Chapter 11
Use of Expert Knowledge to Develop Fuel Maps for Wildland Fire Management

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Contents

11.1 Introduction

Fuel maps are becoming an essential tool in fire management because they describe, in a spatial context, the one factor that fire managers can control over many scales – surface and canopy fuel characteristics. Coarse-resolution fuel maps are useful in global, national, and regional fire danger assessments because they help fire managers effectively plan, allocate, and mobilize suppression resources (Burgan et al. 1998).

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Regional fuel maps are useful as inputs for simulating carbon dynamics, smoke scenarios, and biogeochemical cycles, as well as for describing fire hazards to support prioritization of firefighting resources (Leenhouts 1998; Lenihan et al. 1998). Intermediate- and fine-resolution digital fuel maps are important for rating ecosystem health, targeting and evaluating tactical fuel treatments, computing fire hazard and risk (the potential damage and likelihood of that damage, respectively), and aiding in environmental assessments and fire danger forecasting programs (Pala et al. 1990; Hawkes et al. 1995; Gonzalez et al. 2007). However, landscape-level fuel maps have seen the most use in fire management because they provide the critical inputs for the spatially explicit fire behavior and growth models used to simulate fires so that they can be more effectively managed and fought (Keane et al. 1998, 2006).

Expert knowledge has been involved in the development of most fuel maps currently used in fire management (Keane et al. 2001). Experts in wildfire suppression, fuel management, fire modeling, and prescribed burning have provided the background information needed to create, refine, and validate the primary fuel maps required by fire behavior and growth models. This heavy reliance on expert knowledge is a result of many factors, including the high spatial and temporal variability of fuels, diversity of fuel beds, subjective nature of the fuel classifications, and lack of comprehensive fuel data across forests and rangelands. In this chapter, we summarize past, present, and potential future use of expert knowledge in the mapping of fuels to support fire management, primarily for the USA, but also including knowledge from other countries. We present a detailed example of how expert knowledge was used in the national landscape fire and resource management planning tools (LANDFIRE) mapping project, which created a set of national fuel maps. We also discuss the challenges involved in mapping fuel, review mapping approaches that have integrated expert knowledge in their design, and describe technologies and protocols needed to facilitate the development of accurate digital fuel maps.

11.1.1 Fuel Mapping Background

Wildland fuels comprise all the organic matter available to permit fire ignition and sustain combustion (Albini 1976; Sandberg et al. 2001). Specifically, fuel components are the live and dead surface and canopy biomass that foster the spread of wildland fire. Surface fuel is often divided into duff and litter, downed and dead woody biomass in a range of diameter classes, and live and dead standing vegetation (Fosberg 1970; DeBano et al. 1998). Canopy fuel is aerial biomass (typically >2 m above ground), primarily composed of branches and foliage and also included arboreal mosses, lichens, dead ladder fuels, and other hanging dead material such as needles and dead branches (Reinhardt et al. 2006). The amount (mass or volume) of biomass per unit area is often referred to as the “fuel load.” Most fuels in fire-prone ecosystems accumulate in the absence of fire. Surface fuels usually increase until the decomposition rate equals the deposition rate, and canopy fuels tend to increase as shade-tolerant tree species become established in the understory and overstory (Keane et al. 2002).

Wildland fuels can be mapped using many approaches (Keane et al. 2001; Arroyo et al. 2008). Most efforts have mapped important fuel characteristics such as the fuel model (an abstract classification of fuel used as an input to fire behavior models), fuel bed depth, and canopy bulk density as a function of vegetation type (Agee et al. 1985; Menakis et al. 2000), ecosystem (Grupe 1998), and topography (Rollins and Yool 2002) to create spatial layers in a geographical information system (GIS). Some researchers have qualitatively or quantitatively related fuel information to various forms of remote-sensing data at multiple scales, including digital photographs (Oswald et al. 1999), LANDSAT images (Wilson et al. 1994), ASTER images (Falkowski et al. 2005), AVIRIS images (Roberts et al. 1998), AVHRR images (McKinley et al. 1985; Burgan et al. 1998), microwave-radar images (Arroyo et al. 2008), and LIDAR data (Mutlu et al. 2008). Others have mapped fuels using complex statistical modeling techniques coupled with comprehensive field data (Rollins et al. 2004) and knowledge-based systems (Goulstone et al. 1994; de Vasconcelos et al. 1998). Most efforts have combined two or more of these approaches into an integrated analysis, with the goal of developing more accurate and consistent fuel maps. One resource that has been used as the foundation for most of these mapping efforts was expert knowledge.

For many ecological reasons, it is difficult to map wildland fuels (Keane et al. 2001). The most notable factor that confounds mapping is the high temporal and spatial variability of fuel components (Brown and See 1981; Keane 2008). The components, fuel loads, and properties of the fuels are also highly diverse and vary across multiple scales; a fuel bed, for example, can consist of many fuel components, including litter, duff, logs, and coniferous cones, and the properties of each component, such as its heat content, moisture content, and size, can be highly variable even within a single type of fuel. The variability of fuel loads within a stand, for example, can be as high as the variability across a landscape, and this variability can be different for each fuel component and property (Brown and Bevins 1986). A single wind storm or wet snow can rapidly increase woody fuel load at the surface and change the entire structure of the fuel bed (Keane 2008).

There are also many methodological and technological factors that complicate fuel mapping. First, much of the remotely sensed data used in fuel mapping is derived using technologies that cannot detect surface fuels because the ground is often obscured by the forest canopy (Lachowski et al. 1995). Even if the canopy were removed, it is doubtful that today's coarse-resolution imagery could distinguish subtle differences in the characteristics of all fuel components. High fuel diversity and variability also preclude an accurate standardized measurement and mapping protocol; it is difficult to sample fine fuels (e.g., duff, litter, and fine woody material) and large fuels (e.g., logs) at the same scale, degree of rigor, and accuracy (Sikkink and Keane 2008). Fuel components can vary across different scales (e.g., logs vary over a larger area than fine fuels), and few of these scales match the resolution of the remote-sensing data, the sampling methods, or the available GIS data layers. Moreover, many fuel parameters required by current fire behavior models lack standardized measurement techniques. For example, some fire behavior models use fuel model classifications that were subjectively created to represent expected fire behavior (Anderson 1982).

11.1.2 Fuel Classifications

Because of the abovementioned factors, fire management has turned to the use of fuel classifications to simplify the collection of input data for fire modeling applications. Most fire models use fuel classifications to simplify the inputs for fuel characteristics, but the diversity of these inputs makes accurate, comprehensive, and consistent fuel classification difficult (Sandberg et al. 2001; Riccardi et al. 2007; Lutes et al. 2009). Some fuel classifications are designed to include subjective components and categories that are based on the objective of a given mapping project. For example, fire behavior prediction requires mapping of the fuel loads of downed and dead fine woody materials stratified into the size classes that are required by the fire behavior model (Burgan and Rothermel 1984).

Fuel classifications can be divided into those that were developed to simulate the effects of fire and those that were developed to predict fire behavior. The former fuel classifications summarize actual fuel characteristics (most often fuel load) for diverse fuel components based on vegetation type, biophysical setting, or fuel bed characteristics. Few of these classifications were developed to support unique identification of the classes in the field; most rely on the expertise of the fuel sampler and their ability to match the observed fuel bed conditions to the classification categories. The exception is the fuel loading model (FLM) classification (Lutes et al. 2009), which contains a comprehensive field key (Sikkink et al. 2009).

In contrast, fuel classifications designed to predict fire behavior have categories referred to as fire behavior fuel models (FBFMs), which are a set of summarized fuel characteristics (e.g., fuel load, ratios of surface area to volume, mineral content, heat content) for each fuel component that is required by the fire behavior model (Burgan and Rothermel 1984). The most commonly used FBFM classifications are the 13 models of Anderson (1982) and the 40+ models of Scott and Burgan (2005), all of which are used as inputs to the Rothermel (1972) fire-spread model that is implemented in the BEHAVE and FARSITE fire prediction systems, and the 26 fire danger models of Deeming et al. (1977) that are used in the US National Fire Danger Rating System. FBFMs are not a quantitative description of fuel characteristics, but rather a set of fuel inputs designed to compute an "expected" fire behavior; this is because the inherent complexity of the mechanistic fire behavior models of Rothermel (1972) and Albini (1976) makes it difficult to realistically predict fire behavior from the actual fuel load (Burgan 1987). As a result, a complicated procedure must be followed to develop FBFMs in which fuel loads and other characteristics are adjusted to match fire characteristics that have been observed in the field (Burgan 1987).

Therefore, without prior knowledge of fire behavior in local fuel types, it is nearly impossible to accurately and consistently use and interpret most FBFM classifications (Hardwick et al. 1998), and the identification of fuel models in the field is highly subjective because it is based on an individual's perception of fire behavior rather than on actual measurements of fuel loads. Because classifications based on fire behavior and fire effects form the backbone of most fire management analyses, and because these classifications are inherently subjective and difficult to use, most fuel mapping must rely on expert knowledge and experience during all phases of the mapping process.

11.2 The Use of Expert Knowledge in Fuel Mapping

11.2.1 Who Are the Experts?

The best experts to use when creating wildland fuel maps are people who are actually involved in the management of wildland fire (Table 11.1). Local and regional fire behavior analysts who have extensive experience in predicting fire behavior and effects for both wildfires and prescribed fires are probably the most desirable experts because they can provide integrated knowledge of the influence of topography, vegetation, disturbance, and climate on fuel bed characteristics and the consequences for fire behavior (Keane et al. 2000). Fuel specialists and fire management personnel are also important because they have extensive knowledge of how to implement a fuel model within a fire model and understand the temporal and spatial scales of various fuel characteristics. Any expert who assists in mapping fuels must understand both the conditions and properties of wildland fuels and the expected fire behaviors if these fuel complexes are burned. Experts can be selected from diverse pools; Keane et al. (1998) used fire managers and wildfire suppression specialists; Nadeau and Englefield (2006) used fire scientists; and Reeves et al. (2009) used scientists, managers, and any other fire resource professionals who were available.

Since the quality of the fuel maps used to predict fire behavior is nearly impossible to assess because of the subjective nature of the FBFM (Keane et al. 2001), it is essential that those who use the fuel maps approve of their utility. The complexity, resolution, and detail involved in the mapping procedures, such as whether the latest statistical techniques and state-of-the-art images are used, are less important than producing a map that fire managers trust enough to use. As a result, experts in GIS, digital mapping, analysis of satellite images, fire ecology, and spatial statistical analysis play a lesser role than fire managers in providing expert knowledge. Complex and novel mapping techniques may yield fuel map layers that fire managers may never use, whereas fuel maps developed from simplistic qualitative techniques may be easier for fire managers to understand and employ. This means that fuel mapping, especially for fire behavior prediction, should incorporate knowledge from fire management experts during map development to increase the likelihood

Table 11.1 A summary of the potential experts whose knowledge can be used to more effectively map wildland fuels

Title	Main job	Potential knowledge	Potential mapping tasks
Fire behavior analyst	Predicting fire behavior	FBFM sampling; fire behavior simulation, collecting fuel information as inputs	FBFM assignment and calibration; map validation and verification
Fuel specialist	Sampling, estimating, and treating wildland fuels	FBFM identification; fuel sampling; defining the biophysical context for fuels; prediction of fire effects	Collection of reference field data, estimation and verification of fuel loads
Fire manager	Managing fire in specific areas using fuel treatments, prescribed burning, and controlled wildfires	Local knowledge of wildland fuel characteristics; prediction of fire behavior and effects	Calibration, validation, and verification of local area references
Fire suppression specialist	Suppression of fires	FBFM identification and use; prediction of fire behavior	FBFM calibration; map validation
Fire scientist	Conducting fire and fuel research	Depends on the scientist and their field of study	Fuel collection, sampling, and identification; map validation and calibration
Fire prevention specialist	Fire danger warnings, public information, preventing unwanted ignitions	General fuel information	Map validation and verification

These titles vary among countries and government agencies, and many of these experts have multiple titles and perform multiple duties. *FBFM* fire behavior fuel model

that the resulting maps will be used. This is a somewhat subjective and self-affirming process, but one that is necessary until advances in fire behavior prediction use fuel inputs that can be readily measured, validated, and verified, while also being understood and accepted by fire managers.

11.2.2 How Is Expert Knowledge Used?

There are four general ways that expert knowledge can be integrated into the fuel mapping process. First, expert knowledge can be used in the field to estimate or measure the fuels to provide information that will be used for ground-truthing or as a reference in the mapping process (i.e., for *reference*). FBFMs, for example, must be estimated at a plot level by experts who have been trained to predict fire behavior when assessing fuel (Burgan and Rothermel 1984). Hornby (1935) used a team of experts who traversed the landscapes of the western United States to evaluate fire behavior characteristics from fuel and vegetation attributes, and who used these attributes to delineate differences in fire spread and intensity. Experts in visually assessing fuel loads could choose the most appropriate fuel characteristics classification system (FCCS) category that best describes a sample area (Riccardi et al. 2007). Keane et al. (1998) trained field crews to properly use Anderson's (1982) US National Forest Fire Laboratory fuel models in sample plots. These experts can also build local keys for identifying appropriate fuel models in the field to help other crews to consistently collect useful fuel data. Agee et al. (1985), for example, used local fire and fuel experts to construct and refine FBFM fuel keys for use in the field.

Second, fuel information can be assigned to the categories or values of other GIS layers, such as vegetation or topography, using expert knowledge to create the fuel maps (i.e., for *calibration*). In this approach, experts assign fuel characteristics, such as an FBFM, FLM, or FCCS category, to each combination of mapped categories across selected data layers (Keane et al. 1998). Vegetation maps are most often used in fuel mapping projects (Menakis et al. 2000), and experts have assigned fuel classification categories to combinations of potential vegetation (i.e., biophysical setting), cover type, and structural stage (Keane et al. 1998, 2000; Schmidt et al. 2002; Reeves et al. 2009). In Canada, Hawkes et al. (1995) used experts to assign fuel types based on tree height, canopy closure, crown type, and cover type, and Nadeau and Englefield (2006) integrated the opinions of forest fire scientists using a fuzzy-logic engine to combine spatial data layers of land cover, biomass, and leaf area to create a map of Canadian Forest Fire Danger Rating System fuel types for Alberta. Keane et al. (2000) used experts to select the most appropriate FBFM for the combination of categories across three vegetation maps in New Mexico.

A third approach is to review fuel maps to refine mapping methods and update the input databases using expert knowledge (i.e., for *validation*). Reeves et al. (2009) asked fire management experts to evaluate portions of the preliminary LANDFIRE fuel maps to refine the mapping protocols so that they accounted for local conditions. This approach is commonly referred to as the "sniff test," because fuel and fire experts use their local knowledge to determine whether things "make sense"; that is, based on their experience, they critique the value and reliability of the fuel map with respect to their management objectives, and suggest ways to improve map quality (Keane et al. 2006). Keane et al. (2000) conducted workshops on the Gila National Forest in which fire managers refined the mapping of surface fire behavior model assignments to vegetation map categories based on their knowledge of the fuels in the mapped areas.

Last, fire and fuel experts can be used to create the spatial reference or ground-truthing information needed to assess the accuracy and precision of fuel maps (i.e., for *verification*). Local fuel experts can delineate important fuel types on maps that can then be used as a ground-truthing reference for the development and evaluation of the spatial fuel information. Previous fuel maps or mapping efforts developed based on expert experience can also be used as a validation tool, as can vegetation and stand maps that can be correlated with fuel properties.

11.2.3 How Is Knowledge Obtained from the Experts?

Perhaps the most common vehicle for obtaining expert knowledge is a workshop in which experts participate in a focused meeting to build the background knowledge that will be used for developing the fuel maps. These workshops can be attended in person, by telephone, or using videoconferencing technology. Extensive preparation is critical so that the experts can efficiently and effectively summarize their knowledge while staying focused on the specific mapping objective. For example, Keane et al. (1998) prepared detailed worksheets for combinations of vegetation classification categories in the Selway-Bitterroot Wilderness area so that fuel specialists could more easily assign a surface fire behavior model (Anderson 1982) to each vegetation category for their area. To improve workshop efficiency, it is sometimes beneficial to provide default knowledge or a "straw man" for workshop participants to critique and improve. For example, Keane et al. (2000) assigned fuel models to New Mexico vegetation types and then asked fire managers to review and update these assignments.

The workshop participants should agree beforehand on the process and parameters that will be used for the fuel model assignments and map development, and they should attempt to reach consensus on the assignments to create more consistent maps. For example, some fuel specialists may select a fuel model based on severe drought conditions at the height of a wildfire season, but that may be inappropriate if the fuel map will be used to predict the spread of prescribed fires during less dangerous portions of the fire season. Therefore, it is important that the group work together, based on a clear understanding of the map's objectives, to permit calibration and increase consistency.

Other means of obtaining expert knowledge include surveys and interviews. Though these avenues can be easier to implement, they are less desirable because they fail to provide a process by which the experts can calibrate their expertise relative to the mapping objective and the knowledge of others. In contrast, Hirsch et al. (2004) interviewed 141 fire managers to obtain their knowledge about fireline efficiency and initial attack productivity, because the context for this information was the same for each expert and the goal was to create statistical distributions that described this body of information. Although many researchers believe that the interview process should be relaxed and confidential, Keane et al. (1998) found that a more active dialog that included challenges to statements and assignments was needed to ensure that the information was consistent across respondents. Sometimes experts have little knowledge of a specific fuel characteristic, but have considerable experience in assessing fire behavior when fuel with this characteristic is burned. In these cases, surveys and workshops can let researchers infer information about the fuel from the expert's assessment of the fire behavior characteristics in that fuel. For example, experts can be shown photos of vegetation types with known fuel loads and asked to estimate potential flame lengths; if fuel loads are unknown, fire behavior models can be used to work backward to approximate the fuel loads needed to achieve the estimated flame lengths (Reeves et al. 2009). The expert knowledge collected from workshops, interviews, and surveys can be synthesized using many types of technology. For example, Nadeau and Englefield (2006) used fuzzy logic to summarize the opinions of fire scientists, whereas others have stored expert assignments and estimates in databases (Keane et al. 1998; Reeves et al. 2009).

11.3 The LANDFIRE Fuel Mapping Effort

The LANDFIRE project mapped wildland fuels, vegetation, and fire regime characteristics across the USA to support multiagency, multiscale fire management (Rollins 2009; Rollins and Frame 2006). This project was unique because of its national scope and its creation of an integrated suite of spatial data at 30-m spatial resolution, with complete coverage of all lands within the lower 48 states in the USA, comprising 64 mapping zones. The LANDFIRE fuel maps were created to support the use of critical fire behavior models such as FARSITE (Finney 1998) and FLAMMAP (Finney 2006). LANDFIRE was the first project of its kind to offer high-resolution, wall-to-wall wildland fuel spatial data for the USA (eight fuel data layers were mapped by LANDFIRE).

11.3.1 Surface Fuel Mapping

Two LANDFIRE surface fire behavior fuel model layers [FBFM13 for the 13 fuel models of Anderson (1982) and FBFM40 for the 40 fuel models of Scott and Burgan (2005)] and the two surface fuel load classifications [FCCSM for the FCCS models of Riccardi et al. (2007) and FLM of Lutes et al. (2009)] were used in this project. They were mapped by linking unique combinations of categories from several vegetation classifications that described the existing vegetation, plant height, canopy cover, and biophysical setting (Reeves et al. 2009) to the categories in the two FBFM classifications (Keane et al. 2001) and to the categories in the two fuel loading classifications (FCCSM, FLM; Fig. 11.1). Assignments for the FBFMs assumed environmental conditions that typify the fire weather that is normally encountered during the peak of the burning season for each geographic region being evaluated.

Very few agencies have sufficient georeferenced field data on fuels to permit fuel mapping, so plot-level data were mostly unavailable to facilitate the assignment of surface FBFMs, FCCSMs, or FLM to the LANDFIRE vegetation data products for all regions (Caratti 2006). Therefore, all fuel mapping rules (assignments) were accomplished using a qualitative approach based on the experience and knowledge

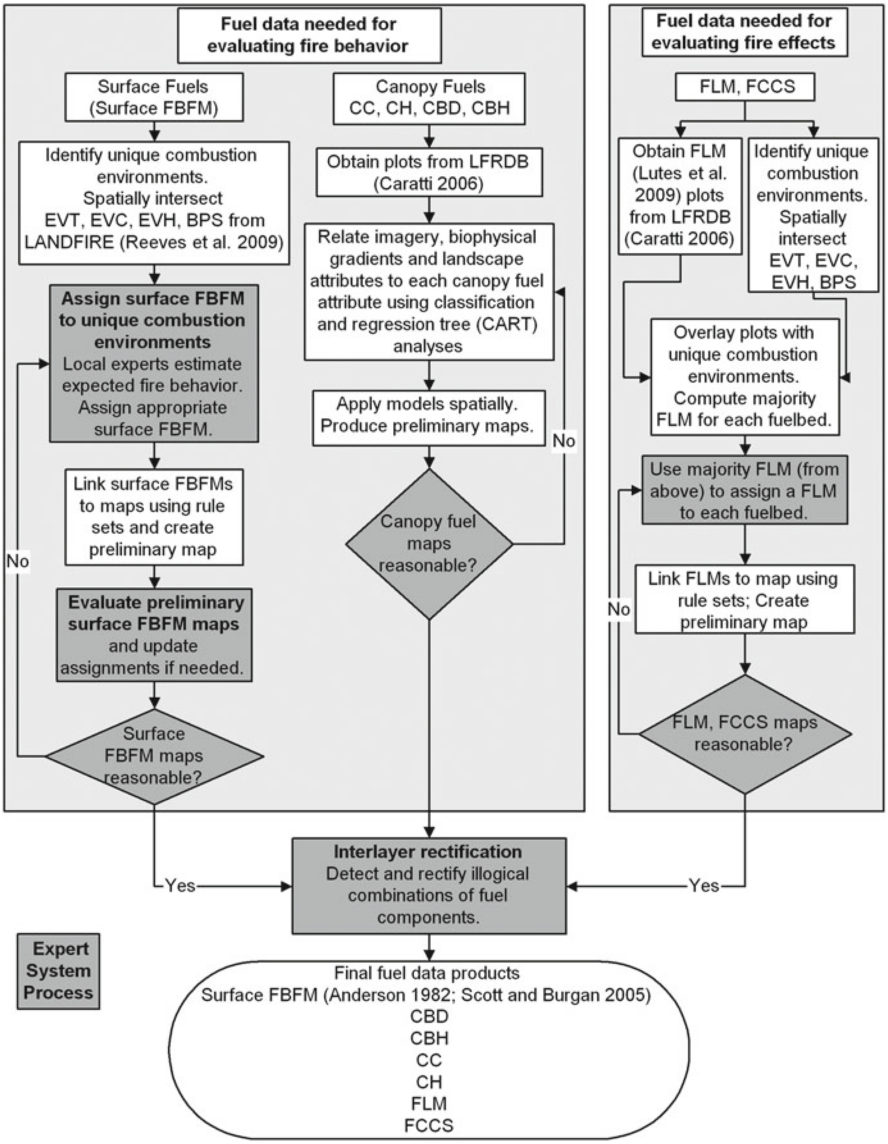

Fig. 11.1 A flowchart showing the procedures used to map surface and canopy fuel characteristics in the LANDFIRE national mapping project. The dark gray boxes indicate when expert knowledge was used to create, validate, and refine fuel maps. *BPS* biophysical setting, *CC* canopy cover (%), *CBD* canopy bulk density (kg m^{-3}); *CBH* canopy base height (m), *CH* canopy height (m), *EVC* existing vegetation cover (%), *EVH* existing vegetation height (m), *EVT* existing vegetation type, *FBFM* fire behavior fuel model, *FCCS* surface fire characteristics classification system, *FLM* fuel loading model, *LFRDB* LANDFIRE Reference DataBase

of the fire and fuel experts. These experts were usually fire behavior specialists who understood the fire behavior typically associated with the area being evaluated, but included other people associated with fire management (see Table 11.1), because many regions had no local fire behavior experts. In a series of integrated workshops, the fire experts evaluated each unique combination of vegetation classifications and predicted the fire behavior based on their experience. When experts were not available for a given LANDFIRE mapping zone, assignments from an adjacent mapping zone were used.

Initial review maps were created for each of the 64 LANDFIRE mapping zones once all unique combinations of the vegetation layers had been assigned surface fuel models. Each review map was then evaluated by a separate group of local fire and fuel specialists to detect areas where the surface FBFMs were obviously mischaracterized. During this intensive review period, approximately 5–20 local specialists updated, refined, and improved the review maps, and all disagreements between participants were resolved through majority vote when consensus could not be reached. When few experts were available for a mapping zone, experts from adjacent mapping zones were used. If obvious errors were detected, only the rule sets used to compare the surface FBFMs to the vegetation components were revised instead of subjectively updating individual pixels in the surface FBFM map.

11.3.2 Canopy Fuel Mapping

Four canopy map layers were created to describe canopy fuels – canopy bulk density (CBD, kg m^{-3}), canopy base height (CBH, m), canopy cover (CC, %), and canopy height (CH, m) – using regression-tree statistical modeling, in which field-referenced estimates were related to satellite imagery, biophysical gradients, stand structure, and vegetation composition data. The regression-tree models were formulated using the algorithm as implemented in the Cubist software (Rulequest Research, St. Ives, Australia). Canopy cover and height (CC, CH) were mapped using the methods of Zhu et al. (2006), and the CBH and CBD layers were mapped using the methods of Keane et al. (2006). The CBH and CBD canopy characteristics were estimated for each field plot using the FuelCalc software, which uses the algorithms of Reinhardt et al. (2006). Regression-tree models for CBH and CBD were developed using the spatially explicit predictor variables available in the LANDFIRE system (Keane et al. 2006), such as satellite reflectance, biophysical gradients, and vegetation structure and composition data (Reeves et al. 2009). Each regression tree was then applied across each mapping zone to produce preliminary maps of CBH and CBD. A gamma log-link generalized linear model (McCullagh and Nelder 1983) was then used to refine the CBD map by ensuring that the CBD predictions made sense in relation to CC (e.g., to eliminate high CBD values in areas of low CC; Reeves et al. 2009).

The resultant CBD, CH, CBH, and CC maps were evaluated by local experts in a series of workshops to eliminate illogical combinations. These experts determined thresholds for acceptable canopy fuel behavior stratified by other LANDFIRE mapping categories. This critical expert analysis ultimately improved the efficacy and accuracy of the canopy fuel maps. For example, during the interlayer rectification, experts assigned a CBH of 10 m and a CBD of 0.01 kg m^{-3} to deciduous stands to ensure that crown fires would not be simulated in this forest type.

A tenfold cross-validation procedure was used to assess the accuracy of the CBD and CBH regression-tree models by comparing plot-level estimates with mapped predictions at the same locations. No accuracy assessment was performed for the surface FBFMs because there were few independent datasets available and because different evaluators tend to estimate surface FBFMs differently, though consistent estimates between observers can sometimes be achieved (Burgan and Rothermel 1984). Despite this lack of an accuracy assessment for surface fuels, the abovementioned qualitative evaluation was performed during rule set development, expert review, and the annual postfire-season reviews (Fig. 11.1). Annual postfire-season reviews offered users of the LANDFIRE fuel data products a chance to discuss any issues with the data. Most of the maps derived from expert knowledge had low accuracies (<50%) and contained inconsistencies. Future improvements to this process must therefore include georeferenced field data to guide, evaluate, and eventually replace expert opinions. One advantage of using expert assignments of fuel attributes to the LANDFIRE vegetation map categories is that the successional models developed for LANDFIRE contain development pathways that can eventually be used to update the fuel maps for changes in the vegetation.

11.4 The Future of Expert Knowledge in Fuel Mapping

Expert knowledge has been indispensable in building contemporary fuel maps, and without this input, it is doubtful that today's fuel maps would be useful to fire managers. However, the goal of any mapping effort should be to minimize subjective bias by replacing qualitative expert knowledge with empirically driven, quantitative, and objective approaches. Although input from experts will continue to play an important role in the development of fuel maps, tomorrow's fuel layers should be designed so that the methods are repeatable, quantitative, and unbiased, and the maps are constructed using a combination of detailed georeferenced field data, high-resolution remote-sensing data, complex ecosystem simulations, novel GIS techniques, knowledge-based systems, and advanced statistical analyses (Keane et al. 2001). The first step is to develop new fire behavior prediction models that use inputs that can be easily defined, measured, and summarized in the field. Then, new surface fuel and canopy fuel sampling methods must be developed and adopted by land management agencies to allow the development of extensive, standardized, spatially explicit databases of fuel conditions that can be used for map development, testing, and validation (Krasnow et al. 2009; Lutes et al. 2009).

A variety of remote-sensing technologies, such as LIDAR (Koetz et al. 2008), radar (Bergen and Dobson 1999), digital photography (Bailey and Mickler 2007), hyperspectral imagery (Jia et al. 2006), high-resolution images (Lasaponara and Lanorte 2007), and a melding of various images (Keramitsoglou et al. 2008; Koetz et al. 2008), will vastly improve fuel mapping compared with current methods that rely heavily on the use of LANDSAT images. Ecosystem simulation models can be used in combination with climate, soil, and topographic information to spatially describe the biophysical environment and thereby improve fuel mapping (Rollins et al. 2004). Progressive GIS techniques can be used to integrate spatial data layers in such a way as to predict the most appropriate fuel model (Hawkes et al. 1995; Chuvieco and Salas 1996). In addition, new statistical analysis techniques, such as regression trees, gradient nearest-neighbor analysis, fuzzy logic, and hierarchical modeling, are needed to integrate the biophysical controls on fuel properties within fuel maps (Ohmann 1996; Ohmann and Spies 1998; Nadeau and Englefield 2006).

In the meantime, innovative analytical techniques must integrate expert knowledge into a repeatable, quantitative map-building process, based on the best expert-systems technologies (Goulstone et al. 1994; de Vasconcelos et al. 1998). For example, CBH can be indirectly estimated by mathematically solving an empirical equation for the CBH required to allow a fire to transition from a surface fire into a crown fire assuming various fire behavior parameters (Reeves et al. 2009). The expert contribution to this technique involves panels of local fire behavior prediction experts who collectively determine the conditions under which a stand will likely transition from a surface fire into a crown fire. This approach combines empirical modeling with expert knowledge and will consistently estimate crown fire activity if the assumed environmental conditions are realized.

Fuel classifications such as those discussed in this chapter could also be improved so that the resulting fuel maps provide higher quality inputs for fire behavior and fire effects models. The first step in this process would be to build fire behavior models that are more sensitive to realistic (i.e., field-based) estimates of fuel inputs (Arroyo et al. 2008). For example, most fire behavior models are implemented in only one dimension (point models), but wildland fire behavior occurs across three dimensions (3D). Thus, 3D fire behavior and fire effects models must be built to account for fire processes that are influenced by the vertical, longitudinal, and horizontal distributions of fuels. For example, radiation and convection are important heat-transfer processes that must be simulated in 3D to fully describe complex fire behaviors in complex fuels (Linn 1997). Once the necessary 3D models are developed, they will require innovative fuel classifications that not only describe fuel properties such as fuel load across components, but also describe how these properties are distributed both spatially (Reich et al. 2004) and temporally (Keane 2008). Future fuel classifications should be based on extensive (regional to continental) and comprehensive (all fuel components) field data (McKenzie et al. 2007), and they should be designed to emphasize differences in fuel bed properties, not only the vegetation type, structure, and topographic setting (Lutes et al. 2009). Last, there should be considerable expert knowledge built into these classifications to ensure that they will be useful to the fire managers who will use them.

We also believe that fuel experts, fire behavior analysts, and fire managers may need to rethink their paradigms for fuel description to allow for the development of higher quality fuel maps in the future. Fuel classifications, though popular, efficient, and easy to use, may be inappropriate in the future because fuel properties are not correlated across fuel components, their properties vary across different scales, and the classification categories are limited, restrictive, and subjective. Fuel components may need to be mapped independently at the most appropriate scale for a given management task to ensure accurate fire behavior prediction. For example, a digital map of coarse woody fuels could be created at a 30-m pixel resolution, whereas a fine-fuel map might require a pixel resolution of 1–5 m. Fuel component definitions should also be investigated to develop more flexible and comprehensive methods for describing the fuels and providing model inputs. For example, the size class distributions for coarse woody debris could be quantified for a fuel bed so that the fuel load can be computed for woody fuels of any size instead of using the four restrictive size classes that are currently used. Designing woody fuel size classes based on the drying time (Fosberg 1970) is probably inappropriate for accurately estimating fuel loadings and carbon pools. Tomorrow's fuel experts must be willing to modify their view of fuel complexes to permit the development of innovative wildland fuel maps. And, for these experts to modify their approach, researchers must present them with a new approach that they can understand, trust, and learn how to apply in their daily work.

11.5 Summary

Expert knowledge is an indispensable tool in the development of wildland fuel maps, and most mapping efforts have extensively used information gained from experts to support many phases of the fuel mapping process. However, the high variability of fuels, coupled with the subjective nature of expert knowledge, will require a stronger reliance on empirical data and statistical analysis to generate effective fuel maps in the future. Although expert knowledge will continue to play a critical complementary and supplementary role in future fuel mapping efforts, fuel mapping must incorporate a less-subjective means of map development. This will be difficult because it will require a complete overhaul of how fire managers think about fuel and the development of new fire behavior models and leads to the design of new fuel classifications and new fuel sampling protocols. For this change in thought to be possible, researchers must find ways to understand the real-world challenges faced by fire managers so that it is possible to communicate the advances in fire science in a way fire managers can understand and accept. Only in this way will the new science be adopted and incorporated into future fire management.

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