathway MFRI" (the mean of the fire probabilities for all succession classes in a PVT weighted by the percent area of the PVT occupied by each succession class in 200 reporting years), "Classified MFRI" (percent of the PVT in each of the five MFRI classes used by Schmidt and others 2002 after the 4500-year simulation), and "Raw MFRI" (mean MFRI for the PVT after the 4,500-year simulation). The percent of Zone 16 that each PVT occupies is also given.

PVT		Pathway MFRI (yrs)	Raw simulated MFRI (yrs)		Classified simulated MFRI (% of PVT)				
Name	**% of zone**	**Mean**	**Mean**	**Std. dev.**	**0**	**1-35 yrs**	**36-100 yrs**	**101-200 yrs**	**200+ yrs**
Alpine	0.33	244	71	290	0.6	39.6	55.8	2.3	1.6
Aspen	2.07	63	33	28	0.0	78.4	21.6	0.0	0.0
Blackbrush	0.36	200	65	142	0.2	9.1	88.7	1.6	0.4
Cool Herbaceous	0.14	25	47	153	0.2	54.6	43.9	0.8	0.5
Douglas-fir / Douglas-fir	3.17	29	32	17	0.0	80.5	19.5	0.0	0.0
Douglas-fir / Lodgepole Pine	0.19	41	33	4	0.0	79.8	20.2	0.0	0.0
Douglas-fir / Timberline Pine	0.47	44	31	29	0.0	89.4	10.6	0.0	0.0
Dwarf Sagebrush	4.48	97	46	73	0.0	23.7	75.9	0.2	0.1
Grand Fir – White fir	7.02	36	31	12	0.0	90.3	9.7	0.0	0.0
Grand Fir – White Fir / Maple	2.61	34	42	133	0.1	57.7	41.2	0.6	0.3
Lodgepole Pine	0.81	60	33	4	0.0	71.6	28.4	0.0	0.0
Mountain Big Sagebrush	8.67	20	32	44	0.0	83.1	16.8	0.1	0.1
Pinyon – Juniper / Gambel Oak	1.44	41	39	112	0.1	65.8	33.4	0.5	0.3
Pinyon – Juniper / Mountain Big Sagebrush / North	1.16	24	34	42	0.0	78.4	21.3	0.2	0.0
Pinyon – Juniper / Mountain Big Sagebrush / South	5.22	30	33	19	0.0	79.3	20.6	0.0	0.0
Pinyon – Juniper / Mountain Mahogany	1.06	58	34	38	0.0	73.7	26.2	0.1	0.0
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / North	2.43	66	48	53	0.0	4.9	94.6	0.4	0.1
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South	16.47	56	39	34	0.0	36.3	63.5	0.1	0.0
Ponderosa Pine	2.48	15	29	19	0.9	93.4	5.7	0.0	0.0
Riparian Hardwood	2.11	72	37	66	0.1	55.4	44.4	0.1	0.1
Riparian Shrub	1.00	64	72	316	1.1	41.8	54.0	1.5	1.5
Salt Desert Shrub	2.13	119	69	197	0.2	2.6	94.5	1.7	1.0
Spruce – Fir / Blue Spruce	1.15	41	32	34	0.0	84.0	15.9	0.0	0.0
Spruce – Fir / Blue Spruce / Lodgepole Pine	0.54	43	34	13	0.0	68.2	31.8	0.0	0.0
Spruce – Fir / Spruce – Fir	7.97	53	32	24	0.0	86.2	13.7	0.0	0.0
Spruce – Fir / Spruce – Fir / Lodgepole Pine	13.25	53	34	12	0.0	72.0	27.9	0.0	0.0
Timberline Pine	0.03	186	32	30	0.0	86.6	13.3	0.0	0.0
Warm Herbaceous	0.73	40	45	151	0.1	56.2	42.6	0.6	0.4
Wetland Herbaceous	0.27	183	48	186	0.3	57.8	40.5	0.6	0.7
Wyoming – Basin Big Sagebrush	4.45	81	54	177	0.2	27.1	70.8	1.2	0.7

Table 2—Mean fire return interval (MFRI) values summarized for each PVT in Zone 19. MFRIs are reported as "Pathway MFRI" (the mean of the fire probabilities for all succession classes in a PVT weighted by the percent area of the PVT occupied by each succession class in 200 reporting years), "Classified MFRI" (percent of the PVT in each of the five MFRI classes used by Schmidt and others 2002 after the 4500-year simulation), and "Raw MFRI" (mean MFRI for the PVT after the 10,500-year simulation). The percent of Zone 19 that each PVT occupies is also given.

PVT		Pathway MFRI (yrs)	Raw simulated MFRI (yrs)		Classified simulated MFRI (% of PVT)				
Name	**% of zone**	**Mean**	**Mean**	**Std. dev.**	**0**	**1-35 yrs**	**36-100 yrs**	**101-200 yrs**	**200+ yrs**
Alpine	0.03	245	39	15	0.00	50.56	48.69	0.74	0.02
Bluebunch Wheatgrass	9.46	26	32	27	0.00	77.27	22.70	0.02	0.01
Bluebunch Wheatgrass / Conifer	0.26	26	33	68	0.01	74.07	25.75	0.14	0.04
Douglas-fir / Douglas-fir	10.52	52	39	13	0.00	42.05	57.66	0.29	0.00
Douglas-fir / Lodgepole Pine	4.19	53	45	15	0.00	24.65	74.71	0.64	0.01
Douglas-fir / Ponderosa Pine/ Douglas Fir	3.03	20	32	7	0.00	72.00	28.00	0.00	0.00
Douglas-fir / Timberline Pine	1.11	48	39	16	0.00	45.79	53.92	0.29	0.01
Douglas-fir / Ponderosa Pine/ Western Larch/	2.43	21	32	14	0.00	77.27	22.49	0.21	0.03
Dry Shrub	1.28	29	40	108	0.01	58.50	40.35	1.04	0.09
Dry Shrub / Conifer	0.21	26	61	169	0.04	19.73	73.14	6.82	0.27
Dwarf Sagebrush Complex / Conifer	0.00	67	36	7	0.00	61.32	38.68	0.00	0.00
Dwarf Sagebrush Complex	0.26	32	40	6	0.00	18.81	81.15	0.04	0.00
Fescue Grasslands	2.02	25	36	36	0.00	60.90	38.84	0.23	0.02
Fescue Grasslands / Conifer	0.46	34	42	29	0.00	36.68	62.18	1.09	0.05
Grand Fir - White Fir	0.82	55	55	37	0.00	12.51	83.79	3.07	0.63
Lodgepole Pine	3.65	85	53	18	0.00	9.62	88.76	1.62	0.01
Mountain Mahogany	0.28	32	37	21	0.00	46.31	53.67	0.02	0.00
Mountain Big Sagebrush Complex/Conifer	0.76	33	41	40	0.00	33.68	65.95	0.36	0.01
Mountain Big Sagebrush Complex	5.20	34	37	14	0.00	48.06	51.91	0.03	0.00
Ponderosa Pine	1.14	13	28	10	0.00	89.55	10.37	0.06	0.02
Riparian Hardwood	1.43	122	46	64	0.00	26.99	71.61	1.26	0.14
Riparian Shrub	0.92	62	48	107	0.02	21.08	77.94	0.87	0.10
Rocky Mountain Juniper	0.12	31	36	32	0.00	52.28	47.69	0.03	0.01
Spruce - Fir / Montane / Douglas-fir	4.01	97	50	23	0.00	17.74	80.29	1.96	0.01
Spruce - Fir / Subalpine	6.69	209	81	48	0.00	2.50	73.28	23.86	0.36
Spruce – Fir / Timberline	8.88	261	81	86	0.01	2.02	77.41	20.43	0.13
Spruce - Fir / Montane/ Western Larch	8.21	73	66	28	0.00	7.50	82.51	9.91	0.09
Threetip Sagebrush / Conifer	0.02	31	38	9	0.00	42.44	57.54	0.01	0.00
Threetip Sagebrush	0.54	32	36	6	0.00	53.15	46.85	0.01	0.00
Timberline Pine / Limber Pine	0.13	211	40	98	0.02	48.08	51.31	0.52	0.07
Timberline Pine / Whitebark Pine	0.44	368	70	250	0.08	6.85	88.65	4.05	0.36
Western Redcedar	0.55	107	65	25	0.00	6.41	86.67	6.68	0.24
Wetland Herbaceous	1.32	180	52	101	0.02	20.84	76.97	1.98	0.20
Wyoming – Basin Big Sagebrush Complex / Conifer	0.50	54	39	32	0.00	41.49	58.31	0.17	0.03
Wyoming – Basin Big Sagebrush Complex	16.72	54	42	28	0.00	19.23	80.70	0.06	0.01

a more detailed explanation). The three severity maps for each zone are shown in figure 8. Both zones were dominated by stand-replacing fires. The mean percentage of stand-replacing fires was 69.8 percent in Zone 16 and 72.5 percent in Zone 19. The mean percentage of non-lethal surface fires was 17.1 percent and 14.5 percent, and that of mixed-severity fires was 6.5 percent and 12.2 percent for zones 16 and 19, respectively. We also examined severity in relation to PVT (tables 3 and 4). In Zone 16, most of the forest PVTs had roughly equal amounts of stand-replacing and non-lethal surface fires, with very few (15 percent or less) mixed-severity fires. A few forest PVTs had almost exclusively stand-replacing fires. Mixed-severity fires were more common in Zone 19, where several PVTs had a mean greater than 20 percent. Timberline pine PVTs had almost exclusively stand-replacing fires, with mean probabilities from 78 percent to 97 percent. In both zones, almost all of the rangeland types had predominantly stand-replacing fires (80 to 100 percent). In Zone 19, only the Riparian Shrub PVT had less than 99 percent stand-replacing fires. Zone 16 shrub and herbaceous PVTs were slightly more diverse in terms of fire severity. In Zone 16, a few PVTs were equally divided between having stand-replacing and non-lethal surface fires and one PVT almost equally divided between stand-replacing and mixed-severity fires. There was fairly close correspondence between the mean percentages for simulated fires and the mean percentages calculated from the pathway probabilities for both zones.

Historical Vegetation Reference Conditions

The simulated historical reference conditions for vegetation were summarized as the area occupied by each succession class in each PVT for every reporting unit across each reporting year. There were 200 reporting years in a simulation with up to 33 succession classes (with an average of 13) per PVT and as many as 26 PVTs (with an average of 11) per reporting unit for Zone 16. For demonstration purposes, figures 9 and 10 show a sample of this data set for the top six succession classes for one forest (Lodgepole Pine) and one rangeland (Mountain Big Sagebrush) PVT in a single simulation landscape (20,000 ha). These figures illustrate the large range of vegetation conditions experienced over the simulation period. In the Mountain Big Sagebrush PVT, for example, Low Cover, Low Height Cool Season Perennial Grass occupied anywhere from zero to almost 90 percent of the PVT for this landscape throughout the 4,000 years of simulation. Other succession classes had less amplitude. Low Cover, Low Height Dry Deciduous Shrub occupied only between zero and 10 percent of the landscape. In general, the Mountain Big Sagebrush PVT appeared to be dominated alternately by Mountain Big Sagebrush and Cool Season Perennial Grass succession classes, with other shrub types at lower levels throughout the simulation. The Lodgepole Pine PVT was generally dominated by Aspen-Birch succession classes, with Lodgepole Pine succession classes dominating for short periods and generally at moderate levels.

Discussion

Limitations of the Simulation Approach for Describing Historical Conditions

Estimating fire parameters—One of the main difficulties in realistically simulating historical fire regimes lies in the estimation of model parameters. Fire history studies remain the primary source for estimating fire probabilities in modeling efforts, particularly fire return interval. However, the data collected in fire history studies pose problems of scale and analysis. First, many fire history studies are conducted in small areas within highly complex landscapes. Topographical features and their orientation, coupled with predominant wind patterns, can influence fire history within a small study area. Second, in a fire history chronology, there are often years in which only a single scar exists and years where nearly every tree in the area is scarred. To be considered in the calculation of mean fire return interval for the study area, a fire year is often determined by a threshold number of trees that show evidence of fires (for example, a "fire year" is one where 10 percent or more of the trees in the area are scarred). The number of fire years incorporated into the calculation of mean fire return interval is highly sensitive to this threshold. Furthermore, if a tree shows no scar, it is difficult to determine whether this is because the tree was not in the area burned by the fire or because the fuel located directly around the tree was insufficient to generate the intensity required to create a scar. Thus, the computed fire return interval is dependent upon not only the number of trees used to identify a fire year, but also upon the number of fire-scarred trees sampled within the study area. To complicate matters further, fire scars are point measures of fire history and do not integrate the complex spatial interactions of fire spread over a study area or landscape. Finally, fire history studies are spatially limited to several key ecosystems (mostly forest) of the United States and document fire events over

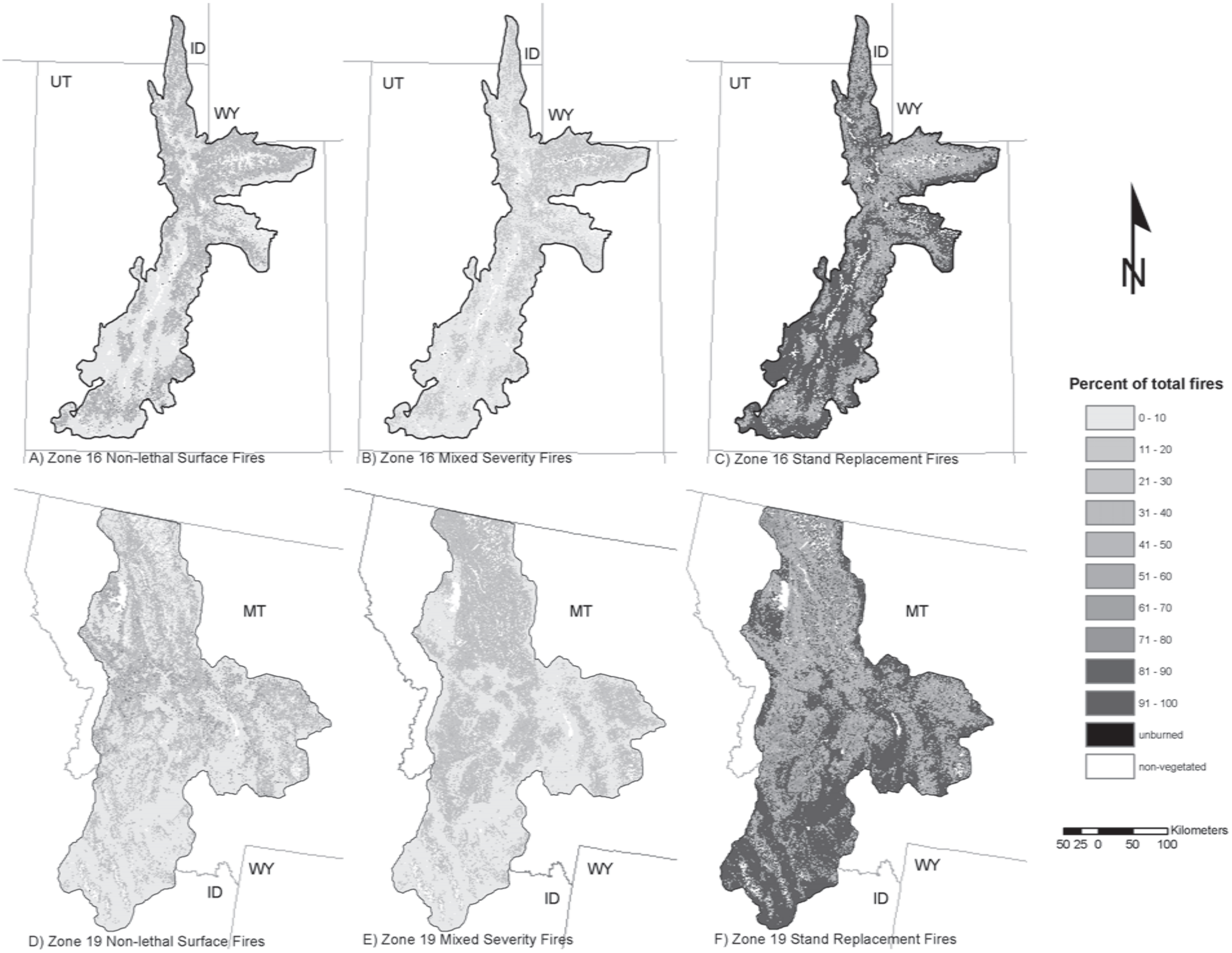

Figure 8—Percentage of simulated fires that were a) stand-replacing, b) mixed-severity, and c) non-lethal surface fires in Zone 16 and d) stand-replacing, e) mixed-severity, and f) non-lethal surface fires in Zone 19. Non-vegetated pixels are those areas with no natural vegetation, such as water or rock, and therefore cannot burn. Unburned pixels are vegetated pixels that never burned during the simulation period.

Table 3—Mean percentage of stand-replacing fire (SRF), mixed-severity fire (MSF), and non-lethal surface fire (NLSF) for each potential vegetation type (PVT) for Zone 16 calculated from the simulated fire severity maps (SIM MEAN) and the vegetation pathways (PATH MEAN). For each severity type, the simulated mean was calculated by taking the mean of the percentage value reported on the severity map for each pixel across each PVT. The pathway mean is the mean of the probabilities for the severity type for each succession class in each PVT weighted by the percent area of the PVT occupied by each succession class over all 200 reporting intervals.

	SRF		MSF		NLSF	
PVT NAME	PATH MEAN	SIM MEAN	PATH MEAN	SIM MEAN	PATH MEAN	SIM MEAN
Alpine	88.0	99.4	0.0	0.0	0.0	0.0
Aspen	61.1	57.4	0.0	0.0	38.9	41.7
Blackbrush	100.0	99.8	0.0	0.0	0.0	0.0
Cool Herbaceous	100.0	99.8	0.0	0.0	0.0	0.0
Douglas-fir / Douglas-fir	42.2	39.3	10.8	11.3	47.0	47.9
Douglas-fir / Lodgepole Pine	47.0	43.8	15.9	16.0	37.2	38.7
Douglas-fir / Timberline Pine	60.2	59.6	4.0	4.0	35.8	34.9
Dwarf Sagebrush	100.0	100.0	0.0	0.0	0.0	0.0
Grand Fir – White fir	40.6	36.8	13.1	13.5	46.3	48.2
Grand Fir – White Fir / Maple	93.5	91.0	6.5	7.9	0.0	0.0
Lodgepole Pine	60.7	56.8	10.7	12.6	28.6	29.2
Mountain Big Sagebrush	100.0	100.0	0.0	0.0	0.0	0.0
Pinyon – Juniper / Gambel Oak	98.2	97.4	1.8	1.7	0.0	0.0
Pinyon – Juniper / Mountain Big Sagebrush / North	86.5	83.7	13.5	15.4	0.0	0.0
Pinyon – Juniper / Mountain Big Sagebrush / South	97.2	95.9	2.8	3.2	0.0	0.0
Pinyon – Juniper / Mountain Mahogany	99.6	99.2	0.4	0.4	0.0	0.0
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / North	98.5	97.5	1.5	1.8	0.0	0.0
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South	96.1	95.7	3.9	3.4	0.0	0.0
Ponderosa Pine	37.4	37.4	5.0	4.6	57.6	56.6
Riparian Hardwood	63.7	59.4	2.1	1.6	34.3	37.6
Riparian Shrub	68.5	56.5	31.5	41.7	0.0	0.0
Salt Desert Shrub	100.0	99.8	0.0	0.0	0.0	0.0
Spruce – Fir / Blue Spruce	41.4	37.5	14.2	15.3	44.4	45.8
Spruce – Fir / Blue Spruce / Lodgepole Pine	42.0	38.1	12.4	13.7	45.5	46.8
Spruce – Fir / Spruce – Fir	54.4	48.5	11.0	13.1	34.7	36.9
Spruce – Fir / Spruce – Fir / Lodgepole Pine	52.4	46.8	12.6	14.6	35.0	37.1
Timberline Pine	97.8	97.8	0.3	0.1	1.9	1.6
Warm Herbaceous	100.0	99.9	0.0	0.0	0.0	0.0
Wetland Herbaceous	100.0	99.7	0.0	0.0	0.0	0.0
Wyoming – Basin Big Sagebrush	100.0	99.8	0.0	0.0	0.0	0.0

a very short time period of approximately three to five centuries. The lack of fire history data for large areas of the United States and the limited temporal depth of evidence of past fires are perhaps the largest obstacles to simulating historical conditions across the nation.

The fire size parameters required by LANDSUMv4 are even more difficult to estimate because sound historical data do not exist at broad scales. While fire scars or pollen records can be used to reconstruct historical fire frequencies, they cannot be used to reconstruct historical fire perimeters or fire sizes. Atlases of fires over time have been compiled for some areas, but the temporal scale is relatively short (Rollins and others 2001). Fire size data from recent decades are available for most of the nation, but these data reflect fire size distributions during an era where fire suppression was common, and thus these fire sizes may not be representative of historical conditions. Moreover, NIFMID data – the only source for nationwide fire data – further compound this problem by including double reports of fires and excluding reports of small fires. Further complicating the attempt to compare historical fire size estimates with fire sizes simulated by LANDSUMv4 is the fact that the model does not simulate small fires. Due to the spatial scale of input data and model efficiency, no fires smaller than 1 ha are simulated. This exclusion removes a portion of the

Table 4—Mean percentage of stand-replacing fire (SRF), mixed-severity fire (MSF), and non-lethal surface fire (NLSF) for each potential vegetation type (PVT) for Zone 19 calculated from the simulated fire severity maps (SIM MEAN) and the vegetation pathways (PATH MEAN). For each severity type, the simulated mean was calculated by taking the mean of the percentage value reported on the severity map for each pixel across each PVT. The pathway mean is the mean of the probabilities for the severity type for each succession class in each PVT weighted by the percent area of the PVT occupied by each succession class over all 200 reporting intervals.

	SRF		MSF		NLSF	
PVT NAME	**PATH MEAN**	**SIM MEAN**	**PATH MEAN**	**SIM MEAN**	**PATH MEAN**	**SIM MEAN**
Alpine	86.9	100.0	0.0	0.0	0.0	0.0
Bluebunch Wheatgrass	100.0	100.0	0.0	0.0	0.0	0.0
Bluebunch Wheatgrass / Conifer	100.0	99.9	0.0	0.0	0.0	0.0
Douglas-fir / Douglas-fir	32.0	46.4	24.2	24.5	28.3	27.6
Douglas-fir / Lodgepole Pine	33.0	45.7	20.7	21.5	32.4	31.3
Douglas-fir / Ponderosa Pine/ Douglas Fir	21.4	29.2	7.1	7.0	64.6	62.4
Douglas-fir / Timberline Pine	71.3	84.1	3.1	2.9	12.2	11.5
Douglas-fir / Ponderosa Pine/ Western Larch	26.1	34.8	7.2	7.2	58.5	56.6
Dry Shrub	100.0	100.0	0.0	0.0	0.0	0.0
Dry Shrub / Conifer	99.2	98.6	0.8	0.7	0.0	0.0
Dwarf Sagebrush Complex / Conifer	100.0	99.9	0.0	0.0	0.0	0.0
Dwarf Sagebrush Complex	100.0	100.0	0.0	0.0	0.0	0.0
Fescue Grasslands	100.0	100.0	0.0	0.0	0.0	0.0
Fescue Grasslands / Conifer	100.0	99.9	0.0	0.0	0.0	0.0
Grand Fir - White Fir	26.6	34.2	23.1	25.4	38.5	38.9
Lodgepole Pine	37.2	62.2	24.0	25.4	12.0	10.9
Mountain Mahogany	99.7	99.3	0.3	0.1	0.0	0.0
Mountain Big Sagebrush Complex/Conifer	84.8	99.0	0.5	0.3	0.0	0.0
Mountain Big Sagebrush Complex	100.0	100.0	0.0	0.0	0.0	0.0
Ponderosa Pine	28.8	33.4	6.7	6.6	59.7	58.6
Riparian Hardwood	47.1	50.0	0.0	0.0	45.7	49.0
Riparian Shrub	66.5	60.7	33.5	38.3	0.0	0.0
Rocky Mountain Juniper	99.4	98.9	0.6	0.4	0.0	0.0
Spruce – Fir / Montane/ Douglas-fir	37.3	53.8	24.1	24.6	20.7	20.1
Spruce – Fir / Subalpine	47.1	67.7	22.1	24.7	7.3	6.1
Spruce – Fir / Timberline Pine	59.0	78.3	13.0	14.1	7.0	6.1
Spruce – Fir / Montane/ Western Larch	31.1	38.9	27.4	29.0	31.7	30.7
Threetip Sagebrush / Conifer	99.6	99.3	0.4	0.2	0.0	0.0
Threetip Sagebrush	100.0	100.0	0.0	0.0	0.0	0.0
Timberline Pine / Limber Pine	82.3	97.1	0.7	0.5	1.9	1.6
Timberline Pine / Whitebark Pine	71.8	94.3	2.6	2.5	2.4	2.0
Western Redcedar	34.3	44.2	25.3	28.5	25.7	25.8
Wetland Herbaceous	100.0	100.0	0.0	0.0	0.0	0.0
Wyoming – Basin Big Sagebrush Complex/Conifer	100.0	99.8	0.0	0.0	0.0	0.0
Wyoming – Basin Big Sagebrush Complex	100.0	100.0	0.0	0.0	0.0	0.0

left end (small fires) of the fire size distribution curve, which is where the largest numbers of fires occur. This effectively increases the simulated mean fire size.

Even though the fire probabilities are estimates only and have inherent problems, we can assume that the simulated MFRIs approach the fire frequencies in the vegetation pathways that were used to parameterize the model (if the model is functioning properly). There are several possible reasons for the differences between the expected MFRIs and the simulated MFRIs, including 1) the role of the pathway fire probabilities in ignition and spread, 2) the spread of fire from PVTs with different fire probabilities, and 3) incorrect model parameterization.

First, the fire probabilities in the pathways represent the likelihood that a point on the landscape will burn given a particular PVT/succession class combination. These probabilities consider both ignition and spread. In LANDSUMv4, ignition and spread are simulated separately, and the fire probabilities influence only fire

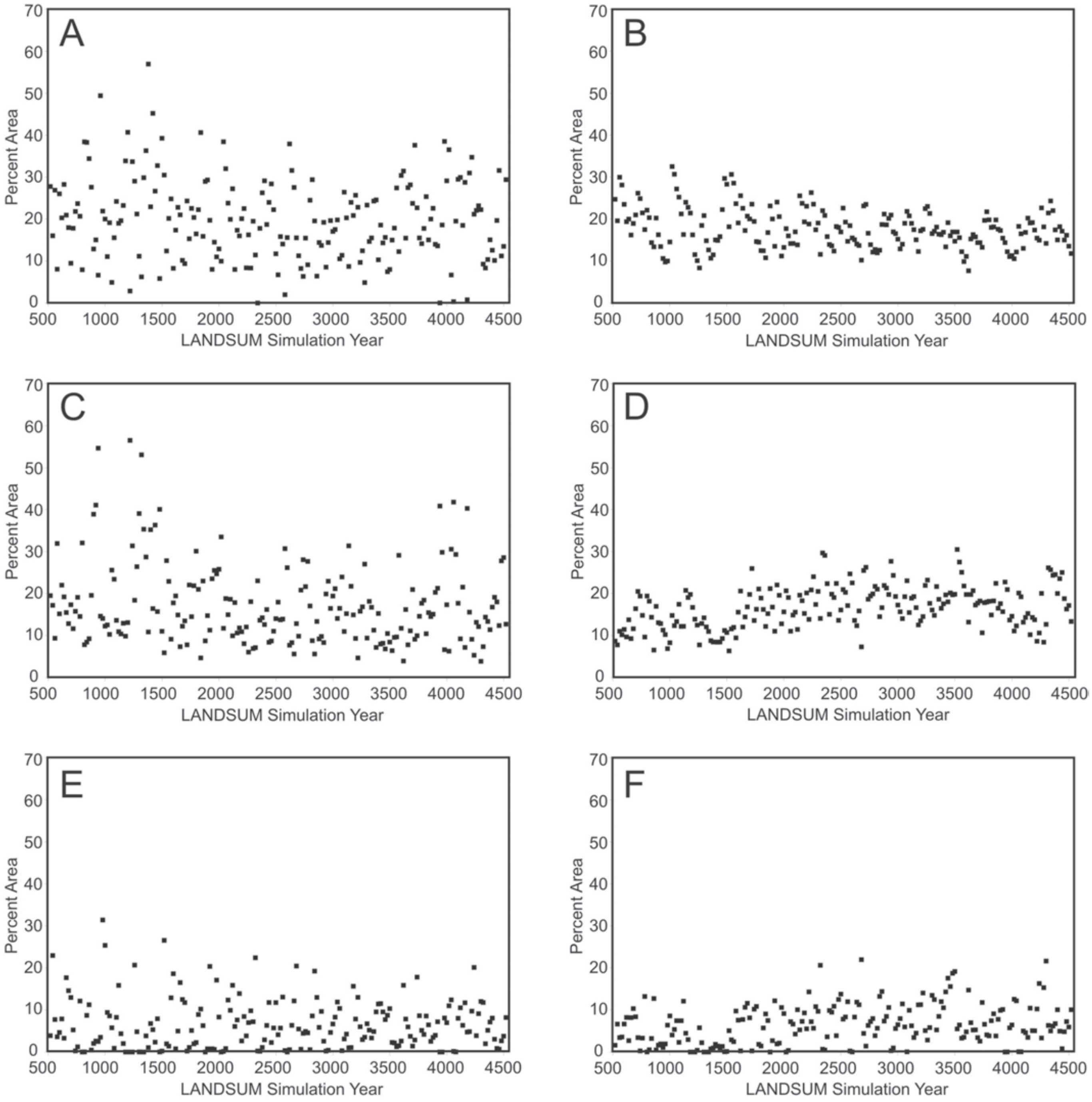

Figure 9—Percent area occupied for each of the top six succession classes in the Lodepole Pine PVT by reporting year for Zone 16. Succession classes shown are a) Aspen - Birch Low Cover, Low Height Forest; b) Aspen - Birch High Cover, Low Height Forest; c) Lodgepole Pine Low Cover, High Height Forest; d) Aspen - Birch Low Cover, High Height Forest; e) Aspen - Birch High Cover, High Height Forest; and f) Lodgepole Pine High Cover, High Height Forest.

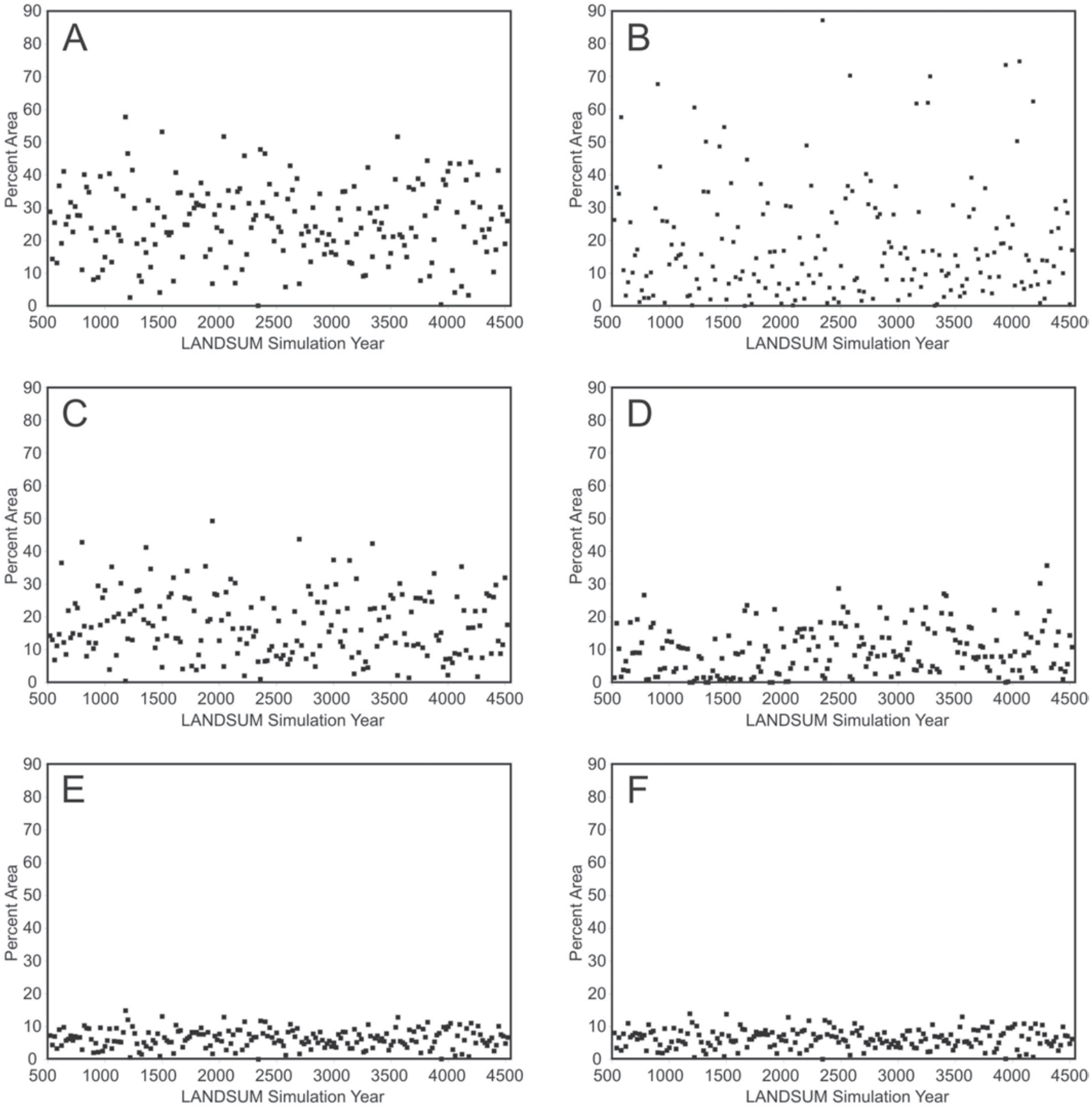

Figure 10—Percent area occupied for each of the top six succession classes in the Mountain Big Sagebrush PVT by reporting year for Zone 16. Succession classes shown are a) Mountain Big Sagebrush Low Cover, Low Height Shrubland; b) Cool Season Grasses Low Cover, Low Height Herbaceous; c) Cool Season Grasses High Cover, Low Height Herbaceous; d) Mountain Big Sagebrush High Cover, Low Height Shrubland; e) Mountain Deciduous Shrub Low Cover, High Height Shrubland; and f) Dry Deciduous Shrub High Cover, Low Height Shrubland.

ignition. Once ignited, fire spread is controlled by wind and slope and can spread equally to all PVTs. Neither vegetation nor associated fire probabilities (estimated from the literature and fire history studies) influence where a fire burns. A PVT with a low fire probability could therefore have many pixels that burn as a result of fire spread, which could cause the simulated MFRI to be quite different than the expected MFRI.

The effect of spatial adjacency on the simulated MFRIs is also related to how fire spread is modeled in LANDSUMv4. Because fire can spread to any adjacent pixel that is burnable, areas adjacent to those with high fire probabilities will tend to burn more often than expected based on the fire probabilities in the pathways. In addition, topography influences fire spread in that areas upslope will burn more often than areas downslope. If MFRI were determined only by fire probabilities for each PVT, we would expect the map in figure 11b to look very similar to the map in 11a. In figure 11a, there are areas with high fire probabilities at the southern end of many of the drainages. In figure 11b, this high fire probability continues up most of the drainage as a result of fire spread, causing shorter MFRIs than expected in vegetation with lower fire probabilities. The fact that so much of the area in figure 11b has shorter MFRIs than expected suggests that fire spread is overwhelming the underlying fire probabilities. This supposition is supported by the observation that the mean fire size simulated by LANDUSMv4 in our test areas using the model parameters for both Zone 16 and Zone 19 was considerably larger than the NIFMID estimate (fig. 4).

In addition, incorrect estimations of the parameters that control fire ignition and fire spread could result in shorter than expected MFRIs. The fact that the simulated MFRIs were shorter than the pathway MFRIs for most PVTs in Zone 16 and many PVTs in Zone 19, combined with the fact that the average fire size was so much larger than any estimates we have for this area, indicates that the fire parameters we used resulted in too much fire on the simulation landscape. Although the fire parameters used in Zone 19 resulted in general correspondence between the simulated MFRIs and the expected MFRIs in our test landscapes, the average simulated fire sizes for these landscapes using these parameters were still much larger than the NIFMID estimate (fig. 4). The spread scale parameter will likely have a stronger influence on the overall fire frequencies because far more pixels will burn as a result of fire spread than fire ignitions. When the simulated fire sizes are too large, the spread of fire and the effect of PVT adjacency may have a disproportionate influence on simulated MFRIs. Keane and others (2003) found that an error of 20 percent in estimating the spread scale parameter could result in an error of more than 50 percent in the fire return interval. The average fire size for all the test simulations in both zones varied with the spread scale parameter (fig. 4). The relationship of the spread scale parameter to the simulated average fire size is directly related to the shape parameter for the maximum fire size equation of the fire spread algorithm (3.0 for LANDFIRE simulations). We did not examine the effect of the shape parameter on the simulated average fire size or on the correspondence of simulated and pathway MFRIs. Although our test simulations were informative, more research is needed as to the effect of these crucial parameters and how they can best be estimated for a particular landscape.

Scale and complexity in fire simulation—Even if sound historical data for estimating fire parameters were abundant, differences between simulated fire regimes and actual historical fire regimes are to be expected. Fire, like many natural processes, is complex. Any attempt to model it is a simplified abstraction of the actual process. Fire operates at many different spatial and temporal scales. Its occurrence is influenced by many factors, such as vegetation, weather, wind, topography, and climate, which also operate at different spatial and temporal scales. As a result of this complexity, it is difficult to realistically simulate fire without building overly complex models that would be difficult to parameterize and inefficient to execute for large landscapes and over long simulation periods. Fire simulation in LANDSUMv4 incorporates mainly large-scale processes. The weather parameters in the model function at a yearly time-step and are generalized for the entire zone. Wind speed and direction are also parameterized for the entire zone and then varied by time–step; they are not varied locally for each fire event (Keane and others 2006). The model does not incorporate daily or localized weather information. Fire ignition is tied only to vegetation in terms of succession class changes, which operate at a coarser grain than fuel build up, and ignition probabilities are constant within a succession class. The most important limitation of the LANDSUMv4 model is absence of the close linkage between fuel, weather, and topography when determining fire effects and pattern (Keane and others 2006). Fire is spread solely on the basis of wind and topography. Because LANDSUMv4 does not integrate the spatial distribution of fuel loading, fuel moisture, and daily weather, the pattern and severity of fire may not be entirely accurate. Integrating fine-scale processes of weather or fuel into the model would make the model computationally intensive and

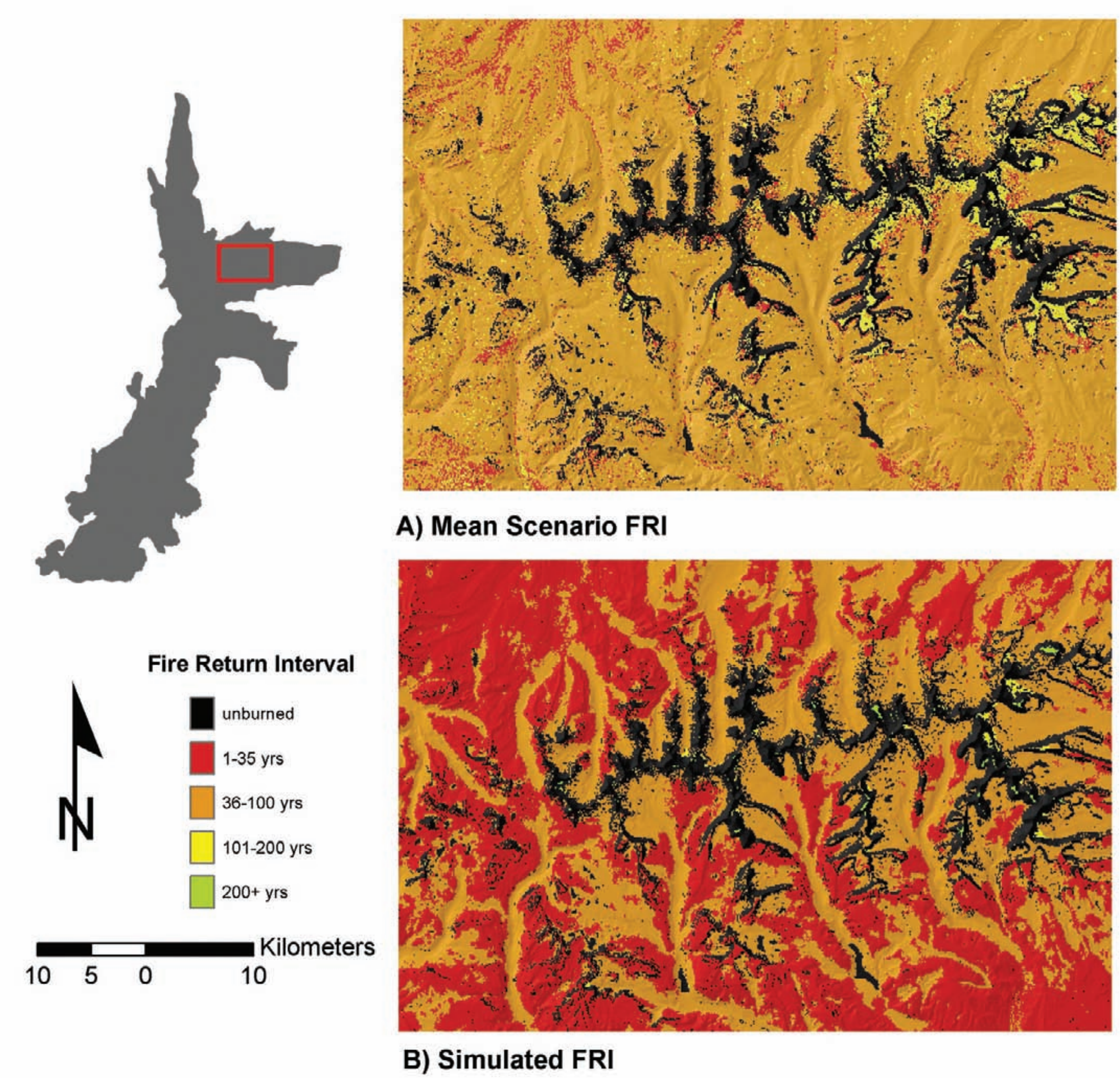

Figure 11—Comparison of mean fire return intervals a) calculated from the probabilities in the vegetation pathways and mapped to the potential vegetation type and b) simulated by LANDSUMv4 during the 4,500-year simulation period for Zone 16. Fire was much more frequent in fire regime maps derived from the spatial simulation of fire in LANDSUMv4 than in maps based solely on the aspatial fire regime information contained in the vegetation pathways.

would dramatically increase the complexity and length of the model executions. Furthermore, estimating even the most generalized fire parameters is difficult, as discussed above. Parameterizing the model for fine-scale processes would be even more difficult, and the problems inherent in estimating these values for historical conditions (on which we have limited data) would result in limited returns for considerable time and effort. It is important to understand that the fire regime results from the model are general and not intended to be applied at the pixel level or yearly time-step at which the model operates.

Fire spread and the simulation landscape—As noted above, we had to simulate each of the mapping zones as a series of smaller simulation landscapes for more efficient processing of the model. One of the problems in defining simulation landscapes lies in the fact that the simulation landscape edges create artificial boundaries that fires cannot traverse. In actual landscapes, water, rock, and topography create real boundaries and influence fire spread, but our simulation landscapes did not follow natural boundaries and sometimes even divided areas of homogeneous vegetation or topography through which fire would naturally spread. This problem is obvious if the simulation landscape is not large enough relative to the size of the larger fires as more fires will tend to run into the arbitrary boundaries of the simulation landscape, and fire will thus not be realistically simulated. Knight (1987) recommends the simulation area be 5 to 10 times the size of the largest fire, whereas Baker (1992) suggests 50 to 100 times the average fire size. Based on estimates of average fire size from NIFIMID, the simulation landscape for both zones should be about 3000 ha. However, using maximum fire size estimates from NIFMID, the simulation landscape should be about 35,000 ha for Zone 16 and 100,000 ha for Zone 19.

Another problem arose from the fact that areas near the edge of the simulation landscape have a limited number of surrounding pixels from which a fire can spread. This problem was exacerbated by wind direction. A single wind direction (60 degrees, randomly varied ±45 degrees) was used for the entire simulation and, because fire is spread by wind and slope, all fires tended to spread from the west-southwest to the east-northeast. As a result, pixels near the south and west edges had the lowest probability of burning, while those near the north and east edges had the highest probability of burning.

As noted above, a 3-km buffer area was placed around each 20,000 ha context area to create the simulation landscape and to decrease the edge effect in the context area or the area from which the reference conditions are defined (fig. 3). If the buffer area is large enough, the position of pixels within the landscape relative to the edge will not influence the chance of burning, and fire frequency will be determined by the input fire probabilities and topography. Areas that were simulated twice, once as part of the buffer and once as part of the context area, proved useful for examining the function of the buffers. Fire probabilities and topography were constant between the two runs, but the position of the pixels relative to the landscape edges changed (fig. 12). Fire should be realistically simulated in the eastern buffer region because most fires burned from the direction of the southwest. If the buffer is large enough, fire should also be realistically simulated in the context area as the buffer should provide an adequate source for fires to spread from the west. If the buffer width is adequate, therefore, the fire frequency in the eastern buffer region should not be substantially different from the fire frequency for this same region when it is part of the context area. However, as shown in figure 12, there still tended to be differences –sometimes by 20 or more fires – between these two areas. This indicates that the 3-km buffer may not be large enough to eliminate the edge effect. We are conducting a more detailed analysis of model behavior with respect to the sizes of the context and buffer areas, which will be used to inform future decisions regarding the simulation landscape.

Selecting simulation time parameters—Another challenge lies in the selection of simulation time parameters that result in efficient model execution over mapping zones while allowing sufficient initialization periods to reduce significant trends in the vegetation. We allowed for a 500-year initialization period before actually collecting data from the model for each mapping zone. In evaluating the vegetation chronosequences for both zones, we found that some succession classes in some PVTs continued to have noticeable trends beyond this 500-year period (fig. 13). Some succession classes had distinct upward trends over thousands of years, others trended downward, and yet other succession classes varied around a mean, as expected. Use of an initialization time that is long enough to allow all succession classes to reach equilibrium is not logistically possible because it would extend total simulation times beyond a reasonable length. Assigning the dominant succession class from the current conditions to each PVT for the initial landscape may have increased the time required to reach equilibrium for some PVTs. In addition, the complexity of the vegetation pathway may also impact initialization time as pathways with more succession classes may take longer to reach equilibrium. More research is being conducted to study the effect of

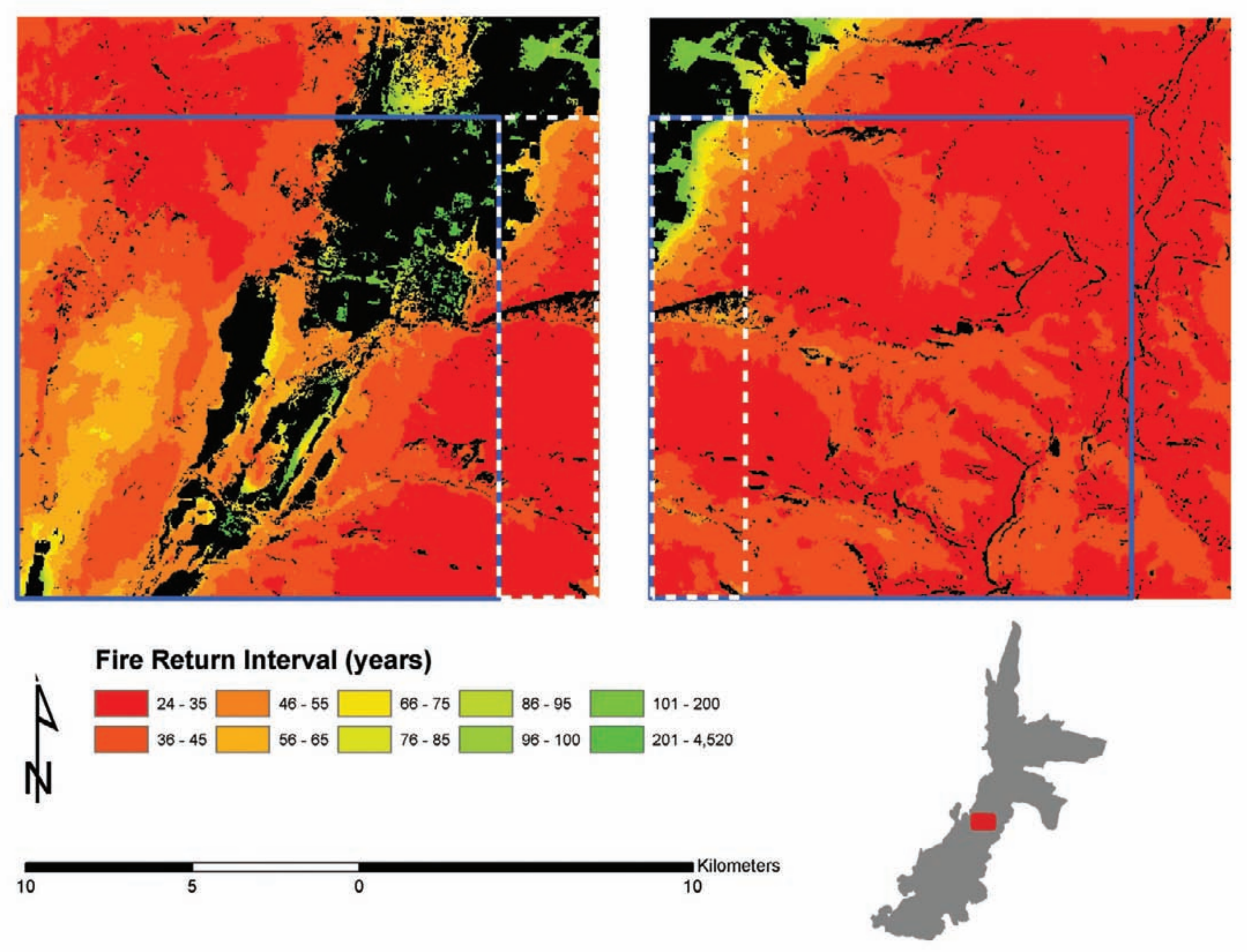

Figure 12—Mean fire return intervals for two adjacent context areas and their north and east buffer areas. The area inside the dashed rectangle is simulated in both landscapes and then smoothed using the mosaic command in ArcInfo. Differences in fire return intervals in the area simulated twice are due to the difference in the amount of the simulation landscape to the south and west from which fires can immigrate.

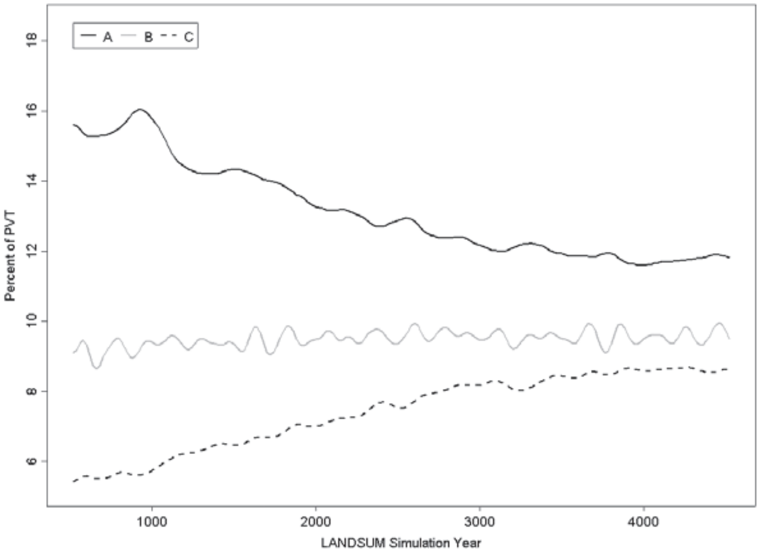

Figure 13—Succession class time series data smoothed using a 20-year lag for succession classes in the Spruce – Fir / Spruce – Fir PVT in Zone 16. Succession classes shown are A) Aspen - Birch High Cover, Low Height Forest; B) Aspen - Birch High Cover, High Height Forest; and C) Douglas-fir High Cover, High Height Forest.

autocorrelation and succession class trends on LANDSUMv4 output and the subsequent departure and FRCC calculations. These results will be used to mitigate the effects of these issues in LANDFIRE National.

Benefits of the Simulation Approach for Describing Historical Conditions

Although simulation models in general and the LANDSUMv4 model in particular have limitations, simulation modeling is still a useful, and perhaps the most viable, approach for generating historical reference conditions of vegetation and fire regimes across the entire nation. While data on actual historical conditions are limited, simulation modeling can estimate the reference conditions efficiently and in a consistent manner across the United States. Simulated historical reference conditions are not intended to replace actual historical data where they exist, but they can provide information where it is currently lacking.

In addition to effectively increasing the spatial extent of empirically derived historical reference conditions, simulation modeling can increase the temporal depth. Although the fire and climate data used to parameterize LANDSUMv4 are taken from historical databases and represent a narrow time frame, data can be simulated for much longer time spans (Keane and others 2003; Keane and others 2002b). It may seem problematic to simulate fire and landscape dynamics over millennial simulation periods while holding climate and fire regimes constant. This would be true if the objective of LANDSUMv4 modeling was to replicate historical fire events. However, the primary purpose of LANDSUMv4 modeling efforts is to document the historical variability of vegetation conditions and fire regimes across landscapes. This documentation of the entire range and variation of landscape conditions and processes serves the important purpose of allowing current conditions to be compared against a realistic and comprehensive reference database. Wherever possible, the modeling effort uses the results of fire history studies to parameterize the models, even though these represent a small duration of time. We selected the last three to five centuries as our reference time span because it is an era for which fire history data are available and is likely the most climatically similar to the present and near future. However, the fire events that actually occurred during this time frame represent only one unique sequence of fire occurrences, and the timing of these events created the unique landscapes observed today. This sampled fire history represents only one record of events. If these events had occurred according to a different timetable or in different locations, an entirely new set of landscape conditions may have resulted. It follows then that documentation of landscape conditions derived solely from historical records would tend to underestimate the variability of conditions that a particular landscape could have experienced and will experience in the future. We therefore attempted to quantify the entire range of conditions by simulating the static historical fire regime for thousands of years. We assume that 3,000 to 5,000 years is a long enough span from which to approximate all the conditions this historical landscape would have experienced. We determined that this is the best way to estimate historical reference conditions because it allows future landscapes to have variable fire ignitions and fire patterns. Despite its limitations, LANDSUMv4 creates the ability to generate a consistent and comprehensive set of data from which to estimate historical reference conditions across the entire nation.

Recommendations for National Implementation

Simulation Landscape Size and Shape

Much of the LANDSUMv4 modeling effort for the LANDFIRE Prototype involved balancing the need for realistic simulations of fire and vegetation dynamics with the often conflicting goal of computational and logistical efficiency, and balancing these two goals will present an even greater challenge as methods are applied for national implementation. We have found that larger simulation landscapes are logistically simpler and produce better simulation results overall, but there is likely some specific landscape size at which the model becomes inefficient and overall processing time to complete a zone increases dramatically. The 20,000 ha landscapes used in the prototype simulations were likely too small, given the expected size of large fires for these regions. We recommend that simulation landscapes larger than 20,000 ha be used for national implementation. Larger landscapes may result in more realistic simulations by reducing the impact of the edge effect and increasing the simulation landscape size relative to the size of the larger fires. At the same time, such landscapes may decrease processing time by reducing areas of overlap and simplifying the logistics involved in a large number of model executions. Tests on 100,000-ha landscapes for Zone 19 demonstrated that these landscapes are, given our current computing resources, too large to run the model efficiently with landscape and pathway complexities similar to those of the prototype effort. Simplified pathways and an improved computing platform could alleviate this problem and allow the simulation of sufficiently large landscapes.

Square simulation landscapes worked well, reducing overlap and simplifying processing. While square landscapes create unnatural landscape edges and fire breaks, the use of buffers mitigates this effect. Although the 3-km buffer we used did help to reduce the edge effect, this buffer may be too small; however, a larger buffer will increase overall processing time as the area of overlap increases (leading to more areas of the landscape that will be simulated twice). Overall, we recommend continuing with square simulation landscapes and using a 5-km buffer to better allow for simulation of fire spread without substantially impacting the total processing time.

Simulation time is another important aspect of the simulation design that impacts the balance between efficiency and realism. The 10,000-year simulations used for Zone 19 appear sufficiently long although the 500-year initialization period may not be adequate for some systems. We recommend simulations of 10,000 years and recommend increasing the initialization period beyond 500 years to the extent possible given computing limitations. In addition, we recommend assigning the historically dominant succession class (rather than the current dominant class) to each PVT for the initial landscape in an attempt to reduce the time required to reach equilibrium.

Determining Model Parameters

In addition to the LANDFIRE Prototype research, past sensitivity analyses indicate that there are several parameters of particular importance to the simulation results that must be accurately quantified for the LANDFIRE National. The ignition average fire size parameter – especially the spread scale parameter – strongly influences fire frequencies and, in-turn, vegetation dynamics. As discussed above, the historical data available for estimating these parameters are limited. A consistent methodology is required for setting these parameters to achieve appropriate fire frequencies. We recommend more research be conducted on the role of the spread shape parameter in these relationships. The NIFMID database contains only information on recent fires, and therefore the fire size estimates based on these data have been affected by fire suppression. Taking this limitation into consideration, we nevertheless recommend starting with the NIFMID estimate as a target average fire size because it represents the only source of recorded data on fire size for the entire United States. Vegetation modelers and ecologists who develop the succession pathway models for LANDSUMv4 present another source of information for estimating historical fire sizes and fire regime parameters. These individuals are presumably familiar with local ecosystems and offer estimates of fire sizes based on their extensive experience in addition to a literature review conducted when developing the pathways. These estimates could be used in combination with the NIFMID information to establish a target average fire size. Until further research is completed, we recommend executing the model over several test landscapes and varying both parameters until the average simulated fire size approaches the estimated average fire size for the zone and the fire frequencies simulated for each PVT approach the probabilities set in the pathways.

Error-checking

Another key to efficient and accurate simulations lies in the development of a consistent methodology for testing the pathways and parameters established for a mapping zone to check for errors and problems before the entire zone is simulated. We found two main sources for problems related to LANDSUMv4 executions: inconsistencies or errors in the input data and problems or “bugs” in the code. LANDSUMv4’s extensive error-checking routine scans the input data for inconsistencies between the various input files, which can cause problems during simulation. However, there are problems with the input data that the error-checking routine does not recognize as inconsistencies but may still lead to unexpected results. In addition, although the LANDSUMv4 model underwent an extensive de-bugging process, it is always possible that some new, unique circumstance will arise in a new mapping zone that will cause unexpected results. We recommend performing a thorough quality assurance and quality control (QA/QC) process for the pathways once they are developed by the vegetation modelers. Once the pathways have passed this QA/QC, three to five landscapes – distributed throughout the mapping zone and containing a variety of topography and PVTs – should be simulated. Vegetation and fire regime information should be summarized for these test simulations and given to the vegetation modelers (or other experts) to check for any unexpected results. If there are any suspicious results, further analysis should be performed to determine the source of the unexpected results before proceeding with simulations for the full zone. Results from the test landscapes do not always reveal problems that can develop when the entire zone is simulated. Because simulating an entire zone may take six weeks or more, we recommend developing a systematic way to periodically check the output from the individual simulation landscapes within the zone as they are completed.

Further Study

Finally, although the LANDSUMv4 model has been tested (Keane and others 2002a; Keane and others 2003) this testing was conducted with earlier model versions, on smaller landscapes, and using parameters different from those being used in LANDFIRE. And while the prototype effort has contributed much information concerning the parameterization of the model for the national implementation of LANDFIRE, it has also raised many questions. Extensive testing and revision of the LANDSUMv4 model has begun, focusing on the application of the model for LANDFIRE purposes and examining the effects and interactions of several simulation parameters, including simulation time, context and buffer sizes, and fire size parameters. Separate studies are also planned to evaluate issues of scale in summarizing the data and the effect of autocorrelation and trends in the vegetation output of LANDSUMv4 on the computation of departure and FRCC. It is our recommendation that the national implementation of LANDFIRE incorporate, to the extent possible, the information from these studies as it becomes available. Furthermore, the model and the key parameters should be tested as they are applied to different regions of the country.

Conclusion

The methods outlined in this chapter were successful in producing estimates of historical reference conditions for vegetation and fire regimes in a manner that can be applied consistently across the nation. While the methodology used for simulating reference conditions for the LANDFIRE Prototype was generally sound, we recommend that more research be conducted to facilitate a more thorough understanding of the effect of various parameters on model behavior. Furthermore, we propose that development of consistent methods for setting appropriate values for key parameters, particularly the fire spread parameters, before proceeding with national implementation be a top priority. Finally, it is extremely important to consider the assumptions and limitations of the simulation approach and LANDSUMv4 when applying the results of the model. When the strengths and limitations are carefully considered, the use of simulation modeling, and LANDSUMv4 in particular, appears to be an effective and feasible way to generate estimates of historical reference conditions for vegetation composition and structure and wildland fire regimes for large landscapes on a national scale.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Appendix 10-A—Vegetation and Disturbance Dynamics Database

The Vegetation and Disturbance Dynamics Database (VADDD) is structured to store all vegetation and disturbance dynamics information used as input to LANDSUMv4. VADDD served as the primary reference for the codes and labels for all map unit classifications developed in LANDFIRE, including PVT, cover type, and structural stage. In addition, this database was designed to efficiently check for errors in the succession and disturbance information prior to input into simulation modeling and to provide a standardized set of LANDSUMv4 parameters for subsequent applications of the model in different settings.

The database is composed of two general components. The first set of tables is primarily for reference only and serves as lookup tables for the PVT, cover type, structural stage, succession class, and disturbance codes used in the modeling process. The second set of tables is used for creating the LANDSUMv4 inputs and describes succession and disturbance dynamics for each succession class, including subsequent effects and the probability of those effects occurring. The "VEGDEV" table contains important vegetation development information about every succession class by PVT, including successional development parameters and descriptors that quantify the pathways of successional development without disturbance. The "DISTURB_PARM" table quantifies the consequences of disturbance for a PVT/succession class combination and the "SCENARIO_PARM" table contains data regarding the probabilities of a particular disturbance occurring in a PVT/succession class combination.

App. 10-A: Table 1—Field names and descriptions for the potential vegetation type table in VADDD.

Field name	Field description
PROJECT	Project code
REGION	Region ID number
PVTUnique	PVT ID number
PVTLABEL	Unique header to use as labels on graphs and tables
PVTNAME	Unique name to use for report writing and data file building
PVTDESC	Brief description of this type

App. 10-A: Table 2—Field names and descriptions for the cover type table in VADDD.

Field name	Field description
PROJECT	Project code
REGION	Region code
COVTYPE	Unique cover type ID number
CTLABEL	Unique header to use as labels on graphs and tables
CTNAME	Unique name to use for report writing and data file building
CTDESC	Brief description of this type

App. 10-A: Table 3—Field names and descriptions for the structural stage table in VADDD.

Field name	Field description
PROJECT	Project code
REGION	Region code
SSTAGE	Unique structural stage ID information
SSLABEL	Unique header to use as labels on graphs and tables
SSNAME	Unique name to use for report writing and data file building
SSDESC	Brief description of this type

App. 10-A: Table 4— Field names and descriptions for the succession class table in VADDD.

Field name	Field description
PROJECT	Project code
REGION	Region code
SCLASS	Unique succession class ID number
COVTYPE	Unique cover type ID number
SSTAGE	Unique structural stage ID information
SCLABEL	Unique header to use as labels on graphs and tables
SCNAME	Unique name to use for report writing
SCDESC	Brief description of this type

App. 10-A: Table 5—Field names and descriptions for the disturbance type table in VADDD.

Field name	Field description
PROJECT	Project code
REGION	Region code
DISTURB	Unique disturbance type ID number
DISTLABEL	Unique header to use as labels on graphs and tables
DISTNAME	Unique name to use for report writing and data file building
DISTDESC	Brief description of this type

App. 10-A: Table 6—Field names and descriptions for the vegetation development (VEGDEV) table in VADDD.

Field name	Field description
PROJECT	Project ID number
REGION	ID number for geographical region
PVT	PVT ID number
SCLASS	Unique succession class ID number
BYEAR	Beginning year of this succession class
EYEAR	Ending year of this succession class
NEXT_SCLASS	Next succession class this class goes to once AGE > EYEAR
PROB	Probability that this transition will occur

App. 10-A: Table 7—Field names and descriptions for the disturbance parameter (DISTURB_PARM) table in VADDD.

Field name	Field description
PROJECT	Project ID number
REGION	ID number for geographical region
PVT	Unique PVT ID for this disturbance information
SCLASS	Unique succession class ID for this disturbance information
DIST	Unique ID number of disturbance or management action in question
GOTO_SCLASS	Ensuing structural stage resulting from this disturbance
PROB	Probability of this disturbance transition
NEXT_AGE	Successional age to set resultant succession class after this disturbance
AGE_INC	Number of years to add/subtract from pixel age

App. 10-A: Table 8—Field names and descriptions for the scenario parameter (SCENERIO_PARM) table in VADDD.

Field name	Field description
PROJECT	A unique ID naming the project application of these data
REGION	A unique ID naming a geographic management region to apply data
SCENARIO	The ID code of the scenario
PVT	Unique PVT ID for this disturbance information
SCLASS	Unique succession class ID for this disturbance information
DIST	Unique ID number of disturbance or management action in question
PROB	Probability of occurrence for this disturbance

Appendix 10-B

Values for LANDSUMv4 model parameters used in the Zone 16 and Zone 19 simulations and the information source used for estimating the parameters. In the source column, “Preliminary Testing” refers to parameters estimated from simulations done on several test landscapes (see *Methods* section for more information) and “LANDFIRE” refers to model execution parameters set to meet the needs of the LANDFIRE Project.

Parameter	Description	Zone 16	Zone 19	Source
Simulation time	Number of years to simulate	4520	10500	Preliminary Testing
Age initialization	Controls how age is assigned to initial stands (0 - use age in stand info., 1 - random, 2 - midpoint of stage, 3 - entered beg. age in PVT)	1	1	Keane and others 2002a
Reporting interval	Interval (yrs) to print results to output maps and tabular files	20	50	Preliminary Testing, Keane and others 2002a
Initialization time	Year to start recording output results to maps and tabular files	520	550	Preliminary Testing, Keane and others 2002a
Disturbance exclusion	Specifies which disturbance to exclude (0 - include all dist., 1 - exclude all dist., 2 - exclude all but fire)	0	0	LANDFIRE
Random number scheme	0 = different every time, 1 = repeatable random	0	0	LANDFIRE
Random number generator	0 = system, 1 = Ran1, 2 = Ran2	0	0	Keane and others 2006
Fire spread model	Model of spatial spread simulation (1 - cell automata, 2 - cookie-cut shapes, 3 - cell spread percolation)	3	3	Keane and others 2002a
Fire weather multiplier	Number of years that a dry, normal and wet year occurs in a decade (must sum to 10)	3/5/2	1/6/3	Palmer Drought Severity Index Reconstructions
Average fire size - ignition	Average fire size (ha) for ignition equation	90	30	NIFMID, Preliminary Testing
Wind simulation	Mode of wind simulation: 0 - same wind speed/dir. every year, 1 - vary by year, 2 - vary by fire, 3 - vary by time-step, 4 - vary by cell)	3	3	LANDFIRE
Wind speed	Average wind speed in meters per second	5	5	Expert Opinion
Wind direction	Average wind direction for a fire event (azimuths true north)	60	60	Expert Opinion
Fire ignition equation	Equation for computing probability of ignition (1 - Weibull)	1	1	Keane and others 2002a
Years since burn	Years since burn parameter for the ignition equation	3	3	Keane and others 2002a
Shape parameter - ignition	Shape parameter for the ignition equation	2	2	Keane and others 2002a
Fire size equation	Equation for computing fire size (1 - Pareto, 2 - lognormal, 3 - exponential, 4 - uniform, 5 - normal, 6 - extreme, 7 - negative exponential, 8 - logistic, 9 – let burn	7	7	Keane and others)2002a
Fire size distribution magnitude	Magnitude parameter for the fire size equation	30	10	NIFMID, preliminary testing
Fire size distribution shape	Shape parameter for the fire size equation	3	3	Keane and others 2002a

Chapter 11

Using Historical Simulations of Vegetation to Assess Departure of Current Vegetation Conditions across Large Landscapes

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Introduction

Background

The Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, was conceived, in part, to identify areas across the nation where existing landscape conditions are markedly different from historical conditions (Keane and Rollins, Ch. 3). This objective arose from the recognition that over 100 years of land use and wildland fire suppression have dramatically affected wildfire characteristics and associated landscape composition, structure, and function (Turner and others 2001). Metrics were needed to describe the extent and distribution of highly departed landscapes to protect communities, ecosystems, firefighters, and public safety, as outlined in the National Fire Plan (USDA and USDI 2002; U.S. GAO 1999; http://www.fireplan.gov). Accordingly, the Departments of Agriculture and Interior were directed by Congress to develop a cohesive strategy for implementing the National Fire Plan (Laverty and Williams 2000), which resulted in the development of the "Fire Regime Condition Class" (FRCC) classification system for use as a key implementation measure. The FRCC classification is based on the concepts of historical ecology and is intended to represent the departure of current landscapes from the range of variability of historical conditions. Fire Regime Condition Class is defined as: a descriptor of the amount of departure from the historical natural regimes, possibly resulting in alterations of key ecosystem components such as species composition, structural stage, stand age, canopy closure, and fuel loadings (Hann and Bunnell 2001).

The U.S. GAO (2002) further recommended the development of consistent and comprehensive spatial data to identify landscapes at high risk of wildfires. Previous FRCC mapping efforts created coarse-scale (1-km) spatial data layers describing fire hazard and ecological status for the conterminous United States (Hardy and others 2001; Schmidt and others 2002; http://www.fs.fed.us/fire/fuelman). However, the coarse spatial resolution made these maps useful only for national-scale assessments. In addition, these maps were largely a product of expert systems, which limited the repeatability of the process for monitoring purposes. Finer-scale maps, compiled using consistent, quantitative methods, were needed for applications such as national forest plan revision and implementation and assessments related to wildland fire management plans (Rollins and others, Ch. 2). Our challenge in the LANDFIRE Prototype Project was to develop methods, applicable in a systematic and consistent manner across the U.S., which identify and

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map – at a mid-scale spatial resolution – landscapes that have diverged substantially from historical conditions.

Overview

Broad-scale changes have occurred in many landscapes of the U.S., particularly over the last century, due to land management practices and other forms of human intervention. Fire exclusion and grazing have increased tree density and fuel accumulations in many forest communities, especially those adapted to frequent surface fires (Covington and others 1994; Leenhouts 1998). These conditions favor diseases, insects, and high-intensity crown fires, which can kill old-growth trees and alter community structure (Moore and others 1999). Invasions by non-native plant species have also profoundly altered many native plant communities and ecosystems (Gurevitch and Padilla 2004). Exotic insects and pathogens have accelerated the succession cycle by killing important seral tree species, converting mid-successional stands to late-successional (Keane and others 2002). In addition, increasing emissions of atmospheric concentrations of carbon dioxide and nitrogen have altered photosynthetic processes, species richness, and ecosystem function (Farquhar 1997; Jones and others 1998; Stevens and others 2004).

We developed our methods for estimating such departure based on a set of ecological concepts used to detect changes in ecosystem properties and processes across landscapes at multiple scales. Species, ecological communities, and ecosystems vary naturally across spatial and temporal scales in response to disturbances, biotic processes, and environmental constraints (Levin 1978). These biotic and abiotic agents of pattern formation interact over time to produce a range and variability in ecological structures and processes (Morgan and others 1994; Swanson and others 1994). When the mechanisms driving ecological systems, such as disturbance, change dramatically, ecological processes and structures respond and shift that range and variability (Barnes and others 1998). Landscapes experiencing extensive changes may become altered to the point that their ecological properties are well beyond their historical range and variability, especially in their species composition and structure.

The extent of change in any particular ecosystem may be assessed by comparing current vegetation conditions to the range and variability in historical compositions and structures of vegetation communities, or simply their "natural variability." The focus of describing natural variability is not on a single condition, but rather on a range of conditions and the variability under which ecosystems were sustained in the past (Swetnam and others 1999). Characterization of these past ecosystems has been referred to as the "historical range of variability" (Kaufmann and others 1994) or simply "reference conditions" (Moore and others 1999). Ideally, characterization of reference conditions considers all ecosystem components (organisms, structures, biogeochemical cycles, disturbance processes, and abiotic factors) and includes the appropriate time depth and spatial scales for the ecosystem components included in the assessment (Moore and others 1999). However, many of these factors are poorly understood or are difficult to measure (Moore and others 1999). Holling (1992) suggests that a small group of "keystone" or highly interactive organisms and abiotic processes may control ecological thresholds at certain scales. The potential list of important keystone variables may still be relatively long (Aronson and others 1993; Keddy and Drummond 1996), but experience and practical considerations have led researchers to select certain variables that reflect the evolutionary environment (Moore and others 1999; Swetnam and others 1999). For example, fire and autotrophic organisms (trees, shrubs, and herbaceous plants) are used to describe ponderosa pine and sequoia ecosystems (Fulé and others 1999; Moore and others 1999; Stephenson 1999). Other considerations include identifying the historical time period for describing natural variability, including the point in time when ecological systems were considered relatively unaffected by Euro-American settlement (Hunter 1996; Schrader-Frechette and McCoy 1995). Moreover, characterization of past ecosystems should specify whether Native American influences on ecosystems are regarded as natural (Landres and others 1999).

We adopted the natural variability concept to guide our methods for estimating landscape changes from past to present. Specifically, our goal was to describe deviations of current landscape conditions from conditions between the years 1600 A.D. and 1900 A.D. and to describe them at a regional level with a mid-scale spatial resolution to help planning efforts address ecological issues (Keane and Rollins, Ch. 3). We selected this time frame for our reference conditions as the appropriate range to represent recent history because fire history reconstructions typically date back to at least 1600 and because we determined that 1900 A.D. best approximates the start of significant Euro-American influences on western U.S. landscapes (Keane and others 2002; Keane and Rollins, Ch. 3). Also, we assumed that the influence of Native Americans on landscapes was inherent in our depiction of reference conditions.

To develop methods that estimate landscape changes from this historical time period, we needed to address a number of questions. What were the historical dynamics of plant communities across the diverse ecosystems of the nation? How do we measure plant community change? At what point does the magnitude of change drive an ecosystem beyond its historical boundaries to some uncharacteristic condition and warrant ecosystem restoration? In this chapter, we outline several approaches to 1) addressing each of these questions within the ecological framework of plant community function in fire-adapted environments and 2) creating maps of ecological departure over large regions. Our chief premise for the LANDFIRE Prototype Project was that fire and other disturbances regulate succession by regeneration, reproduction, and maintenance of plant species and assemblages. That is, fires kill existing stands and set the process of regeneration in motion for the next forest; fire as a selective force elicits asexual and sexual reproduction; and periodic surface fires reduce vegetation encroachment and competition for light, soil water, and nutrition and kill understory-tolerant seedlings (Barnes and others 1998). The frequency, intensity, extent, and timing of fires (in other words, fire regimes) are characteristic of different regional and local ecosystems (Barnes and others 1998). We assumed that under each unique fire regime, plant communities approach some dynamic equilibrium in their composition and structure. When fire regime characteristics change, the character of a plant community shifts and distributions of pioneer, mid-successional, and late-successional species or assemblages become altered. The magnitude of this change can be used to prioritize, plan, and implement restorative treatments (Hann and others 2004).

Our general approach involved developing a historical spatial database that describes the natural variability of vegetation across landscapes over time and quantitatively compares that historical distribution to the current vegetation patterns for two large study areas in the western United States. For example, the current vegetation pattern on a landscape might have changed by 70 percent from vegetation distributions observed in historical records, indicating a strong divergence (fig. 1). To quantify landscape patterns, we chose the metric of landscape composition and delineated composition by classifying landscapes according to their potential vegetation type (PVT), cover type, and structural stage (Frescino and others, Ch. 7; Zhu and others, Ch. 8). The PVT map identified areas with similar climate, landform, and geomorphic processes (biophysical settings) where distinct plant communities are assumed to develop in the absence of disturbance (Arno and others 1985; Steele and Geier-Hayes 1989). The cover type map depicted the existing dominant plant species or assemblages, and the structural stage map approximated the stages of vegetation development for the various cover types, ranging from stand initiation to old-growth, as described by height and percent cover (Zhu and others, Ch. 8). We integrated the cover type and structural stage maps such that each unique combination described a discrete stage along succession pathways, which we call a "succession class" (Long and others, Ch. 9; see also Long and others, Ch. 6 and Zhu and others, Ch. 8 for descriptions of the cover types and structural stages used in the LANDFIRE Prototype Project). We then combined the succession class and PVT maps to describe landscape composition in a spatial context.

The collective area of each succession class in a PVT functions as our measure of the conditions of a landscape, which we refer to as the "vegetation composition." We chose to use the combination of PVT and succession class as a descriptor of vegetation composition because it provided the finest classification resolution possible for evaluating landscape dynamics. That is, the PVT-succession class classification integrates the biophysical environment with existing vegetation, which discriminates between major site types. For example, we can differentiate ponderosa pine types occurring in a Douglas-fir PVT from ponderosa pines growing in a Ponderosa Pine PVT. Other landscape composition classifications are available, such as fuel models, cover types, and structural stages. However, we felt that classifying landscapes by PVT – succession class would be the most meaningful and useful depiction for the purposes of land managers, who typically use similar classification schemes for depicting landscape condition. It should be noted that landscape composition can also be described by measures other than area by vegetation class, including relative richness, diversity, dominance, and connectivity (Turner and others 2001). Similarly, landscape pattern can be described by landscape configuration instead of landscape composition using measures such as contagion, patch-based metrics, and fractals. We chose not to use these landscape metrics and measures because they are not yet widely used in management or would have required prohibitively expensive computer resources. Vegetation composition, on the other hand, was far more feasible to map, comprehend, and implement in management applications.

Comprehensive and consistent spatial estimates of historical vegetation composition were used in the LANDFIRE Prototype to identify natural variability. We

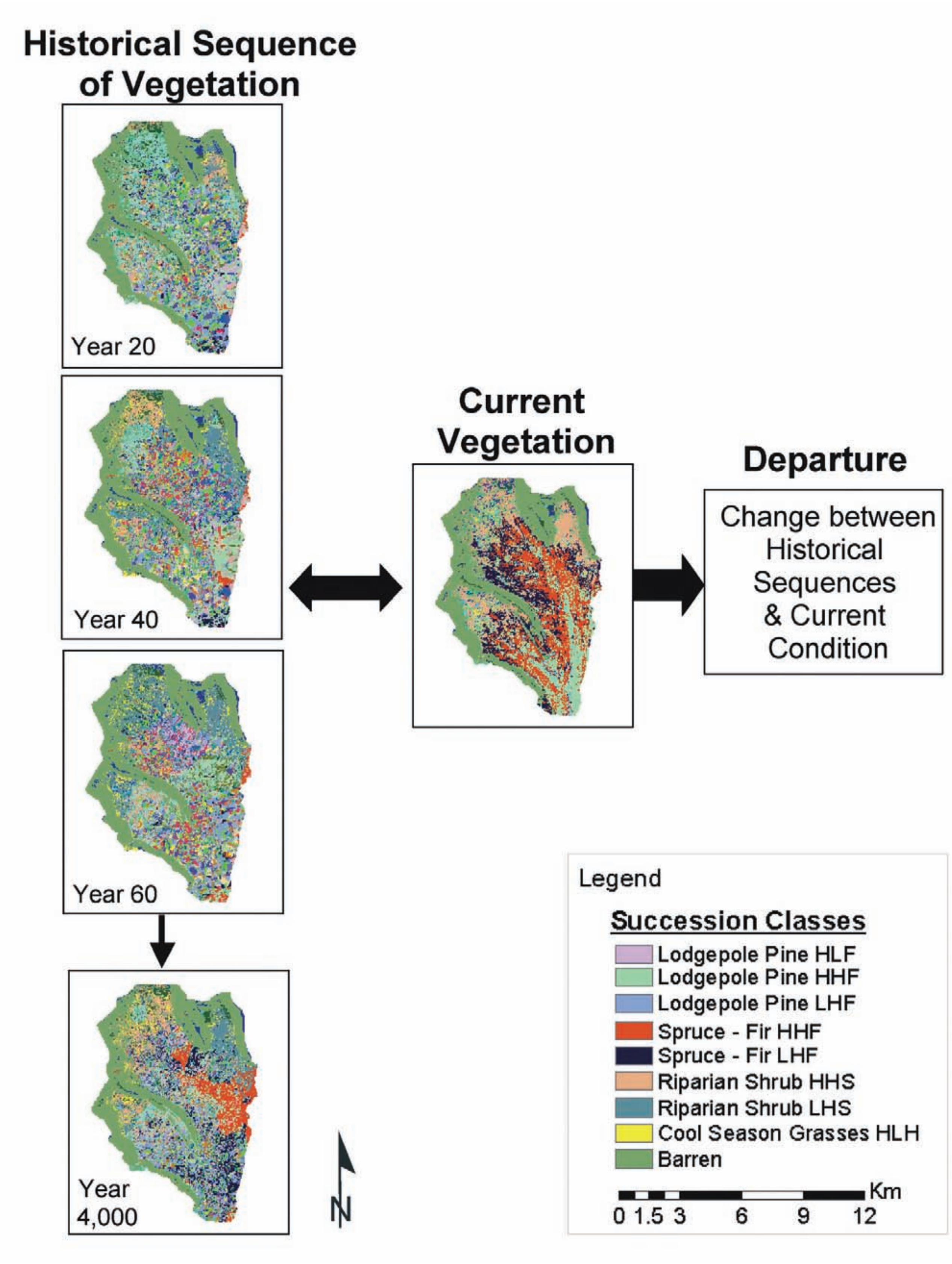

Figure 1—Example of general approach for estimating departure in a 6th hydrologic unit code (HUC). Vegetation patterns (described here by succession classes) of historical sequences are quantitatively compared to those of the current landscape to estimate departure. See table 7 for explanation of succession class codes.

relied on simulation modeling to generate a time series of data for estimating the potential range and variability of historical vegetation for our large regional areas (Keane and Rollins, Ch. 3; Pratt and others, Ch. 10). We chose to use a moderately detailed simulation model, called LANDSUMv4, because it balanced the simulation of complex ecosystem processes with computational efficiency and thereby allowed for the acquisition of time series estimating historical conditions for large regions in a timely manner (Keane and others 2003; Keane and others 2006). The justification for simulation modeling and implementation of LANDSUMv4 to develop time series representing reference conditions are described in detail by Pratt and others, Ch. 10. Results from LANDSUMv4 simulation modeling do not represent actual historical records, but they are our best approximation of how vegetation responded to fire disturbances in the past.

We developed two methods to measure the extent of change, which we refer to as "departure," between the simulated time series estimating historical vegetation composition and the current vegetation composition on landscapes. The purpose of the first method was to implement a field-based procedure, developed by Hann and others (2004), within a digital mapping context. Hann and others' (2004) Interagency FRCC Guidebook (http://www.frcc.gov) details field-based protocols by which land managers can assess the departure of current vegetation composition from that of historical conditions to meet the objectives of the National Fire Plan and Healthy Forests Restoration Act (http://www.fireplan.gov; http://www.healthyforests.gov) and also for reporting purposes, such as to the National Fire Plan Operations and Reporting System (http://www.nfpors.gov). Our implementation of this method, which we refer to as the "FRCC Guidebook approach," compares the current vegetation composition to the simulated historical time series; we do not, however, compare fire frequency and fire severity, as outlined in the FRCC Guidebook field procedures (Hann and others 2004), because contemporary conditions can be difficult to define, quantify, and depict spatially.

Calculations based on vegetation composition using the FRCC Guidebook approach require that the simulated historical time series data be summarized and distilled to represent one state or observation. As such, the FRCC Guidebook approach is very limited in its ability to characterize the full range and variability of vegetation reference conditions within the simulated historical data. We determined that a more statistically sound approach was needed to comprehensively account for patterns of temporal variation in the simulated historical landscapes (Steele and others, in preparation). Hence, we implemented a statistical method, which we refer to as the "Historical Range and Variability–Statistical" or "HRVStat" approach, to evaluate all states observed in the simulated historical time series and compares them to the current landscape to provide a complete assessment of departure. The HRVStat approach also measures the strength of evidence for the estimated departure value, which we call the "observed significance level" (Steele and others, in preparation).

Both the FRCC Guidebook and HRVStat approaches for describing vegetation change estimate departure on a continuous scale with values ranging from 0 to 100. However, the previous coarse-scale (1-km) map of FRCC (Hardy and others 2001; Schmidt and others 2002) and the FRCC Guidebook field procedures (Hann and others 2004) describe departure simply in terms of three classes, including: FRCC 1 – minimal departure from the central tendency of the natural disturbance regime, FRCC 2 – moderate departure, and FRCC 3 – high departure. Using the FRCC Guidebook and HRVStat approaches, we likewise classified our departure estimates into three categories to be consistent with the FRCC Guidebook field procedures and to facilitate comparisons with the coarse-scale map of FRCC from Schmidt and others 2002.

The development of methods for estimating departure was one of the most important objectives of the LANDFIRE Prototype Project. Documentation of these procedures is the purpose of this chapter and is presented below in detail. These procedures can serve as the foundation for estimating departure as the LANDFIRE Project is implemented across the entire United States (Keane and Rollins, Ch. 3). In the process of developing these protocols, we identified various areas in need of improvement and further research, which we outline as recommendations for developing departure indices at the national level. The methods described here may not necessarily reflect protocols followed when the LANDFIRE Project is implemented nationally, and results and specific findings may change as protocols are improved. We present results from our current methods to demonstrate their implementation and to compare procedures.

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on the procedure followed in developing maps describing the departure of current from historical landscape conditions, which served as important core data products of the LANDFIRE Prototype Project.

In this chapter, we describe: 1) the key spatial layers used for estimating departure and preliminary considerations for identifying cover types for analyses; 2) the data sets for estimating departure; 3) the FRCC Guidebook approach; 4) the HRVStat approach; 5) a detailed demonstration for estimating departure using these two approaches; and 6) a comparison of departure between areas with different simulated fire return intervals. We implemented the FRCC Guidebook and HRVStat approaches across two large regions in the western United States: one in the central Utah highlands and a second in the northern Rocky Mountains of Idaho and Montana (LANDFIRE mapping zones 16 and 19, respectively; see fig. 1 in Rollins and others, Ch. 2).

Key Spatial Layers and Preliminary Considerations

Key spatial layers—Of the four maps essential for estimating departure in both the FRCC Guidebook and HRVStat approaches, three described vegetation: the PVT, existing cover type, and existing structural stage maps (Frescino and others, Ch. 7; Zhu and others, Ch. 8), and the fourth partitioned each zone into smaller map areas or "landscape reporting units" (LRUs) so that departure could be estimated for each LRU (Pratt and others, Ch. 10). The determination of appropriate units held great importance because, measurements of landscape change being scale-dependent, departure estimates vary with landscape size. (Gardner 1998).

In general, the most appropriate ecological scale for detecting change matches the scale at which key processes affecting ecosystems (such as fire and succession) interact to limit landscape dynamics at a point in time (Parker and Pickett 1998). Identifying that scale is a challenging problem (Gardner 1998) but may be accomplished by evaluating the change in variance in a landscape metric with changes in spatial extent (Levin and Buttel 1986; O'Neill and others 1991) or by using more mathematically complex methods, such as the gliding-box method (Gardner 1998). Due to time constraints, we did not conduct such analyses, but we expected that the appropriate ecological scales in Zones 16 and 19 would vary depending on the dominant landscape fire and succession processes. For example, in landscapes subject to small, low intensity disturbances that kill vegetation in patches of only a few trees, the stand scale (about 1-10 ha) (Urban and others 1999) would likely be the most appropriate for measuring departure; however, departure may be better estimated at the landscape scale (10^3 to 10^6 ha) (Mladenoff and others 1993, 1994; Spies and others 1994) in areas subject to large, intense, stand-replacing disturbances that kill vegetation in big patches. Another consideration was the scale that would be most useful to management, which is often at a smaller spatial extent approaching the stand scale and at which subtle changes to cover type and structural stages, such as those caused by fuel treatment, can be detected (Keane and Rollins, Ch. 3).

Ultimately, we balanced our selection of LRU-scale based on both ecological and management considerations (see Pratt and others, Ch. 10 for additional details). We chose as reporting units uniform squares of 900-m by 900-m (81 ha) but coded these squares so that they could be grouped and summarized at the sub-watershed level (average area of 6,450 ha). We determined that summarizing departure to these 900-m by 900-m squares would capture stand-level processes and provide land managers with a sufficient data resolution. If a landscape-level measurement was desired, we included information that facilitates the aggregation of data over 6th level Hydrologic Unit Codes (HUCs). We are currently conducting additional analyses to systematically evaluate the appropriate reporting unit size for estimating departure.

Identifying cover types for analyses—Certain cover types would skew departure estimates and provide little useful information for conservation and restoration of landscapes. Specifically, the cover types water, barren, and ice/snow change little over time and always contribute to low departure. Conversely, agriculture and urban areas always contribute to high departure since current conditions such as these did not exist in the majority of the U.S. during the reference period. If a large proportion of any of these five cover types occur within an LRU, they can overwhelm the departure estimate and mask the condition of vegetation types present. For example, suppose that an LRU composed almost entirely of barren rock contains a small amount of vegetation that historically was perennial grasslands but is now teeming with exotic weeds. If we included the barren cover type in our departure measurements, we would calculate a very low departure, and this LRU may go unnoticed by land managers. Alternatively, consider an LRU that is predominately urbanized but contains vegetation uncharacteristic of historical conditions having missed numerous fire intervals. If we included the urban cover type in our departure estimate, we would not know whether the high departure estimate was due to the urban or the vegetation component. Hence, land managers would have potentially ambiguous information for assessing that landscape.

The main purpose of assessing departure is to prioritize areas for management and to allow for assessments of management efforts aimed at lowering departure values. Because agriculture and urban areas typically cannot be managed nor departure in these areas reversed, we decided that it was best to exclude these land cover types from departure calculations. Similarly, since water, barren, and snow/ice types may obscure the need for management in surrounding vegetation types, these also were excluded from departure estimates. It is important to note, however, that we made these decisions after completing the Zone 16 maps. Time constraints prevented us from rectifying this error, and water, agriculture, barren, snow/ice, agriculture, and urban cover types were included in Zone 16 departure estimates. For Zone 19, on the other hand, we treated these cover types as effectively immutable and removed them from departure estimates.

Data Sets for Estimating Departure

Simulating historical reference conditions—Using the LANDSUMv4 simulation model, we created a historical reference data set to describe succession patterns continuously across broad regions and with temporal depth (Pratt and others, Ch. 10). The LANDSUMv4 model simulates disturbances (primarily fire, but also insect and disease infestations) spatially across landscapes and predicts the resulting effects of fire on vegetation using a framework of succession pathways (Keane and others 2006). The LANDSUMv4 output provided a time series describing vegetation dynamics in terms of succession classes within PVTs for all 30-m pixels in a mapping zone (see Pratt and others, Ch. 10). Specifically, the LANDSUMv4 output file described the total area (m^2) for each of the succession classes occurring within the PVTs in each LRU across a zone at every time interval over the simulation period. Details of the LANDSUMv4 simulations pertinent to departure estimates are described here, additional information can be found in Pratt and others, Ch. 10, and a detailed description of succession pathway development is available in Long and others, Ch. 9.

Ideally, one simulation would have been conducted for an entire zone; however, because of computer limitations, we partitioned the zones into smaller units of 20,000-ha and ran LANDSUMv4 separately for each of these landscapes, which we called "simulation landscapes." Figure 2 shows Zone 16 (6-million ha) divided into 427 simulation landscapes (20,000-ha each). Within each simulation landscape, we again partitioned the area into 256 LRUs of 81 ha each (fig. 2). LANDSUMv4 simulated succession and disturbance across the entire 20,000-ha landscape but reported only the composition of succession classes by PVTs contained within each LRU. For example, in figure 2, there are five PVTs distributed across the LRU. For each of the five PVTs and at every reporting interval, LANDSUMv4 reported the composition of succession classes summarized collectively across all stands of the same PVT.

A key requirement for measuring departure through the HRVStat approach was the acquisition of a statistically valid number of temporally uncorrelated observations from the LANDSUMv4 time series. Early testing of HRVStat indicated that a minimum of 200 observations from a LANDSUMv4 time series at reporting intervals long enough to minimize temporal autocorrelation was needed. Because fire disturbance dynamics tend to occur at longer frequencies, short annual reporting intervals result in correlated observations, but succession class distributions become less correlated with longer reporting intervals (Pratt and others, Ch. 10). Initial tests indicated that intervals of 20-years or more showed relatively little autocorrelation, and, using this interval, we executed the model for a 4,000-year simulation period to obtain 200 observations for Zone 16. Further examination, however, revealed that PVTs in Zone 16 (except Aspen, Wetland Herbaceous, Cool Herbaceous, and Alpine) showed notable autocorrelation (fig. 3a). Based on the autocorrelation in Zone 16, we extended the reporting interval to 50 years for Zone 19 and executed the model for a 10,000-year simulation period to obtain 200 observations. Although the autocorrelation in Zone 19 was not as pervasive as that for Zone 16, it was still present to some degree for most PVTs. Several PVTs, particularly forest PVTs, had moderately high correlation coefficients, even with a 50-year time lag (fig. 3b). It was logistically impractical to further increase the reporting interval and the simulation time to the length necessary to minimize autocorrelation in all PVTs because the total simulation time would become prohibitively long, given our computing resources. Further research is being conducted to study the effect of autocorrelation and succession class trends on LANDSUMv4 output and the subsequent departure calculations. It is important to note that the FRCC Guidebook approach had less rigorous requirements for representing historical conditions, requiring only one observation that describes the

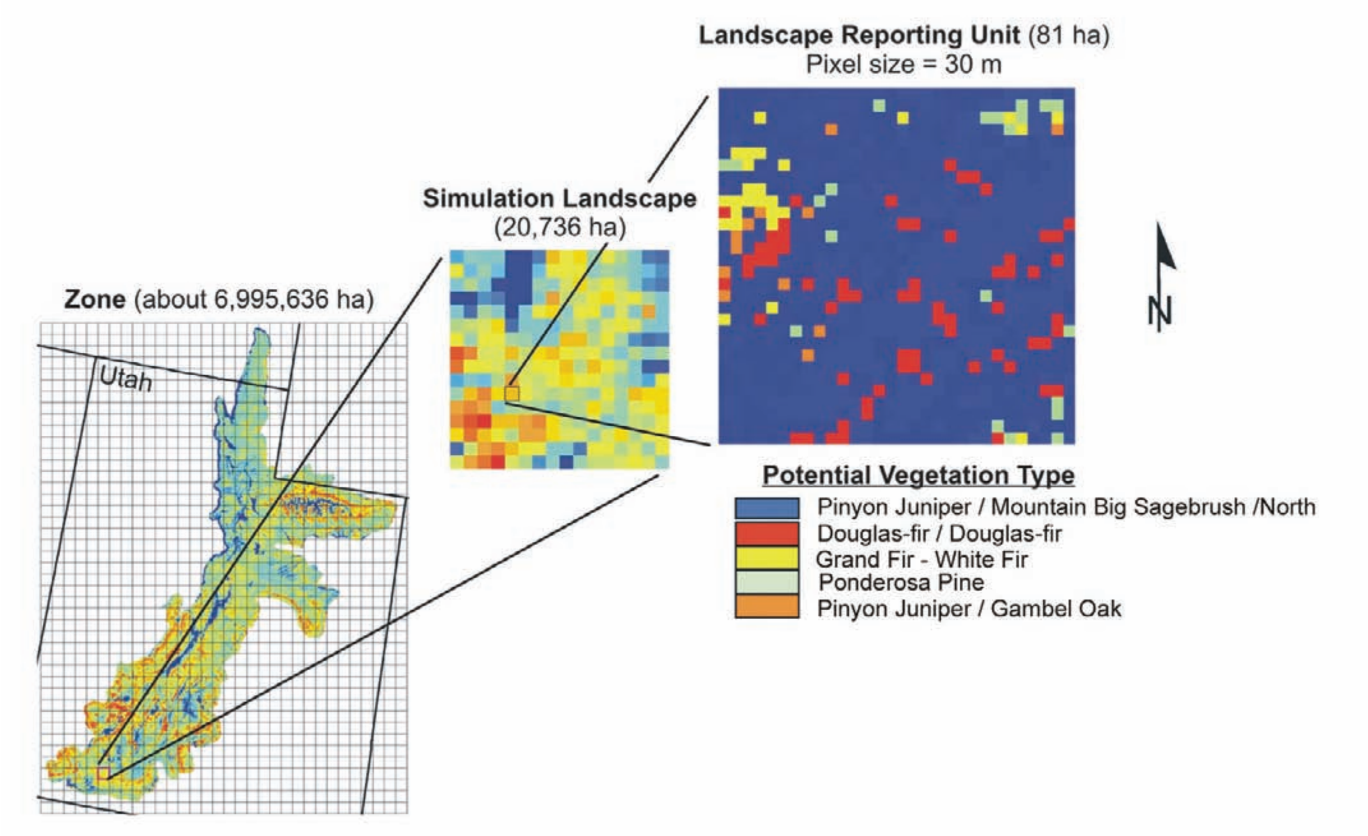

Figure 2—Example of the hierarchical configuration of spatial reporting units used to estimate reference conditions from LANDSUMv4. The broadest extent is the zone; followed by the 20,000-ha simulation landscape; and lastly, the landscape reporting unit which displays the spatial distribution of PVTs for this example in Zone 16.

central tendency of long-term natural dynamics (Hann and others 2004).

Depicting current vegetation conditions—Whereas succession class distributions by PVT were simulated by LANDSUMv4 to estimate reference conditions, current vegetation was described using existing cover type and structural stage maps derived from recent satellite imagery (Zhu and others, Ch. 8). Excepting classes with non-native or exotic cover types (Long and others, Ch. 9) established over the last (twentieth) century — which we considered a recent invasion to plant communities — we classified existing cover type and structural stage maps into the same set of succession classes used for the historical simulation modeling. The dominance of an exotic species in current succession class maps represented a distinct change from the simulated historical conditions. We then spatially combined the PVT, existing cover type, existing structural stage, and LRU layers such that all unique combinations of spatial input variables were tabulated. The result of this process depicted the areal extent for each of the succession classes within each PVT occurring within every LRU across the zone.

Compiling the final data sets for estimating departure—We combined the data set for existing vegetation with the time series from LANDSUMv4 to develop data sets for estimating departure. That is, the departure data sets from the LANDSUMv4 output summarized the total area in each PVT-succession class combination within an LRU for the current time period and for each reporting interval (20 or 50 years, in this effort). In these data sets, current vegetation was depicted by only one instance in time for each PVT-succession class, whereas the simulated historical conditions were represented by 200 observations sampled from the LANDSUMv4 simulations for each PVT-succession class.

Departure was estimated by comparing the succession class distributions for the five PVTs contained in

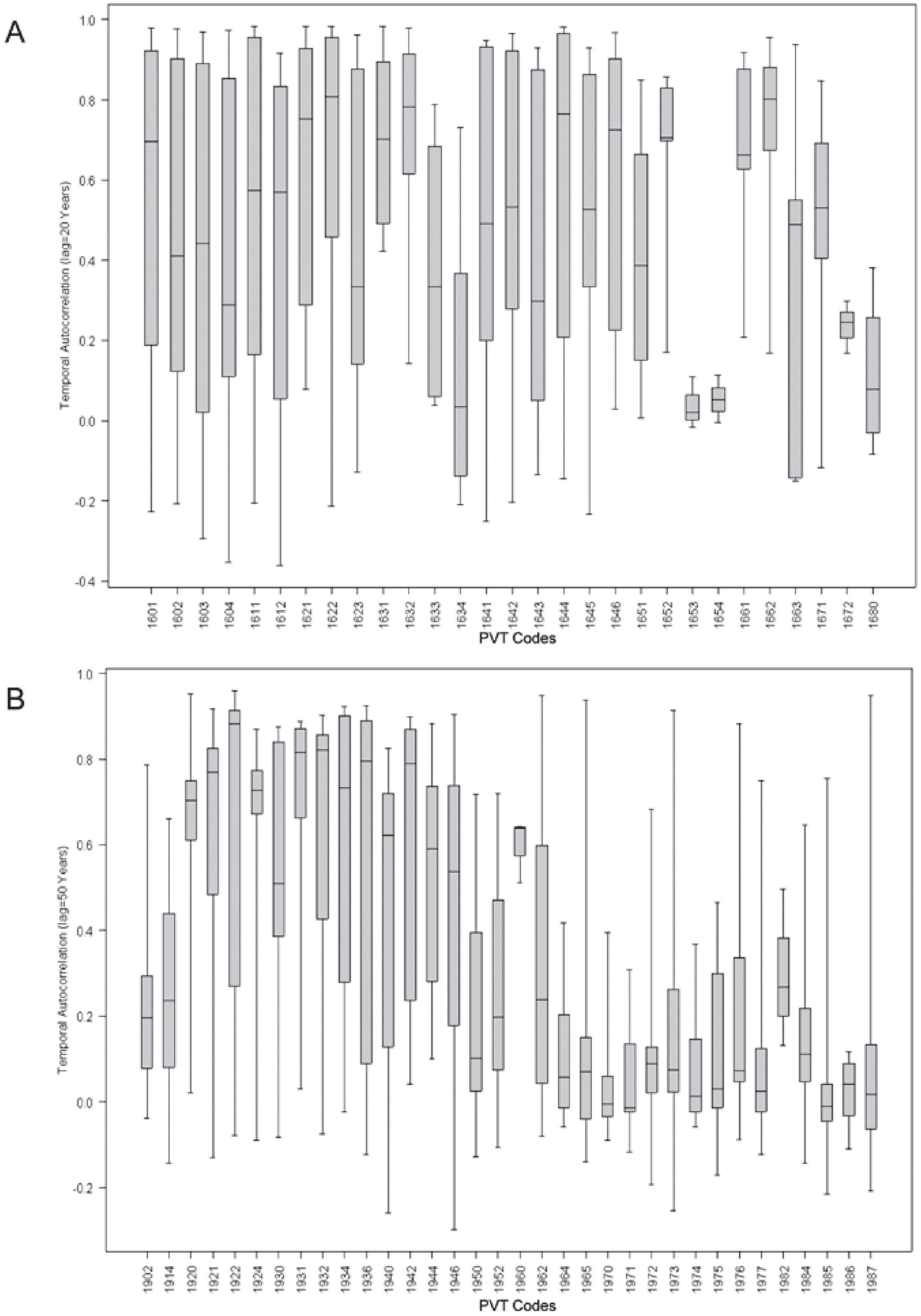

Figure 3—Box and whiskers plots showing the mean autocorrelation coefficient across PVTs in (A) Zone 16 with a 20-year lag and (B) Zone 19 with a 50-year lag. A correlation coefficient of zero represents no autocorrelation. See appendix 11-A for key to PVT codes.

the example LRU as simulated by the LANDSUMv4 model (with 200 observations possible for each unique succession class within each PVT) to succession class distributions for the same five PVTs in the current landscape (with only one observation for each PVT-succession class) (see, for example, figure 2). Put another way, the spatial arrangement of PVTs did not change between LANDSUMv4 simulations and the current landscape, but succession class distributions within PVTs did vary – and that change was the basis for measuring departure.

Implementing the FRCC Guidebook Approach

In implementing the FRCC Guidebook approach, we explored a number of options for representing reference conditions and estimating departure and applied them to Zone 16, as will be described below. Based on these and additional analyses, we developed a final method, which was applied to Zone 19.

One of the main challenges for this approach was distilling the time series of LANDSUMv4 model output with 200 observations for each PVT-succession class (within an LRU) down to a single observation for that PVT-succession class, as required by the FRCC Guidebook field procedures (Hann and others 2004). That is, the calculations of departure outlined in the FRCC Guidebook field procedures (described below) require a single value for each succession class within a PVT (within an LRU) for comparisons to the current conditions. In Zone 16, we evaluated two ways to reduce the LANDSUMv4 model output. In the first method, termed the “temporal snapshot,” we elected simply to use conditions from one reporting interval across the entire time series of the LANDSUMv4 output, and we chose year-1,000. This approach provided a “snapshot” of the simulated historical landscape. In other words, the total area that a succession class occupied within a given PVT (of a LRU) in year-1,000 of the LANDSUMv4 time series was used to represent its reference conditions.

In the second method, termed “multi–temporal,” we aimed to capture temporal variation in the simulated historical succession class distributions but with the inherent constraint of using a single value for each PVT-succession class combination (within an LRU) among the 200 values in the LANDSUMv4 time series. Various metrics were possible — such as the maximum, median, mean, and the minimum — with a succession class distribution (n = 200) showing values for the median and various percentiles of the percent area observed for that succession class across the simulated time series (fig. 4). Metrics emphasizing the maximum or minimum ranges of succession class distribution can capture variability to some extent. For example, consider two succession class distributions with the same mean, but one has low variability and the other high variability. The maximum value for each of these distributions will be different, and the distribution with low variability will have a smaller maximum value than the distribution with high variability. For Zone 16, we chose to use 90 percent of the maximum area for each succession class within a PVT (within an LRU) in an effort to portray the variability in the upper end of the distributions for succession classes; for simplicity, we term this metric the “90 percent of maximum.” For Zone 19, we chose to use the 90th percentile of the area (in other words, the value that is as large as 90 percent of all values in the data set and smaller than 10 percent of all values) for each PVT-succession class (within an LRU) to, again, capture the upper range of the succession class distributions. But using the 90th percentile, we more effectively eliminated inordinately high outliers. We term this metric the “90th percentile.”

Determining the 90 percent of maximum and 90th percentiles from the LANDSUMv4 output was a straightforward process. We searched the LANDSUMv4 output and extracted the appropriate value for each PVT-succession class found in each LRU. For example, if the 90th percentile was used to represent reference conditions, the value that was as large as 90 percent of all values in the pool of LANDSUMv4 observations was chosen to represent reference conditions. The extracted values for each succession class were then converted from area to percent of the PVT that they occupied.

After choosing the metric to represent reference conditions, a second key decision involved determining the appropriate extent or spatial domain for summarizing the LANDSUMv4 time series data. Choosing the correct spatial domain was problematic because different spatial domains leads to different estimates of reference conditions for any given succession class. For example, if reference conditions were summarized across watersheds, then each PVT-succession class combination would be assigned the same reference conditions across an entire watershed, regardless of any spatial variability within that landscape.

In Zone 16, we evaluated three spatial domains for calculating reference conditions to describe the 90 percent of maximum for each PVT-succession class over the time series: 1) mapping zones (6 to 10 million ha), 2) simulation landscapes (approximately 20,000 ha), and 3) individual LRUs (81 ha) (fig. 3). For Zone 19, we evaluated only the LRU-level to focus the spatial domain

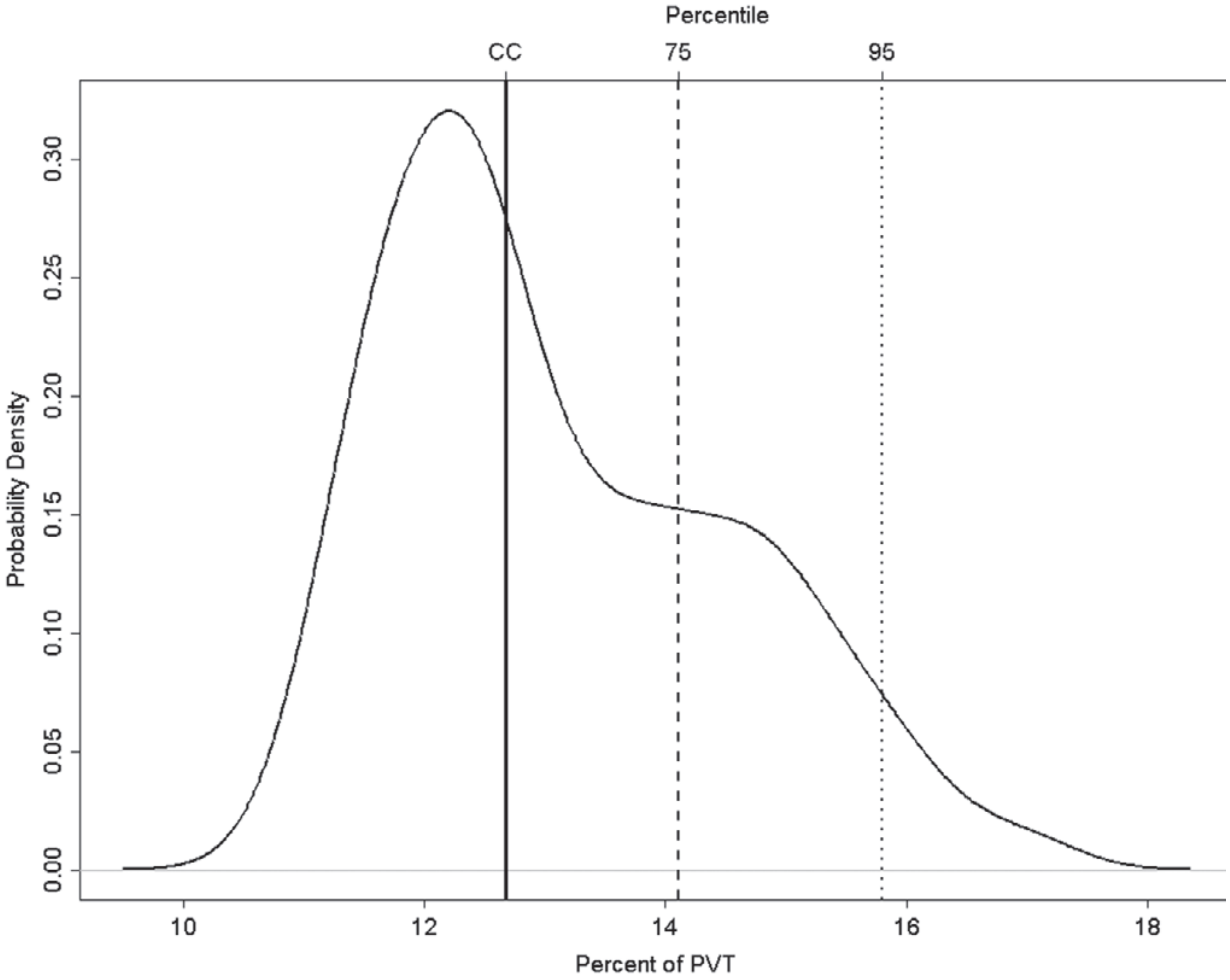

Figure 4—Empirical probability density distributions fitted to the frequency of observed percent area occupied by a slightly departed succession class (Aspen – Birch High Cover, High Height) in the LANDSUMv4 time series data (n=200). The 75th and 95th percentiles (in the percent area observed for that succession class across the simulated time series) occur in 14.1 percent and 15.8 percent of the PVT; the current conditions (CC) data point is at 12.7 percent and corresponds reasonably well to the median of the simulated reference conditions distribution but is relatively distant from the 75th and 95th percentile measurements. Data for each succession class was taken from a 20,000-ha spatial unit within Zone 16 dominated by the Spruce – Fir / Spruce – Fir / Lodgepole Pine PVT containing that succession class.

on local variability (and used the 90th percentile metric). The process of aggregating the LANDSUMv4 time series to the various spatial domains was a straightforward process. First the LANDSUMv4 output was examined across a given spatial domain, and all instances of a given PVT-succession class were identified. Second, for each occurrence of a PVT-succession class combination across the spatial domain, the desired reference conditions (such as the 90th percentile) were identified from the pool (n = 200) of LANDSUMv4 output.

Current conditions were easily calculated by converting area to the percent that a succession class occupied for each PVT across an LRU. For example, table 1 demonstrates that the PVT-succession class combination of the Pinyon–Juniper / Mountain Big Sagebrush / South PVT with the Juniper–High Cover, High Height succession class occupied 38.71 percent of the total area in the example LRU.

Comparing current to simulated historical vegetation conditions enabled the calculation of departure, which

Table 1—Example of computation of current conditions for a landscape reporting unit (LRU) showing relative distributions of succession classes expressed as the percent area occupied within each potential vegetation type (PVT) contained in the LRU. See table 7 for structural stage codes.

PVT	Structural stage	Cover type	Current conditions (% of area occupied)
Pinyon – Juniper / Mountain Big Sagebrush / South	HHW	Juniper	38.71
Pinyon – Juniper / Mountain Big Sagebrush / South	LLW	Juniper	11.52
Pinyon – Juniper / Mountain Big Sagebrush / South	LHW	Juniper	1.23
Pinyon – Juniper / Mountain Big Sagebrush / South	LLW	Pinyon – Juniper	19.20
Pinyon – Juniper / Mountain Big Sagebrush / South	HHW	Pinyon – Juniper	17.05
Pinyon – Juniper / Mountain Big Sagebrush / South	LHW	Pinyon – Juniper	0.77
Pinyon – Juniper / Mountain Big Sagebrush / South	LHS	Mountain Deciduous Shrub	9.37
Pinyon – Juniper / Mountain Big Sagebrush / South	HHS	Mountain Deciduous Shrub	2.00
Pinyon – Juniper / Mountain Big Sagebrush / South	HLS	Mountain Big Sagebrush Complex	0.15
Total Percent Area			**100**
Pinyon – Juniper / Gambel Oak	LLW	Pinyon – Juniper	44.76
Pinyon – Juniper / Gambel Oak	HHW	Pinyon – Juniper	41.26
Pinyon – Juniper / Gambel Oak	LHS	Mountain Deciduous Shrub	7.69
Pinyon – Juniper / Gambel Oak	HLS	Mountain Deciduous Shrub	3.50
Pinyon – Juniper / Gambel Oak	HLS	Mountain Deciduous Shrub	2.80
Total Percent Area			**100**
Wyoming – Basin Big Sagebrush	HLS	Wyoming – Basin Big Sagebrush Complex	85.71
Wyoming – Basin Big Sagebrush	LLS	Wyoming – Basin Big Sagebrush Complex	10.71
Wyoming – Basin Big Sagebrush	LLS	Rabbitbrush	3.57
Total Percent Area			**100**
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South	LLW	Juniper	50.00
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South	HLS	Wyoming – Basin Big Sagebrush Complex	29.41
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South	LLS	Wyoming – Basin Big Sagebrush Complex	2.94
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South	LLW	Pinyon – Juniper	14.71
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South	HLS	Dwarf Sagebrush Complex	2.94
Total Percent Area			**100**
Ponderosa Pine	LLF	Ponderosa Pine	58.82
Ponderosa Pine	LHF	Ponderosa Pine	23.53
Ponderosa Pine	LLF	Juniper	5.88
Ponderosa Pine	HHF	Ponderosa Pine	5.88
Ponderosa Pine	LLF	Pinyon – Juniper	5.88
Total Percent Area			**100**

was then classified to represent FRCC. The measure of departure relied on the computation of "similarity," discussed in depth by Hann and others (2004). We calculated this simple metric by comparing current and reference conditions in the same LRU for a given PVT. The percent composition of each succession class in the current condition map was compared with that of the reference conditions for each PVT within an LRU, and the lesser of the two was termed "similarity." Across each PVT, the similarity values were totaled throughout the entire LRU. Departure was subsequently calculated for each PVT as:

$$\text{Departure} = 100 - \text{Similarity} \tag{1}$$

where Similarity is the summation of individual similarity values for each of the PVTs across an entire LRU, given as:

$$\sum_{i=0}^{SClasses} Similarity(i) \tag{2}$$

where Similarity is computed as the smaller area of either current vegetation or that of the reference conditions for each succession class encountered in a PVT. Aggregation of estimated Similarity values from individual PVTs to the LRU was performed on an area-weighted basis. We conducted this process in two steps. First, the area and departure of each PVT within a given LRU were computed (table 2). In the second step, we computed the final departure estimate by weighting each PVT-based departure by its respective area and summing these values across the entire LRU (table 3). For visual simplification and to allow for identification of areas with low, moderate, or high departure, we classified departure for Zone 16 using the following threshold values from the FRCC Guidebook field procedures (Hann and others 2004): departure < 33; 33 ≤ departure < 67; and departure ≥ 67, which correspond to FRCC 1, 2, and 3, respectively. For Zone 19, we used FRCC classification thresholds that were different from those used for Zone 16 to match values subsequently modified by managers implementing the FRCC Guidebook procedures in the field; these were: departure < 5, 5 ≤ departure < 52.5, and departure ≥ 52.5, which correspond to FRCC 1, 2, and 3, respectively (Hann, personal communication).

Implementing the HRVStat Approach

In developing and implementing the HRVStat approach, we wanted to employ a statistical test that could detect whether a single observation of current vegetation was unusual compared to a set of observations representing historical vegetation composition. That is, we wanted to consider every observation in the simulated historical record for all succession classes in a PVT and compare this set to the current conditions. This approach was fundamentally different from the FRCC Guidebook method, which measures departure using only one value to represent the time series of simulated historical conditions for any PVT-succession class combination.

To estimate departure using a range of historical conditions, Steele and others (in preparation) developed a new statistical technique based on measuring the extent that a suspected outlier (in our case, the current observation) can be estimated from the simulated historical observations. This multivariate statistical approach uses concepts from matrix algebra to compute linear approximations and measurements of approximation error (Leon 2002). Essentially, this method computes the best possible approximation of the current observation that can be formed as a linear function of the simulated historical data. Usually, there is some error in the approximation, and the square root of that error is the estimated departure value using the HRVStat method. More specifically, departure is calculated as the square root of the error sum-of-squares after normalizing the current observation vector. If the measured error (that is, departure) is small, the current observation is similar to the simulated historical data. Conversely, a current observation inconsistent with historical patterns will be poorly approximated, and the error will be relatively large, as will the estimated departure value. Steele and others (in preparation) considered other approaches to identifying whether an observation is dissimilar from other observations in a data set. Some of these methods are based on the measure of the distance of a single observation from measures of central tendency (for example, the mean), such as Mahalanobis distance. More commonly, these methods concentrate on measuring distance along particular eigenvector axes extracted from the sample variance matrix. A simulation study showed that the HRVStat approach is far better at detecting unusual observations and particularly effective for use with our highly-dimensional (in other words, having numerous categories of PVT–succession class combinations) data sets comprised of count data (Steele and others, in preparation). We adopted this new method, termed herein as the "best linear approximation," to measure the extent to which current vegetation composition in an LRU differs from simulated historical vegetation composition – which we call the "observed departure."

We also wanted a measure that expressed the strength of evidence for a given observed departure estimate, or

Table 2—First step in computing departure in example LRU using the FRCC Guidebook method. This LRU has 12 PVTs, but only 5 are shown here for brevity. See table 7 for structural stage codes. Note: current conditions are also shown in table 1.

PVT	Structural stage	Cover type	Current conditions	Reference conditions	Similarity	Sum of similarity	Departure
Pinyon – Juniper / Mt. Big Sagebrush / South	HHW	Juniper	38.71	0.04	0.04	18.52	81.48
Pinyon – Juniper / Mt. Big Sagebrush / South	LLW	Pinyon – Juniper	19.20	10.00	10.00		
Pinyon – Juniper / Mt. Big Sagebrush / South	HHW	Pinyon – Juniper	17.05	0.11	0.11		
Pinyon – Juniper / Mt. Big Sagebrush / South	LLW	Juniper	11.52	2.51	2.51		
Pinyon – Juniper / Mt. Big Sagebrush / South	LHS	Mt. Deciduous Shrub	9.37	2.31	2.31		
Pinyon – Juniper / Mt. Big Sagebrush / South	HHS	Mt. Deciduous Shrub	2.00	4.71	2.00		
Pinyon – Juniper / Mt. Big Sagebrush / South	LHW	Juniper	1.23	0.62	0.62		
Pinyon – Juniper / Mt. Big Sagebrush / South	LHW	Pinyon – Juniper	0.77	2.47	0.77		
Pinyon – Juniper / Mt. Big Sagebrush / South	HLS	Mtn. Big Sagebrush Complex	0.15	25.30	0.15		
Pinyon – Juniper / Gambel Oak	LLW	Pinyon – Juniper	44.76	7.12	7.12	21.55	78.45
Pinyon – Juniper / Gambel Oak	HHW	Pinyon – Juniper	41.26	0.44	0.44		
Pinyon – Juniper / Gambel Oak	LHS	Mt. Deciduous Shrub	7.69	16.70	7.69		
Pinyon – Juniper / Gambel Oak	HHS	Mt. Deciduous Shrub	3.50	40.20	3.50		
Pinyon – Juniper / Gambel Oak	HLS	Mt. Deciduous Shrub	2.80	7.61	2.80		
Wyoming – Basin Big Sagebrush	HLS	Wy.–Basin Big Sagebrush Complex	85.71	6.98	6.98	21.02	78.98
Wyoming – Basin Big Sagebrush	LLS	Wy.–Basin Big Sagebrush Complex	10.71	17.60	10.70		
Wyoming – Basin Big Sagebrush	LLS	Rabbitbrush	3.57	3.33	3.33		
Pinyon – Juniper / Wy.– Basin Big Sagebrush / S	LLW	Juniper	50.00	1.12	1.12	25.70	74.30
Pinyon – Juniper / Wy.– Basin Big Sagebrush / S	HLS	Wy.–Basin Big Sagebrush Complex	29.41	14.60	14.60		
Pinyon – Juniper / Wy.– Basin Big Sagebrush / S	LLW	Pinyon – Juniper	14.71	4.60	4.60		
Pinyon – Juniper / Wy.– Basin Big Sagebrush / S	HLS	Dwarf Sagebrush Complex	2.94	2.39	2.39		
Pinyon – Juniper / Wy.– Basin Big Sagebrush / S	LLS	Wy.–Basin Big Sagebrush Complex	2.94	16.70	2.94		
Ponderosa Pine	LLF	Ponderosa Pine	58.82	2.24	2.24	32.51	67.49
Ponderosa Pine	LHF	Ponderosa Pine	23.53	37.60	23.50		
Ponderosa Pine	LLW	Juniper	5.88	0.50	0.50		
Ponderosa Pine	LLW	Pinyon – Juniper	5.88	0.36	0.36		
Ponderosa Pine	HHF	Ponderosa Pine	5.88	23.00	5.88		

Table 3—Second step in computing departure for example landscape reporting unit using the FRCC Guidebook method. Departure is calculated as 100 – similarity. The final estimate of departure is computed by weighting the departure for the 12 PVTs across the entire landscape reporting unit (LRU) by their respective areas. All 12 PVTs are shown here.

PVT	Sum of similarity for PVT	Departure for PVT	Area of PVT	Weighted departure
Douglas-fir / Douglas-fir	14.20	85.80	1.44	1.24
Grand Fir – White Fir	16.72	83.28	0.67	0.56
Grand Fir – White fir / Maple	0.82	99.18	0.11	0.11
Mountain Big Sagebrush	13.86	86.14	0.11	0.10
Pinyon – Juniper / Gambel Oak	21.55	78.45	15.89	12.47
Pinyon – Juniper / Mountain Big Sagebrush / South	18.52	81.48	72.33	58.94
Pinyon – Juniper / Mountain Mahogany	1.12	98.88	0.22	0.22
Pinyon – Juniper / Wy.– Basin Big Sagebrush / South	25.70	74.30	3.78	2.81
Ponderosa Pine	32.51	67.49	1.89	1.27
Riparian Hardwood	20.57	79.43	0.22	0.18
Spruce – Fir / Blue Spruce / Lodgepole Pine	5.94	94.06	0.22	0.21
Wyoming – Basin Big Sagebrush	21.02	78.98	3.11	2.46
Departure for entire LRU				**80.55**

an "observed significance level." The observed significance level is similar to a p-value measurement, which estimates the probability that a type I error (rejecting a true null hypothesis) occurred. However, this formal interpretation requires independent observations from LANDSUMv4 simulations within an LRU – a condition which could not necessarily be met due to possible autocorrelation across time and space. As previously discussed, we observed evidence of temporal autocorrelation using a 20-year reporting interval and, to some extent, a 50-year reporting interval. LRUs may also be spatially correlated because areas close in space tend to have similar vegetation and fire disturbances. Moreover, if we conducted formal tests for each of the tens of thousands of LRUs across a mapping zone, we may obtain a significant result by chance alone, and adjustments would be needed to avoid such type I errors. Hence, the observed significance values reported here are used only to provide a quantitative measure of the evidence of departure for comparisons between LRUs, and not for formal testing (Steele and others, in preparation).

To determine the observed significance level of a departure estimate, we first constructed an empirical distribution using the current and simulated historical observations for each LRU (Steele and others, in preparation). That is, after calculating the observed departure, as described above, we next calculated the departure for each observation *within* the simulated historical data of an LRU, using the best linear approximation calculations. We used the term "divergence" to describe the best linear approximations of the simulated historical time series – to avoid confusion with the "observed departure" term used to estimate differences between the current and simulated historical time series. We calculated divergence within the simulated historical data set by removing each observation from the data set and computing its divergence from the remaining data (for example, we measured the divergence between year-20 and years 40 to 4,000 in the LANDSUMv4 data set for Zone 16). We then combined the divergence estimates (n = 200) with the observed departure (n = 1) to produce the empirical distribution for each LRU. Finally, we computed the observed significance level by calculating the proportion of divergence values in the distribution that are at least as large as the observed departure (Steele and others, in preparation).

To help illustrate the statistical procedures in the HRVStat approach, we provide a simplified example in figure 5. Consider two LRUs that contain only one PVT with one succession class, the same mean area over time for reference conditions (percent of the area is 0.2 in fig. 5A), and the same observed area for current conditions (percent of the area is 0.8 in fig. 5A). However, LRU-A has lower variability in the percent areas of the succession class than LRU-B. In figure 5B, we show the distribution of the divergence estimates and the observed departure. The divergence estimates similarly show that LRU-A has less variability for divergence estimates and a lower mean divergence than LRU-B, whereas observed departures are the same for both LRUs (fig. 5B). In figure 5C's empirical distributions of the divergence, we show the observed significance level for each LRU as the proportion of values greater than or equal to the

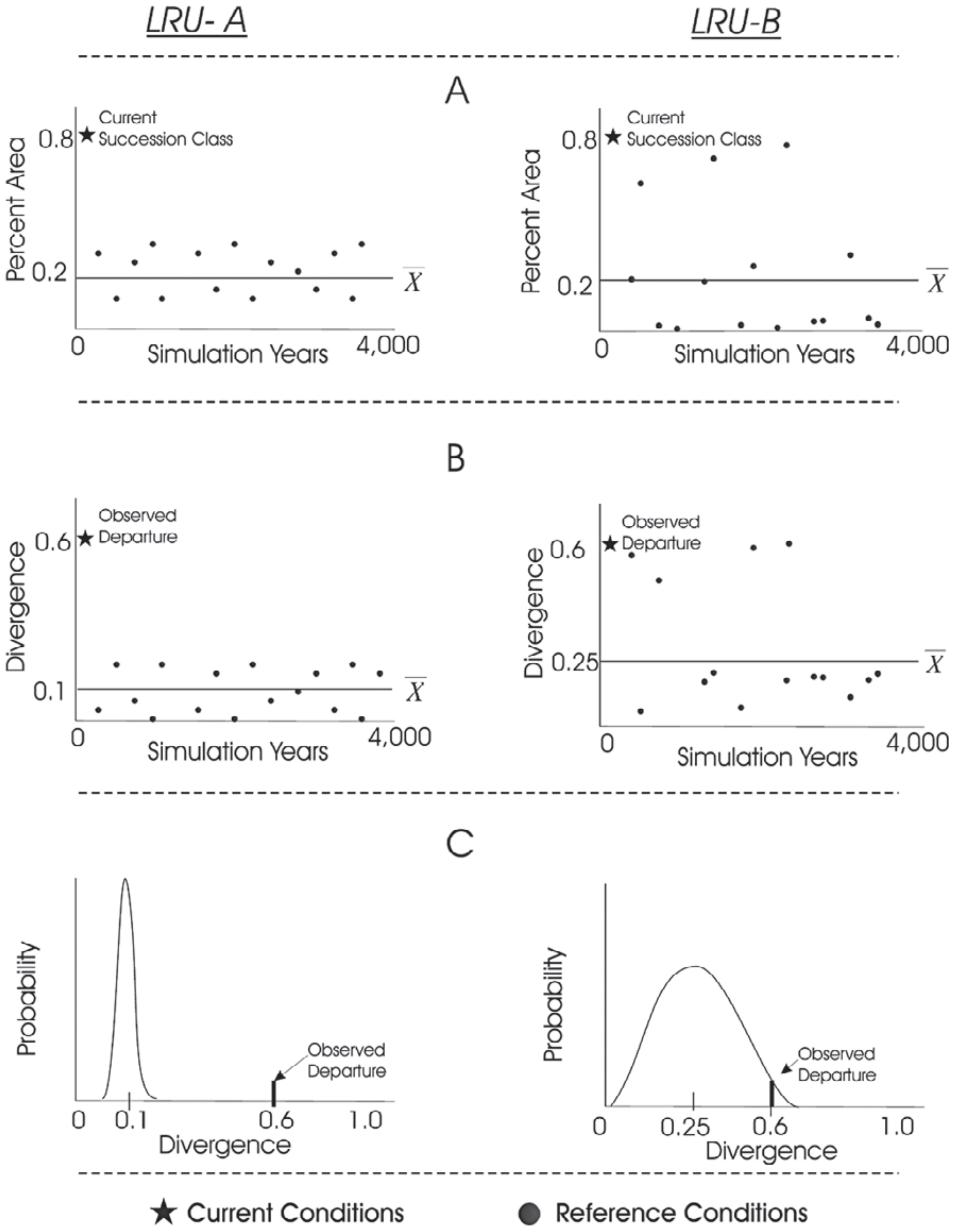

Figure 5—Hypothetical, simplified example demonstrating HRVStat for two landscape reporting units (LRU-A and LRU-B) that contain only one PVT with one succession class under current and reference conditions. Set A shows that LRU-A and LRU-B have the same current percent area for that succession class (current succession class) and that the reference conditions have similar mean percent areas ($\overline{X}$), but LRU-A has less variability than LRU-B. Set B shows estimates for observed departure from and divergence within reference conditions. LRU-A and LRU-B have identical observed departures, but LRU-A has a lower mean divergence ($\overline{X}$) and variability than LRU-B for reference conditions. Set C shows the probability distributions of divergence, where the area under the curve above the observed departure represents the observed significance level. Observed significance level is less in LRU-A than LRU-B because LRU-A has less variability in the reference conditions.

observed departure, where the observed significance value is higher in LRU-B than LRU-A. In summary, we have the same estimate of observed departure for LRU-A and LRU-B, but evidence for that observed departure is greater in LRU-A because of less variability in the distribution of the succession class in the historical time series. In reality, calculations in an actual LRU from Zone 16 or Zone 19 would be far more intensive because of the large number of PVT-succession class combinations (up to 220).

Creating maps for comparing departure estimates—Our last task was classifying HRVStat results to make comparisons with the 1-km coarse-scale FRCC maps (Schmidt and others 2002) and the FRCC Guidebook approach maps, which classify departure as low (FRCC 1), moderate (FRCC 2) and high departure (FRCC 3). We determined that the most informative classification scheme integrates both the departure and observed significance level estimates from HRVStat to describe not only the degree of departure in a landscape but also the evidence supporting the departure estimate.

Both departure and observed significance level values ranged from 0 to 1.0. We classified these parameters into three groupings by choosing two thresholds for partitioning values (table 4). For observed significance level, we chose thresholds of 0.01 and 0.1 to describe high, moderate, and low observed significance within our departure estimate, based on value limits commonly used in statistics to assess significance. To partition departure into classes, we chose threshold values of 0.33 and 0.67, as recommended in the FRCC Guidebook field methods (Hann and others 2004) and also used in the FRCC Guidebook approach for Zone 16. We call the three classes “classified HRVStat departure” estimates, instead of FRCC, to avoid confusion with the classified departure values from the FRCC Guidebook approach. Accordingly, the classified HRVStat departure values of Class 1, Class 2, and Class 3 correspond to the categories of FRCC 1, FRCC 2, and FRCC 3. We determined that managers would be most interested in areas where the strength of evidence (observed significance) for a departure estimate was highest, and we assigned those areas relatively higher classification values. For example, an LRU may have a relatively low departure estimate (less than 0.33), but if the observed significance value was less than <0.01, we assigned a Class 2 value to the unit. Conversely, we gave lower classification values to areas where evidence in the departure estimate was low; for example, an LRU with a high departure estimate (≥ 0.67) and a high observed significance (≥ 0.1) would be assigned a Class 1 value.

Table 4—Classified HRVStat departure as assigned to each departure/observed significance grouping and the percent of each zone in these categories for zones 16 and 19.

	obs. sign. < 0.01	0.01 ≤ obs. sign. < 0.1	obs. sign. ≥ 0.1
Classified HRVStat departure:			
d < 0.33	2	1	1
0.33 ≤ d < 0.67	3	2	1
d ≥ 0.67	3	3	2
Percent area of zone:			
Zone 16			
d < 0.33	60.34%	22.27%	9.96%
0.33 ≤ d < 0.67	5.69%	0.01%	0
d ≥ 0.67	1.73%	0	0
Zone 19			
d < 0.33	61.42%	6.88%	6.12%
0.33 ≤ d < 0.67	12.67%	0.03%	0.00%
d ≥ 0.67	11.99%	0.90%	0.00%

Operational process for HRVStat—The steps for developing the departure, observed significance level, and classified HRVStat departure map layers were three-fold (fig. 6). First, we extracted the relevant fields from the LANDSUMv4 database, including reporting interval, LRU, PVT, succession class, and area, and combined these data with the associated current landscape data to create the input file. Next, we ran the HRVStat program using GAUSS software (Aptech Systems, Inc. 2004) in addition to an independent platform of the HRVStat program. The HRVStat program produced output files containing departure, observed significance level, and classified HRVStat departure values for each LRU. We then linked the HRVStat output files to the LRU map, and created maps of departure, observed significance level, and classified HRVStat departure.

Detailed Demonstration of Departure Estimates using the HRVStat and FRCC Guidebook Approaches

For illustration purposes, we provide a detailed demonstration of departure calculations for a selection of LRUs using both the FRCC Guidebook and HRVStat approaches. We chose three LRUs in Zone 16 with classified HRVStat departure and FRCC estimates of 1, 2 and 3. To demonstrate the FRCC Guidebook approach, we present a detailed description of estimation procedures for only one LRU (FRCC 3) because we determined one example was sufficient, given the simplicity of the calculations. Because the HRVStat approach is less easily comprehended, we provide examples for all three LRUs. Specifically, we present the distributions of succession

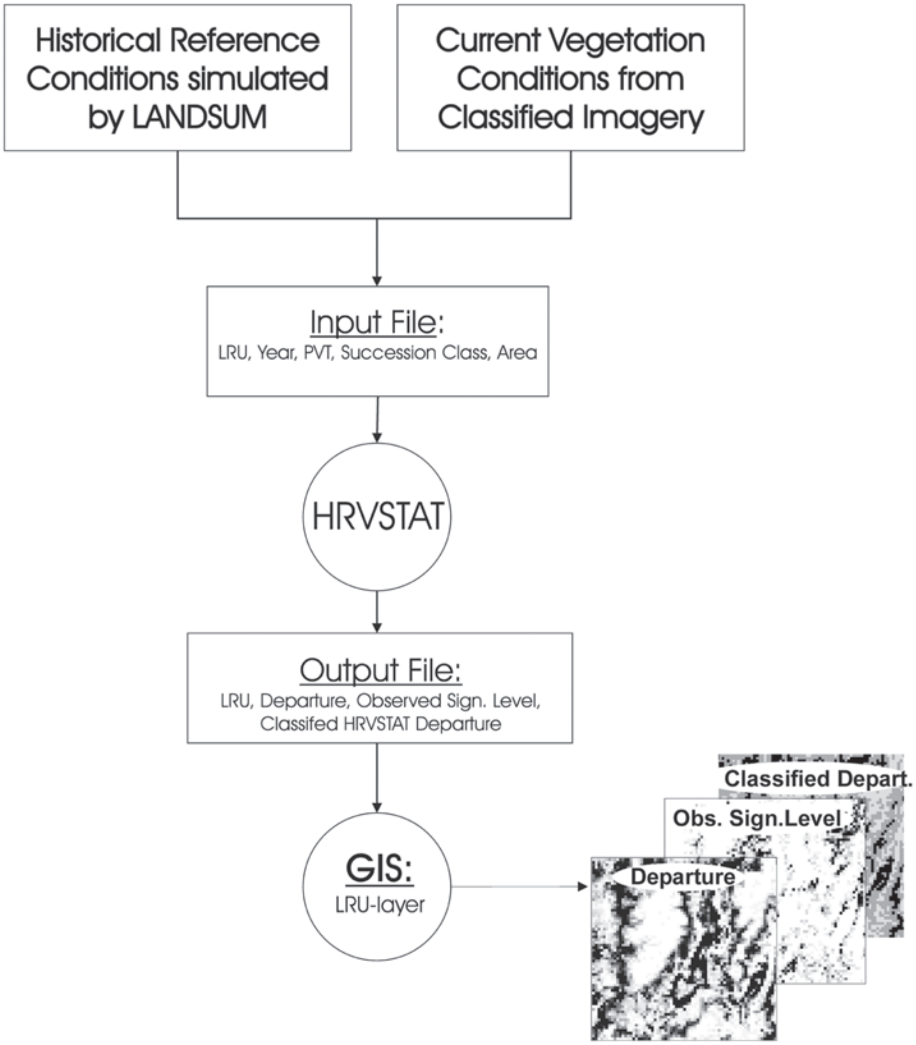

Figure 6—The flow diagram for developing the departure, observed significance level, and classified HRVStat departure maps using the HRVStat method. Data from LANDSUMv4 simulations are combined with current landscape data to build input files containing the attributes of landscape reporting unit (LRU), PVT, succession class, and area (m^2). HRVStat calculates departure statistics for each LRU and produces an output file with departure, observed significance, and classified HRVStat departure estimates for each LRU. Departure statistics are linked to the LRU spatial layer to build maps of departure, observed significance level, and classified HRVStat departure.

classes by PVT and qualitatively describe the succession classes contributing most to departure for individual LRUs. We also present the empirical distributions of divergence and observed departure estimates, from which observed significance values are derived.

Departure Estimates by Fire Return Intervals

The national coarse-scale project evaluated the relationship of estimated FRCCs on current landscapes to estimates of historical fire return intervals (Schmidt and others 2002), and the LANDFIRE Prototype Project conducted similar analyses for comparison. One of the map layers created by the LANDSUMv4 model described fire return intervals (the number of years between successive fires for each pixel in the mapping zone), which was classified into four categories to be compatible with the fire regime maps developed for the national coarse-scale project, including: 0-35 year frequency, 36-100 year frequency, 101-200 year frequency, and 201+ year frequency (Pratt and others, Ch. 10). We compared the departure indices estimated by the FRCC Guidebook and HRVStat approaches to the classified fire return interval layer to evaluate whether departure becomes higher in areas where more fire is observed under simulated historical conditions.

Results

We present maps and other results from the exploratory stages in our method development for Zone 16; for Zone 19, we present our resultant recommended method for estimating departure. However, even for Zone 19, results reflect a work in progress, and more analysis and research is needed to further improve the FRCC Guidebook and HRVStat approaches. Hence, the specific findings presented here should be considered primarily as a demonstration of method development and as a comparison of approaches to estimating departure. Maps and computed values for departure statistics may change as these procedures are refined for the national implementation of the LANDFIRE Project.

FRCC Guidebook Approach

A comparison of the temporal snapshot and multi-temporal methods for deriving reference conditions revealed that the snapshot approach produced the highest zone-wide estimates of departure, with a zonal mean of 73 (fig. 7A) compared to means ranging from 23 to 63 using the multi-temporal method (fig. 7B-7D). We expected this result because many of the currently present succession classes did not exist in the year-1,000 LANDSUMv4 output. Simply stated, if reference conditions for a succession class are 0 (the succession class, by chance, did not occur in year-1,000 LANDSUMv4 output) then there would be no similarity and thus, complete departure. Once we recognized the ineffectiveness of the snapshot method for deriving reference conditions, we focused our efforts on the multi-temporal approach.

Using the multi-temporal approach for deriving reference conditions, we discovered that for Zone 16, each progressively smaller spatial domain (fig. 2) produced noticeably lower estimates of departure (fig. 7B-7D), with a zonal mean of 63 using the zone as the spatial domain, 45 using the simulation landscape, and 23 using the LRU as the spatial domain; furthermore, the proportions of the zone belonging to FRCC 3 were highest using the zonal-spatial domain (41 percent) and lowest using the LRU-spatial domain (1 percent) (table 5). For all three spatial domains, departure and FRCC were higher in the area surrounding the Uinta Mountains and in the southern portions of the mapping zone (figs. 7B-7D and 8). Examining the LRU-spatial domain alone, the departure estimates for Zone 16 ranged from 0 to 96 with a mode of 11 (fig. 9A). For Zone 19, we evaluated only the LRU-spatial domain to derive reference conditions and observed a zonal departure mean of 42, mode of 43, and a range of 0 to 100 (fig. 9B); in addition, most (74 percent) of Zone 19 belonged to FRCC 2 (table 5). Departure and FRCC were generally higher in the northern portions of the zone and in scattered clusters in the central and eastern portions of the zone (fig. 10).

To assess how the various vegetation types contributed to departure, we also evaluated the mean departures for each PVT across the mapping zones by constructing simple spatial overlays of departure and PVT maps for each zone (appendices 11-B and 11-C). For Zone 16, using all three spatial domains for computing reference conditions, the highest departure was estimated to occur in the Douglas-fir / Timberline Pine PVT (appendix 11-B), but this PVT occupied only a small fraction (0.47 percent) of the zone. The Pinyon-Juniper / Mountain Big Sagebrush / South PVT had the second highest estimate of departure across all three spatial domains (appendix 11-B) and was the most abundant PVT (17 percent) in the zone. In Zone 19, the Bluebunch Wheatgrass PVT had the highest estimated departure (62), followed by the Dry Shrub PVT (58) (appendix 11-C), but they occupied relatively small portions of the zone (six and one percent, respectively). The most abundant PVTs were Wyoming – Basin Big Sagebrush Complex (15 percent

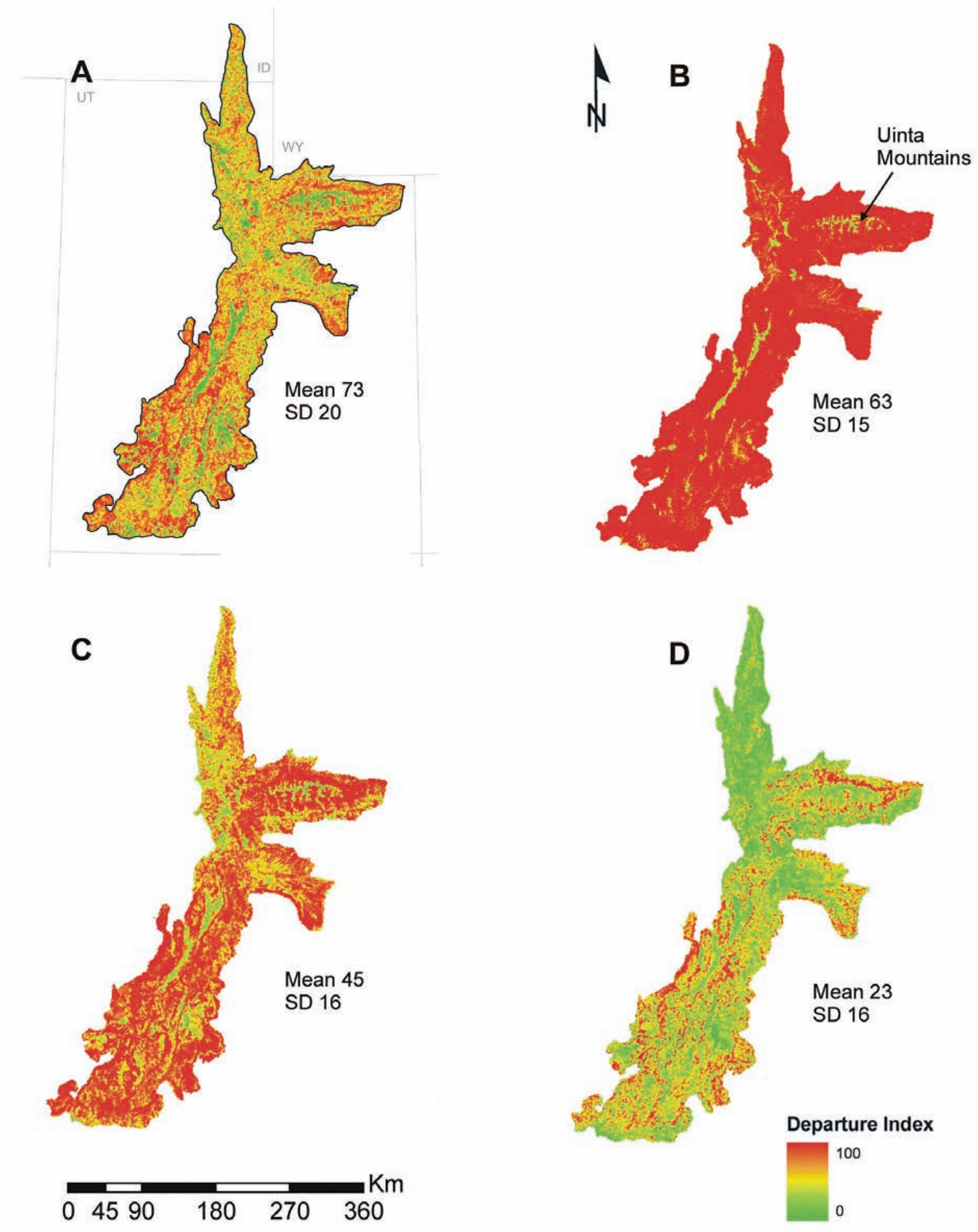

Figure 7—Departure estimates using FRCC Guidebook approach for Zone 16 based on reference conditions derived from: (A) LANDSUMv4 output at simulation year-1000 and 90 percent of the maximum percent area observed for each succession class in a PVT across the simulated time series for three spatial domains (the areal extent for summarizing the LANDSUMv4 time series data) including: (B) the entire zone, (C) individual simulation landscapes, and (D) individual landscape reporting units.

Table 5—Proportion of each mapping zone in the three classes describing (1) classified HRVStat departure, (2) FRCC using the FRCC Guidebook approach for each of the three spatial domains of mapping zone, simulation landscape (SL), and landscape reporting unit (LRU) in Zone 16 and for the LRU spatial domain only in Zone 19, and (3) FRCC from Schmidt and others 2002.

Class	Classified HRVStat departure	FRCC Guidebook approach using zonal spatial domain	FRCC Guidebook approach using SL spatial domain	FRCC Guidebook approach using LRU spatial domain	Schmidt and others 2002
Zone 16					
1	32%	5%	24%	77%	62%
2	60%	54%	67%	22%	34%
3	8%	41%	9%	1%	4%
Zone 19					
1	13%	n/a	n/a	1%	37%
2	70%	n/a	n/a	74%	40%
3	17%	n/a	n/a	25%	23%

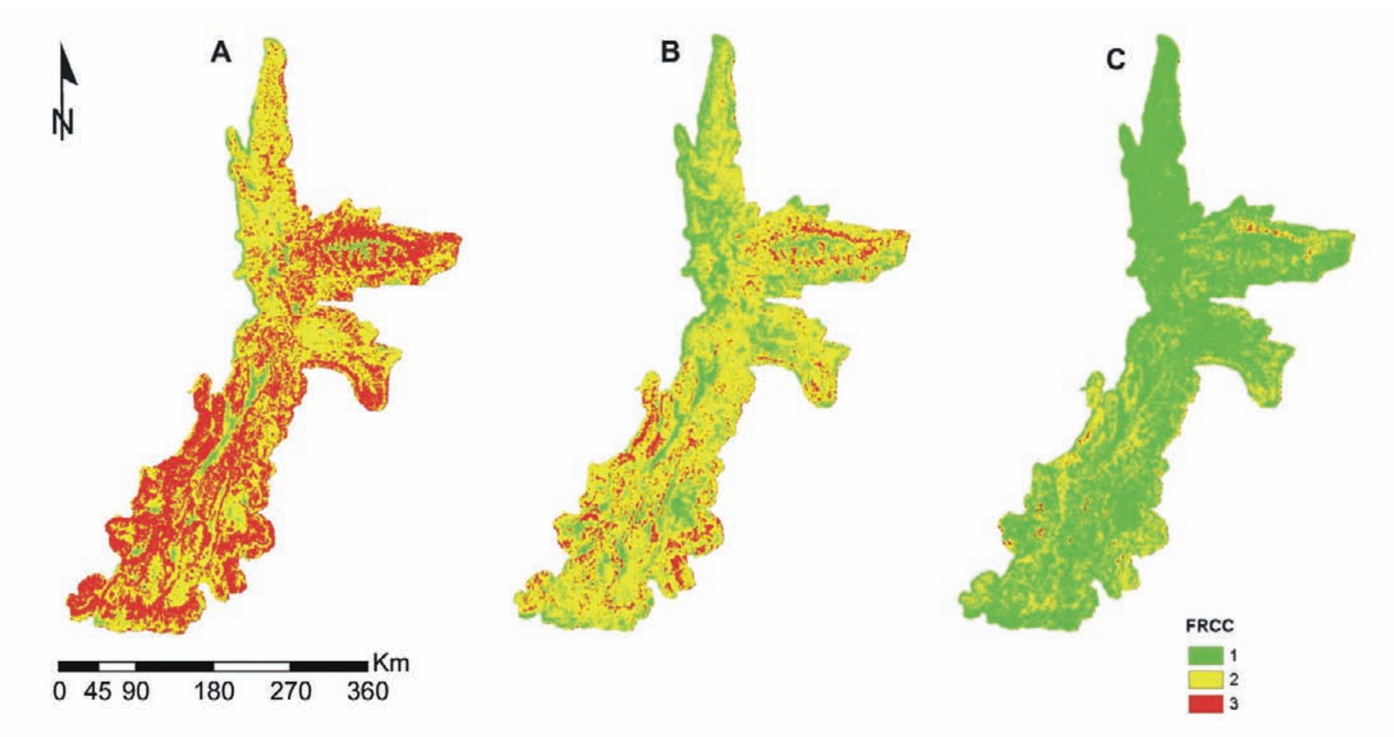

Figure 8—Fire regime condition class (FRCC) for Zone 16 using the FRCC Guidebook approach and based on reference conditions derived from 90 percent of the maximum percent area observed for each succession class in a PVT across the simulated time series for three spatial domains (the areal extent for summarizing the LANDSUMv4 time series data) including: (A) the entire zone, (B) individual simulation landscapes, and (C) individual landscape reporting units.

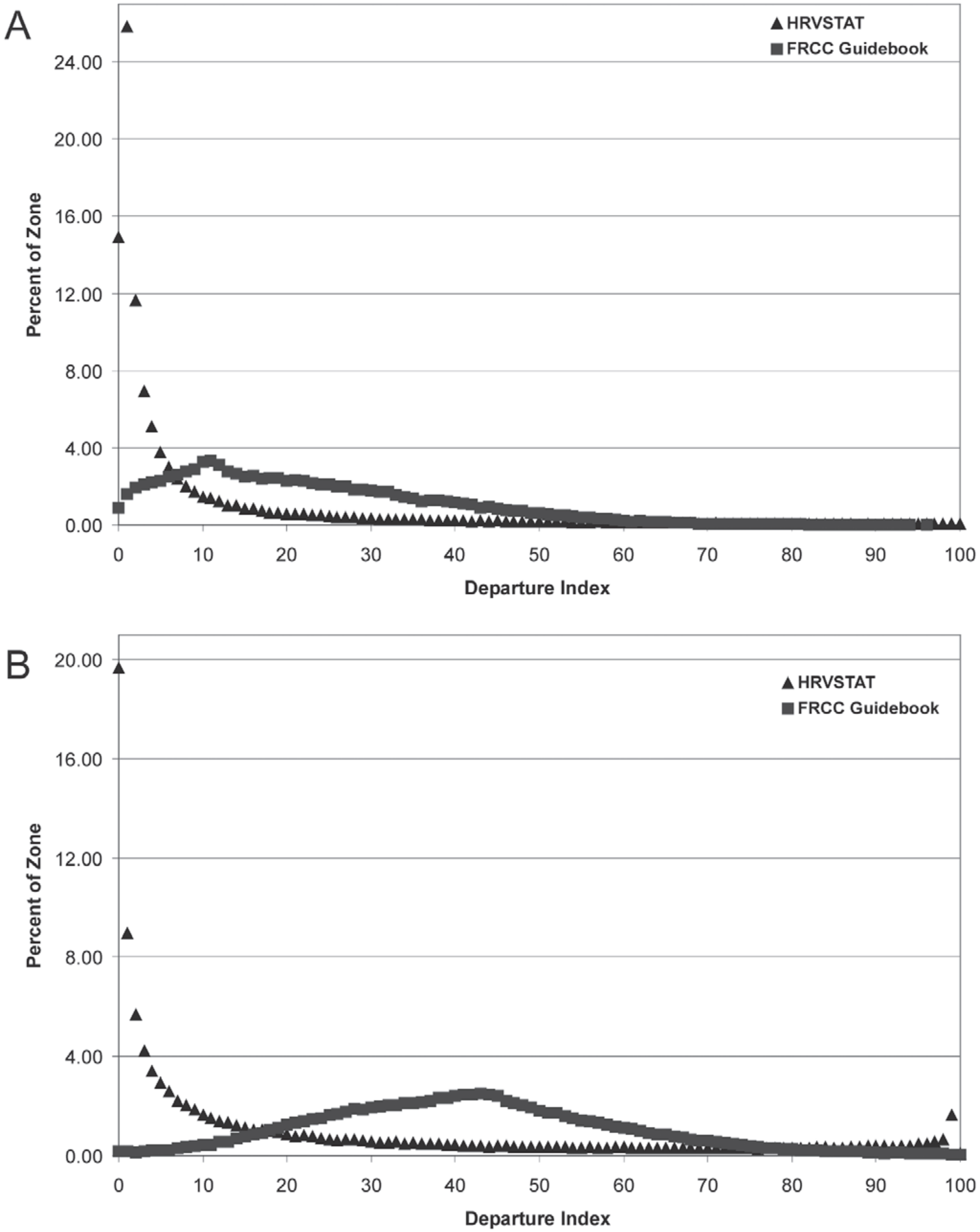

Figure 9—Frequency distribution of departure estimates using the HRVStat and FRCC Guidebook approaches for (A) Zone 16 and (B) Zone 19. Departure values from HRVStat were rescaled from 0-1.0 to 0-100 to match the scale of the FRCC Guidebook values. FRCC Guidebook estimates use the LRU as the spatial domain.

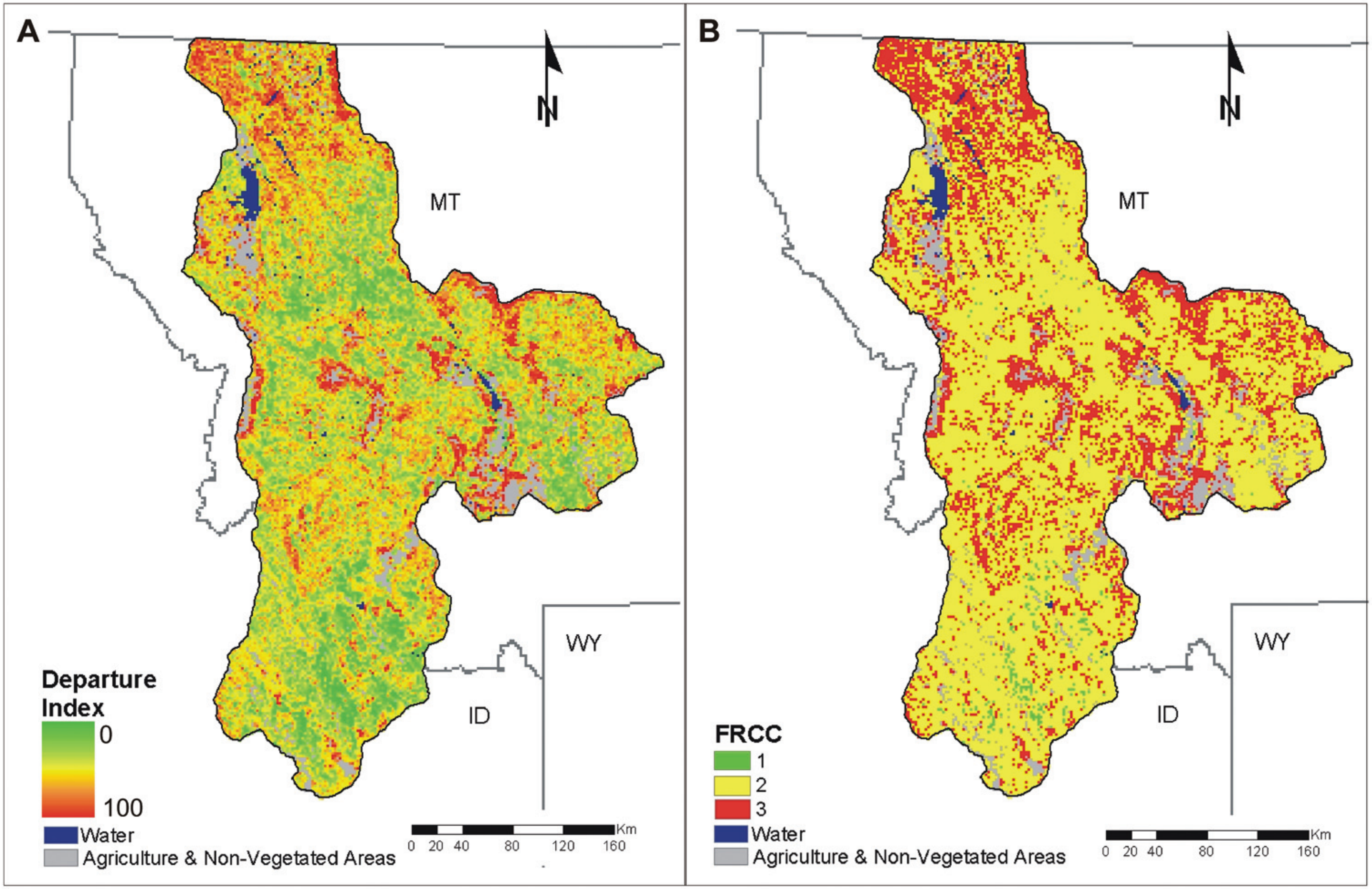

Figure 10—FRCC Guidebook approach results for (A) departure and (B) FRCC for Zone 19 based on reference conditions derived from the 90th percentile of percent area observed for each succession class in PVTs across the simulated time series using the landscape reporting unit as the spatial domain (the areal extent for summarizing the LANDSUMv4 time series data).

of zone) and Douglas-fir / Douglas-fir (11 percent), and they had relatively low departures of 39 and 34, respectively.

It should be recognized that these results do not precisely estimate the degree to which each vegetation class contributed to departure. That is, the results presented were produced through simple overlays (for example, a departure layer overlaid on a PVT layer), and the amount that any of these vegetation classes contributed to the measured departure within LRUs could not be precisely measured. For example, an LRU with a high departure estimate may be composed of 90 percent Douglas-fir PVT and 10 percent Cool Herbaceous PVT. In these simple spatial overlays, both PVTs would be reported as having high departure. However, the Douglas-fir PVT would likely be the dominant contributor to the high departure estimate. The Cool Herbaceous PVT may be only slightly departed, but we would not observe its true value given our overlay methods. More extensive programming and analysis are needed to more precisely describe departure by vegetation class.

HRVStat Approach

The final products using the HRVStat method were sets of three maps representing departure, observed significance level, and classified HRVStat departure (figs. 11 and 12). In Zone 16, departure estimates were generally higher in the southern portion of the mapping zone, and correspondingly, most occurrences of high classified HRVStat departure (Class 3) were in the southern area, as well. Departure and classified HRVStat departure in Zone 19 were generally higher in the central and eastern portions of the zone. Overall, estimates of departure were lower in Zone 16 (0.086) than in Zone 19 (0.285), but observed significance values were similar (0.039 and 0.014 in zones 16 and 19, respectively). Most departure estimates for individual LRUs were less than 0.1 in Zone 16 and less than 0.3 in Zone 19 (fig. 9), and observed significance levels for individual LRUs were generally less than 0.1 in both zones. The proportions of each mapping zone belonging to the three classified HRVStat departure categories were similar between zones, with the majority (60-70 percent) belonging to Class 2 (table 5).

To obtain an overall sense of the extent to which each of the vegetation classes contributed to estimated departure, we also evaluated departure estimates by PVT using simple spatial overlays of departure, observed significance, and classified HRVStat departure layers with the PVT layer (appendices 11-D and 11-E). The highest departure (mean values greater than 0.1) observed in Zone 16 occurred primarily in non-forest PVTs (pinyon-juniper types and the Salt Desert Shrub PVT), had relatively low observed significance (mean values of 0.01 to 0.03), and comprised 28 percent of the mapping zone; some forest PVTs (Ponderosa Pine, Douglas-fir / Timberline Pine, and Douglas-fir / Douglas-fir) had similarly high departure and low observed significance and comprised 6 percent of the mapping zone (appendix 11-D). Results for the distributions of classified HRVStat departure by PVT were similar. Of those areas in Zone 16 categorized as Class 3, the most prevalent were non-forest PVTs, including: Pinyon – Juniper / Mountain Big Sagebrush / South PVT (comprising approximately 26 percent of the zone), Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South (24 percent), and Salt Desert Shrub (9 percent).

In Zone 19, the PVTs with the relatively highest departure estimates (>0.5) and low observed significance (<0.01) were also non-forest (bluebunch wheatgrass types, the Dry Shrub PVT, and Fescue Grasslands PVT) and encompassed about 10 percent of the mapping zone. PVTs with relatively moderate departure (<0.5 and >0.3) were a mixture of forest and non-forest types and comprised approximately 6 percent of the zone (appendix 11-E). The lowest departure (<0.3) observed in the mapping zone occurred mainly in forest PVTs (about 55 percent of the zone) but also occurred in sagebrush-related PVTs (about 20 percent). It should be noted that approximately 10 percent of Zone 19 was composed of water, agriculture, and non-vegetated areas, which were omitted from departure estimates. Of the areas in Zone 19 categorized as Class 3, the most abundant PVTs were a mixture of grass, shrub, and forest: Bluebunch Wheatgrass (14 percent of the mapping zone), Wyoming – Basin Big Sagebrush Complex (19 percent), and Douglas-fir / Douglas–fir (8 percent).

When evaluating the extent to which a landscape has diverged from simulated historical conditions, we can also examine which current succession classes within a given PVT contribute the most to departure. A complete presentation of departure estimates by all PVTs and succession classes for each mapping zone is beyond the scope of this report; however, we present an example from Zone 16 for illustration purposes (table 6). Succession classes within the Pinyon – Juniper / Mountain Big Sagebrush / South PVT with the highest mean departure indices across Zone 16 were Juniper High Cover, High Height (0.45) and Pinyon – Juniper High Cover, High Height (0.37) (table 6). Both of these succession classes are late-seral classes that were less prevalent under reference conditions perhaps because

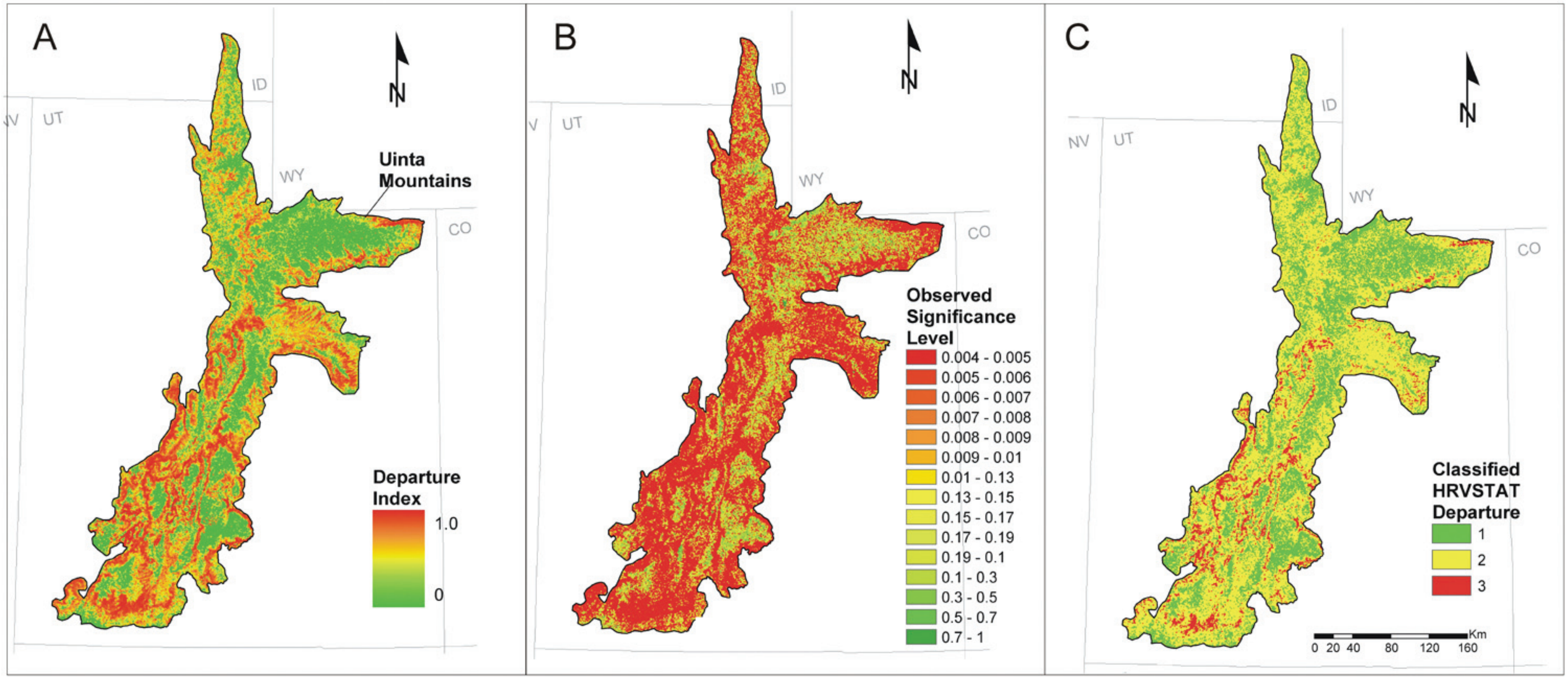

Figure 11—Zone 16 HRVStat results for (A) departure, (B) observed significance level, and (C) classified HRVStat departure, as categorized from departure and observed significance level.

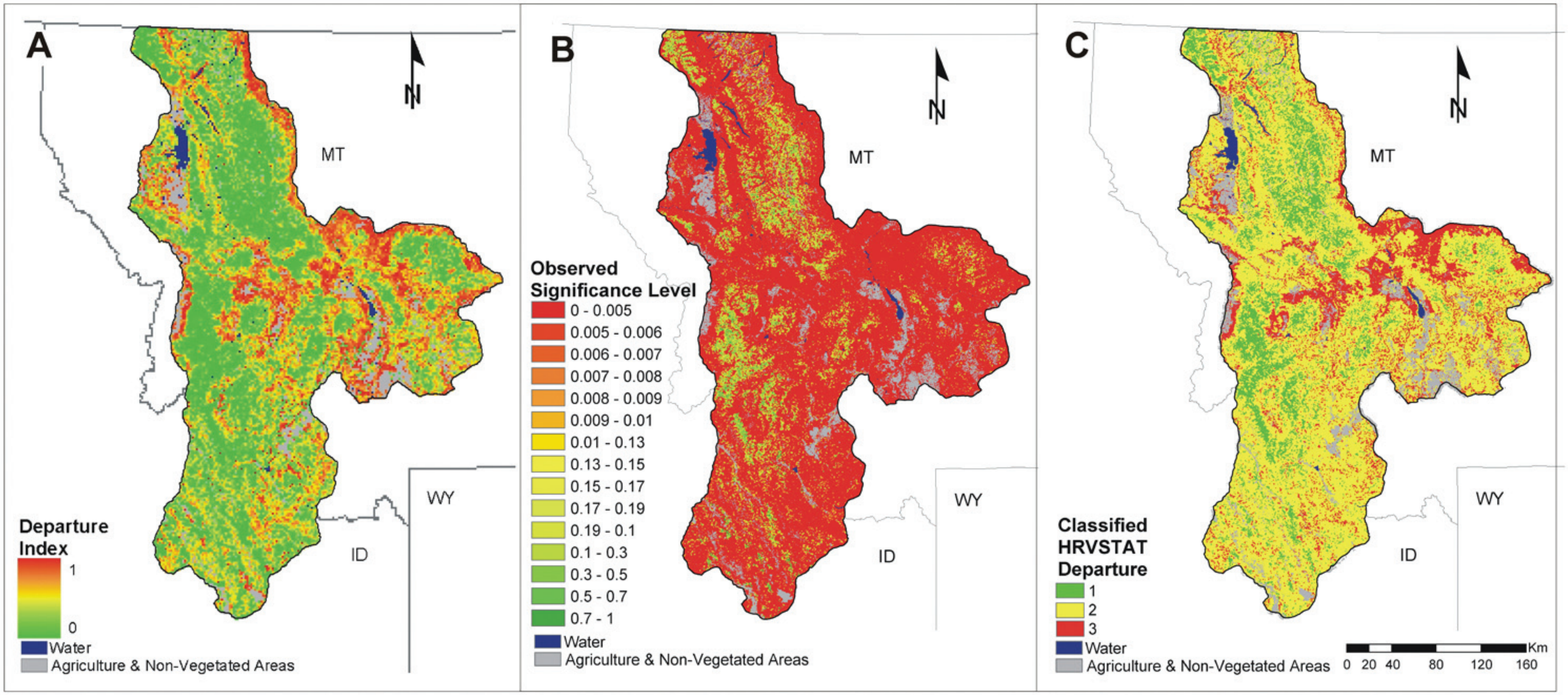

Figure 12—Zone 19 HRVStat results for (A) departure, (B) observed significance level, and (C) classified HRVStat departure, as categorized from departure and observed significance level.

Table 6—Mean departure estimates and observed significance, using HRVStat methods, for each succession class in the Pinyon – Juniper / Mountain Big Sagebrush / South PVT, as well as the percent by area of each succession class for the PVT in Zone 16. See table 5 for definitions of structural stage codes in succession class names.

Succession class	Mean departure	Mean observed significance	Percent of PVT in zone
Juniper HHW	0.45	0.004	14.27%
Pinyon – Juniper HHW	0.37	0.004	12.74%
Juniper LHW	0.33	0.004	1.68%
Pinyon – Juniper LHW	0.31	0.005	1.03%
Juniper LLW	0.26	0.006	26.92%
Mountain Deciduous Shrub LHW	0.26	0.006	9.15%
Pinyon – Juniper LLW	0.22	0.006	24.42%
Cool Season Grasses HLH	0.21	0.006	0.08%
Dry Deciduous Shrub HLS	0.19	0.007	0.16%
Mountain Deciduous Shrub HHS	0.18	0.008	5.84%
Exotic Forbs HLH	0.17	0.006	0.01%
Mountain Big Sagebrush Complex HLS	0.14	0.010	3.06%
Mountain Big Sagebrush Complex LLS	0.12	0.012	0.53%
Dry Deciduous Shrub LLS	0.07	0.019	0.12%

fires were simulated with higher frequencies than occurs in current landscapes. Exotic Forbs (High Cover, Low Height) within this PVT also had relatively high mean departure estimates (0.17) (table 6). Users of the spatial data layers can easily perform similar analyses with the HRVStat data sets for estimating departure.

Detailed Demonstration of Departure Estimates using the HRVStat and FRCC Guidebook Approaches

We demonstrate the process for computing FRCC through the FRCC Guidebook method using an LRU with an estimated FRCC of 3 that was located in the southern portion of Zone 16 (tables 2 and 3; fig. 13). We provide just one example because it is a simple calculation relative to that required using the HRVStat approach. We estimated departure for the example LRU in two steps. First, we computed the departure for each PVT within the LRU of interest (table 2). Although there are 12 PVTs in the LRU examined in table 2, for brevity, we present only the calculations for the five most dominant PVTs in the LRU (table 10). Note that there is one overall departure calculation for a given PVT, but each succession class within a PVT also has a unique departure value. This reflects the fact that the similarity values for each succession class are summed across the PVT in which they reside. Once the overall departure is calculated for each PVT, the first step is complete. In the second step, we computed the area of each PVT in the LRU (table 3). These data were then used to scale departure measures for every PVT on an area-weighted basis (table 3). This process is accomplished by multiplying the proportion of each PVT within an LRU by its respective departure estimate and summing these values for the entire LRU. In our example calculation (tables 2 and 3), the Pinyon – Juniper / Mountain Big Sagebrush / South PVT had the highest departure (81.48). This high departure greatly affected the final departure estimate for the entire LRU because the Pinyon – Juniper / Mountain Big Sagebrush / South PVT also occupied the largest area (72%).

To demonstrate the characteristics of LRUs with departure estimates derived through the HRVStat approach, we present three examples of LRUs with classified HRVStat departures of 1, 2, and 3. Our example of a Class 3 LRU was composed primarily of two PVTs: the Pinyon – Juniper / Mountain Big Sagebrush / South PVT (72 percent) and the Pinyon – Juniper / Gambel Oak PVT (16 percent) (fig. 13). For the Pinyon – Juniper / Mountain Big Sagebrush / South PVT, current distributions of succession classes were very different from those of simulated historical conditions, which lead to a high departure estimate. The dominant succession classes under simulated historical conditions were low shrub and grassland types, whereas the pinyon and juniper succession classes dominated the current vegetation (fig. 14A; table 7). The second and more minor component of this LRU was the

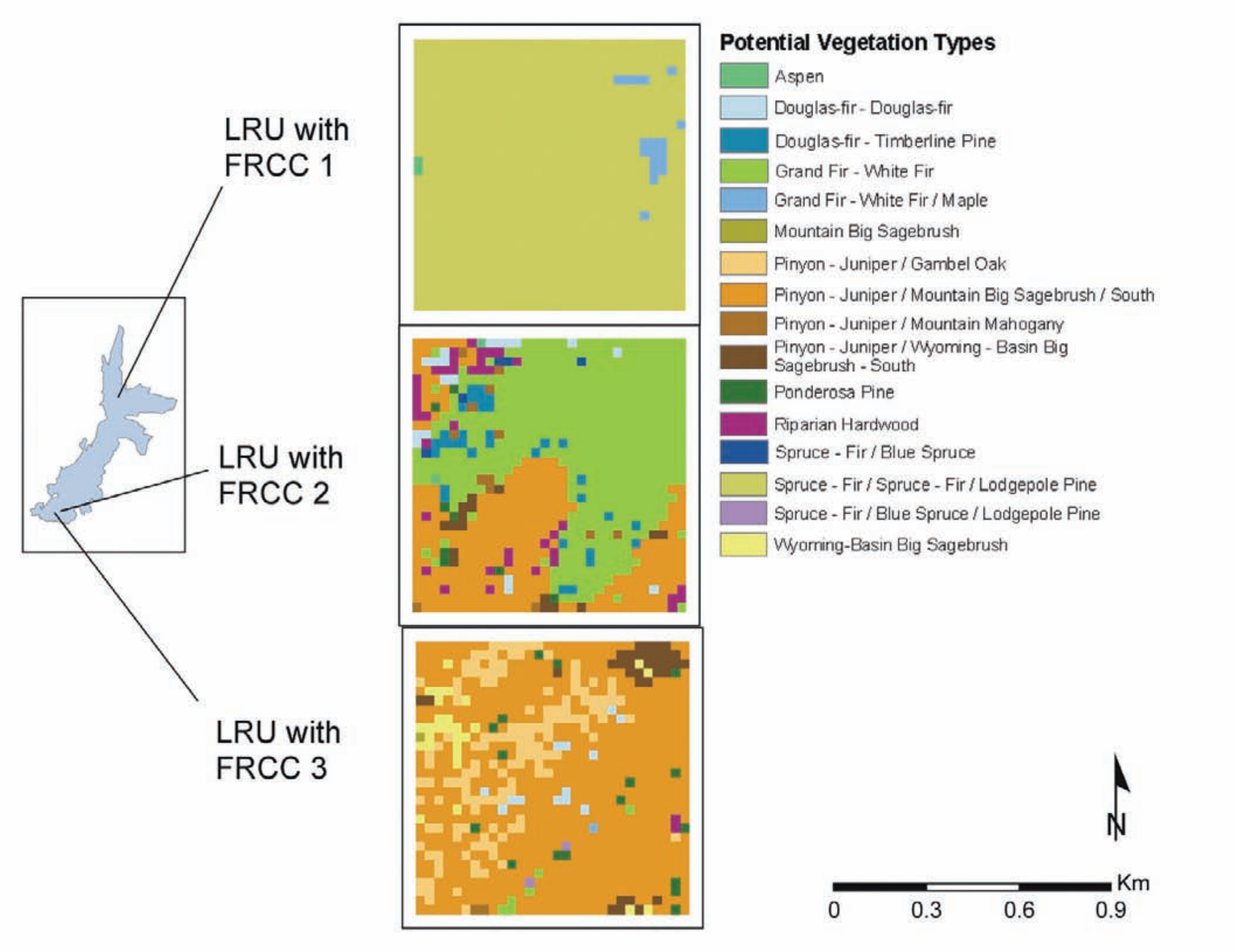

Figure 13—Three LRUs in Zone 16 assigned by the FRCC Guidebook and HRVStat methods to three classes (described here as FRCC 1, 2, and 3) and the spatial distribution of PVTs within each of these LRUs.

Pinyon – Juniper / Gambel Oak PVT, which also showed considerable differences between historical and current succession class distributions. Under simulated historical conditions, this PVT was composed mainly of low shrub and grassland-related succession classes, whereas the current landscape contains mainly pinyon and juniper type succession classes (fig. 14B; table 7). Figure 15 shows that the observed departure estimate (0.74) is much greater than the distribution of divergence estimates, resulting from the dissimilarities in succession class distributions between current and reference conditions; moreover, these dissimilarities lead to a low estimate for the observed significance level (0.005).

To illustrate the characteristics of a Class 2 LRU derived using the HRVStat approach, we chose a unit with an estimated moderately low departure index (0.25) but high observed significance value (0.005) (table 4). The LRU contained mostly the Grand Fir – White Fir PVT (53 percent) but also a substantial amount of the Pinyon – Juniper / Mountain Big Sagebrush / South PVT (32 percent) (fig. 13). For the more abundant Grand Fir – White Fir PVT, succession class distributions were only moderately dissimilar between current and simulated historical conditions, contributing to a relatively low departure estimate. Simulated historical conditions contained numerous succession classes (27), which consisted primarily of the Douglas-fir and Aspen-Birch types. The current landscape also contains a substantial amount of Aspen-Birch in addition to a dominant Grand Fir succession class and various others (fig. 16A, table 7). The second PVT revealed greater differences in succession class distributions between current and

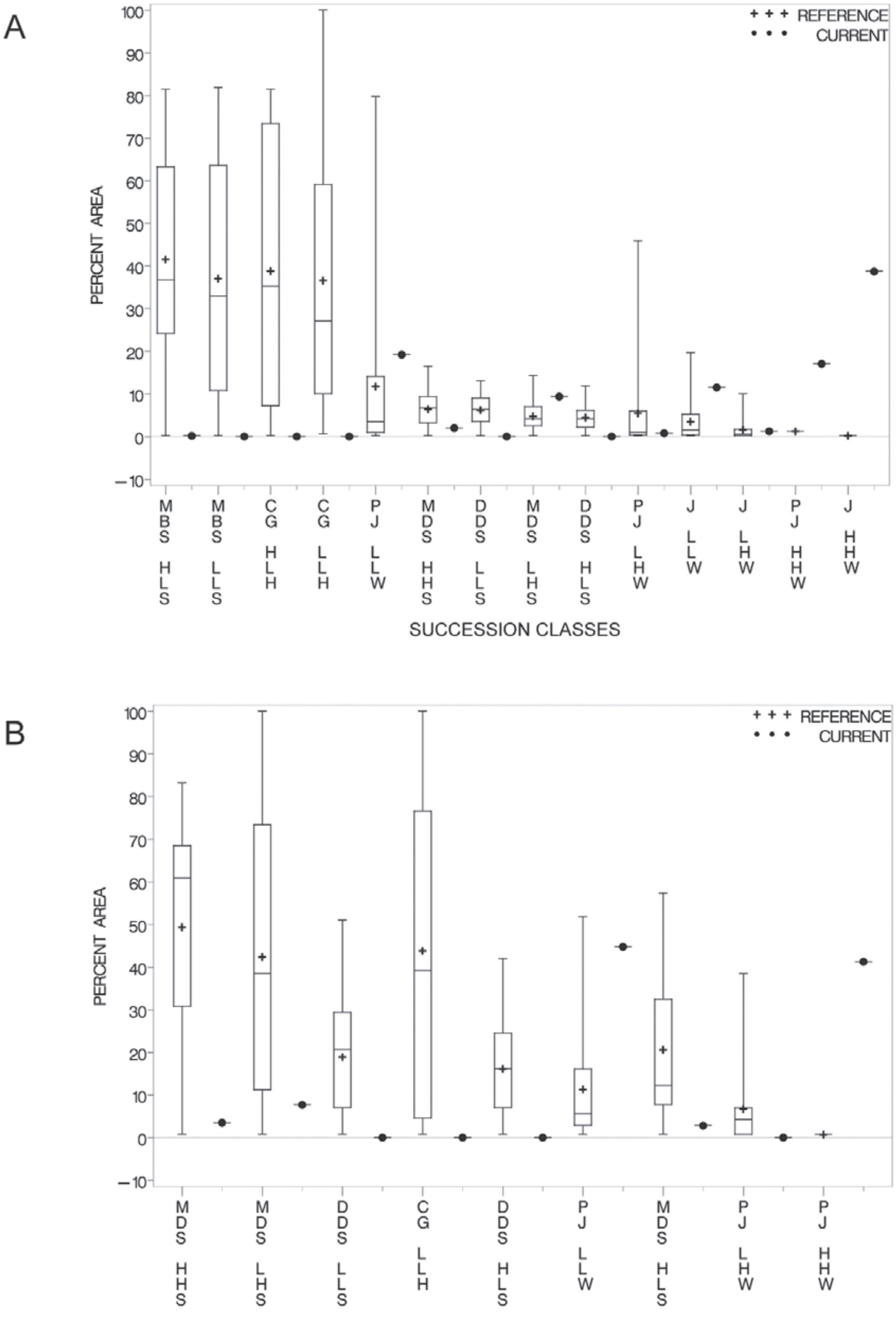

Figure 14—Distribution of succession classes in the two dominant PVTs, for reference and current conditions, in a landscape reporting unit with a classified HRVStat departure of 3 (departure index = 0.74 and observed significance level = 0.005) in Zone 16: (A) Pinyon – Juniper / Mountain Big Sagebrush / South covers 72 percent of the landscape reporting unit and (B) Pinyon – Juniper / Gambel Oak covers 16 percent of the landscape reporting units. See table 7 for explanation of succession class codes.

Table 7—Succession classes for PVTs in landscape reporting units demonstrating classified HRVStat departure in figures 14, 16, 18 and 22 – using the HRVStat approach. Codes defining succession class are described first by cover type and then by structural stage.

Cover type code	Cover type
Forest types	
AB	Aspen − Birch
DF	Douglas-fir
GF	Grand Fir−White Fir
LP	Lodgepole Pine
PP	Ponderosa Pine
SF	Spruce − Fir
TP	Timberline Pines
WH	Western Hemlock
Woodland types	
J	Juniper
PJ	Pinyon – Juniper
Shrub & Grassland types	
CG	Cool Season Grasses
DDS	Dry Deciduous Shrub
ES	Montane Evergreen Shrubs
MBS	Mountain Big Sagebrush Complex
MDS	Mountain Deciduous Shrub
NF	Native Forbs
Structural stage code	**Structural stage**
LLF	Low Cover, Low Height Forest
HLF	High Cover, Low Height Forest
LHF	Low Cover, High Height Forest
HHF	High Cover, High Height Forest
LHW	Low Cover, High Height Woodland
HHW	High Cover, High Height Woodland
LHW	Low Cover, High Height Woodland
LLS	Low Cover, Low Height Shrubland
HLS	High Cover, Low Height Shrubland
LHS	Low Cover, High Height Shrubland
HHS	High Cover, High Height Shrubland
LLH	Low Cover, Low Height Herbaceous
HLH	High Cover, Low Height Herbaceous

simulated historical conditions. Specifically, the most frequent succession classes under simulated historical conditions were rare to absent under current conditions, and vice versa (fig. 16B). Figure 17 demonstrates that the observed departure estimate (0.25) is greater than the distribution of divergence estimates for the simulated historical conditions, resulting in a low observed significance value (0.005).

The unit chosen to demonstrate the characteristics of a Class 1 LRU had a low departure estimate (0.002), a relatively high observed significance (0.2475), and was composed almost entirely of one PVT: 99 percent Spruce-Fir / Spruce-Fir / Lodgepole Pine (fig. 13). Most of the succession classes were relatively rare in the simulated historical data sets (fig. 18; table 7), and the current conditions' dominant class of Aspen-Birch Low Cover / High Height was relatively abundant in the historical data. Figure 19 shows that the observed departure estimate (0.002) was similar to the median (0.001) of the divergence estimates from the simulated

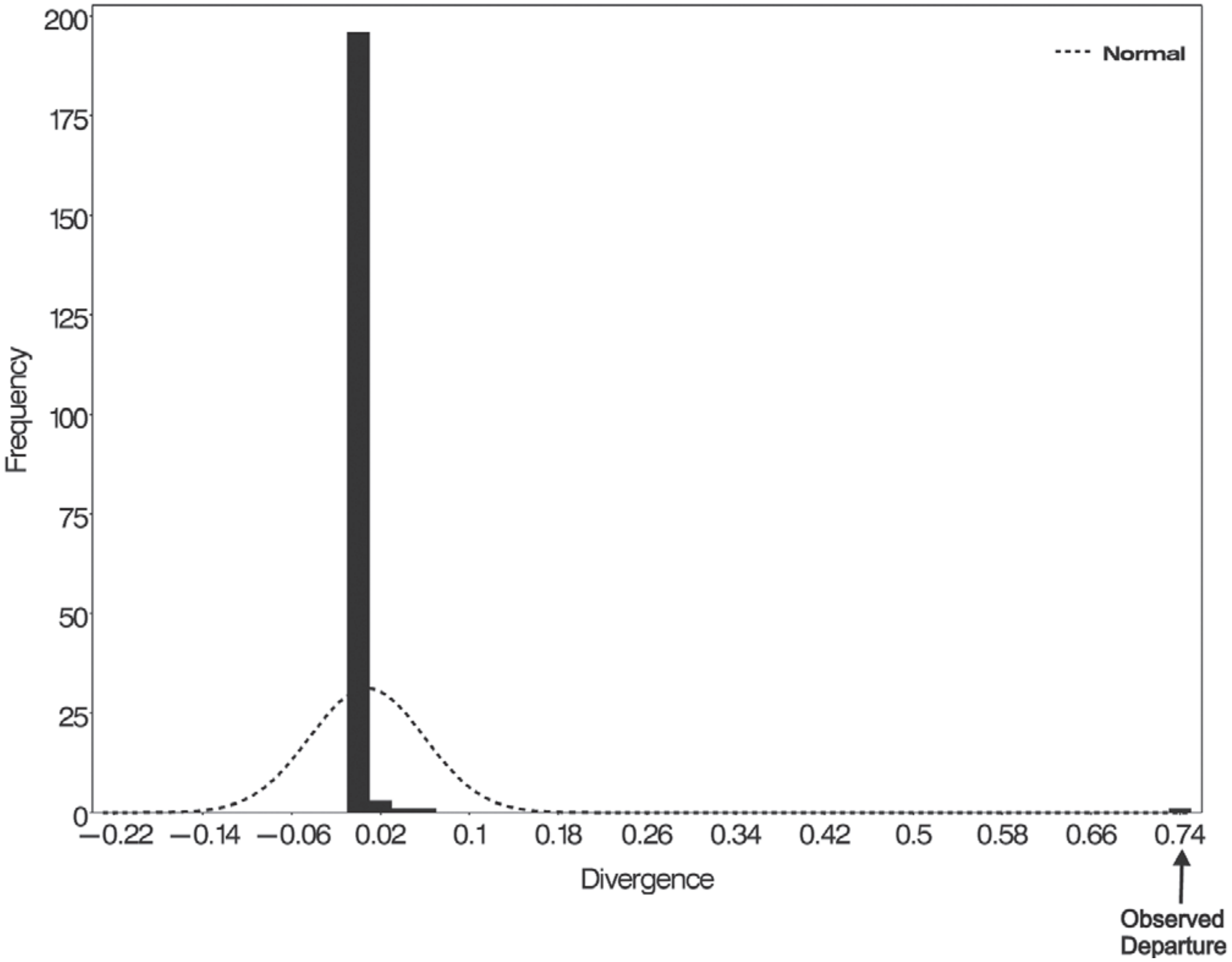

Figure 15—Frequency distributions for divergence estimates in the example landscape reporting unit with a classified HRV-Stat departure of -3, the normalized probability distribution (dashed line), and an observed departure for current conditions of 0.74. The proportion of area under the probability distribution above the observed departure is 0.005, which is the estimated observed significance level.

historical data set, leading to a relatively high observed significance (0.2475).

Departure Estimates by Fire Return Interval

Evaluation of departure results by fire return interval classes suggested that, under simulated historical conditions, areas with short simulated fire return intervals tended to have higher departure estimates (table 8). In Zone 16, HRVStat departure estimates were highest (9.42 on a scale of 1 to 100) in areas with short fire return intervals (0-35 years) under reference conditions. In contrast, areas with long fire return intervals (201+ years) had the lowest departures (3.16 on a scale of 1 to 100) under reference conditions. The FRCC Guidebook departure estimates showed a less clear but somewhat similar trend, with higher departure (mean value of 35.22) in areas with short simulated fire return intervals (0-35 years) and somewhat lower departure (mean value of 27.27) in areas where long fire return intervals (201+ years) were simulated (table 8).

Results from Zone 19 showed similar patterns (table 8). HRVStat departure estimates were highest (mean value of 38.13 on a scale of 1 to 100) in areas with short fire

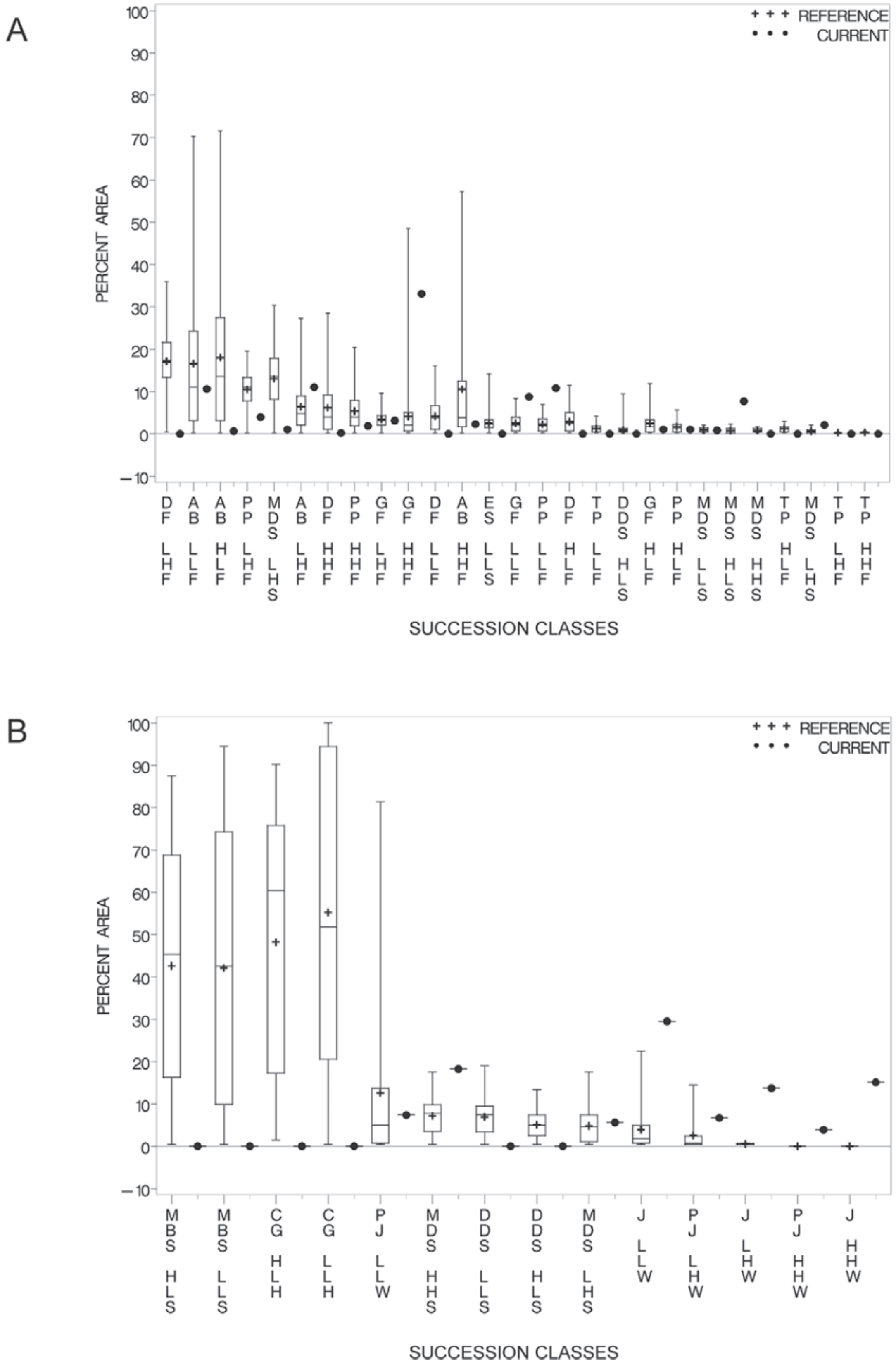

Figure 16—Distribution of succession classes in the two dominant PVTs, for reference and current conditions, in a landscape reporting unit with a classified HRVStat departure of -2 (departure index = 0.25 and observed significance level = 0.005) in Zone 16: (A) Grand Fir – White Fir covers 53 percent of this landscape reporting unit and (B) Pinyon – Juniper / Mountain Big Sagebrush / South covers 32 percent of the landscape reporting units. See table 7 for explanation of succession class codes.

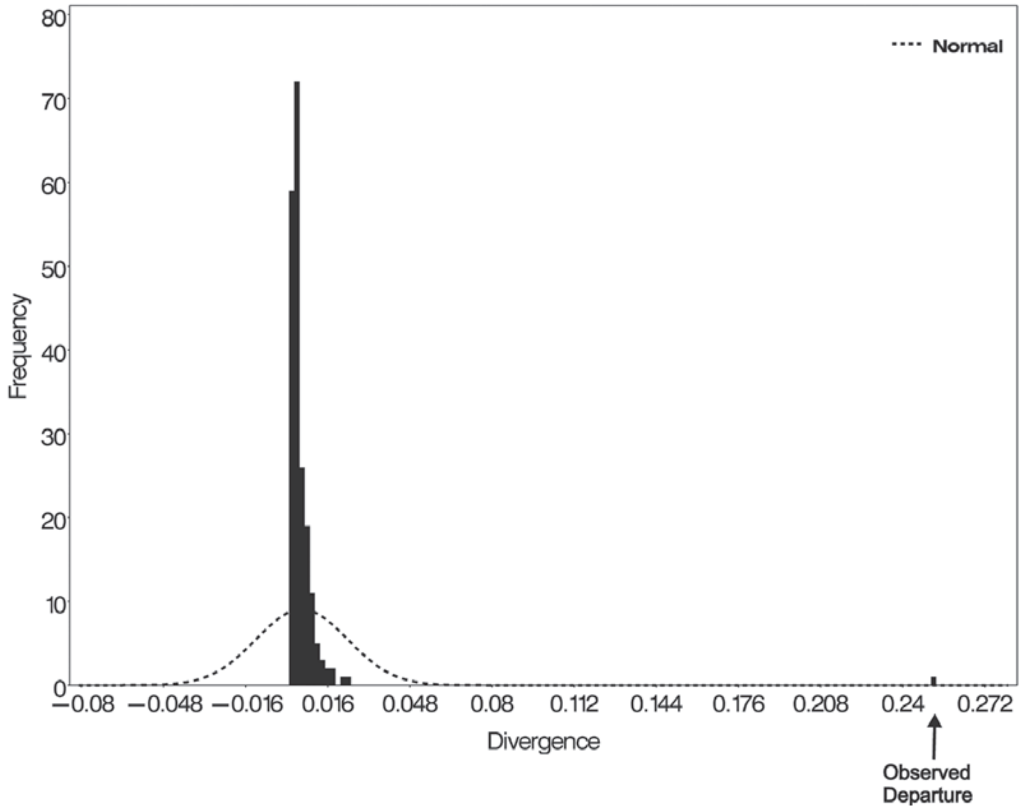

Figure 17—Frequency distributions for divergence estimates in the example landscape reporting unit with a classified HRVStat departure of -2, the normalized probability distribution (dashed line), and an observed departure for current conditions of 0.25. The proportion of area under the probability distribution above the observed departure is 0.005, which is the estimated observed significance level.

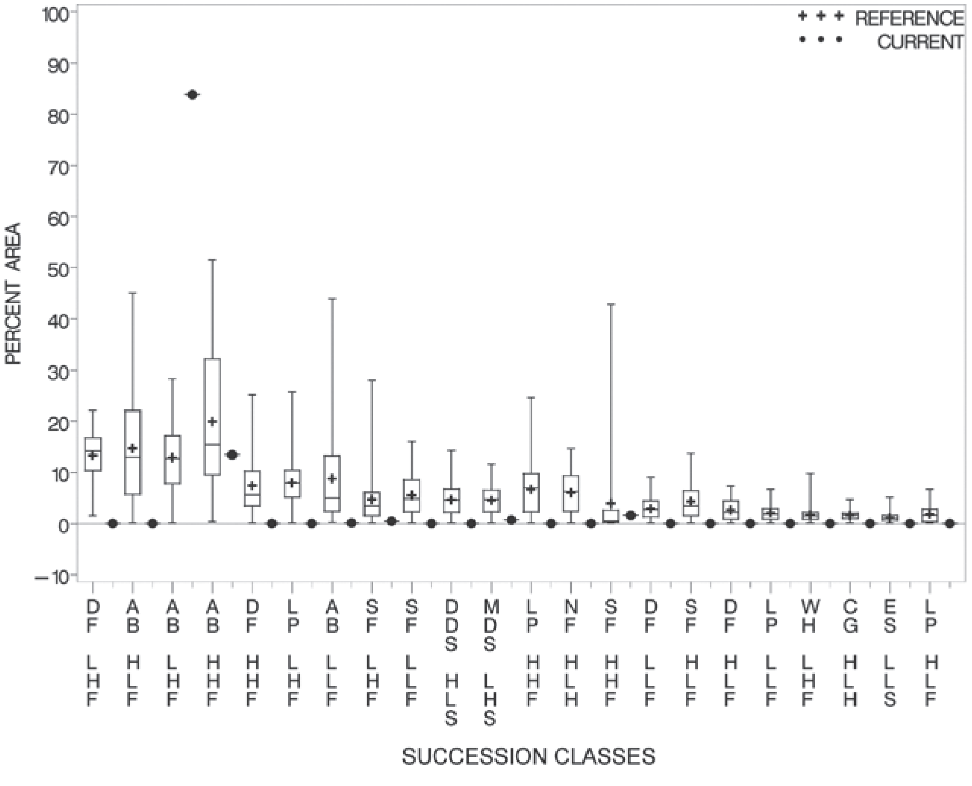

Figure 18—Distribution of succession classes by percent area, under reference and current conditions, for the Spruce – Fir / Spruce – Fir / Lodgepole Pine PVT that dominates a landscape reporting unit with a classified HRVStat departure of -1 (departure index = 0.002 and observed significance level = 0.25) in Zone 16. See table 7 for explanation of succession class codes.

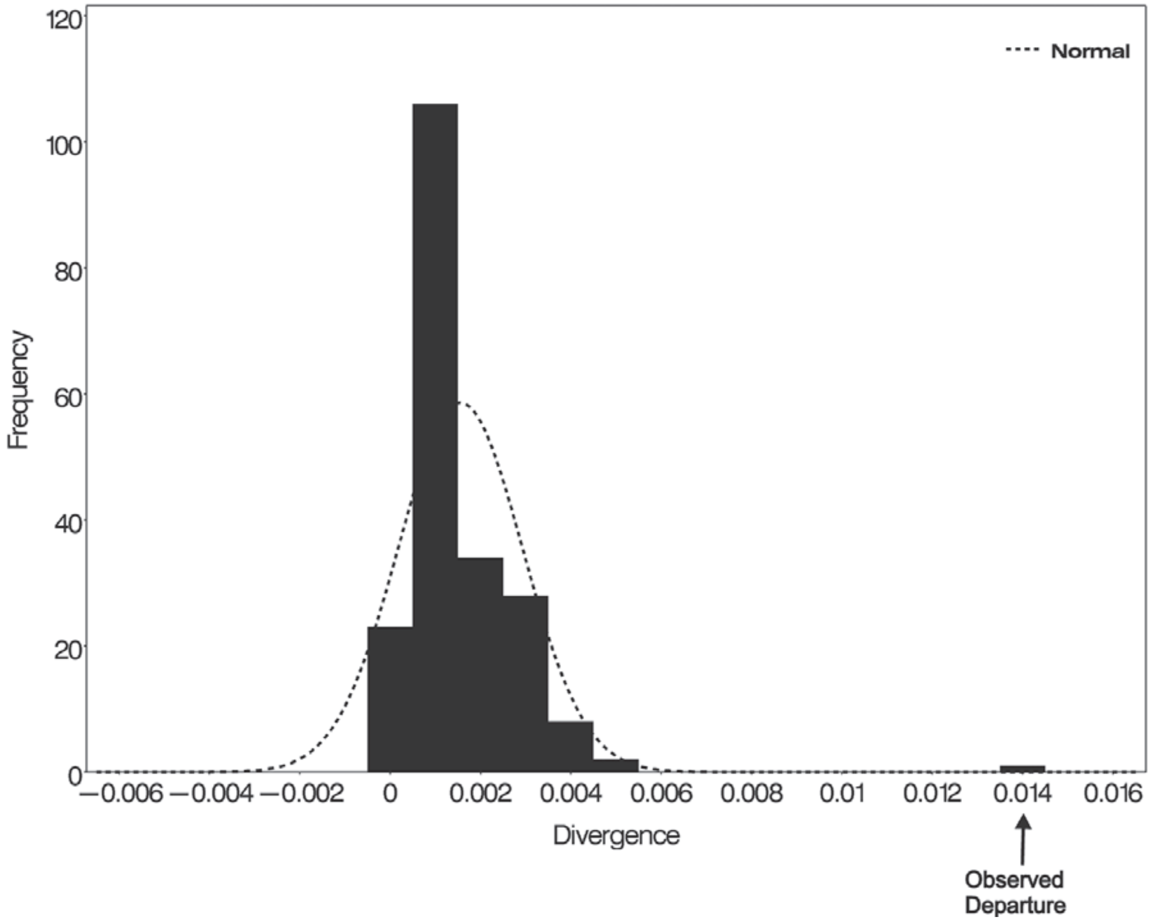

Figure 19—Frequency distributions for divergence estimates in the example landscape reporting unit with a classified HRVStat departure of -1, the normalized probability distribution (dashed line), and an observed departure index for current conditions of 0.002. The proportion of area under the probability distribution above the observed departure index is 0.2475, which is the estimated observed significance level.

Table 8—Summary of departure estimates (area weighted mean) by historical fire return interval classes using the HRVStat and FRCC Guidebook methods. In the FRCC Guidebook method, the spatial domains were the individual landscape reporting units. Note: the HRVStat departure index was rescaled from 0-1 to 0-100 to match the FRCC Guidebook departure range.

Fire frequency class	Departure using HRVStat approach	Departure using FRCC Guidebook approach
Zone 16		
1 - 35 years	9.42	35.22
36 – 100 years	7.78	31.50
101 - 200 years	7.92	22.92
201+ years	3.16	27.27
Zone 19		
1 - 35 years	38.13	20.15
36 – 100 years	16.08	16.59
101 - 200 years	4.37	16.41
201+ years	14.77	17.06

return intervals (0-35 years) under reference conditions. Average departure decreased as fire return intervals increased (with a mean value of 16.08 for the 36 to 100 year group and 4.37 for the 101-200 year group); however, in areas with the longest fire return intervals (201+ years), the mean departure estimate was intermediate (14.77). The FRCC Guidebook departure indices in Zone 19 showed the most departure (20.15) in areas with short simulated fire return intervals (0-35 years) and somewhat lower departure in the areas with longer return intervals (17.06 for 201+-years).

Discussion

We developed two methods for creating maps describing the departure of current landscape conditions from simulated historical conditions. Both methods are standardized, both can be applied across large, continuous landscapes, and both can be automated to produce maps efficiently. The methods were designed for different applications: the FRCC Guidebook approach was intended to implement field-based procedures in a GIS environment, whereas the HRVStat approach was intended for use in the development of a statistically rigorous method that incorporates the temporal variability in a complex, spatial database describing historical conditions. Correspondingly, each method produced divergent results in the maps of departure and their classifications (figs. 7, 8, 10, 11 and 12; table 5). To interpret these disparities and ranges, we need to recognize the strengths and weaknesses of each approach and understand their differences and commonalities.

Strengths and Limitations of the FRCC Guidebook Approach

The FRCC Guidebook method is simple, flexible, and designed to be easily understood by managers. This approach does not require advanced statistical techniques or large data sets, and the metrics used to represent the simulated historical conditions in the departure calculation can be easily changed. For Zone 16, we used the 90 percent of the maximum percent area observed for each succession class in a PVT as the metric through which to summarize the reference conditions' time-series; for Zone 19, we used the 90th percentile of the percent area observed for each succession class in a PVT. However, median, mean, minimum, or other metrics characterizing the reference conditions data set could also be substituted. The FRCC Guidebook approach does not require the simulated historical data set to have a minimum temporal depth (as does the HRVStat approach) and can use a data set describing PVT-succession class distributions that is limited to one observation, such as is demonstrated in figure 7A where only one reporting interval was used. Since the departure estimate is based on a procedure currently being applied by federal managers to characterize ecosystems with regard to hazardous fuel accumulation (Hann and others 2004), many managers should already be familiar with the calculations and readily understand the process by which spatial data are produced using the FRCC Guidebook approach.

Despite these merits, the FRCC Guidebook approach fails to provide a consistent and comprehensive measure of departure. Specifically, this approach requires that reference conditions are represented by a single observation, but departure estimates are very sensitive to the metric chosen to represent that point statistic. To compare the PVT-succession class distributions of current and reference conditions, we must choose a metric to reduce the 200 observations from the simulated time series to one observation. However, the choice of vegetation metric (median, mean, minimum, 90 percent of maximum, or 90th percentile) for summarizing reference conditions cannot aptly represent all cases of vegetation composition distributions, and the chosen metric will bias departure estimates in different ways, depending on the composition of an LRU. This shortcoming is illustrated in table 9 where departure ranged from 0 using the 90 percent of maximum and 90th percentile metrics to 32 using the median as the metric.

We chose metrics for describing reference conditions (90 percent of maximum and 90th percentile) that would be more sensitive to variation on the upper end of succession class distributions (Hann, personal communication). We used the 90 percent of maximum metric for estimating reference conditions in Zone 16, but determined that the metric over-emphasized the upper end of distributions and consequently over-predicted departure – particularly in cases where an extreme, rare event triggers large but brief fluctuations in vegetation composition. In other words, departure would be measured only by evaluating the reference conditions for a PVT-succession class combination at its widest ranges, even though the remaining time series may be primarily in a narrower range. The 90th percentile metric proved more suitable because it filtered the rare, large oscillations in vegetation conditions and better represented the upper range of variation in vegetation classes. However, the 90th percentile metric represented the simulated time series poorly towards the median and lower end of succession class distributions. For example, the current vegetation composition may be very similar to the dominant vegetation composition

Table 9—Example departure calculations using three vegetation metrics to characterize reference conditions. Note that, using the logic of the FRCC Guidebook field procedures (Hann and others 2004), reference conditions are non-orthogonal (the summation of their area exceeds 100 percent) with respect to the total area that the succession classes occupy within a PVT. See table 7 for codes to structural stages within succession class categories.

PVT	Succession class	Reference condition	Current condition	Similarity	Sum of similarity
		90th percentile			
Ponderosa Pine	Ponderosa Pine / LLF	60	15	15	100
Ponderosa Pine	Ponderosa Pine / LHF	90	85	85	
Pinyon – Juniper / Mountain Big Sagebrush / South	Juniper / HHW	85	65	65	100
Pinyon – Juniper / Mountain Big Sagebrush / South	Pinyon-Juniper / LLW	75	35	30	
Pinyon – Juniper / Mountain Big Sagebrush / South	Pinyon-Juniper / HHW	35	0	0	
Departure estimate					**0**
		90 % of max.			
Ponderosa Pine	Ponderosa Pine / LLF	70	15	15	100
Ponderosa Pine	Ponderosa Pine / LHF	95	85	85	
Pinyon – Juniper / Mountain Big Sagebrush / South	Juniper / HHW	90	65	65	100
Pinyon – Juniper / Mountain Big Sagebrush / South	Pinyon-Juniper / LLW	85	35	35	
Pinyon – Juniper / Mountain Big Sagebrush / South	Pinyon-Juniper / HHW	45	0	0	
Departure Estimate					**0**
		Mean			
Ponderosa Pine	Ponderosa Pine / LLF	3	15	3	56
Ponderosa Pine	Ponderosa Pine / LHF	53	85	53	
Pinyon – Juniper / Mountain Big Sagebrush / South	Juniper / HHW	45	65	45	80
Pinyon – Juniper / Mountain Big Sagebrush / South	Pinyon-Juniper / LLW	53	35	35	
Pinyon – Juniper / Mountain Big Sagebrush / South	Pinyon-Juniper / HHW	28	0	0	
Departure estimate					**32**

observed in the simulated time series, as shown in figure 4, with an Aspen – Birch High Cover, High Height succession class in a Spruce-Fir / Spruce–Fir / Lodgepole Pine PVT. Using the 90th percentile for our metric, we would estimate a relatively high departure – a seemingly incongruous result since current conditions are similar to the historical conditions.

We avoided using metrics that evaluate central tendencies (in other words the mean or median) because they can overlook or understate variation. For example, succession classes may have the same mean occurrence in the simulated historical record regardless of whether variability around the mean was low or high, and the resulting departure estimates would also be the same – even though the succession class occurrence for the current conditions might fall well within the simulated historical range when the data contain high variability. In short, the similarity calculation in the FRCC Guidebook approach is very sensitive to the metric used to represent reference condition time series data, and we expect that departure estimates for Zones 16 and 19 would look very different if other metrics were used.

An additional limitation to spatial application of the FRCC Guidebook approach is that illogical calculations can result. Specifically, we must select a single value to represent the percent of each succession class occupying a PVT across a time series. Because these selected values are not likely to occur at the same time interval (as in the temporal snapshot approach illustrated in fig. 7A), the sum of the area for all succession classes in a PVT will not equal 100 percent. In a simple hypothetical example, an LRU consists entirely of one PVT with three succession classes occurring across the simulated time series such that their 90th percentiles are: 65 for succession class A in year 150; 40 for class B in year 4,550; and 20 for class C in year 7,050. The total percent area for the reference conditions sums to 125 percent — an area greater than the possible size of an LRU. Table 9 also demonstrates that, for a given PVT, the sum of the succession class areas does not necessarily total 100 percent, such as in the case of the Ponderosa Pine PVT where, using the 90th percentile as the reference condition metric, the sum of the succession classes totals 150 percent. Such nonsensical results in the total summed area occur regardless of the metric used. For example, in table 9, the sum of succession classes for the Ponderosa Pine PVT, using the mean as the reference condition, was 56 percent. These incongruities do not occur in the field implementation of the FRCC Guidebook field procedures (Hann and others 2004) because reference conditions are estimated for a discrete point in time. In the simulation environment, however, we encountered the problem because we applied the FRCC field-based procedures to a time series of data. Despite the illogical calculations in our FRCC Guidebook implementation, departure estimates were constrained to values from 0 to 100 because the calculation does not rely on total area, but instead uses the value for the least abundant succession (the smaller of reference or current conditions) to determine similarity and ultimately the departure estimate.

Another problem — stemming from the requirement of using a point statistic to represent reference conditions — is that departure estimates are sensitive to stochasticity in the LANDSUMv4 simulations. Because the LANDSUMv4 model includes stochastic processes in the simulation of fire and vegetation processes, the likelihood of a rare event increases with greater simulation time. Consequently, departure estimates could be inconsistent between LANDSUMv4 runs and, potentially, substantially different, depending on simulation length. For example, a catastrophic fire may not occur during a 4,000-year simulation but is more likely to occur during a 5,000-year simulation. Use of the 90th percentile to represent reference conditions for Zone 19 helped minimize the potential effects of rare disturbances on the upper range of succession class distributions. Because point statistics cannot completely represent the full range and variability of a data set, the other possible metrics (median, mean, 90th percentile, etc.) would also be limited in their ability to moderate the effects of extreme stochastic events and would only impose different biases.

A final limitation of the FRCC Guidebook approach relates to the fact that the number of succession classes in a PVT affected the calculation of the departure index. That is, greater complexity in the succession models used to model reference conditions for each PVT led to an increase in the FRCC departure index. As the succession pathway complexity increased in the simulated historical data, the percent area occupied by any one succession class became dispersed across more classes, leading to a lower percent area for each individual class over the simulation period. Lower area values for each succession class leads to lower similarity indices when comparing reference conditions to the current, and consequently higher, departure estimates (see table 2 for examples of similarity and departure calculations). The effect of PVT succession pathway complexity on departure estimates is also demonstrated in the departure maps for Zone 16, in which the three spatial domains of mapping zone, simulation landscapes, and LRUs were explored (figs. 7B-7D). The number of succession classes per PVT in the reference conditions was highest in the zonal spatial domain, followed by the simulation landscapes domain, and lowest in the LRU domain; correspondingly, the departure estimates were highest in the largest spatial domain (zone) and lowest in the smallest (LRU). The effect of PVT succession pathway complexity on departure estimates highlights the need to identify ways to standardize succession pathways across all areas of consideration.

Strengths and Limitations of the HRVStat Approach

The HRVStat approach statistically compares current succession class distributions to simulated historical distributions, integrating every observation of PVT and succession class as they fluctuate across landscapes in the time-series. The data sets for these analyses were complex: the number of PVTs and succession classes occurring within any one LRU ranged from 1 to approximately 220, and each of these classes varied in percent area for each landscape reporting interval across the time series. HRVStat was able to incorporate the variance structure within the entire time-series of this highly dimensional data set to produce a measure of departure using the best linear approximation approach and estimate an observed significance for measuring the evidence for departure estimates (Steele and others, in preparation).

One limitation of this approach was the requirement by HRVStat for certain characteristics in the simulated historical data set. As discussed above, an adequate reference time series for HRVStat requires minimal temporal autocorrelation, stationary processes in vegetation class distributions, and a sufficiently long record. These requirements led to longer simulation times, larger data sets, and higher computational demands. However, the overall quality of the resulting data sets was enhanced, enabling the HRVStat approach to provide results with reasonable statistical rigor (Steele and others, in preparation).

In turn, statistics for HRVStat were developed that were specific to the simulated historical data set and that explicitly recognized the stochasticity that was intrinsic to LANDSUMv4. As discussed above, the LANDSUMv4 model simulates disturbance stochastically such that the resulting vegetation composition in a landscape will vary somewhat between repeated simulations and with longer simulation periods as the likelihood increases for rare and extreme disturbance events (such as a catastrophically large fire). The HRVStat departure statistic accommodates such stochasticity because it incorporates every observation in the historical record. Specifically, stochastic differences between simulation runs will produce different vegetation distributions, possibly including unusual vegetation compositions resulting from extreme disturbances. However, because the departure statistic emphasizes dominant patterns by integrating all observations, departure estimates should be relatively robust to rare, extreme disturbance events.

We suspect a limitation in the statistical calculations of HRVStat because the number of PVT and succession class combinations within any LRU affects departure estimates – a problem also apparent with the FRCC Guidebook approach but with opposite effects. As the number of PVT-succession class combinations increased within LRUs, estimates of departure by HRVStat tended to decrease. This observation is based on a cursory examination of an assortment of LRUs and a general comparison of forested versus non-forested areas. In evaluating various LRUs in zones 16 and 19, we generally found lower departure in LRUs with few PVTs and simple succession pathways, as opposed to the higher departure found in LRUs with more complex vegetation composition. Comparisons of forested to non-forested areas showed that forest PVTs, which generally had more classes in their succession pathways, also had lower departure estimates. However, the lower departure estimates in forest PVTs may also be attributed to the generally longer fire return intervals because the effects of fire exclusion would be less evident since fewer intervals would have been missed over the last century and the process of departure from historical vegetation composition would be slower than in those PVTs with more rapid succession and disturbance processes. Alternatively, we may simply be better able to model forested systems than non-forested systems because more information exists describing vegetation and disturbance (particularly fire) processes in forests (Long and others, Ch. 9). As with the FRCC Guidebook approach, the influence of succession pathway complexity on HRVStat departure estimates warrants further evaluation and should include exploration of techniques to standardize the succession pathways or parameters in the multivariate statistics of the HRVStat approach.

Comparison of Approaches

We categorized our FRCC and HRVStat departure estimates into three classes to compare results with the earlier nationwide coarse-scale (1-km) mapping project (Hardy and others 2001; Schmidt and others 2002). For Zone 16, the HRVStat map showed little correspondence to the coarse-scale map, both in terms of patterns observed and relative area in each class (fig. 20; table 5). Among the three FRCC Guidebook maps produced for Zone 16, the FRCC map based on the LRU spatial domain corresponded best to the coarse-scale map and showed similar patterns of low and moderate departures (FRCC 1 and 2) throughout the zone (figs. 7D and 20). For Zone 19, overall patterns of both the HRVStat and FRCC Guidebook maps were relatively different from those of the coarse-scale map (fig. 21). However, some correspondences existed between the coarse-scale and FRCC Guidebook maps, with high departure observed in the northern region of Zone 19. We did not compare these maps in any quantitative detail because the coarse-scale map was intended for use at the regional level. Furthermore, the accuracy in any of the maps was not known, and an extensive field campaign would be needed to evaluate the accuracy of maps such as these. Moreover, the thresholds used to categorize departure estimates into three classes are arbitrary, and if different thresholds were used, completely different patterns in the maps of FRCC and classified HRVStat departure would result.

To avoid the classes imposed by the FRCC Guidebook method, we examined the unclassified departure maps produced by the HRVStat and FRCC Guidebook methods and compared the distributions of continuous departure estimates. Figure 9 shows frequency distributions of departure estimates using the HRVStat and FRCC Guidebook methods (with LRUs as the spatial domain), and figures 7, 10A, 11A and 12A show maps of departure for Zones 16 and 19. Generally speaking, compared to the HRVStat approach, distributions of departure estimates for each zone were dominated by higher values using the FRCC Guidebook approach (fig. 9). In terms of spatial pattern, some similarities were apparent in the southerly portions of Zone 16 (figs. 7D AND 11A). Zone 19 showed more spatial pattern correspondences in that higher departure estimates were observed in the northern portions of the zone (in the North Fork Flathead River Valley and along the Rocky Mountains' eastern front) and in the central part of the zone (in the Clark Fork River Valley and eastern prairie of Montana) (figs. 10A and 12A). We suspect that the greater correspondence in Zone 19 resulted from using the 90th percentile metric instead of 90 percent of maximum to represent reference conditions in the FRCC Guidebook approach. As in the case of the FRCC / classified HRVStat departure maps, we do not have field validation data with which to assess which departure index is most effective. At best, we can qualitatively look for consistency between map results to obtain an overall picture of vegetation conditions across broad regions. Consistent evidence of ecosystem change from these two departure maps can serve to highlight landscapes that have potentially undergone extensive ecological change. Additional information, such as site-specific field data and expert opinions, could supplement the departure estimates to evaluate how to best manage an ecological system (Landres and others 1999). It is important to note, however, that similar measures from the different approaches could also signify that the measures are simply both equally erroneous.

Dissimilarity between results from the two departure methods reveals potential weaknesses in both approaches. For example, departure estimates were different in Zone 16's Uinta Mountains in areas dominated by the Spruce-Fir / Spruce-Fir / Lodgepole Pine PVT – a PVT with a complex succession pathway. Figure 22 shows succession class distributions in an LRU dominated by that PVT, which is typical for this area of the Uintas. In the reference conditions, LRUs were occupied by as many as 22 succession classes, whereas only a few classes dominated the landscape under current conditions. The HRVStat method tended to produce low departure estimates for LRUs in the Uintas, resulting potentially from the abundance of succession classes in the reference conditions. Conversely, the FRCC Guidebook approach tended to produce high departure estimates in these LRUs because the percent area in any one succession class of these complex PVTs was reduced since the total area was spread across many succession classes. As previously mentioned, both methods require further refinement to ensure that departure estimates are not biased by the complexity of the succession class pathways.

Departure Estimates by Fire Return Intervals

We compared departure estimates by fire return interval classes in a manner similar to that used in the evaluations conducted in the coarse-scale project (Schmidt and others 2002). For both zones 16 and 19, we found that departure estimates were higher in areas with shorter fire return intervals. Similarly, Schmidt and others (2002) generally found that landscapes with estimated historical fire return intervals of 100-years or less had higher proportions of landscapes categorized as FRCC 3 (analogous to classified HRVStat departure-3), whereas areas with fire return intervals of 200-years or more had the least proportion of highly departed landscapes. We expect that the impacts of fire exclusion during the past 100 years are more evident in areas that historically had more frequent fires because such ecosystems have missed more fire return intervals

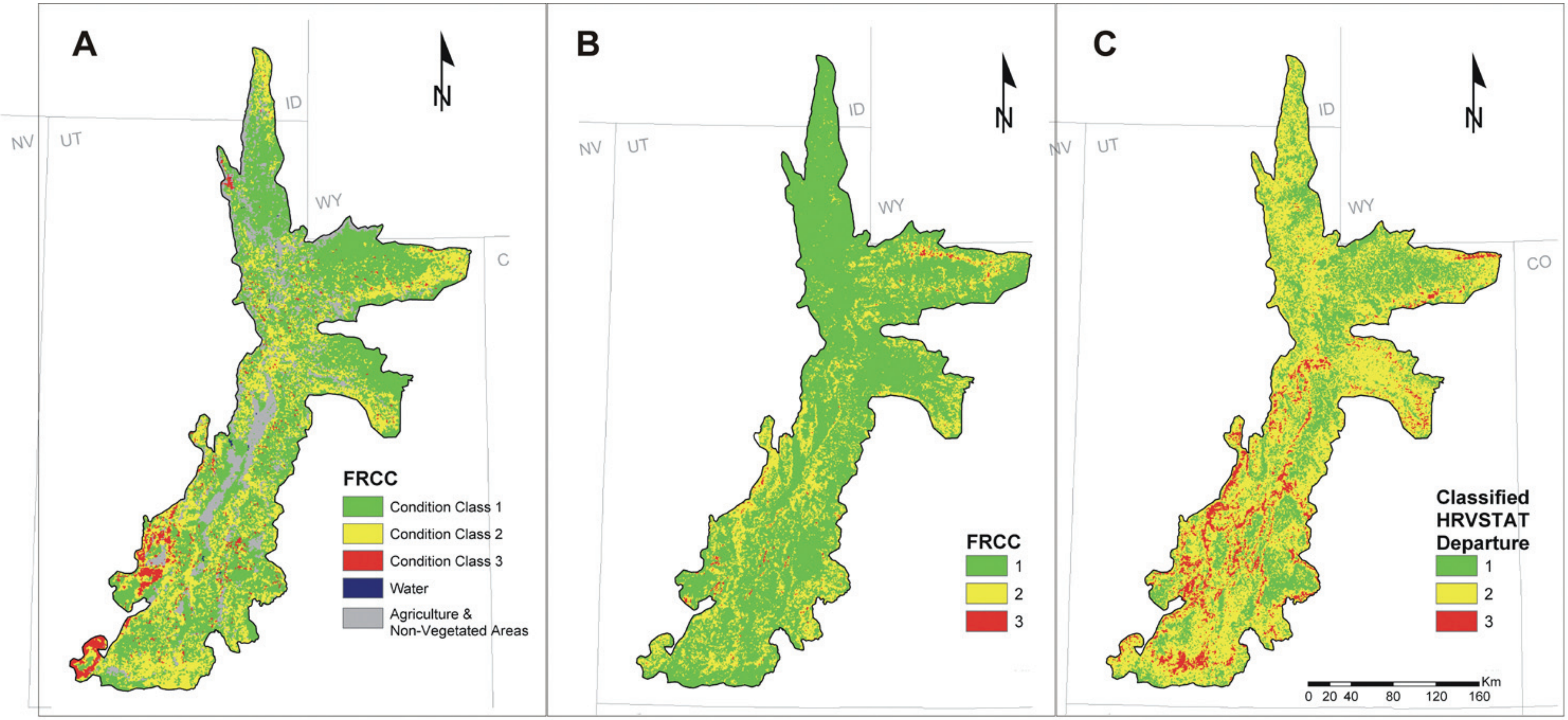

Figure 20—Comparisons between (A) FRCC estimated by Schmidt and others 2002, (B) FRCC calculated using the FRCC Guidebook method, and (C) classified HRVStat departure for Zone 16.

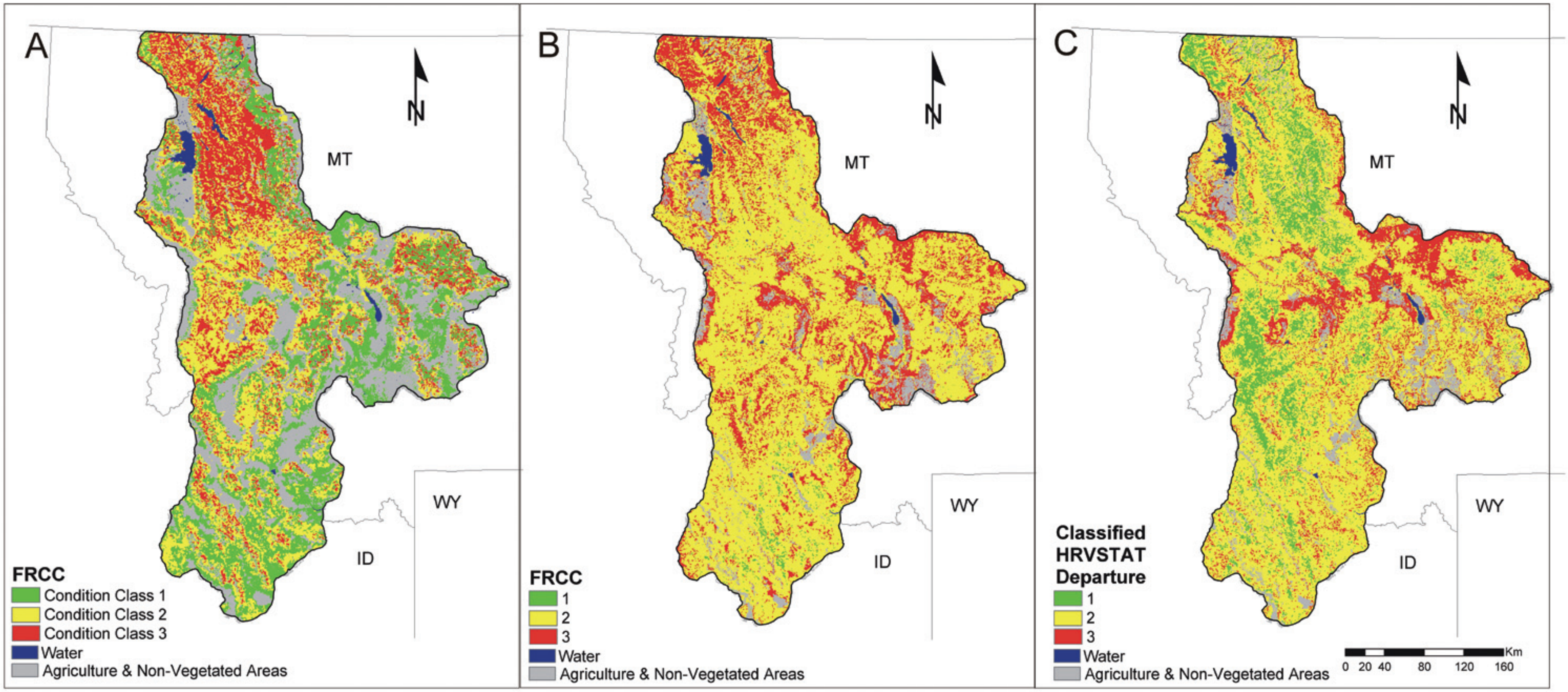

Figure 21—Comparisons between (A) FRCC estimated by Schmidt and others 2002, (B) FRCC calculated using the FRCC Guidebook method, and (C) classified HRVStat departure for Zone 19.

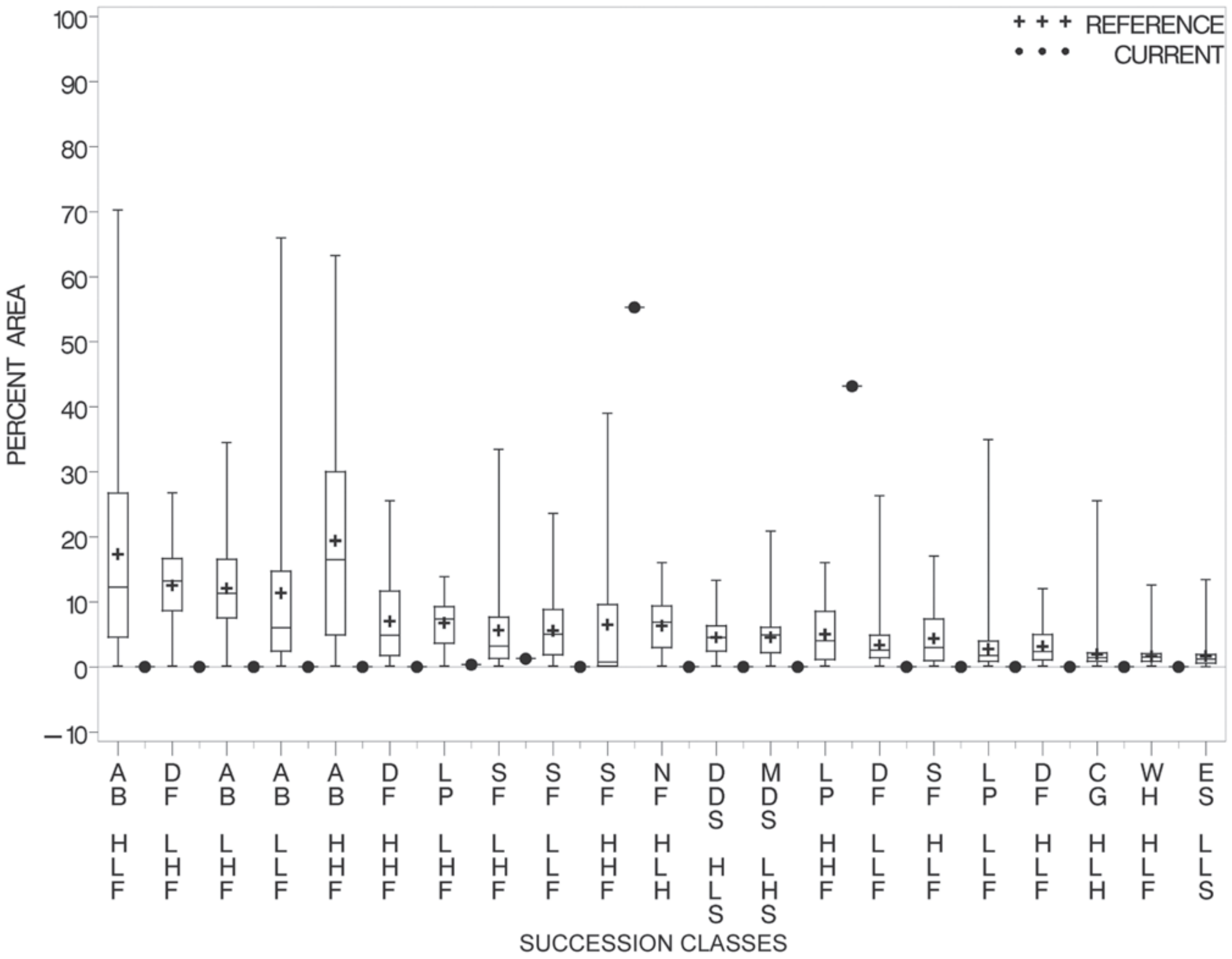

Figure 22 – Distribution of succession classes by percent area under reference and current vegetation conditions for the Spruce – Fir / Spruce – Fir / Lodgepole Pine PVT that dominates a landscape reporting unit in the Uinta Mountain Range of Zone 16. See table 7 for explanation of succession class codes.

and, as a result, have become more highly departed in their vegetation composition than systems with longer fire return intervals.

However, this assessment is predicated on the assumption that our understanding and simulation of historical fire return intervals is reasonably accurate. Indeed, fire history in different vegetation types may be poorly understood, and considerable uncertainty may exist for describing fire frequencies in some ecosystems (Baker and Ehle 2001; Baker and Shinneman 2004). For example, pinyon-juniper woodlands have been described by some as having a frequent, low severity fire regime (Brown and others 2001; Gottfried and others 1995; West 1999;), while others identify the vegetation type as having a high-severity (Floyd and others 2000) and less frequent fire regime (Baker and Shinneman 2004). Another example can be found in ponderosa pine forests, where fire return intervals were typically reported as 2-25 years, but recent work suggests that return intervals may range between 22 and 308 years (Baker and Ehle 2001). Such uncertainty in fire history information emphasizes the need for thorough evaluations of the best available data to determine the appropriate data for inclusion in LANDSUMv4 simulations. If we assume that fire return intervals that are shorter than their actual intervals, we are likely to overestimate departure; conversely, if the assumed fire return intervals are longer than the actual, departure will likely be underestimated.

Recommendations for National Implementation

Before departure indices are computed for the national implementation of the LANDFIRE Project, the limitations of each approach need to be addressed, or at least recognized. Specifically, the effect of succession pathway complexity on departure estimates in both approaches should be evaluated. To ensure consistency across the nation, we propose using a simple, standardized model with a limited number of succession stages (for example, only five succession classes per PVT). Such a set structure may more closely characterize information on vegetation structure and fire regimes available across the nation. Also, limitations inherent to the FRCC Guidebook approach need to be addressed; these include: 1) the inability to capture the range and variability across all succession classes, 2) inconsistencies in area comparisons between current and reference landscapes, and 3) potential inconsistencies in departure estimates with longer or repeated LANDSUMv4 simulations. Additionally, if multiple departure maps are developed using different approaches, instructions must be provided for the interpretation and application of the maps both on a nationwide basis and at the local level. Furthermore, prior to national implementation, a policy decision must be made regarding the treatment of certain land cover types for modeling reference conditions and estimating departure. As discussed above, inclusion of immutable land cover types (urban, agriculture, water, barren, and snow/ice) in departure estimates can mask ground conditions and conceal the need to restore departed landscapes or to conserve healthy landscapes.

Another consideration for national implementation is the use of other ways to measure landscape condition that describe landscape configuration instead of landscape composition. Landscape configuration depicts the physical distribution or spatial character of patches within the landscape (McGarigal and Marks 1995). Such patch-based metrics can be used to identify landscapes that have become highly fragmented and possibly beyond their historical distributions of patches within landscapes (Spies and others 1994; Wallin and others 1996), and these metrics include patch size, shape, density, and relative location (Farina 2000). We did not use these metrics in the LANDFIRE Prototype Project because they are computationally intensive, but if better computer resources become available for national implementation, such metrics may be informative and preferable.

Research Recommendations

In developing methods for the LANDFIRE Prototype, a number of questions emerged that require further research before implementing LANDFIRE across the nation. We first describe recommended research pertaining to the HRVStat approach and then propose a series of other lines of research.

Adequate simulation of historical reference conditions is a key factor in developing HRVStat statistics. Two main factors determine the adequacy of the LANDSUMv4 simulations for generating historical reference conditions: (1) sufficient number of sampling observations and (2) adequate spatial representation. Prior to executing LANDSUMv4 simulations for zones 16 and 19, we conducted analyses to address these two factors. We focused on developing the best data sets of simulated historical reference conditions, given our time constraints and computer resources. Other alternatives for producing simulated historical data sets should be explored as described below.

Our initial evaluations of sample size found that 200 observations from LANDSUMv4 simulations would adequately describe simulated historical landscape dynamics. However, it is important to ensure that enough sampling observations are reported to estimate the effects of periodic rare and large fire events. For example, infrequent catastrophic fires maintained large patches of old-growth ponderosa pine in a non-equilibrium state in the Black Hills of South Dakota and Wyoming (Shinneman and Baker 1997). If we under-sample LANDSUMv4 simulations with such fire regimes, we may observe only one dominant vegetation condition and miss a different state that was an important component of historical conditions. If that unobserved state is now the current condition of the landscape, we would overestimate departure and underestimate the observed significance level (that is, describe evidence for departure as higher than its true value). We suggest further analysis that examines the sensitivity of departure statistics to the number of sampling observations, given a fixed current landscape.

An additional issue related to sample size involves the way observations are sampled in simulations and the influence on temporal autocorrelation. We sampled data within one simulation at reporting intervals that were determined long enough to minimize temporal autocorrelation. An alternative approach is to run multiple simulations at shorter time periods, sampling only once from each simulation. These separate executions with different random number streams would ensure independence in sampling observations and eliminate any chance of temporal autocorrelation. We recommend comparing departure statistics from one long simulation to many shorter simulations (for example, a 10,000-year simulation with 50-year reporting intervals versus 200 simulations of 1,000-year length) to evaluate the influence of temporal autocorrelation. We anticipate that any differences detected would primarily affect the observed significance level. That is, the observed significance from one long simulation would be smaller than that produced from many shorter simulations because the number of independent observations and therefore degrees of freedom will be less where autocorrelation exists. If temporal autocorrelation within reporting intervals does substantially influence observed significance level estimates, we suggest exploring additional statistical techniques to minimize the effects before implementing the approach of multiple simulations. Multiple simulations, although potentially preferable, would prove costly because of the need for substantially longer simulation periods and could therefore be prohibitive to national implementation of the LANDFIRE Project.

Temporal autocorrelation may also affect departure statistics for landscapes that express a periodicity in their vegetation characteristics matching the reporting interval. For example, if a PVT alternates between two succession classes at 50-year intervals and we sample at 50-year intervals, we may only observe one of those two succession classes. In this case, the observed departure would be underestimated and observed significance level would be overestimated. We suspect that the likelihood of coinciding vegetation and reporting intervals is low, but recommend exploring the use of a restricted randomization scheme to avoid this possibility. For example, we might choose random numbers between 50 and 10 to sample the simulation data and generate reporting intervals such as 50, 75, 90, and so on.

Besides the adequacy of sampling observations, satisfactory spatial representation of vegetation composition is vital to estimating departure and is influenced by two main components: 1) LANDSUMv4 simulations and 2) the spatial grain of LRUs. In simulating historical vegetation conditions using LANDSUMv4, the main concern regarding spatial representation is simulating the full distribution of succession classes within a PVT on the landscape and, specifically, ensuring detection of all states that may currently exist on the landscape. Some of the primary LANDSUMv4 input components are fire regime parameters, fire size, and landscape simulation size (Pratt and others, Ch. 10). Accordingly, a given fire regime and fire size will have an optimum landscape simulation size for simulating fire spread and the corresponding effects on succession. Sensitivity analyses on the scale of LRUs are needed to identify the appropriate sizes for estimating departure. As the size of LRUs decreases, temporal variability may increase in fire and vegetation characteristics. If LRUs are too small, we may observe a limited and highly variable distribution of succession classes within a stand than would be expected at the optimal size for describing its vegetation characteristics. Conversely, if LRUs are too large, important components within LRUs needing restoration or conservation could be missed. In performing these various sensitivity analyses, we expect to identify thresholds at a relatively narrow range of sizes, which will give the most effective estimates of departure. We also expect that these optimal sizes will vary from ecosystem to ecosystem, especially if fire regimes are very different, and this source of variation should be included in sensitivity analyses.

Other kinds of research are also critically needed to fully investigate the implications of calculating departure and determining FRCC. One line of research should focus on the implications of calculating departure from an array of possible methods, including the two presented here (FRCC Guidebook and HRVStat). Numerous limitations were noted, particularly in the FRCC Guidebook approach, in the methods for computing ecological departure, prompting the exploration of other departure methods. We have developed a computer program, called DEPART, that computes various other ecological indices of similarity, including Sorenson's Index, Jaccard's Index, and Similarity Ratio (Mueller-Dombois and Ellenberg 1974). Departure estimates determined from all these indices should be evaluated and compared for their sensitivity to and consistency in detecting vegetation change. A second line of research should pursue the development of field methods that can be used to validate the departure and FRCC maps created by the LANDFIRE Project. A final research track should investigate the implications of collapsing departure measures into an ordinal classification, as with the FRCC and classified HRVStat departure groupings. Specifically, identification of appropriate breakpoints should be based on standardized methods to best represent departure estimates and avoid arbitrary classifications, which may skew assessments of landscapes.

Conclusion

Spatial data describing historical and existing conditions were successfully implemented in both the Interagency FRCC Guidebook approach and the HRVStat approach to quantify ecological departure across two large western study areas. Each method for quantifying ecological departure had strengths and limitations. The FRCC Guidebook approach proved relatively easy to use, but was not statistically rigorous. Conversely, the HRVStat approach was computationally complex, but provided a statistically sound measurement of the departure of current conditions from simulated historical conditions. While each approach has promise, more research related to the application of fire history information and the spatial units for measuring departure is needed to develop a consistent map of ecological departure across the United States.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Appendix 11-A—Names of PVT codes for zones 16 and 19

Zone 16 PVT code	Zone 16 PVT name	Zone 19 PVT code	Zone 19 PVT name
1601	Spruce Fir – Blue Spruce	1902	Western Redcedar
1602	Spruce Fir – Blue Spruce – Lodgepole Pine	1914	Grand Fir – Rocky Mtn. White Fir
1603	Spruce Fir – Spruce Fir	1920	Spruce – Fir / Western Larch
1604	Spruce Fir – Spruce Fir – Lodgepole Pine	1921	Spruce – Fir / Douglas-fir
1611	Grand Fir – White Fir	1922	Spruce – Fir / Timberline Pine
1612	Grand Fir – White Fir - Maple	1924	Spruce – Fir / Lodgepole Pine
1621	Douglas-fir – Timberline Pine	1930	Douglas-fir / Western Larch
1622	Douglas-fir – Douglas-fir	1931	Douglas-fir / Ponderosa pine
1623	Douglas-fir – Lodgepole Pine	1932	Douglas-fir / Lodgepole Pine
1631	Timberline Pine	1934	Douglas-fir / Timberline Pine
1632	Ponderosa Pine	1936	Douglas-fir / Douglas-fir
1633	Lodgepole Pine	1940	Lodgepole Pine
1634	Aspen	1942	Ponderosa Pine
1641	Pinyon Juniper–Mtn. Big Sagebrush - North	1944	Timberline Pine / Limber Pine
1642	Pinyon Juniper–Mtn. Big Sagebrush - South	1946	Timberline Pine / Whitebark Pine
1643	Pinon Juniper-Wyoming-Basin Big Sagebrush-North	1950	Rocky Mountain Juniper
1644	Pinyon Juniper-Wyoming-Basin Big Sagebrush-South	1952	Riparian Hardwood
1645	Pinyon Juniper – Mountain Mahogany	1960	Riparian Shrub
1646	Pinyon Juniper – Gambel Oak	1962	Mountain Mahogany
1651	Blackbrush	1964	Dry Shrub
1652	Salt Desert Shrub	1965	Dry Shrub/Conifer
1653	Warm Herbaceous	1970	Dwarf Sagebrush Complex
1654	Cool Herbaceous	1971	Dwarf Sage/Conifer
1661	Dwarf Sagebrush	1972	Mtn. Big Sagebrush Complex
1662	Wyoming-Basin Big Sagebrush	1973	Mtn. Big Sage/Conifer
1663	Mountain Big Sagebrush	1974	Threetip Sagebrush
1671	Riparian Hardwood	1975	Threetip Sage/Conifer
1672	Riparian Shrub	1976	Wyoming/Basin Big Sagebrush Complex
1673	Wetland Herbaceous	1977	Wyoming/Basin Big Sage/Conifer
1680	Alpine	1980	Wetland Herbaceous
1690	Open Water	1982	Alpine
1691	Urban - Developed	1984	Fescue Grasslands
1692	Barren	1985	Fescue Grasslands/Conifer
1693	Agricultural	1986	Bluebunch Wheatgrass
1694	Snow - Ice	1987	Bluebunch Wheatgrass/Conifer
		1990	Open Water
		1991	Urban - Developed
		1992	Barren
		1993	Agricultural
		1994	Snow - Ice

Appendix 11-B

Mean and standard deviation (SD) of departure estimates and a ranking of the five PVTs with the greatest departure across each of the three spatial domains of mapping zone (Zone), simulation landscape (SL), and landscape reporting unit (LRU) across Zone 16 using the FRCC Guidebook method. Overall, the PVTs with the highest departure were similar across the three spatial domains, but departure values generally decreased as the size of the spatial domain decreased (from Zone to SL to LRU). For the smallest spatial domain of LRU, departure values for each PVT were generally higher using the FRCC methods.

PVT	Zone level mean	Zone level ank	Zone level SD	SL-level mean	SL-level rank	SL-level SD	LRU-level mean	LRU-level rank	LRU-level SD
Agricultural	28		15	20		11	13		8
Alpine	37		17	22		14	11		7
Aspen	54		9	31		11	11		9
Barren	41		17	32		14	17		9
Blackbrush	54		16	31		15	10		9
Cool Herbaceous	61		13	45		12	28		9
Douglas-fir / Douglas-fir	64		9	44		13	19		14
Douglas-fir / Lodgepole Pine	69	3	7	53	3	12	33	4	15
Douglas-fir / Timberline Pine	77	1	15	65	1	18	42	1	18
Dwarf Sagebrush	55		12	35		13	17		12
Grand Fir – White Fir	65		9	47		12	25		13
Grand Fir – White Fir / Maple	54		11	31		12	12		8
Lodgepole Pine	65		10	50		14	24		14
Mountain Big Sagebrush	63		9	41		13	14		13
Open Water	33		20	25		15	14		12
Pinyon – Juniper / Gambel Oak	62		12	39		15	21		13
Pinyon – Juniper / Mountain Big Sagebrush / North	62		8	42		10	23		11
Pinyon – Juniper / Mountain Big Sagebrush / South	75	2	8	57	2	11	36	2	15
Pinyon – Juniper / Mountain Mahogany	62		11	39		15	19		13
Pinyon – Juniper / Wy. – Basin Big Sagebrush / N	66		13	44		17	19		15
Pinyon – Juniper / Wy. – Basin Big Sagebrush / S	71	5	12	52	5	15	28		15
Ponderosa Pine	62		12	49		13	30		14
Riparian Hardwood	54		10	29		11	8		6
Riparian Shrub	56		17	40		15	19		10
Salt Desert Shrub	63		14	48		15	35	3	18
Spruce – Fir / Blue Spruce	66		9	48		12	26		13
Agricultural	28		15	20		11	13		8
Alpine	37		17	22		14	11		7
Aspen	54		9	31		11	11		9
Barren	41		17	32		14	17		9
Blackbrush	54		16	31		15	10		9
Spruce – Fir / Blue Spruce / Lodgepole Pine	68	4	12	53	4	17	31	5	17
Spruce – Fir / Spruce – Fir	67		9	51		13	24		14
Spruce – Fir / Spruce – Fir / Lodgepole Pine	67		11	49		14	23		17
Urban–Developed	24		13	17		8	13		6
Warm Herbaceous	56		10	40		11	26		11
Wetland Herbaceous	56		13	36		16	22		12
Wyoming – Basin Big Sagebrush	63		13	38		14	17		13

Appendix 11-C

Mean and standard deviation (SD) of departure estimates and ranking (up to 5) for each PVT for the landscape reporting unit (LRU) spatial domain across Zone 19 using the FRCC Guidebook method. Departure values for each PVT were generally higher than those estimated using HRVStat methods.

PVT	LRU-level mean	LRU-level rank	LRU-level SD
Alpine	43.94		15.07
Bluebunch Wheatgrass	62.42	1	19.56
Bluebunch Wheatgrass / Conifer	47.71		16.03
Douglas-fir / Douglas-fir	33.96		13.80
Douglas-fir / Lodgepole Pine	36.57		14.09
Douglas-fir / Ponderosa Pine	40.51		13.88
Douglas-fir / Timberline Pine	35.38		13.86
Douglas-fir / Western Larch	42.35		12.29
Dry Shrub	57.61	2	20.07
Dry Shrub / Conifer	41.69		14.26
Dwarf Sage / Conifer	40.28		12.44
Dwarf Sagebrush Complex	48.32	5	23.50
Fescue Grasslands	47.97		16.88
Fescue Grasslands / Conifer	41.42		14.54
Grand Fir - White Fir	43.62		13.68
Lodgepole Pine	43.34		14.10
Mountain Mahogany	41.14		14.56
Mountain Big Sage Complex / Conifer	39.18		15.07
Mountain Big Sagebrush Complex	31.65		16.21
Ponderosa Pine	45.44		15.68
Riparian Hardwood	48.97	4	16.16
Riparian Shrub	44.01		15.75
Rocky Mountain Juniper	43.52		16.29
Spruce – Fir / Douglas-fir	36.87		14.03
Spruce – Fir / Lodgepole Pine	47.81		15.80
Spruce – Fir / Timberline Pine	42.42		15.72
Spruce – Fir / Western Larch	39.60		17.27
Threetip Sagebrush / Conifer	35.63		11.28
Threetip Sagebrush	30.74		13.62
Timberline Pine / Limber Pine	36.30		13.88
Timberline Pine / Whitebark Pine	34.95		11.92
Western Redcedar	52.22	3	14.98
Wetland Herbaceous	45.84		15.81
Wy. – Basin Big Sage Complex / Conifer	40.57		14.91
Wy. – Basin Big Sagebrush Complex	38.66		17.12

Appendix 11-D

Average and standard deviation for departure and observed significance by PVT for Zone 16, estimated using the HRVStat method, percent of classified HRVStat departure groups by PVT across the zone, and percent of zone composed of that PVT. Departure values for each PVT were generally lower than those estimated using FRCC methods.

	Departure		Observed significance		Classified HRVStat departure			% of
PVT	Mean	Std. dev.	Mean	Std. dev.	1	2	3	zone
Pinyon – Juniper / Mountain Big Sagebrush / South	0.28	0.24	0.01	0.01	1.00%	4.98%	25.77%	5.22%
Pinyon – Juniper / Wy. – Basin Big Sagebrush / S.	0.12	0.16	0.01	0.03	9.47%	19.34%	23.66%	16.47%
Salt Desert Shrub	0.29	0.36	0.03	0.10	1.47%	1.57%	9.69%	2.13%
Grand Fir – White Fir	0.09	0.13	0.02	0.05	4.17%	8.68%	5.87%	7.02%
Ponderosa Pine	0.15	0.17	0.01	0.02	0.78%	3.12%	4.73%	2.48%
Douglas-fir / Douglas-fir	0.12	0.16	0.02	0.06	1.78%	3.76%	4.42%	3.17%
Pinyon – Juniper / Wyo. – Basin Big Sagebrush / N.	0.13	0.17	0.02	0.07	1.39%	2.82%	3.82%	2.43%
Pinyon – Juniper / Gambel Oak	0.17	0.20	0.01	0.04	0.81%	1.51%	3.63%	1.44%
Mountain Big Sagebrush	0.05	0.09	0.03	0.07	8.66%	9.39%	2.76%	8.67%
Wyoming – Basin Big Sagebrush	0.06	0.13	0.04	0.09	4.88%	4.45%	2.63%	4.45%
Dwarf Sagebrush	0.06	0.12	0.06	0.14	5.95%	3.95%	2.29%	4.48%
Pinyon – Juniper / Mountain Mahogany	0.17	0.17	0.01	0.02	0.32%	1.30%	2.26%	1.06%
Pinyon – Juniper / Mountain Big Sagebrush / North	0.15	0.17	0.01	0.01	0.31%	1.50%	2.08%	1.16%
Riparian Hardwood	0.06	0.11	0.02	0.06	1.74%	2.44%	0.98%	2.11%
Grand Fir – White Fir / Maple	0.06	0.09	0.01	0.03	1.39%	3.49%	0.75%	2.61%
Urban–Developed	0.08	0.16	0.02	0.06	0.51%	0.87%	0.64%	0.74%
Agricultural	0.04	0.10	0.02	0.07	1.36%	2.29%	0.60%	1.87%
Douglas-fir / Timberline Pine	0.13	0.14	0.01	0.02	0.18%	0.61%	0.60%	0.47%
Aspen	0.04	0.08	0.04	0.09	2.37%	2.09%	0.55%	2.07%
Barren	0.04	0.07	0.04	0.10	3.19%	2.80%	0.51%	2.76%
Spruce – Fir / Blue Spruce	0.05	0.09	0.05	0.10	1.51%	1.05%	0.41%	1.15%
Spruce – Fir / Spruce – Fir / Lodgepole Pine	0.01	0.03	0.09	0.15	24.51%	8.81%	0.33%	13.25%
Spruce – Fir / Spruce – Fir	0.02	0.03	0.09	0.14	15.04%	5.14%	0.22%	7.97%
Riparian Shrub	0.03	0.08	0.07	0.13	1.62%	0.77%	0.22%	1.00%
Warm Herbaceous	0.04	0.08	0.04	0.09	0.95%	0.69%	0.17%	0.73%
Spruce – Fir / Blue Spruce / Lodgepole Pine	0.03	0.07	0.05	0.11	0.63%	0.54%	0.11%	0.54%
Open Water	0.03	0.09	0.19	0.35	0.67%	0.35%	0.10%	0.43%
Wetland Herbaceous	0.04	0.10	0.05	0.10	0.34%	0.25%	0.10%	0.27%
Blackbrush	0.03	0.07	0.10	0.15	0.68%	0.22%	0.06%	0.36%
Douglas-fir / Lodgepole Pine	0.02	0.05	0.07	0.12	0.31%	0.14%	0.02%	0.19%
Timberline Pine	0.06	0.07	0.02	0.04	0.03%	0.04%	0.01%	0.03%
Lodgepole Pine	0.02	0.02	0.05	0.10	1.08%	0.75%	0.00%	0.81%
Cool Herbaceous	0.01	0.02	0.06	0.11	0.23%	0.11%	0.00%	0.14%
Snow – Ice	0.01	0.05	0.12	0.20	0.00%	0.00%	0.00%	0.00%
Alpine	0.01	0.02	0.11	0.15	0.66%	0.19%	0.00%	0.33%

Appendix 11-E

Average and standard deviation for departure and observed significance by PVT for Zone 19, estimated using the HRVStat method, percent of classified HRVStat departure group by PVT across the zone, and percent of zone composed of that PVT. Departure values for each PVT were generally lower than those estimated using FRCC methods.

	Departure		Observed significance		Classified HRVStat departure			% of
PVT	Mean	Std. dev.	Mean	Std. dev.	1	2	3	zone
Bluebunch Wheatgrass	0.67	0.31	0.00	0.00	0.03%	4.16%	18.65%	6.09%
Wyoming – Basin Big Sagebrush Complex	0.22	0.29	0.02	0.10	9.28%	15.89%	13.80%	14.64%
Douglas-fir / Douglas-fir	0.17	0.22	0.01	0.04	5.65%	12.09%	8.17%	10.56%
Fescue Grasslands	0.53	0.31	0.01	0.00	0.02%	1.65%	5.10%	2.02%
Douglas-fir / Ponderosa Pine	0.23	0.26	0.01	0.02	0.49%	3.29%	4.04%	3.05%
Spruce – Fir / Western Larch	0.11	0.17	0.03	0.08	13.78%	8.45%	3.29%	8.25%
Ponderosa Pine	0.44	0.30	0.01	0.01	0.03%	0.85%	3.21%	1.14%
Mountain Big Sagebrush Complex	0.15	0.22	0.01	0.05	2.40%	6.16%	2.83%	5.09%
Riparian Hardwood	0.43	0.31	0.01	0.01	0.07%	1.33%	2.81%	1.42%
Dry Shrub	0.59	0.33	0.01	0.00	0.03%	1.13%	2.79%	1.27%
Douglas-fir / Lodgepole Pine	0.12	0.20	0.03	0.09	6.37%	4.27%	2.37%	4.21%
Spruce – Fir / Lodgepole Pine	0.09	0.17	0.06	0.11	17.97%	5.78%	2.03%	6.72%
Spruce – Fir / Douglas-fir	0.11	0.18	0.03	0.09	6.47%	4.10%	1.86%	4.02%
Riparian Shrub	0.34	0.30	0.01	0.01	0.07%	0.84%	1.49%	0.85%
Lodgepole Pine	0.10	0.17	0.05	0.12	7.16%	3.56%	1.45%	3.66%
Douglas-fir / Western Larch	0.15	0.19	0.01	0.02	0.42%	3.07%	1.44%	2.44%
Wetland Herbaceous	0.41	0.31	0.01	0.02	0.06%	0.68%	1.34%	0.71%
Douglas-fir / Timberline Pine	0.23	0.24	0.01	0.02	0.27%	1.25%	1.22%	1.12%
Mountain Big Sage Complex / Conifer	0.28	0.26	0.01	0.02	0.12%	0.81%	1.03%	0.76%
Spruce – Fir / Timberline Pine	0.05	0.10	0.07	0.14	26.14%	7.66%	0.96%	8.91%
Western Redcedar	0.37	0.28	0.01	0.00	0.01%	0.56%	0.94%	0.56%
Wy. – Basin Big Sage Complex / Conifer	0.32	0.28	0.01	0.01	0.05%	0.49%	0.92%	0.50%
Fescue Grasslands / Conifer	0.38	0.29	0.01	0.00	0.02%	0.44%	0.87%	0.46%
Bluebunch Wheatgrass / Conifer	0.49	0.29	0.01	0.00	0.00%	0.19%	0.77%	0.26%
Grand Fir- White Fir	0.19	0.19	0.01	0.00	0.01%	1.02%	0.65%	0.82%
Mountain Mahogany	0.31	0.23	0.01	0.00	0.01%	0.29%	0.46%	0.28%
Dwarf Sagebrush Complex	0.39	0.35	0.01	0.02	0.02%	0.29%	0.30%	0.25%
Dry Shrub / Conifer	0.25	0.23	0.01	0.01	0.03%	0.23%	0.26%	0.21%
Rocky Mountain Juniper	0.42	0.28	0.01	0.00	0.01%	0.11%	0.24%	0.12%
Threetip Sagebrush	0.13	0.21	0.01	0.05	0.27%	0.66%	0.21%	0.53%
Timberline Pine / Limber Pine	0.26	0.23	0.01	0.01	0.02%	0.14%	0.18%	0.13%
Timberline Pine / Whitebark Pine	0.11	0.13	0.01	0.02	0.11%	0.59%	0.11%	0.45%
Alpine	0.40	0.30	0.01	0.01	0.00%	0.03%	0.07%	0.03%
Threetip Sagebrush / Conifer	0.17	0.19	0.01	0.01	0.00%	0.03%	0.01%	0.02%
Dwarf Sagebrush Complex / Conifer	0.34	0.26	0.01	0.00	0.00%	0.00%	0.00%	0.00%

Chapter
12

Mapping Wildland Fuel across Large Regions for the LANDFIRE Prototype Project

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Introduction

The Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, required that the entire array of wildland fuel characteristics be mapped to provide fire and landscape managers with consistent baseline geo-spatial information to plan projects for hazardous fuel mitigation and to improve public and firefighter safety. Fuel maps were some of the core deliverables of the LANDFIRE Prototype Project. The LANDFIRE approach for mapping fuel combined information from the LANDFIRE reference database (LFRDB) (Caratti and others, Ch. 4), biophysical gradient layers (Holsinger and others, Ch. 5), maps of potential vegetation (Frescino and Rollins, Ch. 7), and maps of vegetation composition and vegetation structure (Zhu and others, Ch. 8) to produce the entire suite of geo-spatial data for predicting the behavior and effects of wildland fires across the United States.

The fuel layers developed for the LANDFIRE effort were selected on the basis that they provide input to software commonly used in fire management planning. All LANDFIRE fuel layers can be directly used in one or more fire analysis tools, including the FARSITE fire growth model (Finney 1998). Moreover, these fuel layers may also be used for many other applications. Surface fuel layers provide comprehensive inventories of dead biomass that can be used to calculate carbon pools for estimating particulate production and modeling smoke dispersal. Canopy fuel layers provide important information on canopy characteristics that can be used to calculate leaf area index (LAI), shading, rain and snowfall interception, and surface roughness for ecosystem and hydrological modeling. Still other layers provide data on critical stand characteristics that may be used to quantify hiding and thermal cover for wildlife.

Background

Fuel is defined for the LANDFIRE Prototype as any material that can burn in a wildland fire. More specifically, wildland fuel is defined by characteristics of live and dead biomass pools that contribute to the spread, intensity, and severity of wildland fire (Burgan and Rothermel 1984). The primary characteristic used to describe fuel is "loading," which is defined as mass per unit area, or more specifically, the dry weight of a fuel component per unit area (kg m^{-2}). Other characteristics include particle density, surface area-to-volume ratio, packing ratio, and heat content. Fine fuel, such as twigs, grass, and foliage, primarily contributes to the spread of wildland fire, whereas coarse fuel, such as branches and logs, contributes mostly to post-frontal combustion and fire intensity.

Perhaps the most confounding property of fuel is its high variability in space and time (Brown and Bevins 1986). Fuel tends to have a clumped distribution within a stand that is related to the interaction between exogenous disturbance factors, such as windthrow, snowbreak, and

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insects, and the endogenous stand characteristics, such as tree distribution, density, and tree species. Moreover, the spatial distribution of fuel can vary by fuel size class and fuel type (grass, shrub, or woody, for example). Fine fuel (such as foliage or small twigs) tends to fall and accumulate uniformly over time, but the coarser fuel, such as branches and logs, tends to accumulate after episodic events such as windstorms, spring snowfalls, and insect epidemics. These factors contribute to the difficulty in describing, modeling, and mapping fuel (Keane and others 2001).

Two major categories of fuel were mapped in the LANDFIRE Prototype Project: surface fuel and canopy fuel. Surface fuel is composed of those dead and live biomass components that occur on the ground (under 2 m) and is the fuel that contributes to the spread and intensity of surface fire. This type of fuel is typically described by the following fuel components: herbaceous (live or dead), shrub (live or dead), downed/dead woody, litter, and duff. There were five size classes of downed/dead woody fuel used in the LANDFIRE Prototype: 1-, 10-, 100-, 1000-, and 10,000-hour fuel (1-, 2.5-, 8-, and 50-cm upper diameter thresholds). Litter is freshly fallen organic material, and duff is the decomposed organic material. For most fire behavior and effects applications, surface fuel is represented by a set of characteristics, with fuel loading being the most dynamic over time and space. Other characteristics include surface area-to-volume ratios, bulk density, and heat content (Albini 1976; Anderson 1982; Rothermel 1972). Because of the high diversity and variability of surface fuel components (Brown and Bevins 1986), surface fuel characteristics are usually quantified using "fuel models" that are composed of summaries of fuel loading by fuel component for unique ecological or fire behavior conditions (see Anderson 1982 for examples). For LANDFIRE purposes, all surface fuel is represented by fuel models that classify fuel loading by component. For example, a fuel model, as used in this paper, might represent the actual loading of each fuel component (such as litter, duff, and canopy fuel), or a fuel model might represent loadings by fuel component calculated to achieve a desired outcome when simulating fire behavior or effects.

Canopy fuel comprises those aerial biomass components higher than 2 m above the ground that can carry a crown fire and is typically consumed in the crown fire. This fuel is usually the foliage and small branchwood (<2.5 cm diameter) in a tree's crown (Scott and Reinhardt 2002). Unlike surface fuel, which is often described using categorical variables such as fuel component, canopy fuel was described in the LANDFIRE Prototype by four continuous variables: bulk density (kg m^{-3}), canopy cover (%), canopy height (m), and canopy base height (m). These four characteristics are essential for modeling crown fire initiation and propagation in the various fire management software tools (Finney 1998; Scott 1999).

We developed eight layers to describe both surface and canopy fuel for the LANDFIRE Prototype. As mentioned above, these layers were selected because they are essential for predicting fire behavior and effects so that fire hazard analyses and fire management planning may be performed in a spatial domain (Salas and Chevico 1994). These eight layers are:

- Anderson's (1982) 13 fire behavior fuel models (FBFM13).
- Scott's and Burgan's (2005) 40 fire behavior fuel models (FBFM40)
- Fuel characterization classes (FCCs) (Sandberg and Ottmar 2001)
- Fuel loading models (FLM) (Lutes and others, in preparation)
- Canopy bulk density (CBD)
- Canopy cover (CC)
- Canopy height (CH)
- Canopy base height (CBH)

Each classification or continuous variable that was mapped for each layer will be described in detail in the following sections.

The development of the LANDFIFRE fuel spatial data layers was a complex task that required the integration of diverse spatial analyses. For example, the surface fuel maps were created using a classification or rule-based approach, whereas the canopy layers were created using an integration of statistical modeling, classification, and ecosystem simulation. We have therefore stratified the sections of this chapter by surface fuel and canopy fuel for simplicity.

Surface Fuel Layers

In the LANDFIRE Prototype, we mapped four surface fuel model classifications to represent the gamut of surface fuel inputs needed to run commonly used models that simulate both fire behavior and effects. Two of these fuel classifications (fire behavior fuel models) are used to calculate fire behavior variables, such as fire intensity and spread rate, and the remaining two (fire effects fuel models) are used for computing fire effects, such as fuel consumption and smoke production. For the LANDFIRE Prototype, two new classifications describing fire behavior and effects were developed to complement two existing classifications and to match the scale and resolution of the LANDFIRE process. In this chapter, the term "fuel model" is used to represent a unique category in the fuel classification. These categories are unique sets of fuel characteristics (primarily amount of biomass) by fuel component that are linked to vegetation composition and structure. For example, an open ponderosa pine stand would likely be assigned an FBFM13 model 2 and a dense spruce-fir stand would be assigned an FBFM13 model 10.

Fire behavior fuel models—Eleven of the 13 fire behavior fuel models (FBFM13) were originally developed by Rothermel (1972) as input into his spread model for predicting fire behavior (spread and intensity) (table 1). Albini (1976) added two other models to this classification (dormant brush and southern rough) to create the standard 13 fire models used in fire management today (see Rothermel 1983). Anderson (1982) provided vegetation descriptions, stylized pictures, and a key to aid managers in determining fire behavior fuel models. These 13 fire behavior fuel models represent distinct distributions of fuel loading among surface fuel types (live and dead), size classes, and fuel components. They are described by the fuel type or carrier (grass, brush, litter, or slash) most commonly responsible for fire spread and are represented by a variety of characteristics, including biomass loading, surface area-to-volume ratio by size class and component, fuelbed depth, and moisture of extinction. Extensive early fire modeling research revealed that prediction of fire behavior with real-world fuel loading is problematic (Albini and Anderson 1982; Andrews 1980; Rothermel 1983). Therefore, fire scientists

Table 1—The 13 standard fire behavior fuel models developed by Rothermel (1972) and Albini (1976) and described by Anderson (1982).

Fuel Model	Group	Description
1	Grass	Surface fires that burn fine herbaceous fuels, cured and curing fuels, little shrub or timber present, primarily grasslands and savanna
2	Grass	Burns fine, herbaceous fuels, stand is curing or dead, may produce fire brands in oak or pine stands
3	Grass	Most intense fire of grass group, spreads quickly with wind, one third of stand dead or cured, stands average 3 ft tall
4	Shrub	Fast spreading fire, continuous overstory, flammable foliage and dead woody material, deep litter layer can inhibit suppression
5	Shrub	Low intensity fires, young, green shrubs with little dead material, fuels consist of litter from understory
6	Shrub	Broad range of shrubs, fire requires moderate winds to maintain flame at shrub height, or will drop to the ground with low winds
7	Shrub	Foliage highly flammable, allowing fire to reach shrub strata levels, shrubs generally 2 to 6 feet high
8	Timber	Slow, ground burning fires, closed canopy stands with short needle conifers or hardwoods, litter consist mainly of needles and leaves, with little undergrowth, occasional flares with concentrated fuels
9	Timber	Longer flames, quicker surface fires, closed canopy stands of long-needles or hardwoods, rolling leaves in fall can cause spotting, dead-down material can cause occasional crowning
10	Timber	Surface and ground fire more intense, dead-down fuels more abundant, frequent crowning and spotting causing fire control to be more difficult
11	Logging Slash	Fairly active fire, fuels consist of slash and herbaceous materials, slash originates from light partial cuts or thinning projects, fire is limited by spacing of fuel load and shade from overstory
12	Logging Slash	Rapid spreading and high intensity fires, dominated by slash resulting from heavy thinning projects and clearcuts, slash is mostly 3 inches or less in diameter, fire is usually sustained until there is a fuel break or a change in fuel type
13	Logging Slash	Fire spreads quickly through smaller material and intensity builds slowly as large material ignites, continuous layer of slash larger than 3 inches in diameter predominates, resulting from clearcuts and heavy partial cuts, active flames sustained for long periods of time, fire i susceptible to spotting and weather conditions

created synthetic representations of wildland fuel that, when input into the fire model, would simulate realistic fire behavior under known temperature, moisture, and wind conditions. Although the fuel loading used in these models did not represent actual amounts measured in the field, the simulated fire behavior using these artificial amounts was found to approximate reality, especially with respect to the resolution of the fire behavior model. Since their development, FBFM13 have served as the foundation for fire behavior prediction (Andrews and Bevins 1999).

Despite FBFM13's advantages, the resolution of these 13 fuel model categories is so coarse that subtle changes in fuelbed conditions, such as those incurred by fuel treatment activities, often cannot be detected using the FBFM13 categories. In addition, since the FBFM13 models were developed for application during severe fire weather (Anderson 1982), they had limited abilities to predict fire behavior for purposes of prescribed fire and wildland fire use. Additionally, these models had limited abilities for simulating and comparing different fuel treatments' effects on fire behavior. Many fuel treatments do not produce sufficient fuel modification by which to reclassify a stand to a different FBFM13 fuel model category. Scott and Burgan (2005) also mention that new fuel models were needed to better represent fuel types in high humidity areas and forests with litter, grass, and shrub understories. We therefore determined that a finer resolution fire behavior fuel model would be necessary for guiding fuel treatments at a national scale (Keane and Rollins, Chapter 3).

In 2003, the LANDFIRE Prototype Project funded an extensive fuel modeling study, led by the Fire Behavior Research Unit (RWU-4401) of the Rocky Mountain Research Station and Systems for Environmental Management, to create the next generation of fire behavior fuel models. In 2005, Scott and Burgan created a new set of 40 fire behavior fuel models (FBFM40) that are hierarchically organized by fuel strata and fuel loading (table 2). This set of fuel models provides a better tool for fire behavior prediction because it balances the resolution of fuel conditions with the algorithms contained in widely accepted fire behavior models. These 40 fire behavior fuel models have already been implemented in the BehavePlus fire modeling system (Andrews 1986; Andrews and Bevins 1999; Andrews and others 2003) and the FARSITE fire growth model (Finney 1998). Unlike Anderson's (1982) FBFM13 descriptions, subtle modifications in vegetation composition and structure resulting from fuel treatment activities may be detected using FBFM40 under most circumstances.

One limitation of fire behavior fuel model classifications relates to the difficultly in accurately and consistently determining which fire behavior fuel model best describes fuel conditions in a particular stand. Since fire behavior fuel models are assigned according to expected fire behavior, extensive experience in evaluating potential fire behavior under particular fuel conditions is required to assign fire behavior fuel models. Even the most experienced fire modeling specialists have difficulty agreeing on a common fuel model for certain stand and weather conditions. This limitation is exacerbated by the high variability of fuel by component across spatial scales (Keane and others 2001). It is therefore common for a stand to be described by two or more fire behavior fuel models. As a consequence, spatially explicit field data containing estimates of fire behavior fuel models are rare. Another limitation of fire behavior fuel models is that they do not quantify all dead and live biomass pools at a stand level, thus they are not useful for other fire applications such as predicting smoke production and vegetation mortality (Keane and others 1998a; Leenhouts 1998).

Fire effects fuel models—The many fire effects prediction models, such as FOFEM (Reinhardt and Keane 1998; Reinhardt and others 1997) and CONSUME (Ottmar and others 1993), require actual fuel loading estimates by fuel component to simulate fire effects-related processes, such as fuel consumption and smoke generation. However, because fuel loadings for the FBFM13 and FBFM40 classifications were modified to predict realistic fire behavior, the fire behavior fuel models are not useful for computing fire effects. Simulation of fire effects requires classifications of fuel loading across all biomass components that accurately describe real fuel across large landscapes.

There are two main fire effects fuel model classification systems used in the LANDFIRE Prototype mapping effort. The first, called the Fuel Characterization Classification System (FCCS), was developed by Sandberg and others (2001). This system summarizes fuel loading by component using canopy, shrub, surface, and ground fuel stratifications (www.fs.fed.us/pnw/fera/research). Several fuelbed categories that describe unique combustion environments form the foundation of FCCS. These categories were selected based on general characteristics, such as region, stand structure, and stand history. Fuel component loadings for these fuelbeds were summarized into a set of fuel models referred to as the "national default fuelbeds," which we will refer to here as default fuel characterization classes, or FCCs for brevity. These default FCCs can then be modified using specialized

Table 2—Description of the 40 fire behavior fuel models developed by Scott and Burgan (2005).

	Fuel Model Number	Fuel Model Code	Name	Description
GRASS				
	101	GR1	Short, sparse dry climate grass	Grass is short naturally or heavy grazing, predicted rate of fire spread and flame length is low
	102	GR2	Low load, dry climate grass	Primarily grass with some small amounts of fine, dead fuel, any shrubs do not affect fire behavior
	103	GR3	Low load, very coarse, humid climate grass	Continuous, coarse humid climate grass, any shrubs do not affect fire behavior
	104	GR4	Moderate load, dry climate grass	Continuous, dry climate grass, fuelbed depth about 2 feet
	105	GR5	Low load, humid climate grass	Humid climate grass, fuelbed depth is about 1-2 feet
	106	GR6	Moderate load, humid climate grass	Continuous humid climate grass, not so coarse as GR5
	107	GR7	High load, dry climate grass	Continuous dry climate grass, grass is about 3 feet high
	108	GR8	High load, very coarse, humid climate grass	Continuous, coarse humid climate grass, spread rate and flame length may be extreme if grass is fully cured
	109	GR9	Very high load, humid climate grass	Dense, tall, humid climate grass, about 6 feet tall, spread rate and flame length can be extreme if grass is fully cured
GRASS-SHRUB				
	121	GS1	Low load, dry climate grass-shrub	Shrubs are about 1 foot high, grass load is low, spread rate moderate and flame length is low
	122	GS2	Moderate load, dry climate grass-shrub	Shrubs are 1-3 feet high, grass load is moderate, spread rate high and flame length is moderate
	123	GS3	Moderate load, humid climate grass-shrub	Moderate grass/shrub load, grass/shrub depth is less than 2 feet, spread rate is high and flame length is moderate
	124	GS4	High load, humid climate grass-shrub	Heavy grass/shrub load, depth is greater than 2 feet, spread rate is high and flame length very high
SHRUB				
	141	SH1	Low load dry climate shrub	Woody shrubs and shrub litter, fuelbed depth about 1 foot, may be some grass, spread rate and flame low
	142	SH2	Moderate load dry climate shrub	Woody shrubs and shrub litter, fuelbed depth about 1 foot, n grass, spread rate and flame low
	143	SH3	Moderate load, humid climate shrub	Woody shrubs and shrub litter, possible pine overstory, fuelbed depth 2-3 feet, spread rate and flame low
	144	SH4	Low load, humid climate timber shrub	Woody shrubs and shrub litter, low to moderate load, possible pine overstory, fuelbed depth about 3 feet, spread rate high and flame moderate
	145	SH5	High load, humid climate grass-shrub	Grass and shrubs combined, heavy load with depth greater than 2 feet, spread rate and flame very high
	146	SH6	Low load, humid climate shrub	Woody shrubs and shrub litter, dense shrubs, little or no herbaceous fuel, depth about 2 feet, spread rate and flame high
	147	SH7	Very high load, dry climate shrub	Woody shrubs and shrub litter, very heavy shrub load, depth 4-6 feet, spread rate somewhat lower than SH6 and flame very high

(continued)

Table 2 (Continued)

Fuel Model Number	Fuel Model Code	Name	Description
SHRUB			
148	SH8	High load, humid climate shrub	Woody shrubs and shrub litter, dense shrubs, little or no herbaceous fuel, depth about 3 feet, spread rate and flame high
149	SH9	Very high load, humid climate shrub	Woody shrubs and shrub litter, dense finely branched shrubs with fine dead fuel, 4-6 feet tall, herbaceous may be present, spread rate and flame high
TIMBER-UNDERSTORY			
161	TU1	Low load dry climate timber grass shrub	Low load of grass and/or shrub with litter, spread rate and flame low
162	TU2	Moderate load, humid climate timber-shrub	Moderate litter load with some shrub, spread rate moderate and flame low
163	TU3	Moderate load, humid climate timber grass shrub	Moderate forest litter with some grass and shrub, spread rate high and flame moderate
164	TU4	Dwarf conifer with understory	Short conifer trees with grass or moss understory, spread rate and flame moderate
165	TU5	Very high load, dry climate shrub	Heavy forest litter with shrub or small tree understory, spread rate and flame moderate
TIMBER LITTER			
181	TL1	Low load compact conifer litter	Compact forest litter, light to moderate load, 1-2 inches deep, may represent a recent burn, spread rate and flame low
182	TL2	Low load broadleaf litter	Broadleaf, hardwood litter, spread rate and flame low
183	TL3	Moderate load conifer litter	Moderate load conifer litter, light load of coarse fuels, spread rate and flame low
184	TL4	Small downed logs	Moderate load of fine litter and coarse fuels, small diameter downed logs, spread rate and flame low
185	TL5	High load conifer litter	High load conifer litter, light slash or dead fuel, spread rate and flame low
186	TL6	Moderate load broadleaf litter	Moderate load broadleaf litter, spread rate and flame moderate
187	TL7	Large downed logs	Heavy load forest litter, larger diameter downed logs, spread rate and flame low
188	TL8	Long needle litter	Moderate load long needle pine litter, may have small amounts of herbaceous fuel, spread rate moderate and flame low
189	TL9	Very high load broadleaf litter	Very high load fluffy broadleaf litter, may be heavy needle drape, spread rate and flame moderate
SLASH-BLOWDOWN			
201	SB1	Low load activity fuel	Light dead and down activity fuel, fine fuel is 10-20 t/ac, 1-3 inches in diameter, depth less than 1 foot, spread rate moderate and flame low
202	SB2	Moderate load activity fuel or low load blowdown	Moderate dead down activity fuel or light blowdown, 7-12 t/ac, 0-3 inch diameter class, depth about 1 foot, blowdown scattered with many still standing, spread rate and flame low
203	SB3	High load activity fuel or moderate load blowdown	Heavy dead down activity fuel or moderate blowdown, 7-12t/ac, 0-.25 inch diameter class, depth greater than 1 foot, blowdown moderate, spread rate and flame high
204	SB4	High load blowdown	Heavy blowdown fuel, blowdown total, foliage and fine fuel still attached to blowdown, spread rate and flame very high

software (see http://www.fs.fed.us/pnw/fera/research/ for details) to create new, finer-scale FCCs to represent local conditions. In the LANDFIRE Prototype, we mapped the default FCCs, allowing managers to then, through the software, modify these default FCCs to reflect finer-scale, local fuel conditions for project-level fuel treatment planning. Over 200 default FCCs were used in the LANDFIRE prototype effort, thus a table describing each would be prohibitively long and not appropriate for this report.

The default FCCs can be keyed only from vegetation characteristics observed in the field or from variables contained in existing databases. However, there is often a low degree of fidelity between FCCs and LANDFIRE vegetation classes (Long and others, Ch. 6) because of the high variability in fuel loadings within and between fuel components (Keane and others 2001). There are no key criteria in the FCCS that use fuelbed characteristics to uniquely identify default FCCs; that is, it is difficult, if not impossible, to consistently determine FCCs based on fuel data alone.

The high fuel loading variability and large number of default FCCs presented a special scale problem in the LANDFIRE Prototype. We found the default FCCs to be useful at fine spatial scales, but it was difficult to accurately map the default FCCs across large regions with diverse ecosystems because the classification resolution of the FCCS did not match the resolution needed to describe fuel across entire regions. For example, there was an insufficient number of default FCCs in the FCCS to link to all the vegetation conditions quantified by the LANDFIRE mapping process. We therefore created a second, companion fire effects fuel model classification that accounted for the high variability across fuel components and matched the resolution of LANDFIRE mapping process as well as the resolution of the models used to predict fire effects.

The fuel loading model (FLM) classification was developed for the LANDFIRE Prototype by Lutes and others (in preparation) to specifically match the scale of LANDFIRE mapping with the scale of fire effects modeling. They developed a broad classification of fuelbeds based on fuel loading by component that accounts for the high variability of loading within and between fuel components. Instead of assigning fire effects fuel models to vegetation characteristics, Lutes and others (in preparation) analyzed the loading of seven surface fuel components in over 4,000 fuelbeds measured in the field and grouped them using an unsupervised agglomerative clustering approach based on component loading. They then calculated the fire effects of smoke production and soil temperature for each fuelbed and used these outputs in a cluster analysis to obtain an FLM classification, which accounts for the variability of fuel loading and related potential fire effects across the seven surface fuel components. Moreover, a rule set was developed in addition to the FLM classification that can be used to determine the appropriate FLM in the field or from existing field databases containing fuel information. A comprehensive description of each FLM is detailed in Lutes and others (in preparation) and is summarized in table 3.

Table 3—Fuel loading models (FLMs) are combinations of duff/litter and coarse woody debris (CWD) biomass that lead to unique fire effects, as measured by soil heating and PM2.5 emissions. Multiple combinations of duff/litter and CWD may point to one FLM.

	Fuel combination 1		Fuel combination 2		Fuel combination 3		
FLM	**Duff/litter**	**CWD**	**Duff/litter**	**CWD**	**Duff/litter**	**CWD**	**Associated cover types**
	- - - - - - - - - - -	- - - - - -	Tons/acre	- - - - - -	- - - - - -	- - - - - -	
1	<8	<13	>5, <8	<13			Herb and shrub
2	>8, <15	<13					Shrub, woodland
4	>20, <40	<13	<8	>17, <35			Tall shrub, low – mid density forest
5	>8, <20	>13, <35					Low – mid density forest
6	>40, <60	<35					Mid – high density forest
7	>20, <40	>13, <35	<40	>35, <90			Mid – high density forest
8	>60, <80	<35	>40, <80	>35	<40	>90	High density forest, large trees
99							Agricultural, barren, unburnable

Canopy Fuel Layers

The spatial representation of canopy fuel is important for assessing the probability and simulating the characteristics of crown fire across forested landscapes (Chuvieco and Congalton 1989; Finney 1998; Keane and others 1998a; Keane and others 2001). Four main variables describing canopy fuel characteristics are commonly applied in wildland fire simulation and fire management planning; these include canopy bulk density (CBD, kg m^{-3}), canopy base height (CBH, m), canopy height (CH, m), and canopy cover (CC, percent).

Canopy bulk density (CBD) describes the mass of available canopy fuel per unit volume of canopy in a stand (Scott and Reinhardt 2005); it is the dry weight of available canopy fuel per unit volume of the canopy including the spaces between the tree crowns (Scott and Reinhardt 2001). Canopy fuel is typically defined by all foliage and branchwood material less than 1 cm in diameter because this is the fuel that is typically consumed in a crown fire (Keane and others 2005). The bulk density of the canopy determines the initiation of a crown fire and the subsequent rate at which a fire spreads through the canopy (Cruz and others 2003; Finney 1998; Van Wagner 1977; Van Wagner 1993).

Canopy base height (CBH) describes the level above the ground at which there is enough aerial fuel to carry the fire vertically into the canopy. This measurement is commonly thought of as the height from the ground to the bottom of the live canopy (Scott and Reinhardt 2001) but may also include dense, dead crown material that can carry a fire. The CBH determines the likelihood of a crown fire and the interaction between the ground, surface, and canopy fuel layers (Cruz and others 2003).

Canopy height (CH) is the height of the top of the canopy, and canopy cover (CC) is the vertically projected percent cover of the live canopy layer for a specific area. Spatially explicit canopy information combined with topographic and weather data are used to determine when and where the transition from a surface fire to a crown fire may occur (Finney 1998).

Maps of these four canopy characteristics, in conjunction with maps of elevation, aspect, slope, and fire behavior fuel models, are required as input to the FARSITE model to simulate fire growth under various weather and wind scenarios (Finney 1998). FARSITE is currently used by many fire managers to plan prescribed burns and to manage wildland fires. It is designed to model fire behavior over a continuous surface at fine time-steps. These canopy characteristics can also be used in NEXUS to calculate the critical wind threshold for propagating a crown fire (Scott 1999).

The CH and CC map layers were mapped by the USGS Center for Earth Resources Observation and Science (EROS) using field-referenced data, satellite imagery, and statistical modeling (Zhu and others, Ch. 8); however, we describe only the development of the CBD and CBH canopy fuel layers in this chapter. These layers were mapped at the USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (MFSL) in Missoula, Montana using a complex statistical modeling procedure that employs biophysical gradients and satellite imagery to predict these variables across landscapes.

Fuel Mapping

Because of recent advances in fire modeling software and GIS analysis packages, maps of wildland fuel have become essential in wildland fire management and in planning and implementing fuel treatments (Finney 1998; Keane and others 2001). As mentioned, these spatial layers provide critical input to the numerous fire models currently available for fire management (see www.frames.nbii.gov). However, the mapping of wildland fuel is a difficult and costly task for two main reasons.

First, many of the remotely sensed data used in mapping, such as aerial photos and satellite images, are unable to detect surface fuel because the ground is often obscured by the forest canopy (Asner 1998; Elvidge 1988; Lachowski and others 1995). Even if sensors were able to view the ground, the resolution of the imagery makes it difficult to distinguish between fuel components on the ground and between surface fuel and fuel suspended in the canopy (Keane and others 2001). Second, high variability in fuel loading and other vegetation characteristics across time and space is a confounding property of fuel that prevents it from being accurately mapped (Agee and Huff 1987; Brown and See 1981; Harmon and others 1986). Fuel variability within a stand can often equal or be greater than the variability of fuel across the landscape (Brown and Bevins 1986; Brown and See 1981; Jeske and Bevins 1979). Brown and Bevins (1986) found few statistically significant differences in fuel loadings between vegetation types and biophysical settings because of the vast differences in stand histories between areas with similar environments. This finding indicates that fuel is not always related to mapped vegetation categories. Keane and others (2001) summarized four general strategies commonly used to map fuel: 1) field reconnaissance, 2) indirect mapping with remote sensing, 3) direct mapping with remote sensing, and 4) biophysical gradient modeling. The indirect mapping with remote sensing approach recognizes the inability of imagery to directly map fuel; thus, other, more easily mapped ecosystem characteristics are used instead as surrogates for fuel. This approach assumes certain biological properties can be accurately classified from remotely sensed imagery, and these attributes, most often related to the vegetation, correlate well with fuel characteristics or fuel models. Field reconnaissance methods map fuel through direct observation, whereas remote sensing methods assign fuel characteristics using imagery data. (Verbyla 1995). Lastly, the biophysical gradient modeling approach uses environmental gradients and biophysical modeling to create fuel maps. Environmental gradients are those biogeochemical processes, such as climate, topography, and disturbance that directly influence vegetation and fuel dynamics. In the LANDFIRE Prototype fuel mapping effort, we integrated the indirect remote sensing approach with the biophysical gradient modeling approach to map surface fuel, and integrated the direct remote sensing mapping approach with the biophysical gradient modeling approach to map canopy fuel.

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on the procedure followed in developing maps of surface and canopy fuel characteristics, which served as important core products of the LANDFIRE Prototype Project.

Creating the LANDFIRE Fuel Database

The LANDFIRE fuel database was derived from the LANDFIRE reference database (LFRDB) (Caratti, Ch. 4) and compiled so that fuel layers could be directly created based on other LANDFIRE vegetation and biophysical data layers – specifically, the potential vegetation type (PVT) layer (Frescino and Rollins, Ch. 7), the cover type (CT) layer, and the structural stage (SS) layer (Zhu and others, Ch. 8). This database was designed such that each PVT-CT-SS combination was assigned a set of fuel attributes. These fuel attributes were quantified in the following order of priority: 1) from field data, 2) from published literature, and 3) from estimates of experienced wildland fuel professionals.

The LANDFIRE fuel database was used for several purposes: First, it was used to create the surface fuel layers that did not have field data represented in the LFRDB. For example, the FBFM13 and FBFM40 values were rarely recorded in the LFRDB, so these layers were impossible to create using standard mapping and spatial modeling procedures. We had to therefore assign fuel model classification categories to each PVT-CT-SS combination using the myriad of variables describing vegetation composition and condition contained in the LANDFIRE fuel database. This fuel database was also used to assign values to the map where mapping models were in error. Moreover, it could also be used as a quasi-validation or data-check to ensure map consistency. And lastly, it could be used as a reference and guide to step down LANDFIRE fuel assignments to local applications. For example, managers may decide to change assigned fuel models to reflect local conditions.

The database was designed with the following fields:

1. Mapping zone – EROS mapping zone identification number
2. PVT – Potential vegetation type code
3. SCLASS – Succession class code, which represents a combination of cover type and structural stage
4. FBFM13 – Albini (1976) standard 13 fire behavior fuel models (see Anderson 1982) including additional models for water and rock
5. FBFM40 – Scott and Burgan (2005) 40 fire behavior fuel models
6. Default FCCs – Default fuel characterization classes from Sandberg and others (2001)
7. FLMs – Fuel loading models from Lutes and others (in preparation)
8. Canopy height (m) – Uppermost height of the canopy layer
9. Canopy base height (m) — Height at which crown bulk density exceeds 0.011 kg m^{-3}
10. Canopy cover (%) – Percentage of vertically projected tree cover
11. Canopy bulk density (kg m^{-3}) – Maximum bulk density of all vertical layers comprising the forest canopy

Creating Maps of Surface Fuel

The methods used to develop the surface fuel layers were distinctly different from the approach used for the canopy layers. We used a classification or rule-based approach in which fuel model categories from each classification (FBFM13, FBFM40, default FCCs, and FLMs) were assigned to combinations of mapped attributes from other LANDFIRE products using generalized rule sets. A rule set is a hierarchically nested set of rules that assigns surface fuel models to combinations of LANDFIRE data layers using information from the LANDFIRE fuel database (see appendix 12-A). This approach has been used successfully in several recent fuel mapping efforts and fit the design criteria for the LANDFIRE Prototype (Keane and others 1998a; Keane and others 1998b; Keane and Rollins, Ch. 3; Menakis and others 2000). The procedure for the surface fuel mapping process is detailed in Ch. 2: appendix 2-A.

For the LANDFIRE Prototype, the rule-based approach to the mapping of surface fuel was the only available technique for two main reasons: First, statistical modeling approaches could not be used because only a small fraction of the LFRDB contained information about fuel models. This meant that we could not use the classification and regression tree (CART) (Breiman and others 1984) analysis techniques that were applied in other LANDFIRE mapping tasks because there were insufficient reference data to build the statistical functions for spatially predicting surface fuel models. This lack of data was especially a problem in the case of the two new fuel classifications developed during the LANDFIRE Prototype – FBFM40 and FLMs – because they had never been used in the field. Second, there were no existing field and database keys with which to consistently identify fuel models from variables commonly included in field reference databases, such as canopy cover, vegetation type, fuel loading, and tree density. Efforts are currently underway to create field and database keys for each fuel model classification so that fuel models can be assigned to individual plots.

All surface fuel maps were created using rule sets where, in the most simple cases, surface fuel models were assigned to solely PVT-CT-SS combinations (Ch. 2: appendix 2-A). This rule-based approach also allowed for the inclusion of additional data when surface fuel models could not be uniquely described by a PVT-CT-SS combination. In these cases, the PVT-CT-SS stratification was augmented with other data that determine the distribution of surface fuel across landscapes, such as topography or geographic location. For example, a rule set might assign a FBFM13 fuel model to a PVT-CT-SS combination on slopes greater than 50 percent in the northern part of a mapping zone.

We gave confidence rankings to each of the default FCC assignments based on which attributes from the FCCS fuelbed database (Sandberg and Ottmar 2001) were applied. We gave the highest ranking (1) to fuelbeds that had species lists identical to the LANDFIRE PVT and CT species lists. We assigned a confidence ranking of 2 if we needed to associate fuelbeds with unique vegetation classes based on vegetation characteristics and actual and inferred (through expert knowledge) site characteristics. In other words, the default FCCs' vegetation description was similar to but not exactly the same as the LANDFIRE vegetation map units. Finally, using expert knowledge, we assigned a confidence ranking of 3 to the remaining fuelbeds where the information in the FCCs' vegetation description was not represented by the LANDFIRE vegetation map units. For fuelbeds given a confidence ranking of 3, we determined the most appropriate fuelbed based on species composition and structure. In certain cases, we were unable to associate some of the fuelbeds with a unique vegetation class combination because there was not an appropriate fuelbed to represent this situation, even with an expanded definition.

Creating Maps of Canopy Fuel

We developed the two canopy fuel maps (CBD, CBH) for the forested lands of Zone 16 and Zone 19 using a predictive landscape modeling approach (Franklin 1995). This approach integrates remote sensing, biophysical gradients, and field-referenced data to generate maps of canopy bulk density and canopy base height. These canopy fuel characteristics were calculated for numerous plots in the LFRDB and then augmented with a set of mapped predictor variables in a classification and regression tree (CART) approach to predict crown fuel attributes across the two prototype mapping zones.

Calculating canopy fuel characteristics—The first step was to calculate CBD and CBH using FUELCALC, a prototype program developed by Reinhardt and Crookston (2003). FUELCALC computed several canopy fuel characteristics for each field reference plot from the LFRDB based on allometric equations relating individual tree size, canopy, and species characteristics to crown biomass. The canopy characteristics for a stand are computed from a list that specifies the tree species, density (trees per unit area), diameter at breast height (DBH), height, crown base height, and crown class. FUELCALC computes vertical canopy fuel distribution using algorithms that evenly distribute crown biomass over the live crown for each tree. For each plot, the program then divides the canopy into horizontal layers of a user-specified width and reports the CBD value of the layer with the greatest bulk density. The CBH value for each plot is reported as the height of the lowest layer of the canopy that has a bulk density value greater than 0.011 kg m^{-3}. FUELCALC estimates for CH and CC were not used in the mapping process since these maps were created by Zhu and others (Ch. 8).

For the LANDFIRE Prototype FUELCALC canopy fuel calculations we used the Forest Inventory and Analysis (FIA; Gillespie 1999) data from the LFRDB because they provided consistent information and FUELCALC input values across both prototype zones. There were a total of 1,806 FIA plots that fell within the Zone 16 boundary. This included over 32,000 individual tree records. Zone 19 encompassed a total of 1,988 FIA forested plots with over 44,600 individual tree records. We derived crown depth (a FUELCALC input) from the FIA compacted crown ratio attribute, defined as the percentage of the total height of a tree that supports live foliage (Miles and others 2001). We did not attempt to deconstruct the live crown ratio.

Mapped predictor data—Our hypothesis was that plot-level estimates of canopy fuel are correlated with spectral (from satellite imagery) and biophysical (from LANDFIRE computer models) gradients. As a basis for developing a database of mapped predictor variables, we used data from a leaf-on (June 2000) Landsat image and a leaf-off (October 2000) Landsat image. We included three visible bands, three infrared bands, a thermal band, three tasseled-cap transformation bands (brightness, greenness, and wetness) (Huang and others 2001), and a normalized difference vegetation index for each image – totaling 22 variables derived from spectral information (table 4).

The database of mapped predictor variables also included a suite of biophysical gradient layers that were created using WXFIRE, an ecosystem simulation model (Keane and Holsinger 2006; Keane and Rollins, Ch. 3), and four topographic gradient layers. The WXFIRE model integrates DAYMET (Running and Thornton 1996; Thornton and others 1997; Thornton and others 2000) climate data with landscape data and site specific parameters (such as soils and topography) and interpolates 1-km grid DAYMET climate variables to a 30-m grid cell resolution, thereby generating spatially explicit maps of climate and ecosystem variables at fine spatial resolutions. WXFIRE outputs a total of 33 variables (See Holsinger and others, Ch. 5 for detailed information about WXFIRE and biophysical gradient modeling in the LANDFIRE Prototype). However, this exhaustive list was reduced (winnowed) to 16 variables for Zone 16 (table 5) and 18 variables for Zone 19 (table 6) using exploratory analyses of principle components and correlation matrices.

The topographic gradients included four variables derived from the National Elevation Dataset (NED): elevation, percent slope, classified aspect, and a topographic position index. The topographic position index is a metric scaled from 0 to 1 defining the position on a slope, with 0 being the bottom of a valley and 1 the top of a ridge (table 7). In addition to the mapped predictor variables described above, we included four LANDFIRE products as additional predictors: maps of CT, SS, CH, and CC (Long and others Chapter 6; Zhu and others, Chapter 8).

Table 4—Zone 16 and Zone 19 satellite imagery predictor layers for canopy bulk density and canopy base height models.

Variable	Description
onb1	Landsat Leaf-on – band 1 (visible blue)
onb2	Landsat Leaf-on – band 2 (visible green)
onb3	Landsat Leaf-on – band 3 (visible red)
onb4	Landsat Leaf-on – band 4 (near infrared)
onb5	Landsat Leaf-on – band 5 (mid infrared)
onb6	Landsat Leaf-on – band 7 (mid infrared)
onb9	Landsat Leaf-on – band 9 (thermal)
onndvi	Landsat Leaf-on – normalized difference vegetation index
offb1	Landsat Leaf-off – band 1 (visible blue)
offb2	Landsat Leaf-off – band 2 (visible green)
offb3	Landsat Leaf-off – band 3 (visible red)
offb4	Landsat Leaf-off – band 4 (near infrared)
offb5	Landsat Leaf-off – band 5 (mid infrared)
offb6	Landsat Leaf-off – band 7 (mid infrared)
offb9	Landsat Leaf-off – band 9 (thermal)
offtc1	Landsat Leaf-off – tassel-cap transformation (brightness)
offtc2	Landsat Leaf-off – tassel-cap transformation (greenness)
offtc3	Landsat Leaf-off – tassel-cap transformation (wetness)
offndvi	Landsat Leaf-off – normalized difference vegetation index

Table 5—Zone 16 biophysical gradient predictor layers, produced using the WXFIRE model, for canopy bulk density and canopy base height regression tree models.

Variable	Units	Description
aet	kgH20/yr	Actual evapotranspiration
dday	degree C	Degree-days
dsr	days	Days since last rain
evap	kgH20 m^{-2} day^{-1}	Evaporation
gc_sh	s m^{-1}	Canopy conductance to sensible heat
gl_sh	s m^{-1}	Leaf-scale stomatal conductance
outflow	kgH20m^{-2} day^{-1}	Soil water lost to runoff and ground
pet	kgH20 yr^{-1}	Potential evapotranspiration
ppt	cm	Precipitation
psi	-Mpa	Water potential of soil and leaves
rh	%	Relative humidity
snow	cm	Amount of snowfall
srad.fg	w m^{-2}	Shortwave radiation for the site
tmin	degree C	Minimum daily temperature
trans	kgH20 m^{-2} day^{-1}	Soil water transpired by canopy
vmc	scalar	Volumetric water content

Table 6—Zone 19 biophysical gradient predictor layers, produced using the WXFIRE model, for canopy bulk density and canopy base height regression tree models.

Variable	Units	Description
aet	kgH20 yr^{-1}	Actual evapotranspiration
dday	degree C	Degree-days
dsr	days	Days since last rain
evap	kgH20 m^{-2} day^{-1}	Evaporation
gc_sh	s m^{-1}	Canopy conductance to sensible heat
outflow	kgH20 m^{-2} day^{-1}	Soil water lost to runoff and ground
pet	kgH20 yr^{-1}	Potential evapotranspiration
ppfd	umol m^{-2}	Photon flux density
ppt	cm	Precipitation
psi	-Mpa	Water potential of soil and leaves
rh	%	Relative humidity
snow	cm	Amount of snowfall
srad.fg	w m^{-2}	Shortwave radiation for the site
swf	dimension	Soil water fraction
tave	degree C	Average daily temperature
tmin	degree C	Minimum daily temperature
trans	kgH20 m^{-2} day^{-1}	Soil water transpired by canopy
vmc	scalar	Volumetric water content

Table 7—Zone 16 and Zone 19 topographic gradient predictor layers for canopy bulk density and canopy base height regression tree models.

Variable	Units	Description
elev	meters	Elevation
asp	8 classes	Aspect class
slp	%	Slope
posidx	index (0-1)	Topographic position index

Classification and regression trees (CART)—As in the mapping of PVT, CT, and SS (Frescino and Rollins, Chapter 7; Zhu and others, Chapter 8), we used regression trees (Breiman and others 1984) to model and map canopy fuel across zones 16 and 19. Regression tree models are rule-based predictive models in which continuous data values are recursively divided into smaller subsets based on a set of rules. The rules are constructed from available training data in which observations are delineated into smaller subsets of more homogenous classes. For every possible split of each predictor variable, the within-cluster sum of squares about the mean of the cluster on the response variable (the theme being mapped) is calculated. The predictor defines a split at the point that yields the smallest overall within-cluster sum of squares (Breiman and others 1984). For a detailed description of the use of CART in the LANDFIRE Prototype, see Frescino and Rollins, Chapter 7. We tried other statistical approaches, such as nearest neighbor, discriminant analysis, and generalized linear modeling but decided to employ the regression tree approach because it consistently generated valid models that created realistic maps.

The regression trees for modeling canopy fuel were generated using the commercially available machine-learning algorithm, Cubist (Quinlan 1986; Quinlan 1993; Rulequest Research 2004). Cubist offers a fast and efficient means for building regression tree models and applying these models to large areas (Homer and others 2002; Huang and others 2001; Moisen and others 2004; Xian and others 2002; Yang and others 2003). Cubist generates rule-based models with one or more rules defining the conditions in which a linear regression model is established. Cubist can also build "composite models," where a rule-based model is combined with an instance-based (nearest-neighbor) model (Quinlan 1993).

Other features of Cubist include 1) generation of committee models, 2) simplification of (pruning) the models, and 3) extrapolation of the model predictions. First, the committee models are made up of multiple rule-based models where each model "learns" from the prediction errors of the previously built model. The final model's predictions are an average of the predictions of the previously built models. Second, to simplify or prune a model in Cubist, you can specify the percentage of cases that meet the conditions of a rule or explicitly define the maximum number of rules allowed. Third, the extrapolation feature defines the percentage factor in which model predictions can occur outside the range of values determined by the training data (Rulequest Research 2004).

Although not fully automated, the process for modeling and mapping canopy fuel was simplified using a suite of tools developed by Earth Satellite Corporation (2003) in support of the National Land Cover Database (NLCD) project (Vogelmann and others 2001). These tools were developed to integrate the Rulequest Cubist software package (Rulequest Research 2004) with ERDAS Imagine image-processing software (ERDAS, Inc. 2001). We used the NLCD Sampling Tool to set up the input files needed to build the models in Cubist and the NLCD Classifier Tool to generate the final map. The Sampling Tool allows a user to input a spatially explicit layer of field-referenced training data as a dependent variable and multiple spatially explicit gradient layers as independent variables; the tool then outputs the files needed to execute Cubist. The Classifier Tool applies the regression tree model output from Cubist across the specified spatial extent or a specified masked extent.

To meet the input requirements of the NLCD mapping tool and to improve the efficiency of the modeling process, we followed three pre-processing rules: 1) all layers must be ERDAS Imagine images, 2) all layers must have the same number of rows and columns, and 3) all layers must be scaled to size 16-bit or smaller and have positive values. The output from the Sampling Tool includes a data text file, which contains values from the model response and the corresponding value of the model predictor layers for each georeferenced training site, and a file identifying the model input names and data types. We built multiple Cubist models for CBD and CBH for each prototype mapping zone – exploring the different features of Cubist – and selected the model having the lowest error as the model to use for prediction. The final maps of both CBD and CBH were created using the Classifier Tool based on the predictor variables listed in table 8.

Performing QA/QC Procedures

The LANDFIRE fuel layers (both crown and surface fuel) needed to be not only congruent across all fuel layers, but also consistent with all other LANDFIRE layers. It was essential that all pixels in the LANDFIRE data layers have logical combinations of vegetation, fuel, fire, and biophysical parameters. The process used to ensure that pixels across layers were assigned logical map categories was called the LANDFIRE Quality Assurance/Quality Control (QA/QC) procedure. This process was designed for the Zone 16 and Zone 19 fuel maps but not implemented because of administrative problems. In addition, late completion of other LANDFIRE tasks precluded a comprehensive comparison with the fuel

Table 8—Zone 16 and Zone 19 modeled predictor layers for canopy bulk density and canopy base height regression tree models.

Variable	Units	Description
evtr	class	Forest - cover type (rectified)
ssr	class	Forest - structure stage (rectified)
forht	m	Forest - average dominant height
forcov	%	Forest - canopy cover

layers. The LANDFIRE Prototype effort performed only minor logic checks and data scans for inconsistent or abnormal data values. A more comprehensive QA/QC procedure is currently being implemented for LANDFIRE National.

Performing the Accuracy Assessment

Surface fuel layers—Accuracy assessment of the mapped fire behavior fuel models (FBFM13 and FBFM40) proved problematic in the LANDFIRE Prototype for two reasons: 1) there can be more than one correct FBFM assignment in the field and 2) a lack of sufficient geo-referenced field data where FBFM13 and FBFM40 categories were recorded in the field. The FBFM maps were developed to serve as inputs to the fire behavior prediction software (BEHAVE and FARSITE); however, there are numerous other weather, wind, and fuel moisture variables that influence fire behavior simulations. Consequently, more than one FBFM can lead to the same fire behavior characteristics if other environmental variables are adjusted. Accuracy can only be truly tested during specific wildland fires because the primary purpose of the FBFM is to predict fire behavior, not describe fuel characteristics. In such cases, the expected fire behavior can be compared to the observed behavior and the accuracy assessed for that specific situation. The lack of comprehensive field-referenced data prevented a conventional accuracy assessment of all the surface fuel layers. The FBFM40 data were new and therefore hadn't yet been used by field personnel.

The surface fire behavior fuel models (FBFMs), fuel loading models (FLMs), and default FCCS fuelbeds were mapped based on rule sets that were used to link FCCs to unique combinations of PVT, CT, and SS. To test the accuracy of the rule sets, we assigned surface fuel attributes to the PVT-CT-SS combinations for each plot in the LFRDB using the map rule sets. We then compared the assigned surface fuel attribute value of the plot to the corresponding pixel location for that plot on the fuel model maps. We assumed the plot assignment was correct and determined our accuracy based on this surface fuel attribute value.

Canopy fuel layers—We randomly withheld a percentage of the total number of training sites from the LFRDB for each mapping zone for independent accuracy assessment of the final maps. For Zone 16, we withheld 20 percent of the total plots, leaving 1,304 plots for modeling CBD and 325 plots for assessing the accuracy of CBD predictions; we had 1,098 for modeling CBH and 275 for assessing the accuracy of CBH predictions (table 9). Regression trees were pruned and modified based on the cross-validation accuracy assessment.

After analyzing error distribution for Zone 16, we determined for Zone 19 that a subset of only 10 percent of the total plots would be sufficient for assessing accuracy, and the consequent increase in the number of plots used for modeling improved the performance of the model. This resulted in 1,768 plots for modeling CBD, 184 plots for testing CBD predictions, 674 plots for modeling CBH, and 198 for testing CBH predictions (table 9). The data distributions of the model data sets for CBD and CBH (zones 16 and 19) are shown in figure 1. The test data sets had identical distributions.

Table 9—Number of plots used for modeling and accuracy assessment. Error estimates for canopy bulk density (CBD) are in kg m^{-3} and for canopy base height (CBH) in meters.

Zone	Model	Model plots	Test plots	Average error	Relative error	Correlation coefficient
Z16	CBD	1304	325	0.03	0.55	0.76
	CBH	1098	275	1.9	0.65	0.63
Z19	CBD	1768	184	0.05	0.72	0.66
	CBH	1674	198	1.9	0.91	0.38

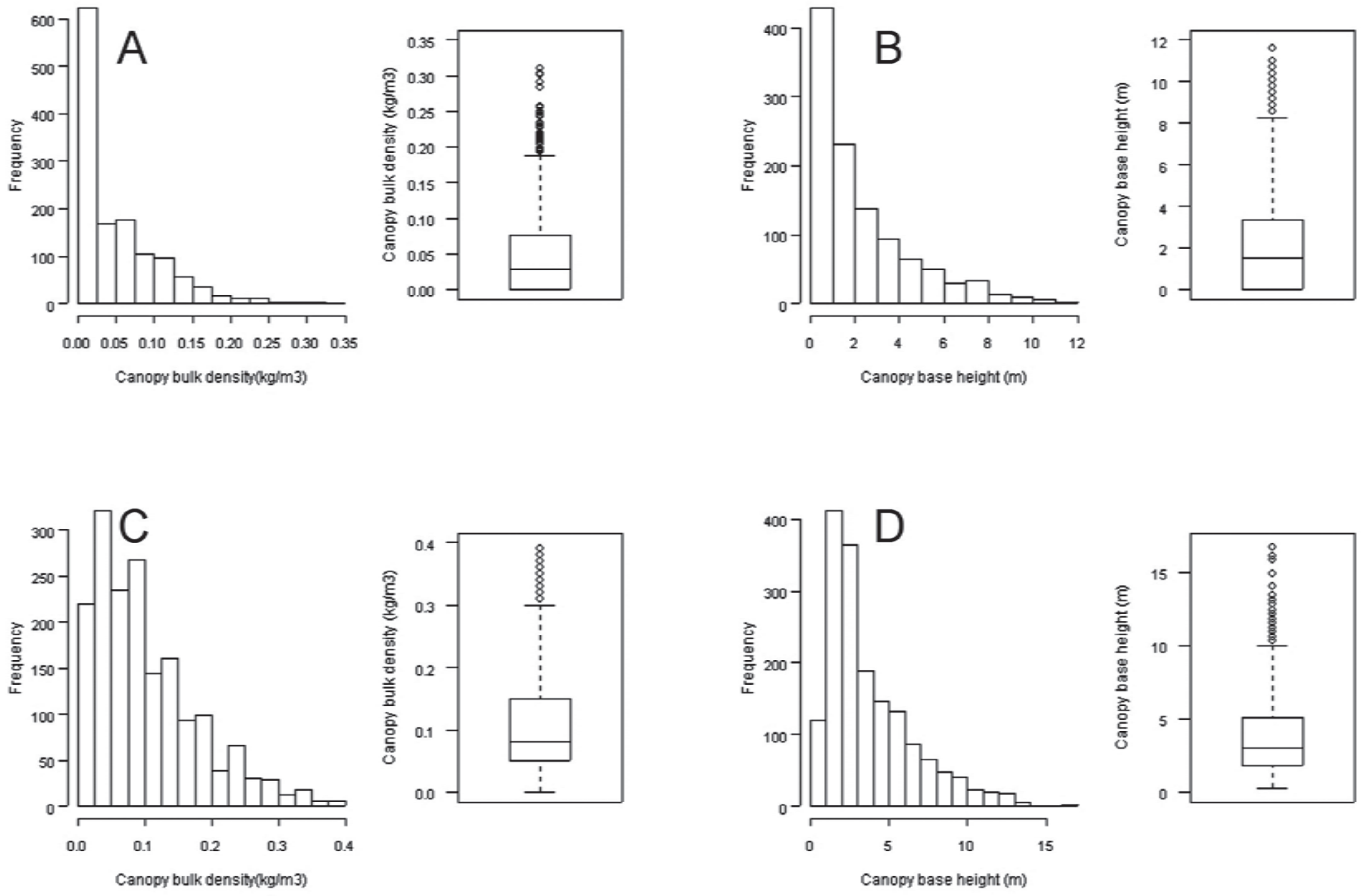

Figure 1—Distribution of plots (frequency) across canopy bulk density (CBD) and canopy base height (CBH) values across the two prototype zones. They are arranged in the following order a) CBD model data set for Zone 16, b) CBH model data set for Zone 16, c) CBD model data set for Zone 19, and d) CBH model data set for Zone 19. The test data sets for CBD and CBH used to validate and assess accuracy of the statistical models had identical distributions for both zones.

Cubist automatically tests the model predictions at each test site and outputs three measures of error: an average error, a relative error, and a correlation coefficient. The average error represents the magnitude of the errors defined by the predicted value compared to the actual value. The relative error is the ratio of the average error to the error that would result from always predicting the mean value. The correlation coefficient measures the agreement between the predicted values and the actual values. Cubist also outputs a scatter plot of the predicted values against the actual values. This is used for visual evaluation of the regression models (Rulequest Research 2004).

Results

Surface Fuel

The FBFM40 and FLM classifications were not completed in time for the mapping of surface fuel models for Zone 16, so only maps of FBFM13 and default FCCs are presented in figure 2. These classifications were completed prior to the mapping of Zone 19, but, unfortunately, the FCCS fuelbeds for this region were unavailable. Therefore, only three surface fuel maps are shown in figure 3 for Zone 19. A summary of the area in each mapping zone by the four fuel classifications is shown in table 10.

Canopy Fuel

Mapping Zone 16—The maps of CBD and CBH for Zone 16 are shown in figure 4. We selected a Cubist model built using a composite model as the best model for predicting CBD across the zone. This model was produced by combining a rule-based model with an instance-based model and adjusting the results based on the seven nearest (most similar) neighbors. Five committee models were built to improve the predictive ability of the model. We set the minimum rule cover at one percent, under the premise that that the conditions associated with any rule should be satisfied by at least one percent of the training cases, and we allowed a ten percent extrapolation of values across the total range of values. Main predictor layers are shown in table 8.

A comparison of the predicted values with our independent test set for Zone 16 revealed an average error of 0.026 kg m^{-3}, a relative error of 0.55 kg m^{-3}, and a correlation coefficient of 0.76 (table 9). The scatter plot is displayed in figure 5a. For CBH, the model selected as having the best predictive power was also built using a composite model. This model was produced by a rule-based model adjusted by six nearest neighbors and four committee models. According to our accuracy measures, the average error was 0.39 m, the relative error was 0.65 m, and the correlation coefficient was 0.63 (table 9). The corresponding scatter plot is shown in figure 5b.

The CBD model included imagery variables that are typical for distinguishing vegetative characteristics (Campbell 1987), biophysical gradients that explain vegetation-water interactions, and topographic gradients explaining the local variation across the zone. The CBH model included transformed imagery variables (offtc1, onb3, and onb5 in table 4), water-related biophysical gradients (aet, pet, ppt, and psi in table 5), and elevation (table 7). The inclusion of transformed imagery variables in the CBH model suggests that there are no direct relationships between CBH and any one band signature. The inclusion of spectral and biophysical gradients as relevant predictors in the models indicates a strong correlation between canopy fuel characteristics and both vegetation and ecological site characteristics.

Mapping Zone 19—The maps of CBD and CBH for Zone 19 are shown in figure 6. For CBD, we created ten committee models, set the minimum rule cover to four percent of the training cases, and allowed ten percent extrapolation. For CBH, we created seven committee models, set a four percent minimum rule, and allowed extrapolation of ten percent.

The accuracy assessment for the CBD model revealed a 0.05 kg m^{-3} average error, a 0.72 kg m^{-3} relative error, and a correlation coefficient of 0.66. For CBH, the errors were quite low, with an average error of 1.9 m, a relative error of 0.91 m, and a correlation coefficient of 0.38 (table 9). The relative error of 0.91 suggests that the model for predicting CBH in Zone 19 did not achieve accuracy any higher than the pure mapping of a mean CBH across the zone. The scatter plot of predicted versus real values, shown in figures 5c and 5d, demonstrates that the model over-predicted low values of CBH and under-predicted high values of CBH.

The set of variables that were important for CBD and CBH discrimination showed patterns similar to those in Zone 16. Imagery variables of onb3, onb5, and offtc1 (table 6) were the prominent variables that defined the splits for the canopy bulk density model; followed by biophysical gradients of pet, ppt, dsr, tmin, rh, elev, and posidx (table 7); and modeled variables of evtr and forht. For Zone 19 CBH, the imagery transformations of offtc1 and offtc2 were prominent again,; with gradients of dday, ppt, evap, srad_fg, dsr, elev, and slp; and modeled variables of evtr and forth (table 7).

Table 10—A summary of the area (km^2) within Zone 16 and Zone 19 occupied by the ten most frequent fuel models from each of the four fuel model classifications stratified by potential vegetation type (PVT). The acronyms are defined as follows: FBFM13 = Anderson (1982) 13 standard fire behavior fuel models; FBFM40 = Scott and Burgan (2005) 40 fire behavior fuel models; Default FCCs = default fuel characterization classes (Sandberg and others 2001); and FLMs = fuel loading models by Lutes and others (in preparation). Note: default FCCs were not mapped for Zone 19 because of an insufficient number of fuelbeds and FLMs and FBFM40 were not mapped for Zone 16 because the classifications were not finished in time to map fuel models for that zone.

FBFM13		FBFM40		Default FCCs		FLM	
Model	**km^2**	**Model**	**km^2**	**Classes**	**km^2**	**Model**	**km^2**
				Zone 16			
		- - Not Available - -				- - Not Available - -	
6	25,333.79			Big Sagebrush Steppe	9,403.89		
8	15,088.17			Pinyon-Juniper Woodland	7,001.88		
5	12,374.84			Western Juniper/Sagebrush Shrubland	6,731.48		
2	6,047.90			Subalpine Fir-Engelmann Spruce-Lodgepole Pine Forest	5,979.98		
10	4,012.47			No Fuelbed Assigned	5,498.27		
Barren	1,944.02			Quaking Aspen Forest with mixed conifer understory	5,434.58		
Agriculture	1,877.33			Quaking Aspen Forest	3,764.33		
1	1,345.12			Big Sagebrush Steppe	3,433.29		
Urban	923.55			Western Juniper/Sagebrush-Bitterbrush	3,196.28		
9	439.63			Montane Bigtooth Maple - Gambel Oak / Ponderosa Pine Mixed Forest	2,304.40		
Water	348.17			Douglas fir (dominated) / Pacific Ponderosa Pine Mixed Conifer Forest w/ shrub	2,130.99		
3	219.84			White Fir / Gambel Oak Mixed Forest	1,966.02		
Snow/Ice	1.54			Barren	1,944.02		
				Black Cottonwood-Alder-Ash Riparian Forest	1,932.22		
				Agriculture	1,877.33		
				Overmature Lodgepole Pine Forest	1,721.88		
				Ponderosa Pine-Pinyon-Juniper	1,191.20		
				Perennial Grass Savanna	975.75		
				Urban	923.55		
				Gambel Oak - Sagebrush Shrubland	852.86		
				Zone 19			
				- - - - - - - - - - - - Not Available - - - - - - - - - - - -			
8	39,958.60	TL3	36,098.67			1	46,296.11
2	28,087.17	GS2	21,196.08			7	25,019.09
1	13,458.08	SH2	12,136.64			4	10,935.65
5	13,209.15	TU5	7,466.23			No Fuel	10,415.65
Agriculture	7,397.57	NB3	7,397.57			2	9,276.64
6	6,359.86	GR4	7,306.96			8	7,435.80
10	1,884.77	GR2	6,528.90			5	3,622.28
Barren	1,456.84	TL1	2,795.22			6	1,159.58
Water	1,184.94	GR1	2,786.51				
9	787.52	GS1	2,746.44				
Urban	362.41	TU1	2,573.01				
Snow/Ice	13.88	NB9	1,456.84				
		NB8	1,184.94				
		SH7	701.63				
		TL6	670.30				
		NB1	362.41				
		TL9	354.45				
		SH1	277.55				
		TL2	106.46				
		NB2	13.88				

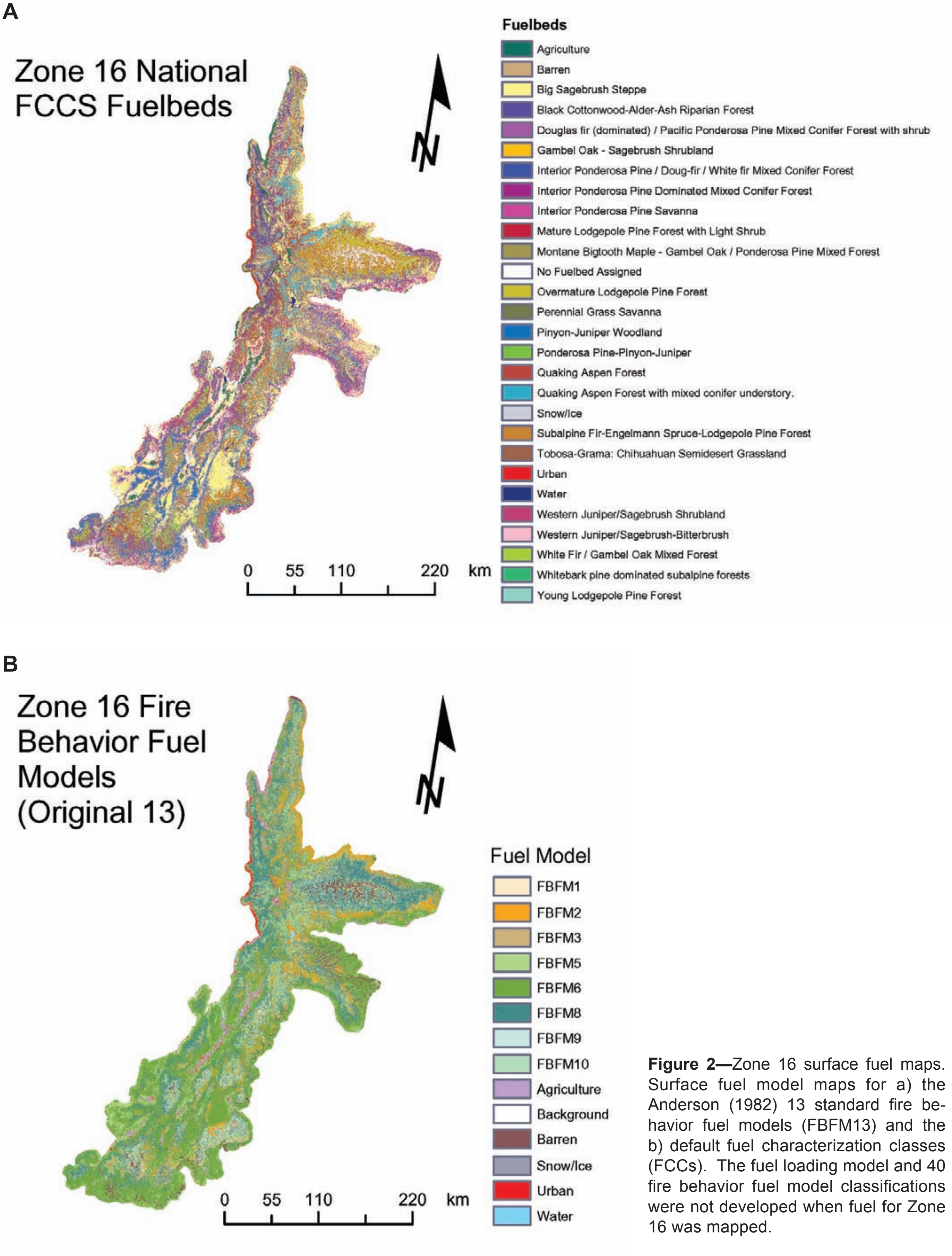

Figure 2—Zone 16 surface fuel maps. Surface fuel model maps for a) the Anderson (1982) 13 standard fire behavior fuel models (FBFM13) and the b) default fuel characterization classes (FCCs). The fuel loading model and 40 fire behavior fuel model classifications were not developed when fuel for Zone 16 was mapped.

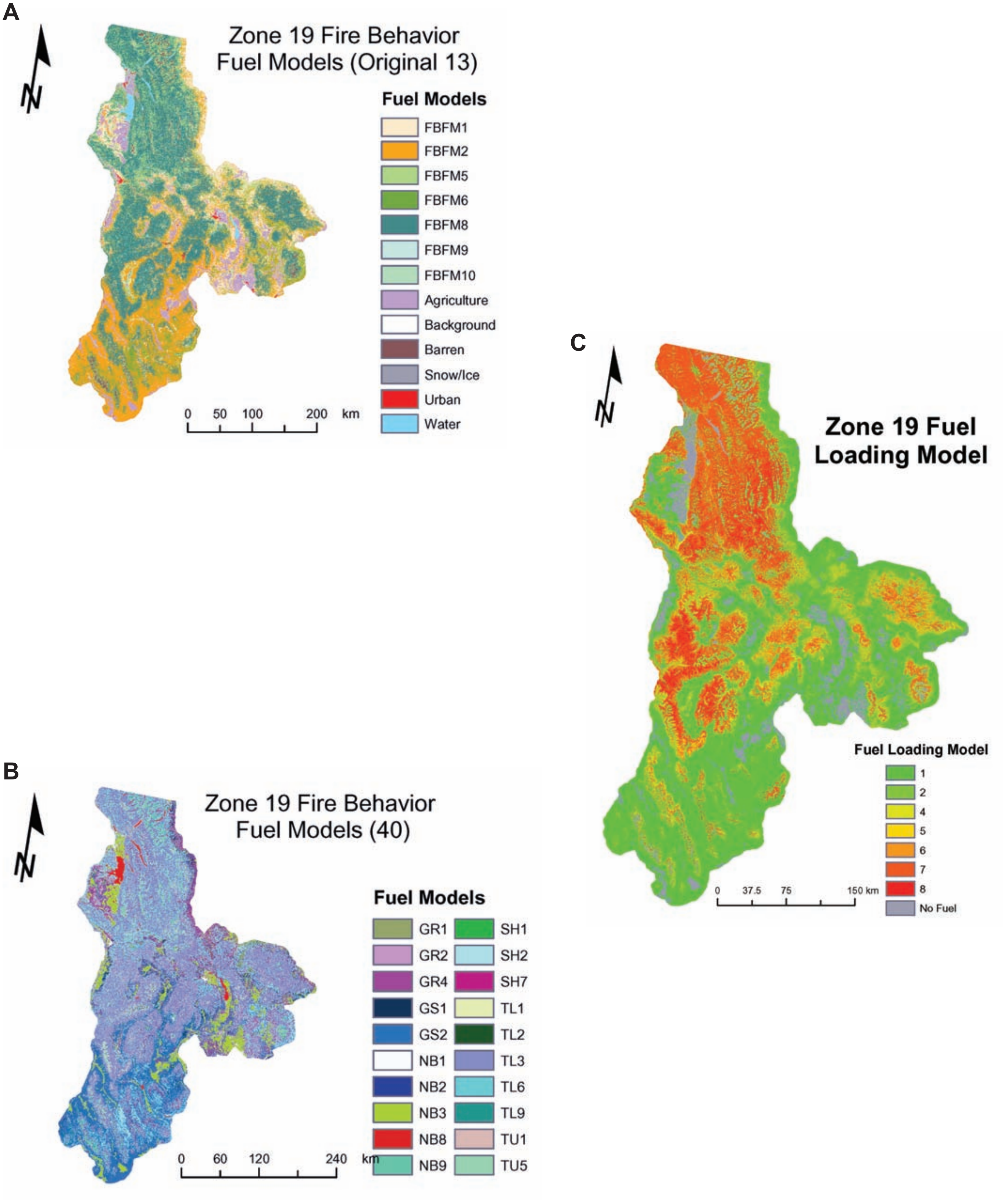

Figure 3—Zone 19 surface fuel maps. Surface fuel model maps for a) the Anderson (1982) 13 standard fire behavior fuel models (FBFM13), b) Scott and Burgan (2005) 40 fire behavior fuel models (FBFM40), and c) the default fuel characterization classes (default FCCs).

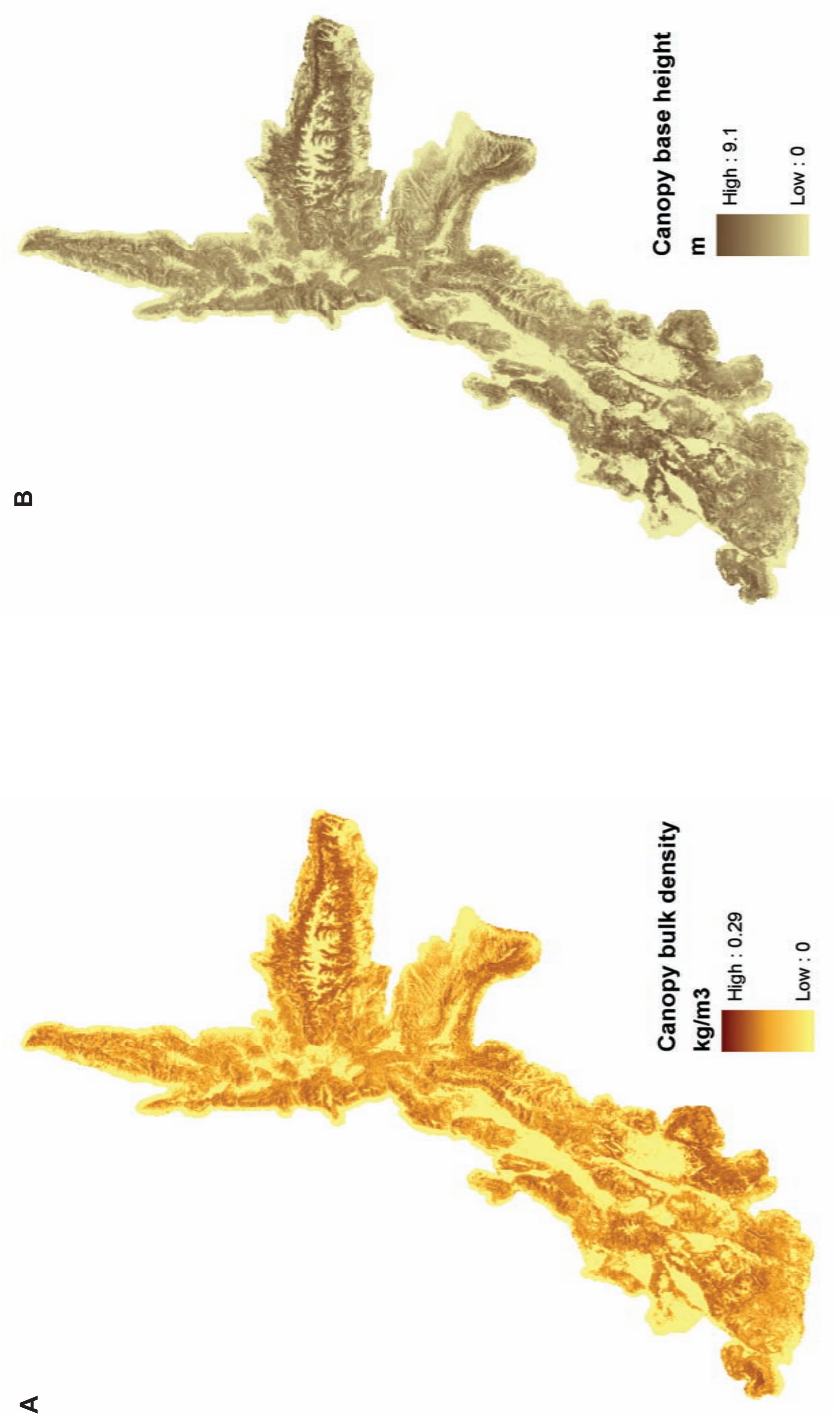

Figure 4—Zone 16 canopy fuel layers. Shown are maps of a) canopy bulk density (CBD) and b) canopy base height (CBH) for Zone 16.

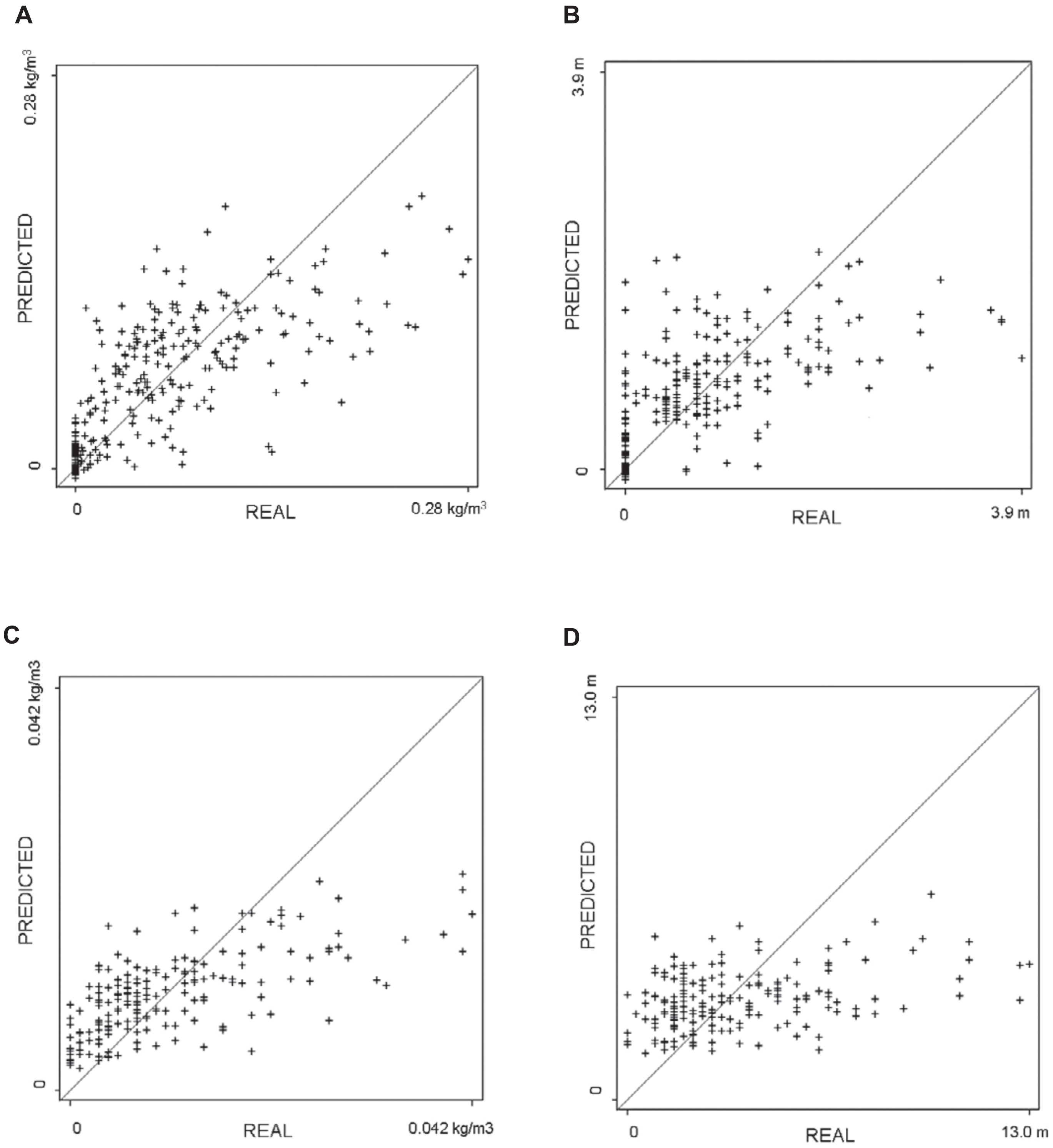

Figure 5—Accuracy assessment of the predicted versus real (observed) values for canopy bulk density (CBD) and canopy base height (CBH) for both mapping zones. The diagonal line indicates full agreement between the model and field data. The scatterplots are: a) Zone 16 canopy bulk density, b) Zone 16 canopy base height, c) Zone 19 canopy bulk density, and d) Zone 19 canopy base height.

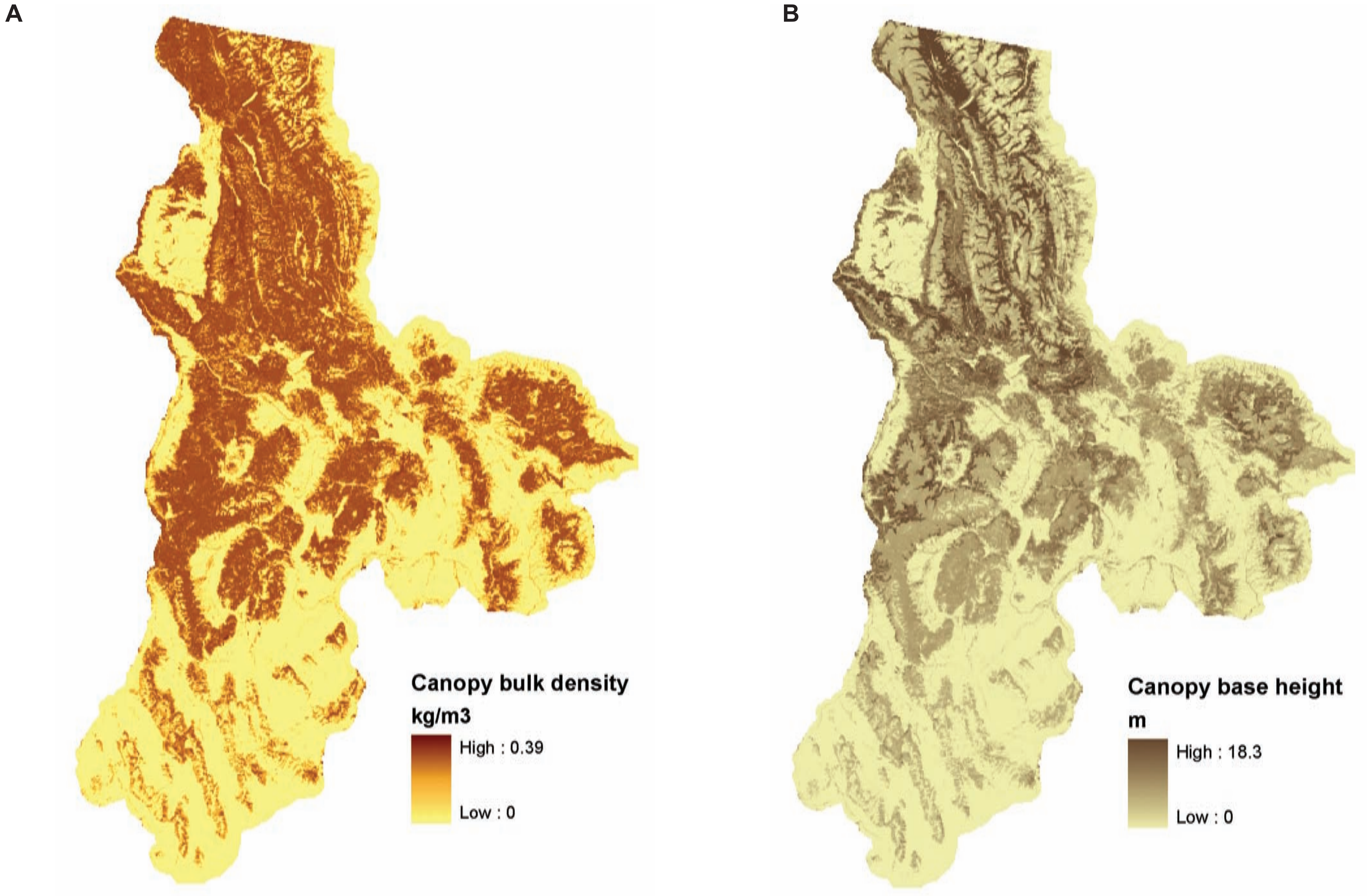

Figure 6—Zone 19 canopy fuel layers. Shown are maps of a) canopy bulk density (CBD) and b) canopy base height (CBH) for Zone 19.

Discussion

Surface Fuel Maps

Rule-based approach to fuel mapping—In the LANDFIRE Prototype, we used the classification or rule-based approach to assign fuel models to combinations of vegetation and biophysical settings. Despite limitations, this approach was the most appropriate given the project guidelines, design criteria, and available data (Keane and Rollins, Ch. 3). The fuel maps described in this chapter are important products of the LANDFIRE Prototype Project because they provide critical inputs to fire behavior and effects models commonly used to explore alternative management strategies for implementation of the National Fire Plan. However, it would have been preferable to use the same gradient-based predictive landscape modeling approaches to surface fuel mapping as those used for the mapping of vegetation and canopy fuel (see Frescino and Rollins, Ch. 7 and Zhu and others, Ch. 8) because:

1) the mapping resolution (30 m pixel) would more closely match the resolution of fuel variability as compared with the mapping resolution of PVT-CT-SS combinations (usually mapped as groups of pixels), and this would eventually result in more accurate fire behavior predictions;
2) the resolution of the fuel model classification categories would more closely match the spatial resolution than the PVT-CT-SS resolution (for example, you could have more than one fuel model within a PVT-CT-SS combination using the gradient approach); and
3) the fuel models would be mapped based on the ecological processes and gradients, such as productivity, species composition, and decomposition, that govern the distribution and condition of wildland fuel across landscapes.

Overall, the lack of consistent and accurate field data on fuel in the LANDFIRE Prototype prevented a statistical modeling strategy for fuel mapping. Therefore, if possible, a comprehensive empirical approach should be employed, as in other LANDFIRE tasks, for fuel mapping in the national implementation of LANDFIRE.

The LANDFIRE Prototype did not deliver all surface fuel map products for a number of reasons. First, the fuel classifications (FBFM40, default FCCs, and FLMs) were not completed in time for the LANDFIRE Prototype mapping effort. For Zone 16, we mapped the default national fuelbeds provided to us by the Fire and Environmental Effects Research Team (FERA) in December of 2003. However, these default FCCs were still in draft format. We found that while the default fuelbed set seemed to apply to a wide variety of vegetation and fuel types throughout Zone 16, over 20 percent of the map area – especially the herbaceous and shrub types – was not well-represented by the default FCCS categories. In addition, we found that the fuelbed list was also missing detailed information for large sections of the country. The default FCCs provided with the FCCS software were developed to represent major fuelbeds of concern to fire managers. Many of these defaults were selected through workshops held throughout the country by fire managers and ecologists who were focusing on the problem fuel types in their respective areas. Less hazardous vegetation and fuel types were not emphasized in the development of the FCCS. However, the LANDFIRE Prototype needed to map all vegetation and fuel conditions found within the mapping zones. We anticipated a new and more comprehensive version of the default FCCs prior to mapping Zone 19 since more than a year had passed since the release of the previous version. Unfortunately, we did not receive the new set in time to map Zone 19. However, during this time we determined through discussions with the FERA team that a better way to create a LANDFIRE fuelbed map would be to modify the default fuelbeds to reflect the vegetation and fuel conditions described in the LFRDB, thereby creating custom LANDFIRE fuelbed classes. These would be more meaningful to the LANDFIRE National Project, and custom development is encouraged by FERA. This approach is currently being evaluated for national LANDFIRE implementation. Lastly, because the FLM classification was not completed in time, it was not extensively tested and validated in the LANDFIRE Prototype effort.

Canopy Fuel Maps

Again, training data were the main limiting factor for the statistical regression tree modeling approached used to map CBH and CBD across both zones. However, this limitation was not as severe as during the surface fuel modeling phase. Low accuracies may also have resulted from the quality of the training data used to build and test the models because regression tree performance depends greatly on the quality of the field data used. We conducted our analysis under the assumption that the data perfectly represented ground conditions; however, the fuel database used to estimate canopy fuel may not have been free of errors. The accuracy of the CBD and CBH calculations is dependent upon the accuracy of the tree measurements on the ground as well as the accuracy of the allometric equations used to derive CBD and CBH. Another assumption was that the positional accuracy of the training data was within spatial tolerances (Vogelmann and others, Ch. 13). In other words, each georeferenced location was assumed to match the corresponding pixel value of each predictor. Another source of error in the fuel database was that the FIA tree data crown dimensions were sampled by visually compacting the crown length to eliminate gaps in the canopy, which subjectively and falsely raises the tree crown base height and results in overestimations of CBH. Lastly, the variable plot sampling used in FIA inventory may tend to oversimplify canopy conditions because not all trees that contribute to canopy fuel are measured in the same area.

Another possible reason for the fuel maps' low accuracies were the scale and resolution difficulties encountered when computing CBD and CBH at the plot level using the FUELCALC program; both values are difficult to assess at a stand or pixel level because they have highly variable distributions in the horizontal and vertical dimensions (Keane and others 2005). The limited information gathered for each tree requires that several assumptions be made in order to compute CBD and CBH at the stand level. For example, the CBH was computed as the lowest layer with greater than 0.037 kg m^{-3} bulk density. This layer's bulk density might have been based on data from only one tree or from a seedling/sapling layer that is well below the overstory canopy. Moreover, the threshold of 0.037 kg m^{-3} is a somewhat arbitrary number suggested by Alexander (1988).

The FUELCALC program served as a critical tool in the calculation of canopy characteristics, but this software presented some major limitations. We used a beta version of the program that contained crown biomass algorithms and crown fuel adjustment factors for only 14 Rocky Mountain conifer species. However, this program was preferable over other biomass calculation software packages, such as BIOPAK (Means and others 1994), because it computes crown biomass by fuel component and integrates the results of an extensive canopy fuel sampling effort into biomass components (Scott and Reinhardt 2002, 2005). More tree species must be included in the software so it can be applied to other ecosystems in the U.S. This program needs to be revised to incorporate a user-friendly interface and an extensive users' manual so that it can be used to compare and contrast LANDFIRE map values at local scales. Lastly, FUELCALC output has not been compared with measured canopy characteristics in many areas of the United States and subsequently refined. This model refinement must be completed to ensure credible canopy fuel estimates are being calculated.

Low accuracies of the CBD and CBH regression tree models posed a major problem in canopy fuel mapping. These low accuracies may indicate that plot-level estimates of canopy fuel are not directly or closely correlated with spectral imagery information and gradients of biophysical and topographic characteristics, resulting primarily from the fact that CBH and CBD are canopy characteristics that are hidden from view. Canopy base height is nearly impossible to detect using passive sensors such as Landsat because it is at the bottom of an obstructing canopy. Only active remote sensing techniques, such as Lidar or Radar, have the ability to detect vertical canopy dimensions (Keane and others 2001). Since the passive sensors do not detect canopy depth, it is difficult to determine which canopy layer has the greatest CBD. This is the main reason our statistical models underestimate both CBD and CBH (figs. 5a and 5c).

The difficulty we experienced predicting canopy fuel characteristics indicates that we may have had an inappropriate or insufficient number of predictor gradients. Satellite imagery is an excellent source for describing vegetation patterns but is limited to dominant overstory features. The modeling of forest structure attributes, particularly that of CBH, requires additional predictors to discriminate patterns. Outputs from the BGC process model (Holsinger and others, Ch. 5), which spatially represents the rates of the hydrologic, carbon, and nitrogen cycles, were not available for the LANDFIRE Prototype and were therefore not included in the models. These ecophysiological gradients have proven to be highly useful in discriminating vegetation characteristics (Keane and others 2001; Rollins and others 2004). It should also be noted that the methods for generating the biophysical gradient layers were still under development during the LANDFIRE Prototype and met with limited success (Holsinger and others, Ch. 5). In the national implementation of LANDFIRE, refined, consistent methods for generating these layers will maximize their utility for all LANDFIRE mapping tasks.

Lastly, we encountered a problem upon combining the surface and canopy fuel layers into the landscape format required by the FARSITE model (Finney 1998). We found many inconsistencies between CBD, CBH, CC, and CH values that should have been detected during the analysis and QA/QC phase. For example, canopy height values were lower than canopy base height values for the same pixel. In addition, many CBD estimates were too low to be useful for FARSITE simulation. These inconsistencies were not errors, but rather resulted from problems with the way canopy characteristics were computed in FUELCALC and the way they were independently mapped using biophysical statistical modeling. A more comprehensive QA/QC procedure for these layers will correct many – but not all – of these inconsistencies. To fix these problems in the LANDFIRE Prototype, we directly assigned CBD and CBH values from the LANDFIRE fuel reference database for each PVT-CT-SS combination.

Recommendations for National Implementation

Above all, we recommend obtaining and/or collecting as many georeferenced field fuel and tree data as possible across the nation to create the six fuel layers for the LANDFIRE National effort. It would be beneficial if these data contained assessments of surface fuel model categories for each plot, but fuel loading data can also be used once the field keys for all fuel model classifications have been developed. These data are critical for all modeling, mapping, accuracy assessment, and parameterization tasks in the LANDFIRE Project (Keane and Rollins, Ch. 3). In addition, the field keys, essential for assessing fuel model categories in the field, must be comprehensive, consistent, and accurate. We highly recommend that simple, easy-to-use field keys be created for all surface fuel model classifications. These keys must be tested and validated before they are released for nationwide use.

We also recommend the implementation of extensive QA/QC procedures that rigorously test the fuel layers to detect any inconsistencies and errors, especially in the context of other LANDFIRE digital maps. This procedure should include all LANDFIRE layers and extensive evaluation based on data contained in the LFRDB. This procedure should be flexible so that it can be adjusted according to the specific vegetation types and fire management strategies of the various mapping zones across different regions of the United States.

In addition, we recommend employing the regression tree-based process described above for creating the canopy fuel layers. The efficiency and nonparametric flexibility make regression trees the optimal model for the national implementation of LANDFIRE. The NLCD mapping tool and Cubist software facilitate the implementation of the trees and offer several features for developing the best model. Moreover, the regression tree model's performance will improve with refined predictor layers and training data, which involves the refinement and integration of the BGC and WXFIRE simulation models.

The LANDFIRE vegetation mapping processes must be integrated so that maps combine logically with regard to vegetation ecology and fuel characteristics. In Zone 16's forested areas, for example, approximately 2.6 percent of the total pixels had a predicted CBH value of greater than or equal to the predicted value of CH (fig. 6). Although this percentage is fairly low, some rectification must occur before these layers are used effectively in programs such as FARSITE. If there is no rectification process for "fixing" these pixels, an alternative method will be necessary.

Furthermore, we strongly recommend that all surface and canopy fuel layers be reviewed by local experts to ensure realistic, accurate mapping products. This includes a review of the LANDFIRE fuel database and the rule set used to assign surface fuel model categories to PVT-CT-SS combinations to identify inconsistencies and errors. In addition, a comprehensive documentation of layer properties in the LANDFIRE metadata record will be critical to a thorough technical review of the fuel layers.

Conclusion

In conclusion, the fuel mapping effort described in this chapter was the last in a series of complex tasks performed in the LANDFIRE Prototype effort. As a result, the time allotted to fuel map development and implementation was much less than that allotted to all other tasks. The resulting fuel map products are only first approximations and do not contain the level of detail and investigation incorporated in the other LANDFIRE Prototype products. The results reported here are therefore not as extensive and conclusive as in most of the other LANDFIRE chapters. We plan to fully investigate and explore the process and products of the fuel mapping effort as LANDFIRE National proceeds.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Appendix 12-A

Vegetation combination assignment rule set for Mapping Zone 16 fire behavior fuel models (FBFMs) (Anderson 1982). See Long and others, Ch. 6 for descriptions of cover types, life forms, and structural stages

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If cover type is an Herbaceous life form, then the primary fire carrier is grass.

If cover type is Wetland Herbaceous, then FBFM 1; else
If Low Height, then FBFM 1

If High Height, then FBFM 3

If cover type is a Shrubland life form and structural stage is a Shrubland type, then the primary fire carrier is grass or shrub.

If cover type is Blackbrush, then FBFM 6

If cover type is Desert Shrub, then FBFM 6

If cover type is Dry Deciduous Shrub and High Cover, Low Height and the

If PVT is a Forest type (except Riparian Hardwood cover types) then FBFM 5

If cover type is Dry Deciduous Shrub and PVT is Riparian Hardwood or a non-forest type,
then FBFM 6

If cover type is Dwarf Sagebrush Complex, then FBFM 6

If cover type is Mtn. Deciduous Shrub where Gambel oak is not the dominant shrub and the structural stage is a Shrubland type, then FBFM 6

If cover type is Mtn. Big Sagebrush, then FBFM 2

If cover type is Montane Evergreen Shrub where mountain mahogany is the dominant shrub and is High Cover, High Height, then FBFM 6 else Montane Evergreen Shrub is FBFM 5.

If cover type is Rabbitbrush, then FBFM 6

If cover type is Riparian Shrub, then FBFM 6

If cover type is Salt Desert Shrub, then FBFM 6

If cover type is Wyoming – Basin Big Sagebrush Complex and Low Cover, then FBFM 5

If cover type is Wyoming – Basin Big Sagebrush Complex and High Cover, then FBFM 6

If cover type is a Woodland life form or structural stage is a Woodland type, then the primary fire carrier is grass, shrub, or timber litter.

If cover type is Pinyon – Juniper or Juniper and Low Height, then FBFM 6

Appendix 12-A — (Continued)

> If cover type is Pinyon – Juniper or Juniper and High Cover, High Height, then FBFM 8
>
> If cover type is Pinyon – Juniper or Juniper and Low Cover, High Height, then FBFM 2
>
> If cover type is Mtn. Deciduous Shrub where Gambel oak is the dominant shrub and Low Height, then FBFM 6
>
> If cover type is Mtn. Deciduous Shrub where Gambel oak is the dominant shrub and High Height, then FBFM 4

If cover type is a Forest life form, then primary fire carrier is grass, shrub, or timber litter.

> If any Forest type and Low Cover, High Height, then FBFM 2
>
> If conifer and Low Cover, Low Height, then FBFM 2
>
> If hardwood and Low Cover, Low Height, then check early growth form.
>
> > If bushy or sprouter, then FBFM 6
> > If single stem, then FBFM 2
>
> If long needle conifer and High Cover, High Height and PVT is moderate/dry, then FBFM 9; (optional) If moist PVT, then FBFM 10
>
> If short needle conifer and High Cover, High Height and PVT is moderate/dry, then FBFM 8; (optional) If moist PVT, then FBFM 10
>
> If hardwood and High Cover, High Height, then FBFM 8
>
> If cover type is Grand Fir or Spruce – Fir and High Cover, Low Height and PVT is moist, then FBFM 8
>
> If cover type is Ponderosa Pine, Lodgepole Pine, Douglas-fir, or Timberline Pine and High Cover, Low Height, then FBFM 6
>
> If hardwood and High Cover, Low Height, then check young growth form.
>
> > If bushy or sprouter, then FBFM 6
> > If single stem, then FBFM 8

Assuming non-drought conditions, we adjusted the rules above after the look-up-table was created based on the logic for modeling fire at the low fuel loading levels found in the Utah Forest Vegetation Simulator – Fire Fuels Extension (FVS-FFE) variant in Reinhardt and Crookston (2003). For example, we adjusted some of the juniper cover types from FBFM 6 to FBFM 5. For mixed-conifer cover types (such as Douglas-fir and Grand Fir – White Fir) we assumed that Low Height meant a stand density >1000 stems/acre.

A moist forest PVT was considered a subalpine forest type and included all Spruce – Fir and Lodgepole Pine PVTs. A moderate/dry forest PVT was considered a montane forest type and included all Grand Fir, Douglas-fir, Timberline Pine, and Ponderosa Pine PVTs.

Chapter
13

Perspectives on LANDFIRE Prototype Project Accuracy Assessment

James Vogelmann, Zhiliang Zhu, Jay Kost, Brian Tolk, and Donald Ohlen

Introduction

The purpose of this chapter is to provide a general overview of the many aspects of accuracy assessment pertinent to the Landscape Fire and Resource Management Planning Tools Prototype Project (LANDFIRE Prototype Project). The LANDFIRE Prototype formed a large and complex research and development project with many broad-scale data sets and products developed throughout its various stages. The scope of the project was defined as mapping and modeling vegetation, wildland fuel, and fire regime characteristics (Rollins and others, Ch. 2). Because of the breadth of the investigation, it is important to base our expectations for accuracy on a clear understanding of the intricacies, interdependencies, and scope of mapping and modeling LANDFIRE products. Our goals in this chapter are to: 1) provide relevant background information regarding accuracies and what was realistically achievable in the LANDFIRE Prototype, 2) provide background regarding our strategies for LANDFIRE National, 3) describe our actual LANDFIRE Prototype accuracy results in broad terms, and 4) provide recommendations for the national implementation of LANDFIRE. This chapter is not intended to provide an exhaustive list and description of all of the various accuracy-related issues and conclusions resulting from the LANDFIRE Prototype (for specific details, the reader will be referred to the appropriate chapters). Rather, this chapter is intended to be broad in scope and to place the many accuracy components within the context of the LANDFIRE Prototype and LANDFIRE National projects. Please note that Lunetta and Lyon (2004) provide an in-depth discussion of the current state of accuracy assessment within the science community.

Background

General Accuracy Tenets and Philosophy

First we will provide the reader with several broad tenets used in defining accuracy assessment for the LANDFIRE Prototype Project and thereby lay the foundation for the more in-depth discussion following.

Tenet 1: Assuming that thematic detail and spatial scale are constant, product accuracy is generally inversely correlated with the size of the region being assessed.

Within the remote sensing literature, there are many references to accuracy levels, and many of the reported values are quite high. These high levels may lead to inflated expectations regarding what types of accuracies will be achievable from LANDFIRE. Many previous studies were conducted within relatively small study

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In: Rollins, M.G.; Frame, C.K., tech. eds. 2006. The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. Gen. Tech. Rep. RMRS-GTR-175. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

areas, often aided by high levels of "hand crafting" during the mapping process and/or in-depth knowledge of the particular study area. We do not have the luxury of spending a great amount of time and effort on any one particular region mapped through the LANDFIRE Project, and the mapping and modeling tasks need to be accomplished through largely automated processes. These limitations do not by any means reduce the value of the products being created through LANDFIRE; however, it should be stated that LANDFIRE products will likely have lower overall accuracies than do data sets derived from more localized studies characterized by large amounts of field data, increased processing effort that may include on-screen digitizing and recoding, and/or iterative refinement of modeled results.

Tenet 2: The higher the thematic detail, the lower the accuracy.

A relatively large number of vegetation classes were mapped for the LANDFIRE Prototype (Long and others, Ch. 6). While the chosen map unit classification system made sense on many levels for the LANDFIRE Prototype, it must be recognized that the proliferation of classes in this or similarly complex systems will imply a relative decrease in accuracy levels. This does not in any way diminish the value of the vegetation products, but is rather simply a result of a more complex map unit classification design. For example, a two-category classification of water and uplands is likely to result in high accuracy, with expected accuracies above 99 percent. This high accuracy does not mean that the *value* of the product is particularly high, but simply reflects that the accuracy for depicting these two classes is high. Additionally, there are difficulties that arise when categorizing continuous phenomena into rigid and discrete classes. For instance, a more detailed map unit classification system might treat juniper and pinyon – juniper ecosystems as several discrete classes even though the boundaries between them are relatively arbitrary and difficult to delineate both in the field as well as within the imagery. With complex vegetation map unit legends, such as that used in the LANDFIRE Prototype, vegetation class accuracy levels can be expected to drop. Nevertheless, LANDFIRE products reliably and consistently describe the distribution of vegetation composition, condition, and structure and associated wildland fuel and fire regimes across broad landscapes. These mapped data are useful for hazardous fuel reduction projects, for a variety of resource management projects, and for both strategic and tactical wildland fire management.

Tenet 3: Field information used for assessing accuracy is not perfect.

As mentioned under Tenet 2, the LANDFIRE Prototype vegetation map unit legends are relatively complex (Long and others, Ch. 6). The map unit classifications are developed using large quantities of field data, and all of the field plots are assigned to one of the many possible classes. Most of these plots are used to generate maps, but some are reserved for use in the accuracy assessment phase of the investigation. We recognize four major potential sources of error associated with field plot data:

- Errors occur frequently in the identification of species and measurement of vegetation structure in the field (for example, in the data for one prototype field plot, a misplaced decimal point indicated a shrub height of 60 feet).
- The vegetation on some field plots has undoubtedly changed between the time the field data were collected and when the imagery was acquired.
- Geo-location errors in plot and imagery data result in inaccurate characterization of some imagery pixels.
- The assignment of plots to specific vegetation classes will have errors associated with the wide array of opinions among professional field ecologists regarding the field classification of any given field plot.

Tenet 4: The modeled results of complex ecological systems will be characterized by ambiguity and controversy.

The products generated from the LANDFIRE Prototype represent our best approximations in depicting the current status of very complex natural phenomena. The information used in our modeling efforts is based on the best available input data and assumptions. However, although our output products represent reasonable and robust depictions of current conditions, we recognize that, due to lack of baseline research, our knowledge of certain ecological systems is imprecise. Use of such information in the modeling process may result in potential flaws in the products, and hence not all of the core LANDFIRE deliverables will be free of error and ambiguity. Nevertheless, the LANDFIRE Project represents an integration of the best available science in remote sensing, ecosystem simulation, landscape fire and succession modeling, predictive landscape mapping, and wildland fire behavior and effects prediction.

We are therefore confident that the products generated represent the best current assessments of the status of these ecosystems with regard to wildland fire and will be of great value to natural resource managers.

Accuracy Assessment Considerations for LANDFIRE

The need for conducting accuracy assessments of the spatial products created from mapping projects has been well documented (Congalton 1991; Foody 2002). Factors that influence map accuracy include (but are not limited to) the remote sensing platform, the quality of ancillary sources of information, the quality of field data, the floristic complexity of the map unit classification system used, and the sampling design. Traditional first-order map accuracy estimates involve generating an error matrix, computing overall accuracy, and estimating "producer's accuracy" and "user's accuracy" (Congalton 1991). In the past, assessment of map accuracy has involved much post-mapping fieldwork in order to develop error matrices. These formal, traditional accuracy assessments involving field campaigns can be labor-intensive, time-consuming, and cost-prohibitive, especially when dealing with projects that cover large regions of diverse and overlapping vegetation composition and conditions (Stehman and others 2000). For this reason, only a few efforts have conducted accuracy assessments across broad expanses such as the entire United States (Stehman and others 2003; Wickham and others 2004).

Techniques that worked well in assessing mapping accuracy across large regions for the 1990s National Land Cover Database (NLCD; Vogelmann and others 2001) employed modifications of traditional accuracy assessment methodologies (Stehman and others 2003; Wickham and others 2004). As background, the 1990s NLCD database was developed using Landsat satellite imagery acquired for the Multi-Resolution Land Characteristics (MRLC) 2001 consortium using methods previously described (Vogelmann and others 1998). During development of the database, it was determined that an accuracy assessment for the large area product was required, and that such an effort would have to be modified from more traditional assessments. The modifications were necessary in part due to the scarcity of field data across the mapped regions, the large size of the area being assessed (and associated high costs of collecting data from a statistically valid number of field locations across the entire conterminous United States), difficulties in assigning unambiguous map unit labels to many field plots, and geolocational errors associated with field plot and satellite-derived mapping information.

Three important lessons learned from the accuracy assessments of the 1990s NLCD effort pertain directly to the accuracy assessment methods used during the LANDFIRE Prototype Project:

- Collecting data for and compiling custom field databases is time consuming and expensive. Similarly, combining data from disparate sources and distilling them into a training database for mapping purposes is time consuming, expensive, and can result in data inconsistencies unless special effort is made to crosswalk and/or standardize input data. On the other hand, using existing field data, rather than collecting custom field data, saves both time and money. In short, for large-area projects, it makes sense to use existing field data for conducting accuracy assessments.
- Determining accuracy values for different subregions is acceptable when mapping large regions. Accuracies are likely to vary across large mapped areas due to region-specific heterogeneity in landscape composition and structure, and it was advantageous to derive an understanding of the geographic variability of accuracies of the products developed for LANDFIRE. To this end, use of a systematic random sampling design can provide optimal results. Such a design ensures that all geographic regions are adequately sampled and thereby ensures that at least some estimates of accuracies exist throughout the entire study region.
- Some errors are more "wrong" than others. For instance, for the LANDFIRE effort, misclassification of a pinyon – juniper stand as a riparian woodland stand will likely have a greater negative impact on the predicted fire behavior than misclassification of a pinyon – juniper stand as a juniper stand. Furthermore, some vegetation types are spectrally and biogeographically very similar to other vegetation types, and even with "perfect" source material, it is difficult to adequately distinguish some of these classes. For example, Douglas-fir and white fir are spectrally very close (fig. 1), and both species inhabit similar ecological niches. In regions where both Douglas-fir and white fir occur, we can expect significant confusion between the two classes. For instance, in central Utah, cross validation accuracies for these two classes were quite low, as anticipated. Nonetheless, we suspect that the errors related to misclassifying similar vegetation types will only minimally impact predicted fire behavior, whereas

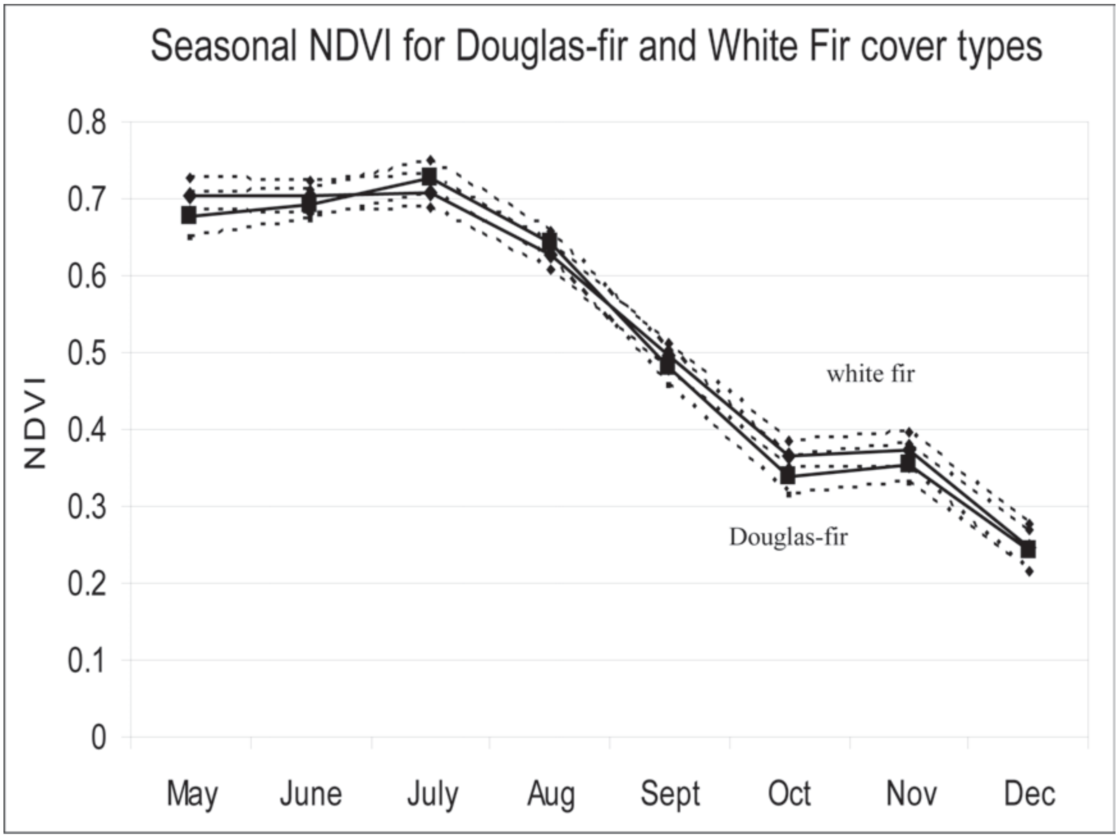

Figure 1—Seasonal normalized difference vegetation index (NDVI) spectral profiles for Douglas-fir and White Fir cover types.

errors related to misclassifications of more dissimilar vegetation types lead to greater negative impact. For this reason, both ecologists and image analysts need to critically analyze error matrices in order to fully understand and characterize the ways in which product errors may affect project objectives.

We took these lessons into consideration in the design of our LANDFIRE accuracy assessment protocol:

- Because LANDFIRE is a large-region project, we tapped into a variety of data sources and made use of existing field data to assess the accuracy of LANDFIRE Prototype products (rather than wasting time and money collecting data for and compiling a custom field database). See Caratti, Ch. 4 for details on the acquisition of data for and compilation of the LANDFIRE reference database.
- Cross-validation error matrices were generated and examined separately for both LANDFIRE Prototype regions.
- For the LANDFIRE Prototype, mappers, ecologists, and wildland fire scientists critically evaluated errors at several stages in prototype product development. These evaluations resulted in aggregation and disaggregation of classes based on the “mappability” and “model-ability” of the vegetation classes. See Keane and Rollins, Ch. 3 and Long and others, Ch. 6 for detailed descriptions of the creation of the final vegetation legends for the LANDFIRE Prototype. This expert-based process for map unit classification refinement is built into the accuracy assessment system for LANDFIRE National.

Overview of Accuracy Assessment Conducted for the LANDFIRE Prototype Project

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes, each involving evaluations of the accuracy of intermediate and final products. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products.

Role of Input Data

Field data accuracy issues—Field data played a critical role in many stages of the LANDFIRE Prototype. These data were essential inputs for developing the vegetation products, percent canopy cover and height data layers, and potential vegetation data layers. See Caratti, Ch. 4 for detailed information on data acquisition for and compilation of the LANDFIRE reference database.

Described below are a number of data quality issues that needed to be addressed in the LANDFIRE Prototype.

- *Number of field plots*: For the LANDFIRE Prototype accuracy assessment, we used all field plot data that met the stringent quality-control criteria (Caratti, Ch. 4) and represented the large number of classes mapped during the vegetation mapping tasks (for details about the vegetation mapping procedures, see Frescino and Rollins, Ch. 7 and Zhu and others, Ch. 8) We used literally thousands of points for each of the two prototype regions. During this process, we recognized that some vegetation classes had limited numbers of field plots. Short of gathering additional plot information (see Keane and Rollins, Ch. 3 for LANDFIRE Prototype design criteria), there was no obvious solution to this problem. We attempted to map these rarely sampled vegetation types, even when we had limited numbers of field plots for those classes. We believe that most of these rare classes were under-represented in the resultant products.
- *Field plot geolocational accuracy*: Field plots must have accurate geolocational coordinates to geographically rectify with the many spatial databases involved in the LANDFIRE process. This was especially important during the vegetation cover and structure characterization phase of the LANDFIRE Prototype, wherein each field plot was matched with a single Landsat pixel and used in the mapping process. Any significant error in the field location coordinates has the potential to match the wrong spectral information with that particular field plot, thereby resulting in mapping error. For the prototype effort, we overlaid plot locations onto satellite imagery to determine whether there were plots that obviously did not match the imagery. While most plot locations appeared to be reasonable, we observed that many plots representing natural vegetation were actually located on major roads. When plot information was originally acquired for these sites, the actual Global Positioning System (GPS) measurements were apparently made at the road locations adjacent to the field plots, rather than within the field plots. Thus, the GPS locations did not exactly match the locations where the field measurements were made. For these sites in the LANDFIRE Prototype, a new set of geolocations was derived to better represent actual field plot locations.

  In another case, we noted (also based upon imagery assessment) that many putative shrub sites were located in obviously forested areas. We later discovered that those plots corresponded to a particular project in which the main focus was to describe shrub vegetation regardless of whether or not it represented the dominant vegetation type. These plots were consequently discarded from the prototype accuracy assessment. Both cases illustrate the need for assessing field plot information in conjunction with satellite imagery to ensure that the field information is accurately recorded.

  Moreover, it should be recognized that satellite imagery can have georeferencing errors as well. As a general rule, the coordinates of most pixels in the imagery used for the LANDFIRE Prototype are within 30 meters of the actual location – but exceptions occur. Even in the case where a pixel has slightly greater than a 15-meter error associated with it, this may be large enough to create a slight yet definite mismatch between the imagery and field information. While there is little that we can do about this problem, we at least need to recognize that some of the error term associated with the products generated will be attributable to this issue.
- *Assignment of field data into discrete vegetation classes*: One of the challenges in generating land cover maps is the stratification into discrete classes of a very complex natural world composed of multiple continuums. Regardless of which vegetation map unit system is used, many vegetation plots will represent elements of two or even more classes, and thus some plots will defy unambiguous categorization. As an example of one such problem, we mapped Juniper and Pinyon – Juniper (PJ) as two distinct classes. In nature, pinyon pine and

juniper often coexist, but sometimes juniper occurs as more-or-less pure stands. We used 25 percent juniper composition as the threshold separating Juniper from Pinyon – Juniper (in other words, if a stand had 75 percent or greater basal area juniper in a stand comprised of both pinyon pine and juniper, it was called "Juniper"; whereas, if it had less than 75 percent juniper, it was called "PJ"). Analysis of seasonal spectral data indicated that many juniper stands were spectrally distinct from many of the PJ stands (fig. 2); however, significant spectral overlap existed between the two classes, as well. After decision tree classification, cross-validation accuracies indicated significant error in the classification of these two cover types (fig. 3). We believe that much of this error is attributable to the artificial boundaries imposed by the classification of a continuum.

- *Temporal correlation between field data and satellite imagery*: Disturbance such as that caused by fire, insects, or logging can alter the sites enough to cause the temporal mismatches between field data and satellite imagery that result in classification problems. For the prototype, we made use of a large volume of existing field data acquired from disparate sources (Caratti, Ch. 4), and much of the field information was acquired over a long period of time. Although information from many plots was relatively old (for example, field data acquired over a 10-year time period prior to imagery acquisition), we determined that many of these plots still contained information that was useful and relevant to the LANDFIRE Prototype. For example, plots located within reasonably intact and undisturbed forests or sagebrush lands, under normal circumstances, do not change much over a 10-year span. After completing the first prototype study in Utah, we recognized the importance of using a change-detection approach and employed such an approach in the northern Rockies prototype region to discard plot information derived from areas that changed between the times when the field information was obtained and when the imagery was acquired.

Geospatial data issues—Landsat imagery data from the MRLC 2001 consortium served as the primary source of spatial data for developing the vegetation and structure products (Homer and others 2004) (refer to

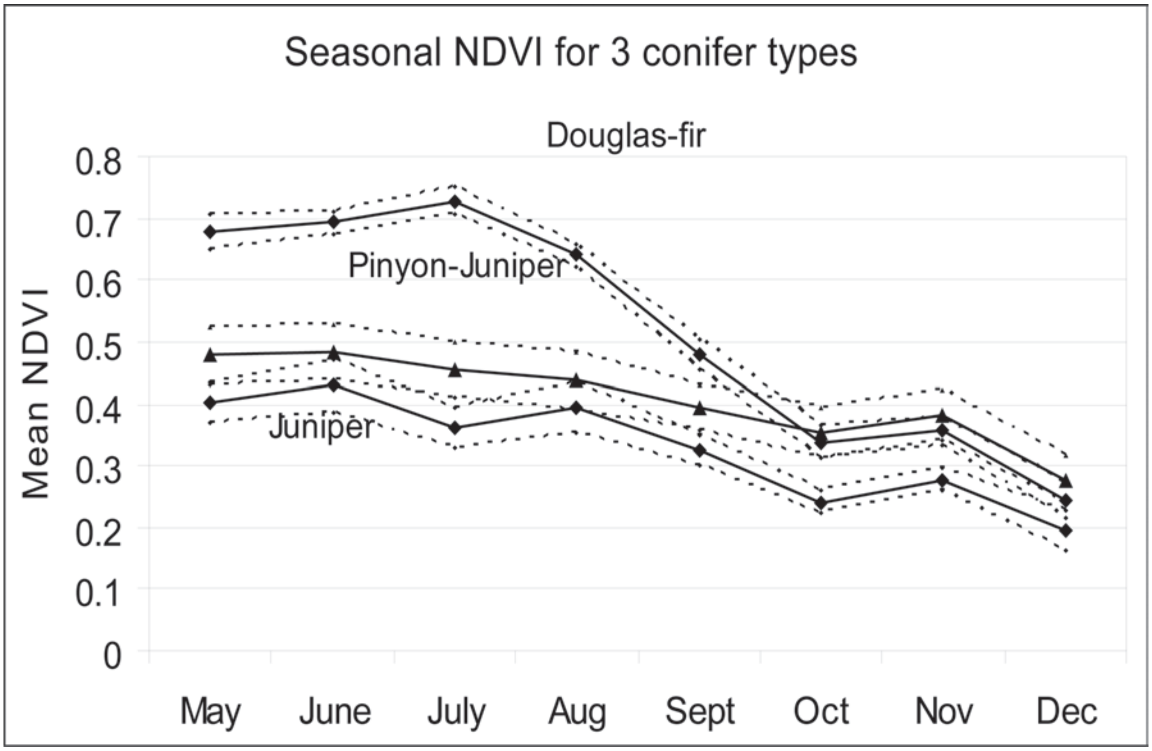

Figure 2—Seasonal normalized difference vegetation index (NDVI) spectral profiles for Douglas-fir, Pinyon – Juniper, and Juniper cover types.

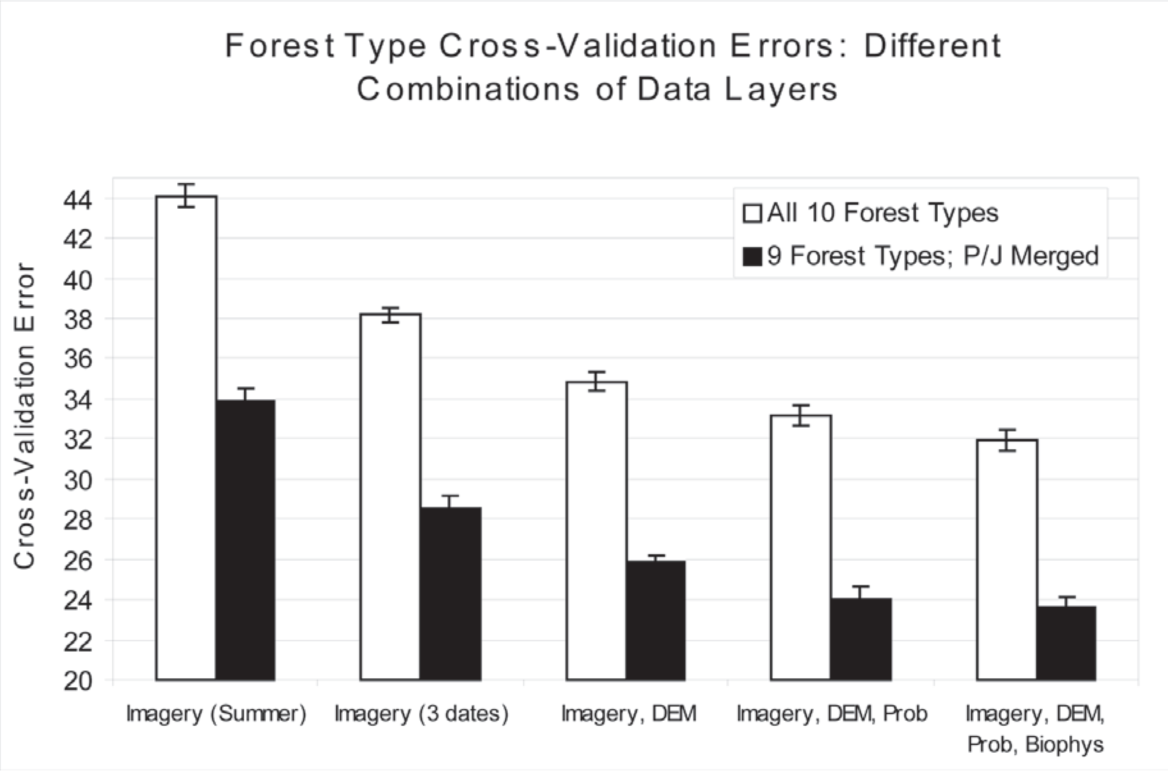

Figure 3—Cross-validation errors for forest types in the Zone 16 prototype study area as a function of different amounts of input source material. Black bars depict the effects of merging the Pinyon – Juniper and Juniper classes.

Zhu and others, Ch. 8 for further discussion regarding the imagery and ancillary data sources used for vegetation mapping in the LANDFIRE Prototype). In general, the images used for the prototype effort were the best data available during the LANDFIRE Prototype and represented three seasonal time periods (leaf-off spring, leaf-on summer, and leaf-on fall). Although the MRLC 2001 data used are of high quality, problems can arise when using any source of remotely sensed information. The foremost imagery-related problems affecting the LANDFIRE Prototype included atmospheric issues, disparate imagery acquisition dates, and geolocational problems.

- *Atmospheric issues*: Most of the acquired image scenes used in the prototype effort were of excellent quality. Even the best scenes, however, have occasional cloud and/or haze problems, which can either totally obstruct the view of portions of landscape or change the digital values enough to impact the mapping process. While not a large problem in the prototype areas, there were a few locations for which imagery quality was sub-par. These issues are inevitable and are likely to be a bigger problem in cloudier locations of the country such as the eastern United States and the upper Midwest.
- *Disparate imagery acquisition dates*: We attempted to use imagery from similar time periods as much as possible; however, due to cloud issues, optimal imagery data were not always available. Using scenes from different dates of the same year, such as using July and September data in the same "leaf-on" mosaic, resulted in problems resulting from phenological differences. Using scenes from different years, such as using one scene from 2002 and an adjacent scene from 2003, resulted in problems related to different weather patterns (for example, vegetation spectral response can be very different during wet versus dry years) and to occasional land cover changes that occurred between years. For the LANDFIRE Prototype, we attempted to minimize these problems through careful selection of scenes and use of spatial "date of acquisition" information in our decision tree and regression tree classifications.

- *Geolocational problems*: Images used in this investigation were processed using the National Landsat Archive Production System methods (USGS Landsat Website 2004). Data were corrected for terrain and projected to a standard projection (Albers Equal Area) using automated software processing. Individual pixel coordinate information was approximately 30 meters from actuality. Thus, even when field information had precise GPS coordinates, the field data were sometimes linked to the wrong pixel due to imagery registration errors. Because of technological, time, and budget constraints, we could not circumvent this problem. Registration methods needed to be consistent and automated to ensure that the process was feasible for application over the entire United States. We simply had to assume that the field data adequately characterized an area broader than the precise location of the plot and that the image pixel used was spectrally representative of its surrounding pixels. Note that in many cases, the quality-control checks performed on the field data mitigated some of these problems.

Ancillary data issues—Other sources of input information for the LANDFIRE Prototype included Digital Elevation Model (DEM) data and derivative products, 1990s NLCD land cover data (Vogelmann and others 2001), 2000s NLCD land cover data (Homer and others 2004), a suite of biophysical gradient data layers (Holsinger and others, Ch. 11; Keane and others 2001; Rollins and others 2004), and potential vegetation information (Frescino and Rollins, Ch. 7). Error terms are associated with each data type. While it is beyond the scope of this chapter to describe in detail all of the sources of errors associated with the many data layers, a few specific points should be made:

- Although not flawless, each data source used in the LANDFIRE Prototype represented the best available science and data quality.
- The source of the DEM data was the National Elevation Dataset (NED) (Gesch and others 2002). Although NED is an excellent source of digital elevation data, it came to our attention during the final stages of the prototype effort that another data source would have been more appropriate: the Elevation Derivatives for National Applications (EDNA) data set (http://edna.usgs.gov). The EDNA data represent a set of data layers derived from an earlier version of the NED. To create the EDNA data layers, the NED data were "smoothed" so that they would be better suited for hydrological modeling purposes. It should also be noted that, regardless of the source of the digital elevation model information, there are horizontal and vertical error terms associated with these data sets tracing back to the original source material. These digital elevation model data sets are regularly improved and updated.
- The 1990s and 2000s NLCD data sets were used for stratification purposes at various stages in the prototype effort, and both data sets have known error terms associated with them. See Yang and others (2001) and Homer and others (2004) for details regarding the accuracies of these products.

Accuracy of Thematic Maps

Cross-validation and points for independent validation—Accuracy assessment is an integral component of land cover mapping work. When a large number of field points are available, a reasonable alternative to generating traditional first-order accuracy estimates (see the above section *Accuracy Assessment Considerations for LANDFIRE*) is cross-validation. To create the LANDFIRE vegetation products, we employed decision tree analysis implemented within the See5 program (Quinlan 1993) using Landsat, DEM, slope, aspect, biophysical gradient, and potential vegetation data layers. The program enables cross-validation, which consists of repeated experiments in which a subset of the sample is used to train a classification model and an unseen subset is used to evaluate the model. In model runs for the prototype effort, we found that a five-fold cross-validation was appropriate. In each model run, the original field point data sets were divided into five subsets of equal size, and each subset was used to evaluate the algorithm trained using the remaining four subsets. Theoretically, this approach is not as thorough as a rigorous, statistically designed post-mapping field accuracy assessment campaign. It has been shown, however, that cross-validation can provide accuracy estimates comparable to these time-consuming and expensive methods (Huang and others 2003). See Frescino and Rollins, Ch. 7 and Zhu and others, Ch. 8 for actual accuracy results and cross-validation error matrices for the vegetation products derived for the LANDFIRE Prototype. For LANDFIRE National, we recommend reserving a set percentage of plots from the decision and regression tree analyses for independent accuracy assessment. See the *Recommendations for National Implementation* section below for details.

Field verification—Although it is not always feasible to conduct a detailed field verification and validation campaign, when possible, field visits at various stages of product development can be highly useful. Field visits, both during and after the product generation phase, provide the technical teams conducting the mapping work with a good basic understanding of the natural vegetation and ecology of the regions in which they are working. Further, field checks of particular sites to determine if they match the modeled results can be very instructive and useful for improving mapping accuracies. For the LANDFIRE Prototype, we made three separate field visits of approximately five days each. We traveled to the central Utah highlands region twice (once before mapping and once after the products were created), and we traveled once to the western Montana region (post-mapping). In all cases, images and/or maps were evaluated in the field, and actual plot measurements were made. Although not statistically rigorous, such efforts provided a better understanding of potential problem areas for future methods improvement. For example, an area of western hemlock was overestimated in the map products, and we were able to trace the overestimation back to problems in the original field sampling methods used to help generate the training data in the mapping process. Although no obvious solution to the problem was apparent, the case illustrates the importance of field visits in methods improvement. In another field activity, spectral measurements of shrub and herbaceous vegetation density were made by one team in the western Montana region to help refine shrub and herbaceous canopy cover methodology. This activity was undertaken in an attempt to improve canopy cover mapping and is being considered for the National Implementation of LANDFIRE.

Consistency checks with data from other sources—Related data sets, generated by other projects and for other applications, are often available and can be used for comparison purposes. The USGS Gap Analysis Program (GAP), for example, generates detailed vegetation maps for conservation management and planning (http://www.gap.uidaho.edu). We compared the GAP products created for the central Utah highlands prototype area with the cover type maps created for the LANDFIRE Prototype. The two sources of data compared reasonably well in some cases and less so in others (see figs. 4 and 5). It should be noted that the GAP products were created using different field databases than those used for the LANDFIRE Prototype. In addition, the vegetation map unit classification systems used were different, which limited the utility of direct, parallel comparison between the GAP products and LANDFIRE products. Although such comparisons may lack statistical rigor, they indicate where major qualitative similarities and differences exist between products and in turn may indicate which classes and regions are the most suspect. In addition, vegetation and structure products should be reviewed by regional experts whenever possible to determine whether noteworthy mapping problems exist and whether additional work is warranted. Such a review is recommended for national implementation of LANDFIRE.

Accuracy of Potential Vegetation Type and Canopy Fuel Maps

We generated potential vegetation type (PVT) data sets using decision tree software and cross-validation routines very similar to those used for generating vegetation maps. We also produced coinciding maps of confidence, which depict the relative prediction errors representing a spatial and visual representation of PVT map accuracy. See Frescino and Rollins, Ch. 7 for detailed descriptions and results of these activities. We estimated the accuracy of canopy fuel layers using regression tree procedures in which correlation coefficients were generated to measure the agreement between the predicted values and actual values. Additionally, we compared with predicted values a set of points randomly selected from the LANDFIRE reference database from each prototype zone. As in the case of PVT, we also produced coinciding maps of confidence. See Keane and others, Ch. 12 for a detailed description of canopy fuel accuracy.

Accuracy of Maps Based on Landscape Simulation Models

Accuracy evaluation of vegetation maps created from satellite imagery and ancillary data is straightforward and is based on a foundation of scientific literature (Foody 2002; Lunetta and Lyon 2004). In contrast, it is often conceptually very difficult to ascertain the quantitative accuracy of many of the products that are generated through complex modeling efforts, such as those employed to create the historical reference conditions for quantifying ecological departure in LANDFIRE. Moreover, it is difficult — if not impossible — to assign an absolute measure of accuracy to an ecological departure product because such a product represents deviation from conditions modeled under a variety of limitations in terms of baseline ecological data. Modeling assumptions, while based on the best available disturbance ecology science, may or may not be completely valid. Without the luxury of time-travel, it is very difficult to validate what the “normal” or historical vegetation condition actually was.

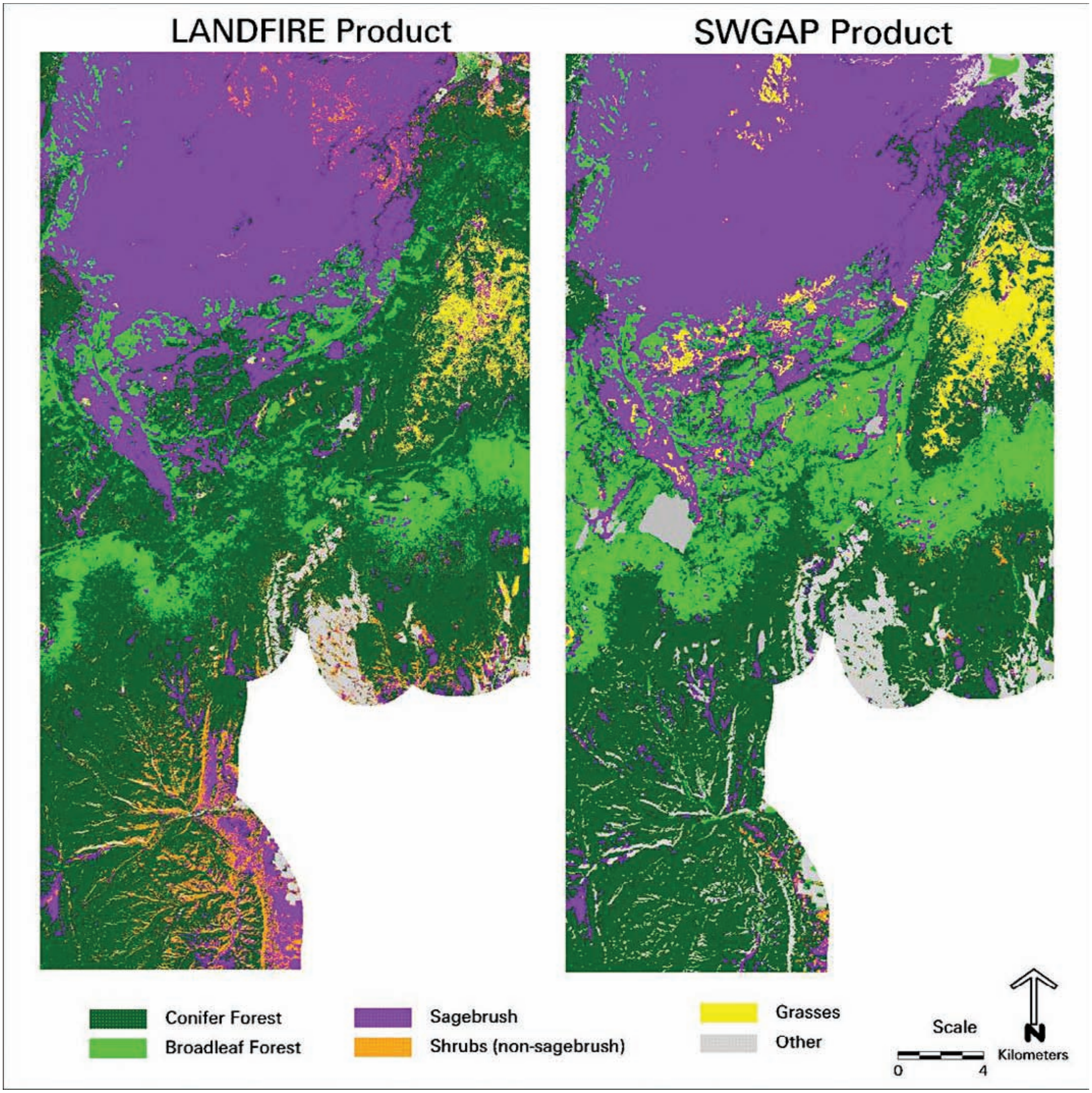

Figure 4—Comparison between a LANDFIRE vegetation type product and a product developed by the Southwest GAP Project in southern Utah. Multiple thematic classes have been combined to facilitate visual comparisons.

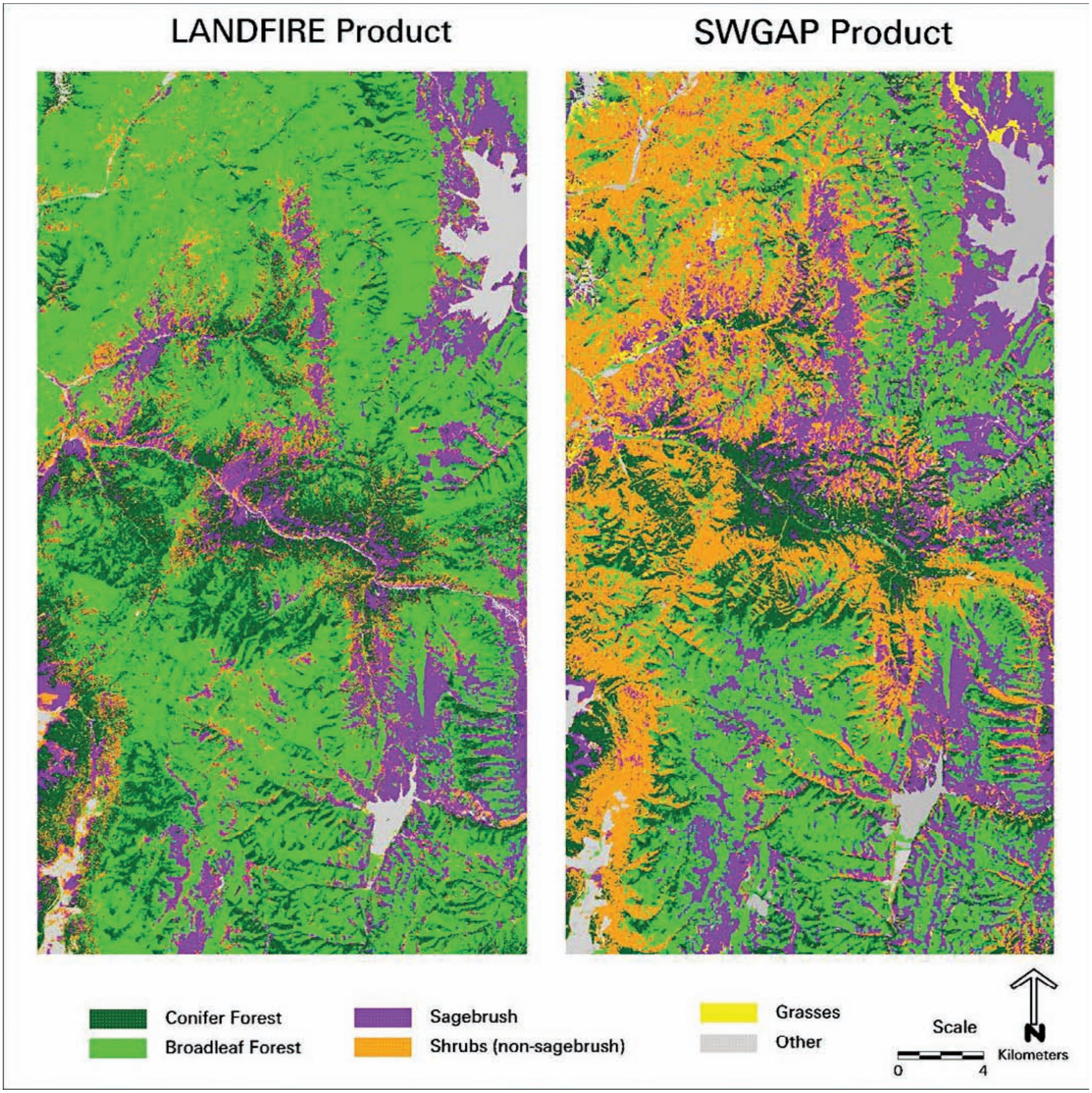

Figure 5—Additional comparison between a LANDFIRE vegetation type product and a product developed by the Southwest GAP Project in southern Utah. Multiple thematic classes have been combined to facilitate visual comparisons. Major differences between shrub and broadleaf forest classes can be traced back to differences in classification systems (Gambel oak and bigtooth maple were categorized as trees in the LANDFIRE map unit classification and as shrubs by GAP).

For accuracy assessment approaches used to evaluate LANDFIRE products based on landscape simulation models, see Pratt and others, Ch. 10 and Holsinger and others, Ch. 11. In addition, see the *Recommendations for National Implementation* section below for suggestions on improving the accuracy assessment of LANDFIRE products based on landscape simulation models.

Recommendations for National Implementation

Source Data

All source data need to be inspected carefully. This is especially true for field data and imagery, which form important foundations for much of the ensuing LANDFIRE tasks. As a matter of course, if field data used for training are inaccurate, then the resulting products will likely have lower levels of accuracy. Imagery quality can also greatly affect accuracy levels of derived products. Although optimal imagery data sets are not always available for a given location, there are usually several excellent options. It is important to ensure that the best possible imagery data sets are used. Below are some specific recommendations regarding the selection of source data.

Number of field plots—As general rule, the more field reference plots, the better. For each LANDFIRE National mapping zone, we anticipate using literally thousands of field plots in order to develop adequate characterizations. These must represent the entire range of conditions that occur throughout the mapping zones. For vegetation map unit classification development, for example, we have a target number of at least 100 plots per class. Fewer plots per class would diminish our confidence in our ability to map that class accurately and would likely result in the inadequate mapping of that particular feature. Rare classes (land cover features limited in occurrence across the landscape) are notoriously difficult to map accurately, largely because there are relatively few field plots representing these classes that can be used for training data. For national implementation of LANDFIRE, we recommend 1) generating vegetation products using all plots, 2) evaluating results, 3) determining which vegetation classes were represented by too few plots, and 4) re-running the map unit classification without these rare classes.

Field plot geolocational accuracy—Field plots with inaccurate coordinates have the potential to cause significant error in mapping results. We recommend that field plot locations be overlaid onto the imagery and that the plot locations be visually inspected to determine if attribute data for each plot are consistent with the imagery. Points located on roads or other locations clearly not characterized by the reference plot should be either omitted or shifted to the appropriate location.

Field data temporal issues—Much of the field information available for the national implementation of LANDFIRE is likely to have been acquired by various organizations over a relatively long period of time. As discussed above, inclusion of plots located in areas where the vegetation has changed between the time the field information was collected and when the imagery was acquired can cause significant mapping problems. The ideal situation is for field data and imagery to be acquired at approximately the same time, but this is impractical due to the large volume of field data necessary for product generation. One option is to discard plots with relatively old information (by imposing an arbitrary cutoff of five or more years); however, including as many plots as possible, even if some include older information, is preferable because even old plots can contain useful information. For this reason, for national implementation, we recommend using the change-detection approach developed for the western Montana prototype area. We recommend using normalized difference vegetation index (NDVI) change between 1990s and 2000s NLCD imagery to locate and isolate plots that have changed markedly over the last 10 years. If a plot is located within a region of high spectral change (based upon imagery analysis) and if the change appears to be related to a land cover change event (such as fire, logging, or insect disease) as opposed to a cloud or cloud shadow, the plot should be flagged and omitted from further analyses.

Imagery data—Imagery acquired by Landsat will likely continue to be the primary source of spatial data for developing vegetation and structure products for LANDFIRE National. The MRLC 2001 consortium, of which the LANDFIRE Project is a partner, is the best source for imagery in part because it is readily obtained and has been consistently pre-processed. Although this imagery represents the best data available, we do anticipate some issues that will need to be addressed. As with the prototype effort, we anticipate the primary imagery-related problems impacting LANDFIRE National to include atmospheric issues, disparate imagery acquisition dates, and geolocational issues (see above section *Geospatial data issues*). It is anticipated that haze and cloud problems will be especially prevalent in the eastern U.S., upper Midwest, and in the Pacific Northwest. Imagery differences related to phenological variables are also likely to impact mapping on a grander scale than was experienced in the prototype effort. When current MRLC data are deemed insufficient for LANDFIRE purposes (based upon visual inspection), additional scenes should be purchased and processed and incorporated into the mosaicking process.

Ancillary data—LANDFIRE will continue to use the best available source data for national implementation. One change that we recommend is using the EDNA data set (USGS EDNA website 2004) as the primary source of digital elevation data. These data are more refined than the data used in the prototype effort. The 1990s and 2000s NLCD data sets will continue to be used for stratification purposes at various stages of LANDFIRE National.

Accuracy of Output Products

Output product inspection—All LANDFIRE products must initially undergo an inspection phase during which the following question is asked: "Do these products make sense?" Although admittedly subjective, many errors will be caught early in the process through such inspections. If performed properly, such an initial evaluation provides a valuable safeguard that can save time and prevent the need to recreate the products.

Cross-validation and error matrices—As in the LANDFIRE Prototype, we recommend the use of cross-validation for approximating accuracies, especially for existing vegetation type and potential vegetation type. Correlation coefficients derived from regression tree analyses should be used when generating continuous variable data sets. Error matrices should be evaluated to facilitate better understanding of the strengths and weaknesses of the vegetation products. Regarding creation of the mapping models, we recommend using 5- or 10-fold cross-validation for each of the individual LANDFIRE mapping zones.

Points for independent validation—For national implementation of LANDFIRE, we recommend reserving a set percentage of plots from the decision tree and regression tree analyses solely for assessing accuracy. Note, however, that the field-referenced data used as input are collected from various projects and agencies, and thus the original source of field data cannot be considered a "random" sample of plots. Any sample of plots selected from a non-random set of points cannot be considered statistically random. Nonetheless, we have determined that withholding a limited number of points for validation purposes provides worthwhile accuracy information.

Nevertheless, we determined that it's better to produce a more accurate set of products with imperfect accuracy information than a less accurate set of products with better known accuracy estimates. We do not want to withhold plots that would best be used for model and product development. As a compromise, we recommend that two percent of the plots be withheld from the modeling activities. These plots will then be used to estimate accuracies for aggregations of LANDFIRE mapping zones or "superzones". We plan to merge data sets from three to four adjacent mapping zones and conduct validation activities for these regions. A target of at least 50 plots for each vegetation class per superzone provides useful information for estimating accuracies.

Stratification of accuracy assessment—In addition to providing general accuracy information at the superzone and individual mapping zone levels, we recommend providing more local estimates of accuracy nested within these other levels. This will be accomplished through spatial stratification of broad areas using biophysical gradient modeling information and other sources of spatial data and through thematic aggregation of similar vegetation types for localized regions. The process of stratifying mapping zones into zones based on the biophysical gradient layers developed for LANDFIRE (see Holsinger and others, Ch. 5) will be used as a basis to further our understanding of product errors, which in turn will enable refinement of future mapping procedures. This stratification process may facilitate the discrimination of different vegetation types with similar spectral signatures that occupy sites having very different environmental characteristics.

Field verification—As discussed above, we recommend conducting a modest level of field verification throughout LANDFIRE National. Field visits provide the technical teams with a basic understanding of the natural vegetation and ecology of the regions in which they are working, and field visits to particular sites serve to verify (or invalidate) the modeled results. Ideally, a field visit should take place at the beginning of each zone's mapping activities for familiarization purposes, and an additional field visit should occur near the end of the mapping process to verify and refine the mapping process.

Consistency checks with data from other sources—Whenever possible, products should be compared with existing independently produced data sets. In some cases, products unrelated to LANDFIRE have been generated for certain local areas, and these can be used to help assess accuracies of LANDFIRE products. Spatial and tabular data potentially provide good general information. In addition, we recommend that LANDFIRE support the generation of local validation data sets, where appropriate.

Accuracy of Maps Based on Landscape Simulation Models

As discussed above, it is generally very difficult to ascertain the quantitative accuracy of products generated through complex landscape modeling efforts. Even so, there are some approaches suitable for assessing the validity of certain LANDFIRE modeled products, such as modeled historical fire regimes.

Although as of yet there are no examples of complete data sets representing historical vegetation conditions for the entire United States at the spatial grain of the LANDFIRE products, there are local historical data sets that can be used to "spot check" the validity of the products generated. For instance, historical aerial photographs and field-based data sets may provide useful information for assessing modeled historical fire regime products. Although not a true quantitative analysis, comparisons with historical data will likely provide information regarding the validity of the products.

As described above, it is important that the outputs from complex modeling activities be scrutinized carefully and checked for obvious flaws or deviations from expected results. As obvious as this seems, we are aware of numerous investigations in which this avenue has been neglected and in which spatial products were produced but not carefully examined. Although this type of evaluation does not yield quantitative error estimates, it can provide valuable insight regarding probable accuracies.

Finally, users of the LANDFIRE data sets should recognize that the inputs to the modeling process, while not always perfect, reflect the most accurate and current information available and are based upon ecologically sound assumptions. For these reasons, LANDFIRE products represent state-of-the-art modeling and technology and thus a significant improvement over other current options.

Conclusion

There is no single recommended procedure for deriving accuracy estimates for LANDFIRE products. Because time- and cost-related constraints, it will not be possible to conduct traditional accuracy assessments for the LANDFIRE mapping region (the entire U.S.). Yet at the same time, we recognize that evaluations of quality and accuracy increase the credibility of the final LANDFIRE products. Additionally, we can learn much by assessing error terms in the products, and this knowledge can be invaluable for future mapping and modeling endeavors. We suggest conducting a suite of accuracy assessment methods for LANDFIRE National, ranging from mostly qualitative assessments (such as the critical inspection of products, consultation with regional experts, and comparisons with existing data sets) to more quantitative analyses (such as cross-validation assessments, traditional accuracy assessments at the superzone level, and select evaluations at local levels). These combined approaches will provide LANDFIRE data users with the accuracy information necessary to facilitate the appropriate use of the data.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Chapter
14

Dissemination of LANDFIRE Prototype Project Data

Jeff Eidenshink

Introduction

The transfer of LANDFIRE data to users is the most important aspect of the Landscape Fire and Resource Management Planning Tools Project (LANDFIRE Prototype Project). The creation of an accurate, consistent, nationwide data set provides the foundation for a successful project. The final step is to make the data readily available to the user community. User capabilities and needs vary widely. Many users require LANDFIRE data to solve day-to-day wildfire management problems such as planning fuel treatments or managing active wildfires. Others use LANDFIRE data to gather information over large geographic areas for strategic planning and analyses. The diversity of users and the variety of applications of LANDFIRE data present an interesting challenge: to develop a data dissemination system that is comprehensive, user-friendly, and flexible. The system must be functional across many levels of technology, ranging from powerful computing capability to support national-scale strategic planning to field-level tactical wildfire operations support. The system must be sustainable, dependable, affordable, and adaptable to various levels of and changes in technology.

The Technical Problem

Most of the LANDFIRE products are developed at a 30-meter grid resolution. Because the overall volume of LANDFIRE data is expected to exceed four terabytes, an effective and efficient distribution mechanism is required to allow for seamless data download for any given polygon area.

Access to LANDFIRE data must be supported on several levels. First, users must be able to view the core deliverables produced by the LANDFIRE Project. The U.S. Geological Survey (USGS), via The National Map, uses Internet map services (IMS) as the primary mechanism for viewing geospatial data layers. With an IMS, a view of selected data layers is rendered as an image for a selected map scale and extent. The LANDFIRE data and information from The National Map are provided through an IMS (fig. 1) that is supported by fully compliant Open Geospatial Consortium (OGC) web map service (WMS) connectors and ArcIMS interfaces. The IMS can also be directly accessed through Geographic Information System (GIS) tools, such as ArcMap. Second, users must be able to download data to their own computers for local application. An interface is needed that enables users to select a segment of data for a geographic region and download the data in a timely manner and standard format. Third, users must be able to perform applications via the Internet, without having to download the data or the application. Examples include running models interactively or producing summary reports from the geospatial data.

In: Rollins, M.G.; Frame, C.K., tech. eds. 2006. The LANDFIRE Prototype Project: nationally consistent and locally relevant geospatial data for wildland fire management. Gen. Tech. Rep. RMRS-GTR-175. Fort Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

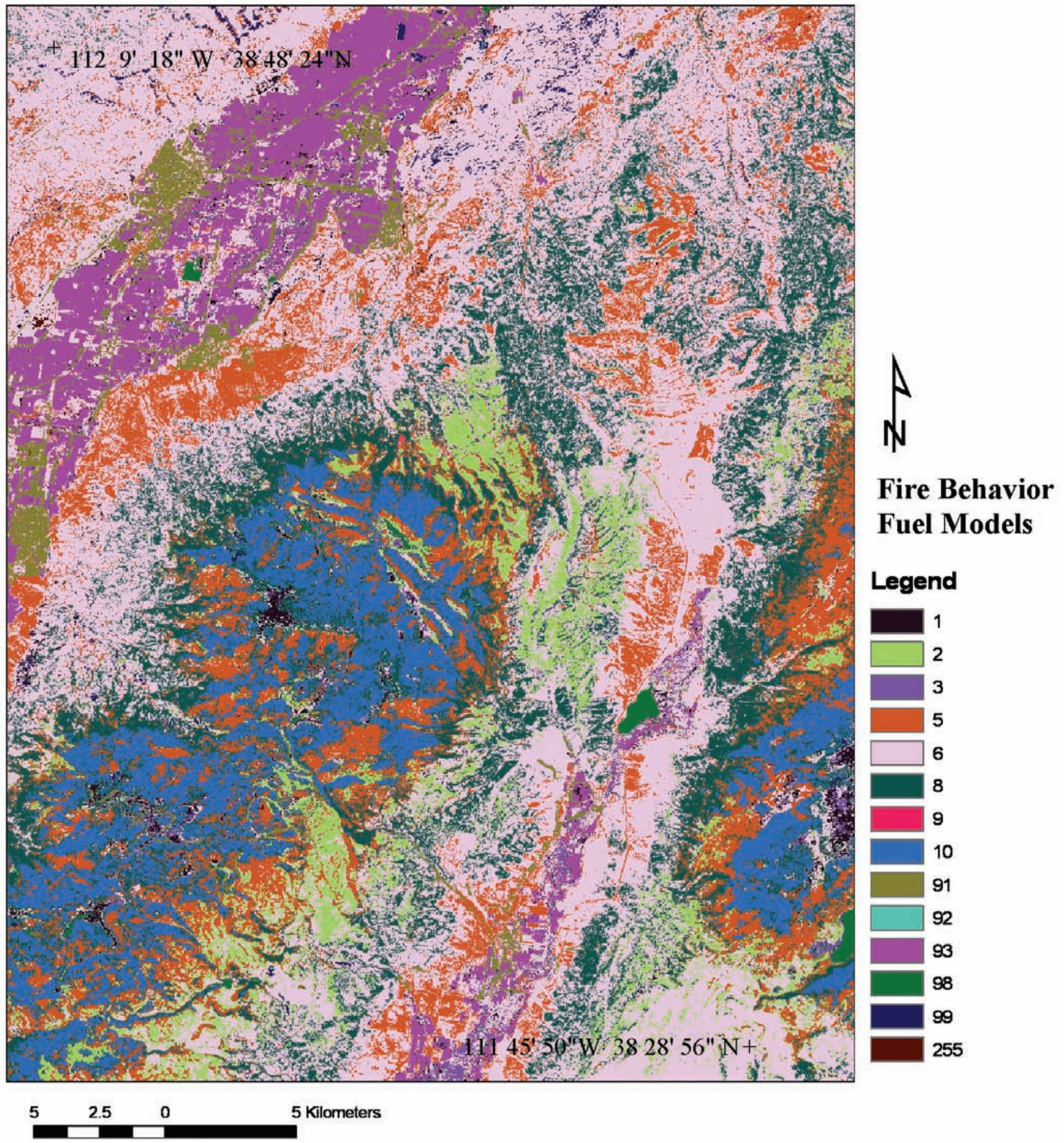

Figure 1—A portion of the LANDFIRE Zone 16 (central Utah) Fire behavior Fuel Models layer from The National Map. The colors represent different fire behavior fuel models. (Please visit the Data Products section of www.landfire.gov for details on the fire behavior fuel models.)

Objectives

The plan for distributing LANDFIRE data capitalizes on the capabilities of The National Map to provide integrated geospatial data within the context of the wildland fire community's data requirements. This approach is logical from the standpoint that the USGS has the necessary technical experience, a long history of delivering geospatial and remotely sensed data, and the required software and hardware resources.

The objectives of the LANDFIRE data distribution plan are as follows:

- to develop a LANDFIRE data access interface based on the technical capabilities of The National Map,
- to develop a document that articulates the requirements for LANDFIRE data delivery, and
- to integrate LANDFIRE products with other geospatial data.

LANDFIRE Prototype Project Data Distribution Approach

The Internet is the enabling technology that will increase the public and private sectors' and individuals' awareness and use of spatial data. Having evolved from a means to view content and deliver products, the Internet encourages the development of more holistic spatial services, stand-alone devices, specialized applications, customized spatial queries, and interactive capabilities. The USGS, via The National Map, is currently employing the Internet as the primary mechanism for improving the availability of geospatial data.

A functional prototype IMS has been developed for LANDFIRE data dissemination (see www.landfire.gov). The two LANDFIRE Prototype mapping zones are used as the foundation for the prototype IMS. As they are mapped, other zones are added to the IMS. The availability of the LANDFIRE IMS will enable users of LANDFIRE products to integrate current GIS capability with LANDFIRE data.

In circumstances where bandwidth capability is limited or where in-house applications require complex data analysis, field practitioners may wish to download the data as opposed to simply viewing the data through an IMS. LANDFIRE data are distributed through the LANDFIRE IMS following the model of the USGS Seamless Data Distribution System (SDDS) (http://seamless.usgs.gov/). The SDDS includes an area of interest selection tool and online direct data downloads. Initially, these data sets can be retrieved interactively by drawing a box around the area of interest. The next level of capability will support the use of a template defining the desired area, such as a county or watershed. The template may be derived from an existing LANDFIRE geospatial layer or from The National Map. Ultimately, the data distribution system will need to accept user-defined templates such as the perimeter of an active wildfire or an administrative unit.

Recommendations for National Implementation

Scientists from the USGS Center for Earth Resources Observation and Science, The Nature Conservancy, the USDA Rock Mountain Research Station Missoula Fire Sciences Laboratory, and the National Interagency Fire Center are cooperating with field personnel to develop the IMS in addition to the data download and delivery capabilities. Recommendations for national implementation address issues affecting the integration of the IMS with GIS technology and existing models. Four main points for refinement have been identified.

"Third-party" Fire and Land Management Models

A major requirement of the LANDFIRE Prototype Project is that it must facilitate the implementation of existing models. Specifically, it must support four standardized analytical fire models: FARSITE, a fire behavior simulation model; FlamMap, a fire potential model; and FOFEM and CONSUME, both fire effects models. Each of these models uses several LANDFIRE layers combined with ancillary data. The models also produce derived layers that need to be catalogued as part of the LANDFIRE database and also made accessible for other users and applications.

The capability to perform interactive modeling using IMS is in the early stages of development. Research will determine how these models will function as part of the analytical tools provided within an IMS. The capability to execute these models through an Internet-based interface would substantially reduce the need to download a large volume of data from remote locations using slow Internet connections. Instead, model results, having a considerably smaller data volume than the input data itself, could be delivered to a field center in a timely manner. The modeling results will be enhanced using ancillary layers (such as those depicting transportation, hydrology, terrain, and/or structures) from The National Map.

Scaling of LANDFIRE Products and Geospatial Data

LANDFIRE products and geospatial data must be useable at spatial scales ranging from that of a watershed to that of the entire nation. LANDFIRE data will be used in decision support systems where emphasis could range from real-time requirements for wildland fire fighting to national planning requirements for allocation of fuel treatment resources. For effective use of LANDFIRE data, a robust scaling capability will be needed to enable land managers to scale LANDFIRE data layers from local to national applications. Users will identify the most appropriate scales for applying LANDFIRE products. Techniques for display of multi-scale data using IMS, at scales that meet the needs of decision support and modeling, are under development.

Updating LANDFIRE Geospatial Data

A LANDFIRE requirement is that data be routinely updated in order to capture varying patterns of fire and fuel in terms of both time and geographic scale. This updating process presents challenges for the LANDFIRE team, the greatest of which will be solving the administrative and technical problems regarding processes for collecting and collating updates from the field. Ideally, every fuel treatment, such as prescribed burns or the mechanical removal of fuel, and all wildfires will be mapped by a land management agency; however, the collection and collation of this information at a national scale across agencies and programs remains a difficult task. Data will be updated through GIS capabilities that integrate with the data dissemination system.

Developing the Technical Infrastructure

Implementing a national LANDFIRE data distribution system can be viewed simply as expanding the prototype effort to the national scale. The data distribution infrastructure, such as data servers, network bandwidth, and data storage, can be improved by incremental expansion of the hardware capability and through routine replacement of old technology. Meeting the technological needs of the users, however, is much more complex. Processes such as formatting data, merging data from disparate sources, and analyzing data become increasingly complex as more users find more ways to employ the data.

Conclusion

The LANDFIRE data dissemination system is built on existing and emerging Internet technology. The LANDFIRE data layers are available for viewing and download using the functional capability of Internet map services. The LANDFIRE data dissemination framework is modeled after The National Map and other geospatial data delivery systems. Unique LANDFIRE requirements will be identified through cooperation with users. The goal is to meet the needs of field-level management as well as those of national strategic planning. The technology of the LANDFIRE data dissemination system will be an effective and affordable solution to the challenge of wildfire management information delivery.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

The Author

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NOTES

RMRS
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