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Spatial fuel data products of the LANDFIRE Project

Matthew C. Reeves[A,D], *Kevin C. Ryan*[B], *Matthew G. Rollins*[C] *and Thomas G. Thompson*[B]

[A]Rocky Mountain Research Station, Missoula Forestry Sciences Laboratory, 800 E Beckwith Avenue, Missoula, MT 59801, USA.

[B]Rocky Mountain Research Station, Missoula Fire Sciences Laboratory, 5775 US Highway 10 W, Missoula, MT 59808, USA. Email: kryan@fs.fed.us; tthompson@fs.fed.us

[C]US Geological Survey, Center for Earth Resources Observation and Science (EROS), Sioux Falls, SD 57198, USA. Email: mrollins@usgs.gov

[D]Corresponding author. Email: mreeves@fs.fed.us

Abstract. The Landscape Fire and Resource Management Planning Tools (LANDFIRE) Project is mapping wildland fuels, vegetation, and fire regime characteristics across the United States. The LANDFIRE project is unique because of its national scope, creating an integrated product suite at 30-m spatial resolution and complete spatial coverage of all lands within the 50 states. Here we describe development of the LANDFIRE wildland fuels data layers for the conterminous 48 states: surface fire behavior fuel models, canopy bulk density, canopy base height, canopy cover, and canopy height. Surface fire behavior fuel models are mapped by developing crosswalks to vegetation structure and composition created by LANDFIRE. Canopy fuels are mapped using regression trees relating field-referenced estimates of canopy base height and canopy bulk density to satellite imagery, biophysical gradients and vegetation structure and composition data. Here we focus on the methods and data used to create the fuel data products, discuss problems encountered with the data, provide an accuracy assessment, demonstrate recent use of the data during the 2007 fire season, and discuss ideas for updating, maintaining and improving LANDFIRE fuel data products.

Additional keywords: decision support, fire behavior, national coverage, remote sensing, seamless GIS products, wildland fuel.

Introduction

Natural resources research and management increasingly rely on spatially explicit, landscape-scale data describing vegetation, infrastructure, and physical land surface features to evaluate landscape-level processes such as insect and disease dynamics (Logan *et al*. 2007), wildlife habitats (Cushman *et al*. 2008; Shifley *et al*. 2008), exotic and invasive species dynamics (Keeley 2006; Meinke *et al*. 2008), hydrologic modeling (Beeson *et al*. 2001; Pierson *et al*. 2008), climate change (Cary *et al*. 2006; Flannigan *et al*. 2006; Lenihan *et al*. 2008), and fire (Keane *et al*. 2001; Rollins *et al*. 2004; Hessburg *et al*. 2007; Wimberly and Kennedy 2008). Fire in particular is a landscape-level process escalating in scope, magnitude and threats to lives and property and is expected to increase with projected climate warming (Keane *et al*. 1997; Brown *et al*. 2004; Cary *et al*. 2006; Flannigan *et al*. 2006; Westerling *et al*. 2006; Lenihan *et al*. 2008). Fire managers need high-quality landscape-scale data for designing fuels treatment and restoration projects and for predicting potential fire behavior to protect resources and infrastructure (Agee *et al*. 2000; Finney 2001, 2005; Finney *et al*. 2005; Calkin and Gebert 2006; Hessburg *et al*. 2007; Keane *et al*. 2007; Arroyo *et al*. 2008; Reinhardt *et al*. 2008). In addition, managers need the capability to predict the potential consequences of fire on infrastructure and natural resources if fire and fuels are to be managed in a cost-effective and safe manner. Such predictive capability requires comprehensive spatial data depicting vegetation and wildland fuel.

A lack of comprehensive national data products describing vegetation and wildland fuel across large regions has hindered efforts to develop programs focussed on allocation of resources to assure that necessary firefighting resources are available to respond to wildland fires and to reduce hazardous fuels in forests and rangelands (GAO 1999, 2002). As a result, the US Government Accountability Office has recommended that comprehensive and consistent geospatial data describing vegetation and wildland fuel are necessary to develop an integrated program for strategic planning of wildland fire management (GAO 2002). Such data are lacking for most lands. Moreover, previous fuels mapping projects have left numerous gaps in spatial coverage that limit their utility to small geographic extents, often within single jurisdictional boundaries (Keane *et al*. 2001; Riaño *et al*. 2002; Andersen *et al*. 2005; Jia *et al*. 2006; Krasnow 2007; Skowronski *et al*. 2007), furthering the need for uniform, consistent fuel data products. To address this need, the US Forest Service and Department of Interior initiated the Landscape Fire and Resource Management Planning Tools (LANDFIRE) Project (www.landfire.gov, accessed 22 April 2009).

The LANDFIRE Project (Rollins and Frame 2006; Rollins 2009) produces nationally consistent and spatially comprehensive fuel data necessary for running critical fire behavior models

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such as FARSITE (Finney 2004), FlamMap (Finney 2006), BehavePlus (Andrews and Bevins 2005), and NEXUS (Scott 1999). LANDFIRE fuel data products include surface fire behavior fuel models (Anderson 1982; Scott and Burgan 2005), canopy cover, canopy height, canopy bulk density, and canopy base height. LANDFIRE is the first project of its kind to offer seamless (i.e. without gaps in spatial coverage) wildland fuel products compiled with the same approach and methods developed from pre-existing plot data for the conterminous United States at a spatial resolution of 30 m. In the present paper, we describe development of the fuel data products, discuss difficulties encountered with the data and their accuracy, provide examples of their application and discuss ideas for updating, maintaining and improving LANDFIRE fuel data products.

Methods

Both surface fire behavior fuel model (FBFM) classifications mapped by the LANDFIRE Project represent average fuel properties needed to drive the surface fire spread model created by Rothermel (1972, 1983). These properties include fuel load by category (live and dead) and size class (0 to 0.64 cm (0 to 0.25 in) 0.64 to 2.54 cm (0.25 to 1.0 in) and 2.54 to 7.62 cm (1.0 to 3.0 in) diameter), surface-area-to-volume ratio of each size class, heat content by category, fuel bed depth, and moisture of extinction (i.e. the moisture limit beyond which fire cannot spread) (Scott and Burgan 2005). These surface FBFMs enable estimates of expected fire behavior under specific moisture conditions (Burgan and Rothermel 1984), while the four canopy fuel data products are necessary for determining the occurrence and severity of crown fire. Canopy cover is used to reduce above-canopy winds (wind adjustment factor) (Albini and Baughman 1979) and to estimate fuel moistures (Rothermel *et al*. 1986) as a function of shading. Canopy height is used for computing spotting distances (Albini 1983*a*, 1983*b*; Morris 1987) and to reduce above-canopy winds (Albini and Baughman 1979). Canopy base height (CBH) is necessary to determine if a burning stand will transition from passive to active crown fire. Canopy bulk density (CBD) is used to determine if an active crown fire is sustainable (Van Wagner 1993; Scott and Reinhardt 2001; Cruz *et al*. 2004, 2005; Scott 2006).

To map this suite of wildland fuel data, we relied on three categories of spatial data and the LANDFIRE Reference Database (LFRDB) (Caratti 2006) including (1) satellite imagery, (2) biophysical gradients (Whittaker 1967; Müller 1998; Rollins *et al*. 2001; Keane *et al*. 2006*b*), and (3) vegetation structure and composition. A brief explanation of these data categories and the LFRDB is required so that the fuels mapping process can be discussed and understood with clarity.

Satellite imagery

The LANDFIRE Project uses the satellite imagery from the Multi-Resolution Land Characteristics 2001 project (Homer *et al*. 2004). There are two key elements from the Multi-Resolution Land Characteristics study that were used in the LANDFIRE Project. First, the LANDFIRE Project uses the same mapping zone delineations as those created for the Multi-Resolution Land Characteristics 2001 project (Fig. 1). Second, the LANDFIRE Project uses satellite imagery that was pieced together to form seamless coverage for each mapping zone in the conterminous US (often yielding seam lines, discussed later). The essential characteristics of this satellite imagery database are as follows: (1) image dates (time of acquisition) range from 1999 to 2003; (2) satellite imagery is supplied by the Enhanced Thematic Mapper and Thematic Mapper sensors; and (3) every mapping zone has three sets of associated satellite imagery (including leaf-on, spring, and leaf-off), each representing a different phenological state (Zhu *et al*. 2006).

Biophysical gradients

Biophysical gradient is a collective term used to describe spatial changes in physiological, physical, ecological, or meteorological processes postulated to influence species distributions (Whittaker 1967). Gradient modeling is a standard technique for describing ecosystem composition, structure, and function (Müller 1998; Rollins *et al*. 2001; Keane *et al*. 2006*b*). Biophysical gradients used to facilitate mapping of CBH and CBD include direct gradients, such as temperature and humidity; indirect gradients, such as slope and aspect; and functional gradients, such as biomass and leaf area index (Table 1). Table 1 also indicates if each layer was used for canopy fuel or surface FBFM mapping. Direct gradients are derived from the DAYMET meteorological database (www.daymet.org/, accessed 22 April 2009), which comprises interpolated surfaces of daily meteorological observations (Thornton *et al*. 1997). Indirect gradients, including slope, aspect and elevation, were derived from digital elevation models (USGS 2008) (http://edna.usgs.gov/, accessed 22 April 2009). The functional gradients were compiled from WxBGC (biogeochemical cycling model) (Keane *et al*. 2006*b*), an ecosystem simulator derived from BIOME-BGC (Running and Gower 1991; Thornton *et al*. 2002) and GMRS-BGC (Keane *et al*. 2002*a*).

Vegetation structure and composition

Existing Vegetation Type (EVT) describes vegetation composition, Existing Vegetation Cover (EVC) describes vegetation cover, Existing Vegetation Height (EVH) describes vegetation height, and Environmental Site Potential (ESP) describes succession without disturbance. These vegetation data were produced early in the LANDFIRE data development cycle because they were needed for the development of the fuel data products (Reeves *et al*. 2006*a*; Zhu *et al*. 2006; Rollins 2009) (Fig. 2). These vegetation data are discussed, at length, in Zhu *et al*. (2006) and Rollins (2009) and only briefly covered here. EVT, EVC and EVH were produced by the US Geological Survey National Center for Earth Resources Observation and Science through a fusion of satellite imagery, field-referenced plot data and landscape information. The EVT product depicts the dominant Ecological System (Comer *et al*. 2003) currently present at each 30-m pixel (Zhu *et al*. 2006). Ecological systems represent 'groups of biological communities that are found in similar physical environments and are influenced by similar dynamic ecological processes, such as fire or flooding' (Comer *et al*. 2003). EVC represents the average percentage of dominant life form, non-overlapping canopy cover for each 30-m pixel (Reeves *et al*. 2006*a*; Zhu *et al*. 2006). Herbaceous and shrub cover were mapped specifically for the LANDFIRE Project, whereas the estimates of forest cover were directly inherited from the

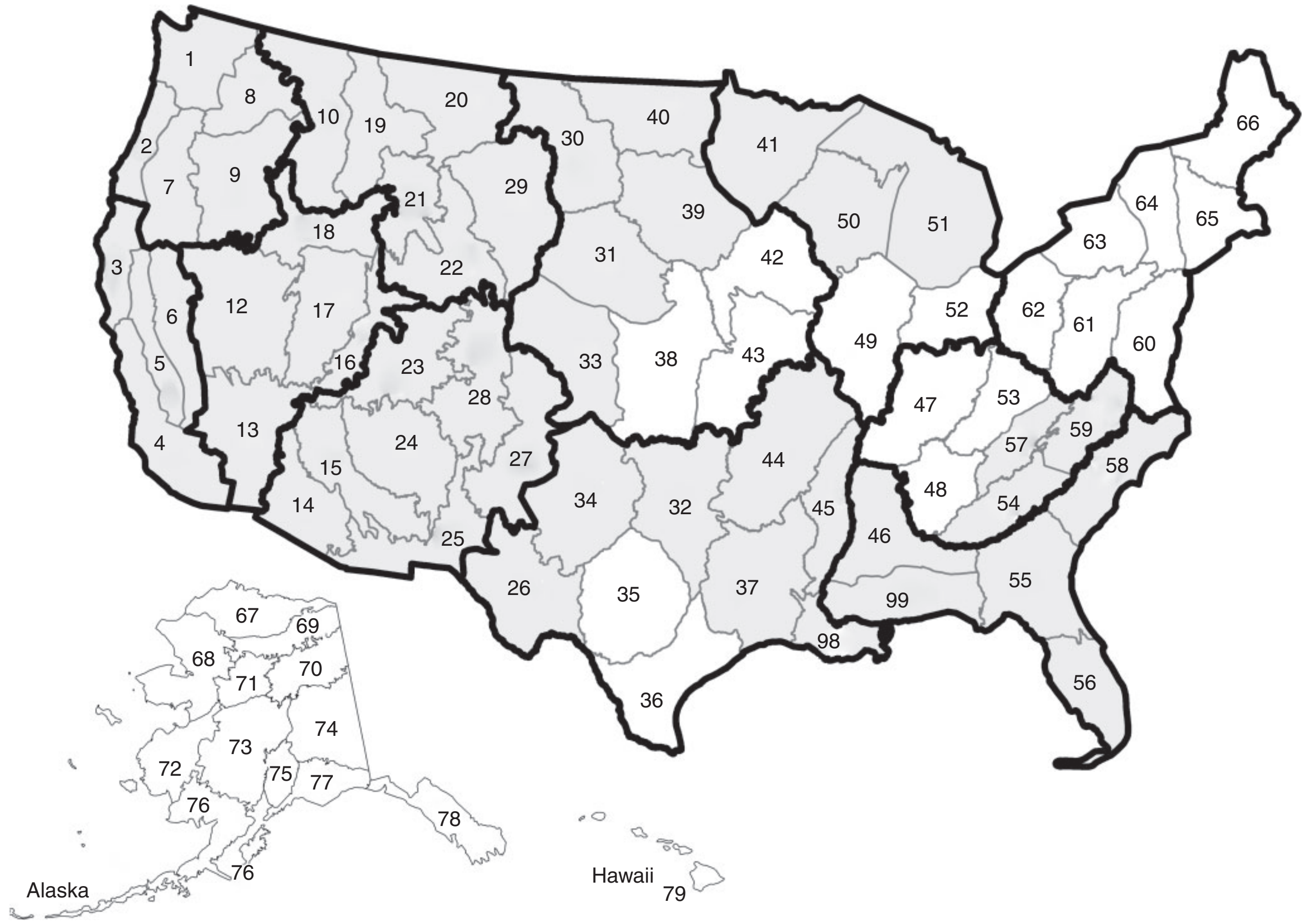

Fig. 1. Numbers represent LANDFIRE mapping zones. Zones are aggregated into larger conglomerates based on regional ecological similarity. Zones covered in gray indicate progress as of 20 March 2008. Thick black lines represent boundaries for computing average canopy fuel characteristics. The LANDFIRE fuel data products will eventually cover all 50 states. Alaska and Hawaii are not shown to scale.

National Land Cover Dataset (Reeves *et al*. 2006*a*; Rollins 2009). EVH represents the average height of the dominant life form for each 30-m pixel, while ESP indicates the plant community that would become established at late or climax stages of succession development in the absence of disturbance.

LANDFIRE reference database

The LFRDB was used for developing training sites for mapping CBD and CBH and assessing the accuracy of the resulting maps and regression tree models. The LFRDB stored all field-referenced plot data needed to estimate CBH and CBD in addition to values for all the spatial predictor variables (e.g. satellite imagery, biophysical gradients, vegetation structure and composition) sampled at each plot location. To obtain these values, all field-referenced plots were overlaid on the entire suite of predictor variables and the value of each underlying spatial dataset was acquired. These data were ultimately used for developing regression tree models.

Mapping surface fire behavior fuel models

The two LANDFIRE surface FBFM products were mapped by linking unique combinations of the EVT, EVC, EVH and ESP LANDFIRE data products (Reeves *et al*. 2006*a*) to expected fire behavior (Keane *et al*. 2001) (Fig. 2). Accomplishing this task required that expected fire behavior be estimated under a set of assumed environmental conditions. The 'assumed' environmental conditions used for the FBFM mapping process are those that typify the fire weather normally encountered during the peak of the burning season in the geographic region being evaluated. Plot data were not used to facilitate assignment of surface FBFM to the LANDFIRE vegetation data products; thus the LFRDB was not needed for mapping surface FBFMs (Fig. 2). All surface FBFM mapping rules (assignments) were developed using a qualitative approach based on the experience and ideas of fire and fuel subject matter experts. These experts were usually fire behavior specialists knowledgeable of fire behavior typically associated with the area being evaluated. Each expert was asked to evaluate each unique combination of EVT, EVC, EVH and ESP and estimate the fire behavior based on their experience. When experts were not available for a mapping zone, assignments from an adjacent mapping zone were used. This assignment process was possible because EVT contains information about the component that will most likely carry the fire. EVC permits some inference of the nature of the understorey.

Table 1. Predictor variables used during the canopy base height and canopy bulk density mapping process

Variables are: ETM, Enhanced Thematic Mapper; NDVI, Normalized Difference Vegetation Index. Sources are: MRLC, Multi-Resolution Land Characteristics Consortium; DAYMET, meteorological database (see www.daymet.org/). Use codes indicate the following: C, the variable was used for developing regression trees to predict canopy base height and canopy bulk density; S, the variable was used for surface fire behavior fuel model mapping

Variable	Source; citation	Units	Use
Satellite imagery			
Landsat ETM band 1 at-sensor reflectance	MRLC; Homer *et al.* (2004)	0.45–0.52 μm	C
Landsat ETM band 2 at-sensor reflectance	MRLC; Homer *et al.* (2004)	0.52–0.60 μm	C
Landsat ETM band 3 at-sensor reflectance	MRLC; Homer *et al.* (2004)	0.63–0.69 μm	C
Landsat ETM band 4 at-sensor reflectance	MRLC; Homer *et al.* (2004)	0.76–0.90 μm	C
Landsat ETM band 5 at-sensor reflectance	MRLC; Homer *et al.* (2004)	1.55–1.75 μm	C
Landsat ETM band 7 at-sensor reflectance	MRLC; Homer *et al.* (2004)	2.08–2.35 μm	C
Landsat ETM tasseled-cap transformation	MRLC; Homer *et al.* (2004)	unitless	C
Landsat ETM NDVI	MRLC; Tucker (1979)	unitless	C
Biophysical gradients			
Average annual shortwave radiation	DAYMET; Thornton *et al.* (1997)	$W\ m^{-2}$	C
Average annual minimum daily temperature	DAYMET; Thornton *et al.* (1997)	°C	C
Average annual maximum daily temperature	DAYMET; Thornton *et al.* (1997)	°C	C
Average annual precipitation	DAYMET; Thornton *et al.* (1997)	mm	C
Average annual vapor pressure deficit	DAYMET; Thornton *et al.* (1997)	mbar	C
Average annual day length	DAYMET; Thornton *et al.* (1997)	minutes	C
Average annual relative humidity	DAYMET; Thornton *et al.* (1997)	%	C
Average annual snowfall	Wx Fire; Keane *et al.* (2006*b*)	cm	C
Average annual dewpoint temperature	Wx Fire; Keane *et al.* (2006*b*)	°C	C
Average annual soil temperature	Wx Fire; Keane *et al.* (2006*b*)	°C	C
Soil water transpired by canopy	Wx Fire; Keane *et al.* (2006*b*)	$kg\ m^{-2}\ day^{-1}$	C
Volumetric water content	Wx Fire; Keane *et al.* (2006*b*)	unitless	C
Actual evapotranspiration	Wx Fire; Keane *et al.* (2006*b*)	$kg\ H_2O\ year^{-1}$	C
Degree-days	Wx Fire; Keane *et al.* (2006*b*)	°C	C
Days since last rain	Wx Fire; Keane *et al.* (2006*b*)	days	C
Evaporation	Wx Fire; Keane *et al.* (2006*b*)	$kg\ H_2O\ m^{-2}\ day^{-1}$	C
Canopy conductance to sensible heat	Wx Fire; Keane *et al.* (2006*b*)	$s\ m^{-1}$	C
Soil water lost to runoff and ground	Wx Fire; Keane *et al.* (2006*b*)	$kg\ m^{-2}\ day^{-1}$	C
Potential evapotranspiration	Wx Fire; Keane *et al.* (2006*b*)	$kg\ m^{-2}\ year^{-1}$	C
Photon flux density	Wx Fire; Keane *et al.* (2006*b*)	$\mu mol\ m^{-2}$	C
Precipitation	Wx Fire; Keane *et al.* (2006*b*)	cm	C
Water potential of soil and leaves	Wx Fire; Keane *et al.* (2006*b*)	Mpa	C
Amount of snowfall	Wx Fire; Keane *et al.* (2006*b*)	cm	C
Soil water fraction	Wx Fire; Keane *et al.* (2006*b*)	%	C
Soil water transpired by canopy	Wx Fire; Keane *et al.* (2006*b*)	$kg\ m^{-2}\ day^{-1}$	C
Elevation	USGS (2008)	m	C
Aspect	USGS (2008)	azimuth	C
Slope	USGS (2008)	%	C
Vegetation attributes from LANDFIRE			
Existing Vegetation Type (EVT)	Zhu *et al.* (2006)	map class	S and C
Existing Vegetation Height (EVH)	Zhu *et al.* (2006)	map class	S and C
Existing Vegetation Cover (EVC)	Zhu *et al.* (2006)	map class	S and C
Environmental Site Potential (ESP)	Rollins (2009)	map class	S and C

For example, in more open tree canopy situations, a greater abundance of understorey vegetation, such as shrubs and herbs, may be expected. EVH also helps distinguish between surface FBFMs. For example, an EVT dominated by grasses will probably burn more like a surface FBFM 1 (Anderson 1982) if it is short (~0.3–0.5 m); however, if the grass is tall and dense, for example ≥1 m, it will likely be categorized as a surface FBFM 3 (Anderson 1982). Drier sites can have different fuelbed properties to wetter sites even if the EVT, EVC and EVH are similar. Thus, ESP was used relatively infrequently to distinguish these drier sites from those that are relatively wetter. Once all unique combinations of EVT, EVC, EVH and ESP were assigned a surface FBFM, a preliminary map was produced. Each preliminary map was reviewed by local fire and fuel specialists to detect areas where surface FBFMs were obviously mischaracterized. During this review period, approximately 5 to 20 specialists per mapping zone were consulted and disagreements between participants were resolved through majority vote. If obvious errors were detected, the rule sets used to cross-walk surface FBFMs to the vegetation components were revised instead of just updating the surface FBFM product by itself (Fig. 2). The rule sets used to produce the final surface fire behavior fuel model

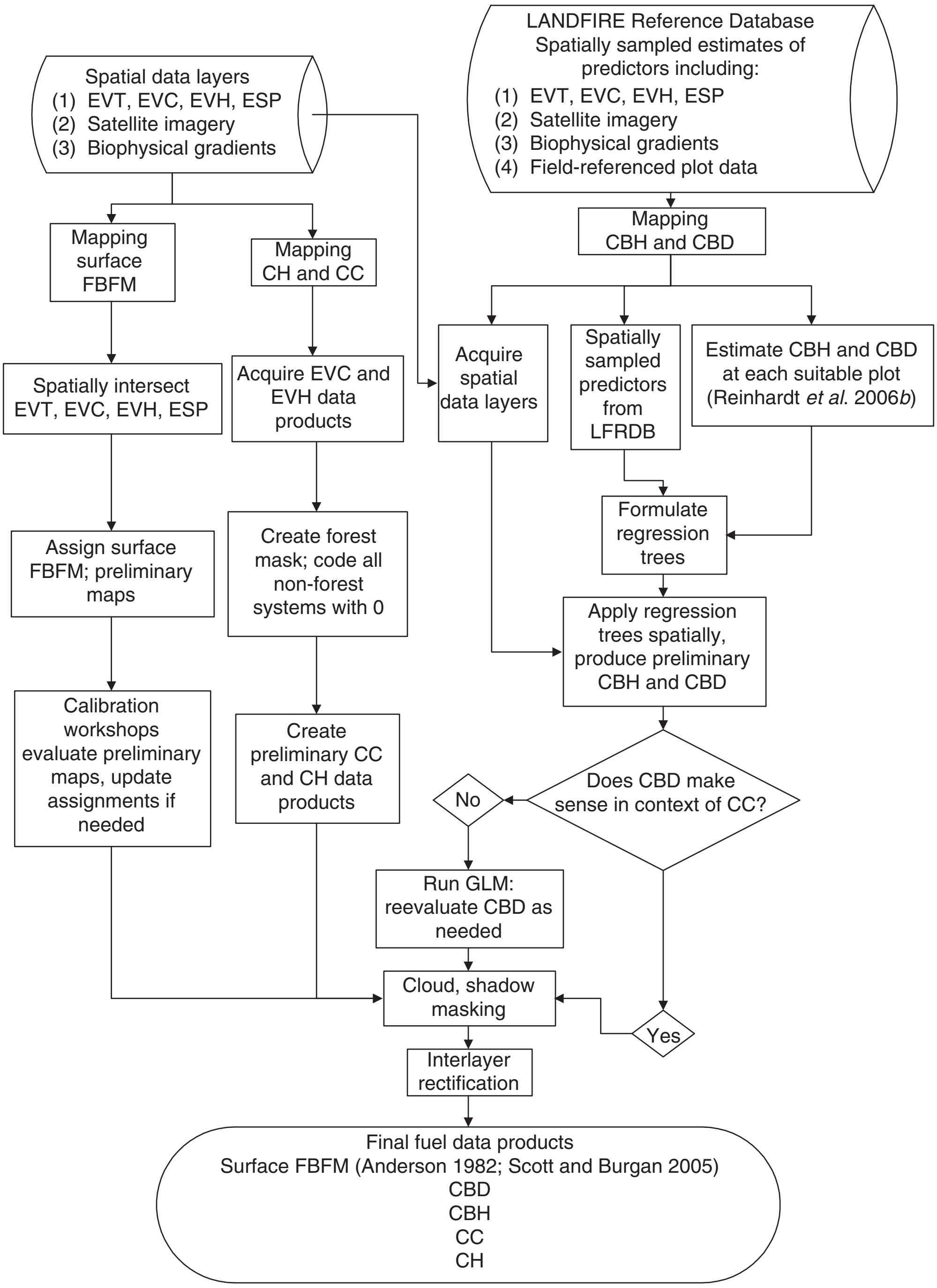

Fig. 2. Flow diagram of the LANDFIRE fuels mapping process. See text for definitions.

products for each mapping zone can be obtained by contacting the LANDFIRE Help Desk at www.landfire.gov.

Mapping canopy fuel

The canopy fuel products include Forest Canopy Cover (CC), Forest Canopy Height (CH), CBH and CBD. Canopy cover represents the average percentage of forested, non-overlapping canopy cover for each 30-m pixel while CH represents the average height of the tree species for each 30-m pixel. CBH represents the lowest point in the canopy at which there is sufficient fuel for propagating the fire vertically, whereas CBD refers to the mass of canopy fuel per unit of canopy volume that would burn in a crown fire (primarily material ≤ 0.6 cm (1/4 in) diameter) (Van Wagner 1977; Scott and Reinhardt 2001; Keane *et al.* 2005). As CBD varies vertically in a stand, the maximum estimated value is often used to represent the stand based on the assumption that crown fire can travel

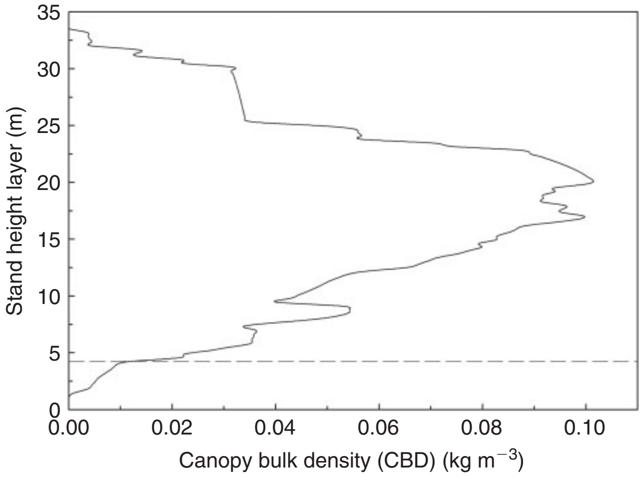

Fig. 3. Typical stand canopy fuel profile generated from *FuelCalc*. Canopy base height (CBH) is estimated to be the lowest point in the profile where canopy bulk density (CBD) ≥ 0.012 kg m^{-3} (represented by the dashed line) (Reinhardt *et al.* 2006*b*). CBD for the stand here is estimated using the maximum value along the profile, ~0.1 kg m^{-3}.

through the densest layer of the canopy (Reinhardt *et al.* 2006*a*) (Fig. 3).

The CBH and CBD mapping process began by deriving field-referenced estimates of CBH and CBD. Approximately 45 000 plots were acquired around the US for estimating CBD and CBH. These plots originated from ~118 projects (Caratti 2006). Field-referenced CBH and CBD were computed using the canopy fuel estimation software *FuelCalc* (Reinhardt *et al.* 2006*b*), which contains logic similar to the Fire and Fuels Extension to the Forest Vegetation Simulator (Beukema *et al.* 1997; Reinhardt *et al.* 2006*b*). The inputs required by *FuelCalc* are tree lists, which include species, diameter at breast height (~137 cm), canopy height, height to live crown, crown class (e.g. dominant, co-dominant and intermediate) (Bechtold and Scott 2005), and trees per acre. Nearly 70% of all plots used in the canopy fuels mapping effort came from the US Department of Agriculture's (USDA) Forest Inventory and Analysis (FIA) program (http://fia.fs.fed.us/, accessed 22 April 2009).

Canopy biomass was estimated in *FuelCalc* using the method of Sando and Wick (1972) in combination with the equations of Brown (1978), Loomis and Roussopoulos (1978), Ker (1980) and Loomis and Blank (1981). Some tree species had no crown biomass equation. In this situation, a published equation for a species with a similar genus was used as a substitute. Not all species were used for computing plot-level CBH and CBD. For example, all *Acer* and *Populus* spp. were excluded from the canopy fuel profile as these and other broadleaved species are considered relatively inflammable and therefore unavailable fuel. In *FuelCalc*, crown fuel is estimated and apportioned from the crown base to the top of each stem measured in the stand, summed in 0.3048-m (1 foot) intervals, and then smoothed using a 4.6-m running mean. The process of deriving field-referenced estimates of CBD and CBH was conducted to create a set of training data for regression tree development. After field-referenced estimates of CBD and CBH were obtained, regression tree models for CBH were developed using the host of predictor variables available in the LANDFIRE system (Keane *et al.* 2006*a*) (Table 1, Fig. 2). Predictor variables were satellite imagery, biophysical gradients and vegetation structure and composition (Table 1). Each regression tree was applied spatially across each mapping zone, producing a map of CBH. The regression tree models used to spatially predict CBD and CBH were formulated using the commercially available Cubist regression tree machine-learning algorithm (Quinlan 1993; Rulequest Research 2007), a fast, efficient, and relatively accurate approach for building regression tree models that can be applied to large areas (Huang *et al.* 2001; Xian *et al.* 2002).

Mapping CBD required one more step than CBH (Fig. 2). As with CBH, a suitable regression tree was formulated and then applied spatially across each mapping zone. In rare cases, the regression tree method yielded relatively high estimates of CBD in stands exhibiting very low canopy cover. Such illogical combinations of stand attributes would create erroneous results when evaluated in a fire behavior model. An example of such a situation would be: assume that the canopy cover at a stand is 15% and the predicted CBD is 0.35 kg m^{-3}. This pairing of stand attributes greatly increases the chance of falsely predicting active crown fire, provided surface fire intensity is sufficient to initiate crown fire. As LANDFIRE fuel data products were used for fire behavior prediction, there was a need to identify these combinations in the context of other LANDFIRE data products and quickly engineer a solution. To address the problem, we used a gamma log-link generalized linear model (GLM) (McCullagh and Nelder 1983) with 25 516 plots and related plot-level CBD to CC, stand height (SH; equivalent to CH) and membership in a pinyon–juniper (*Pinus edulis*, *P. monophylla*, and *P. cembroides* and *Juniperus* spp.) EVT (Fig. 4). The pinyon–juniper (PJ) EVT variable was necessary because pinyon pines and junipers exhibit different relationships between CBD, CC and SH to other conifer species (Fig. 4). The estimated GLM model is:

$$\begin{aligned} \mathrm{CBD_{pred}} = & -2.489 + 0.034(\mathrm{CC}) + -0.357(\mathrm{SH1}) \\ & + -0.601(\mathrm{SH2}) + -1.107(\mathrm{PJ}) \\ & + -0.001(\mathrm{CC} \times \mathrm{SH1}) + -0.002(\mathrm{CC} \times \mathrm{SH2}) \end{aligned} \quad (1)$$

where $\mathrm{CBD_{pred}}$ is the predicted CBD at each stand (or pixel), CC is canopy cover, SH1 and SH2 represent three categories of stand height as 0 to 15 m (SH1 = 0, SH2 = 0), 15 to 30 m (SH1 = 1, SH2 = 0) and 30 to 91 m (SH1 = 0, SH2 = 1) respectively, and PJ is another coded indicator variable determining whether the EVT of the pixel is one of the six pinyon–juniper dominated LANDFIRE EVTs (PJ = 0) or not (PJ = 1). Every variable developed in the GLM was statistically significant to at least the $P < 0.01$ level (Table 2). This GLM was applied spatially across a mapping zone to provide a second estimate of CBD.

We reconciled the two CBD estimates (from regression trees and GLM), arriving at a final estimate of CBD for each pixel. Starting with the GLM estimate, two boundary values (plus 50% and minus 50% of the GLM estimate) were calculated. If the regression tree-derived value fell between these two GLM boundary values, the regression tree estimate was assigned to the pixel. If the regression tree-derived value fell outside the boundary values, the CBD value was then adjusted to the closest of the calculated boundary values and that value was assigned

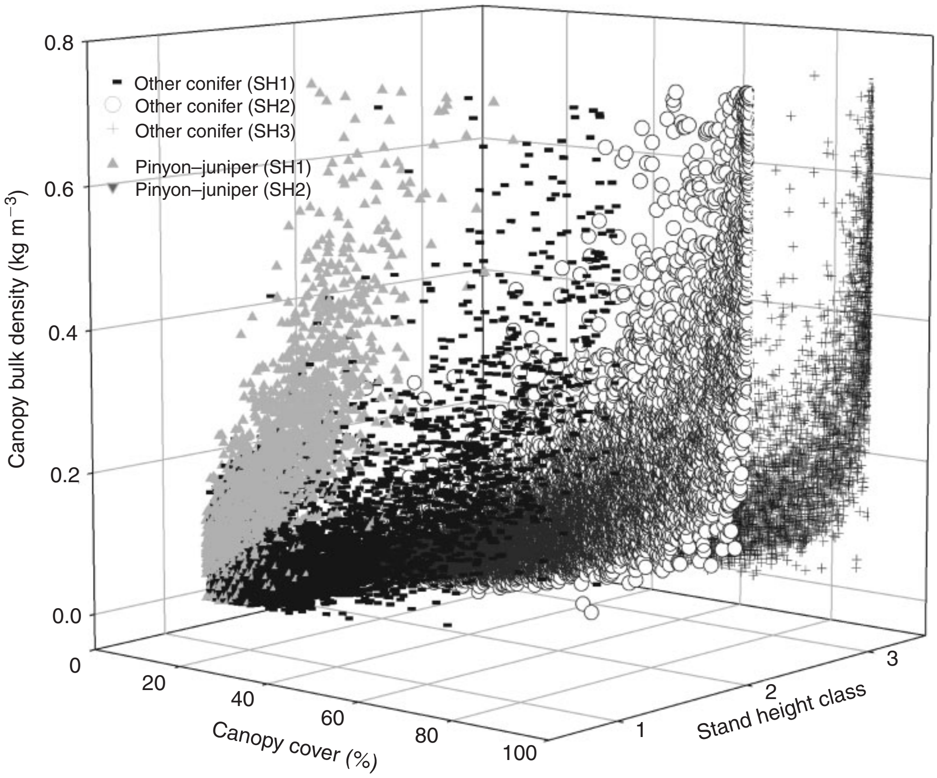

Fig. 4. Relationship between canopy bulk density (CBD), canopy cover (CC) and stand height (SH) for juniper (*Juniperus* spp.) and pinyon pine (*Pinus edulis*, *P. cembroides* and *P. monophylla*) and other conifers. These data were used to produce a generalized linear model of the form $CBD_{pred} = -2.489 + 0.034(CC) + -0.357(SH1) + -0.601(SH2) + -1.107(PJ) + -0.001(CC \times SH1) + -0.001(CC \times SH2)$ where CBD_{pred} is the predicted CBD at each stand (or pixel), SH1 and 2 are coded indicator variables representing three categories of canopy height as 0 to 15 m (SH1 = 0, SH2 = 0), 15 to 30 m (SH1 = 1, SH2 = 0) and 30 to 91 m (SH1 = 0, SH2 = 1), respectively, and PJ is another coded indicator variable indicating whether the Existing Vegetation Type (EVT) of the pixel is one of the four pinyon–juniper dominated LANDFIRE EVTs (PJ = 0) or not (PJ = 1).

Table 2. Results of generalized linear model (GLM) analysis relating canopy bulk density (CBD) to canopy cover (CC), stand height (SH) and conifer type (either pinyon–juniper (PJ) or other conifer)

Coefficient	Estimate	s.e.	t value	*P* value
Intercept	−2.488	0.013	−191.1	$<2 \times 10^{-6}$
CC	0.034	0.000	111.0	$<2 \times 10^{-6}$
SH1	−0.357	0.016	−22.6	$<2 \times 10^{-6}$
SH2	−0.601	0.025	−23.6	$<2 \times 10^{-6}$
PJ	−1.107	0.012	−90.0	$<2 \times 10^{-6}$
CC × SH1	−0.001	0.000	−3.0	0.00230
CC × SH2	−0.001	0.000	−4.1	2.07×10^{-5}

to the pixel. For example, assume that the GLM prediction of CBD is 0.1 kg m^{-3} at a given pixel, whereas the regression tree prediction is 0.22 kg m^{-3}. The GLM boundary values of plus or minus 50% are 0.05 and 0.15 kg m^{-3}. As the regression tree prediction is greater than the upper GLM boundary value, the final assigned CBD pixel value would be adjusted to 0.15 kg m^{-3}.

After CBH and CBD were prepared, the preliminary CC and CH were developed for each mapping zone. Both the CC and CH products are identical to the EVC and EVH data products (Zhu *et al*. 2006) except for non-forested systems. A forest mask, developed from the EVC product, was used to identify all non-forested vegetation. All pixels representing non-forested vegetation were coded with a 0. Once the preliminary canopy fuel data products were prepared, a cloud and shadow masking process was employed.

Although the Multi-Resolution Land Characteristics project carefully selected satellite imagery with minimal snow and cloud cover, a few small areas still had clouds. To rectify this problem, areas containing snow, cloud, and shadow were identified in each mapping zone using a combination of classification and image thresholding techniques (Reeves *et al*. 2006*a*). These areas were filled using one of two values. These 'fill' values were generated using plot data by computing mean CBH and CBD for each EVT–ESP combination (Stage 1) and EVT (Stage 2) occurrence. The field-referenced plot data used to compute these averages were aggregated from groups of ecologically similar mapping zones (Fig. 1). These conglomerates ranged in size from four to nine mapping zones. It wasn't always possible to use Stage 1 filling however, because not every EVT–ESP combination on the landscape had representative plot data with which to compute a mean CBH or CBD. In these instances, the simpler mean CBH or CBD computed for each EVT class was used. This two-stage process was used as the sole method for producing CBH and CBD products for 18 mapping zones dominated by desert, agricultural, or rangeland vegetation. The paucity of sufficient plot data ($<$100 plots) in each of these zones made it impossible to develop sufficiently robust regression tree models for making accurate predictions across the landscape.

The preliminary CBD, CBH, CC, CH and surface FBFM data products were finalized after applying a series of post-processing techniques and logic checks ensuring that the canopy fuel products were logically relevant in the context of the other fuel layers and fire behavior predictions (Fig. 2). Keane *et al*. (2001) stress the importance of this kind of interlayer rectification. First, we processed CBH and CBD with two concurrent 3×3 kernel focal means to smooth areas of high variability (ESRI 2007). Then, a series of interlayer rectification steps were performed where deciduous stands were coded with a CBH of 10 m and a CBD of 0.01 kg km^{-3} to ensure crown fires are not falsely simulated in deciduous stands, which rarely transition from surface to crown fires. This does not imply that crown fire cannot be initiated with a CBH of 10 m; it simply represents the upper end of the data range chosen to use (Reeves *et al*. 2006*a*). We ensured that each stand with a surface FBFM estimate meant to be used with canopy characteristics had canopy characteristic values and that CBH never exceeded CH. Each stand dominated by *Juniperus* spp. (as indicated by the EVT) was coded with a CBH of 0.2 m and all stands with estimates of CBD $>$0.4 kg m^{-3} or CBH estimates of $\geq$10 m were truncated to 0.45 kg m^{-3} and 10 m, respectively. These values represent the upper end of the data ranges that were chosen to use.

Accuracy assessment

A 10-fold cross-validation procedure (Shao 1993) was used to assess the accuracy of the regression tree models used to predict CBD and CBH. CBD and CBH map accuracies were estimated by comparing plot-level estimates with mapped predictions at the same location. All plots with canopy fuel estimates were used during regression tree model development. Thus we used the same plots for accuracy assessment as those used during model formulation. Correlation coefficient (r), mean absolute error (mae) and bias were computed for describing the accuracy of canopy fuel maps and regression tree models. No accuracy assessment was performed on the surface FBFMs because there were no independent data to use for accuracy testing because different evaluators interpret (or estimate) different surface FBFMs for a stand, though consistent estimates between observers can sometimes be achieved (Burgan and Rothermel 1984). Despite the lack of quantitative accuracy assessment for surface FBFM products, qualitative evaluation occurred during both the expert review (calibration workshops) process and annual post-fire-season reviews. Annual post-fire-season reviews offer users of LANDFIRE fuel data products the chance to publicly discuss issues encountered with the data.

Results and discussion

Surface fire behavior fuel models

The surface FBFM products exhibit a fine level of spatial detail, partly a result of the expert review and annual post-fire-season reviews, which yield valuable insight into all LANDFIRE fuel data products (Fig. 5). Use of the expert review enabled local variability to be captured during the mapping process. The calibration process enables the selection of a more representative surface FBFM, even if the existing vegetation has been misclassified. For example, assume a stand of closed-canopy ponderosa pine (*Pinus ponderosa*) was misclassified as Douglas-fir (*Pseudotsuga menziesii*), which initially might be coded with a surface FBFM 8 (Anderson 1982). During review, the fuel model map can be 'calibrated' to the map inputs by adjusting a rule set to estimate a surface FBFM 9 (Anderson 1982) for this stand.

Important issues regarding the surface FBFM products identified during the calibration process and annual post-fire-season reviews include: (1) incorrectly mapped surface FBFMs; (2) seam lines, which are a common artefact generated from adjacent satellite scenes; (3) humid-climate surface FBFMs in the western mapping zones; and (4) scarcity of mapped sparse or barren categories in the surface FBFM products. Estimating surface FBFMs across the landscape is a complex and highly subjective process (i.e. there are no instruments or inventory techniques for measuring a surface FBFM); thus there are no viable means available to quantitatively asses the accuracy of the LANDFIRE surface FBFM products (Burgan and Rothermel 1984). For this reason, we explicitly avoid the term 'accuracy' when discussing the surface FBFM products. There are, however, some obvious errors in the surface FBFM products that will yield inaccurate fire behavior characteristics. Errors in the EVT, EVC, EVH and ESP inputs create problems for the fuels mapping process (Fig. 2). Quantifying the potential compounding errors is difficult and beyond the scope of the current work because each of these inputs could exhibit low accuracy, yet an acceptable surface FBFM product can be still derived using the calibration process. For this discussion, problems due to mismapped surface FBFMs can usually be linked to one or both of two problems. First, incorrect spatial patterns of inputs such as misclassifications in the EVT, EVC, EVH or ESP can yield inappropriate FBFM estimates for an area even after calibration. Second, FBFM assignments developed by experts may lead to inappropriate FBFM estimates (i.e. a rule set might yield a surface FBFM where some evaluators think it should not be). This occurred when a local subject matter expert interpreted expected fire behavior differently from other analysts familiar with the same area. This conundrum has its origins in the subjectivity and non-measurability of FBFMs and points to the difficulty of performing a traditional accuracy assessment of surface FBFMs for a given stand. This situation is exacerbated when seam lines are propagated between or within mapping zones.

Seam lines are artificial boundaries or delineations within or between mapping zones in the LANDFIRE fuel data products. Seam lines between adjacent mapping zones are sometimes caused by differing opinions between expert reviewers in adjacent mapping zones or by differences in satellite imagery or, in the case of CBH and CBD, differences between regression tree models between mapping zones (Fig. 6). Seam lines occurring within mapping zones are usually related to differences in satellite imagery used for mapping EVT, EVC or EVH, which was derived from the Multi-Resolution Land Characteristics project, which pieced together multiple dates of imagery to form seamless coverage for each mapping zone (Zhu *et al*. 2006;

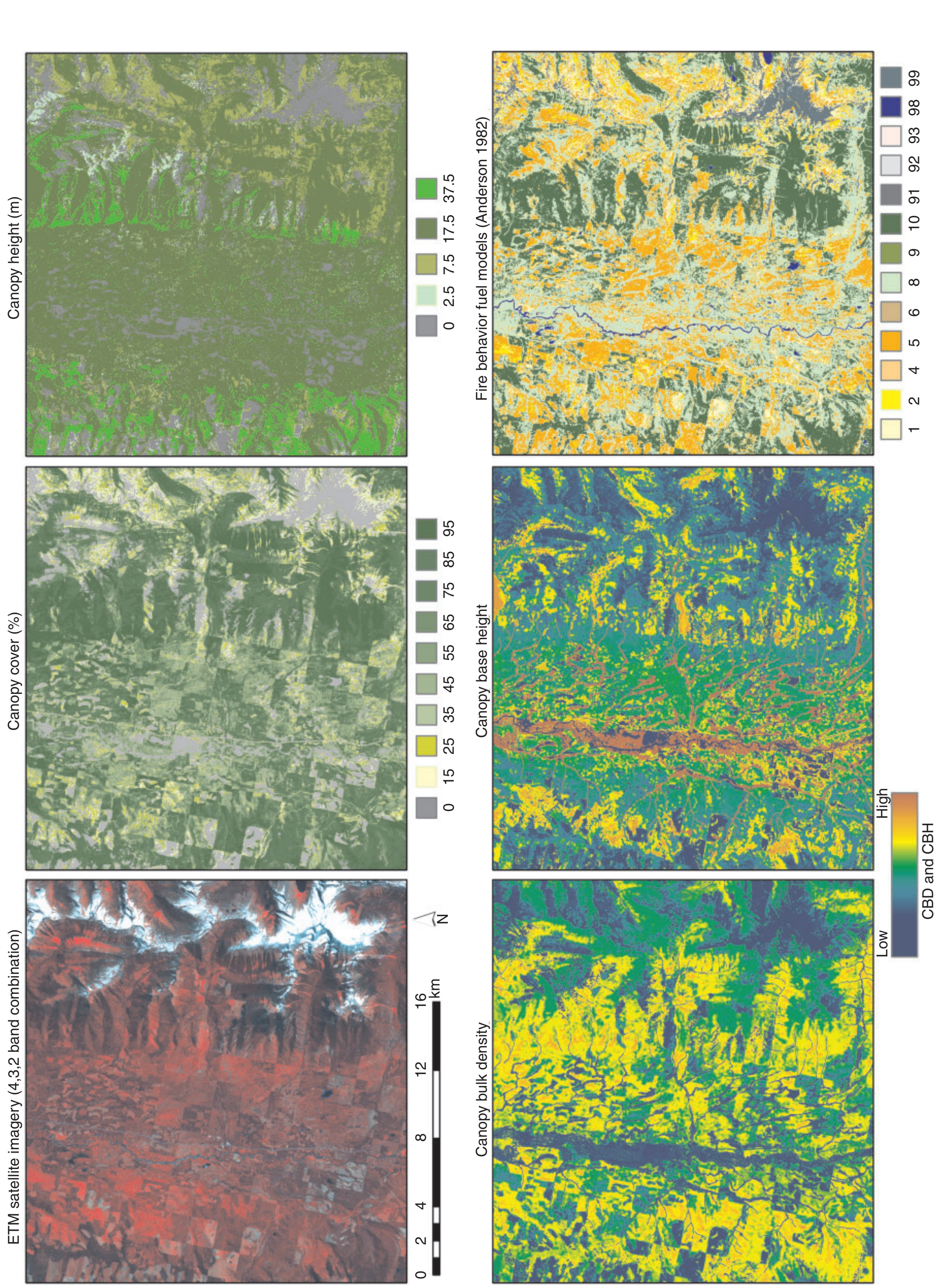

Fig. 5. Spatial linkage and synchronization between observed landscape patterns as demonstrated by the Enhanced Thematic Mapper (ETM) satellite image and LANDFIRE fuel data products.

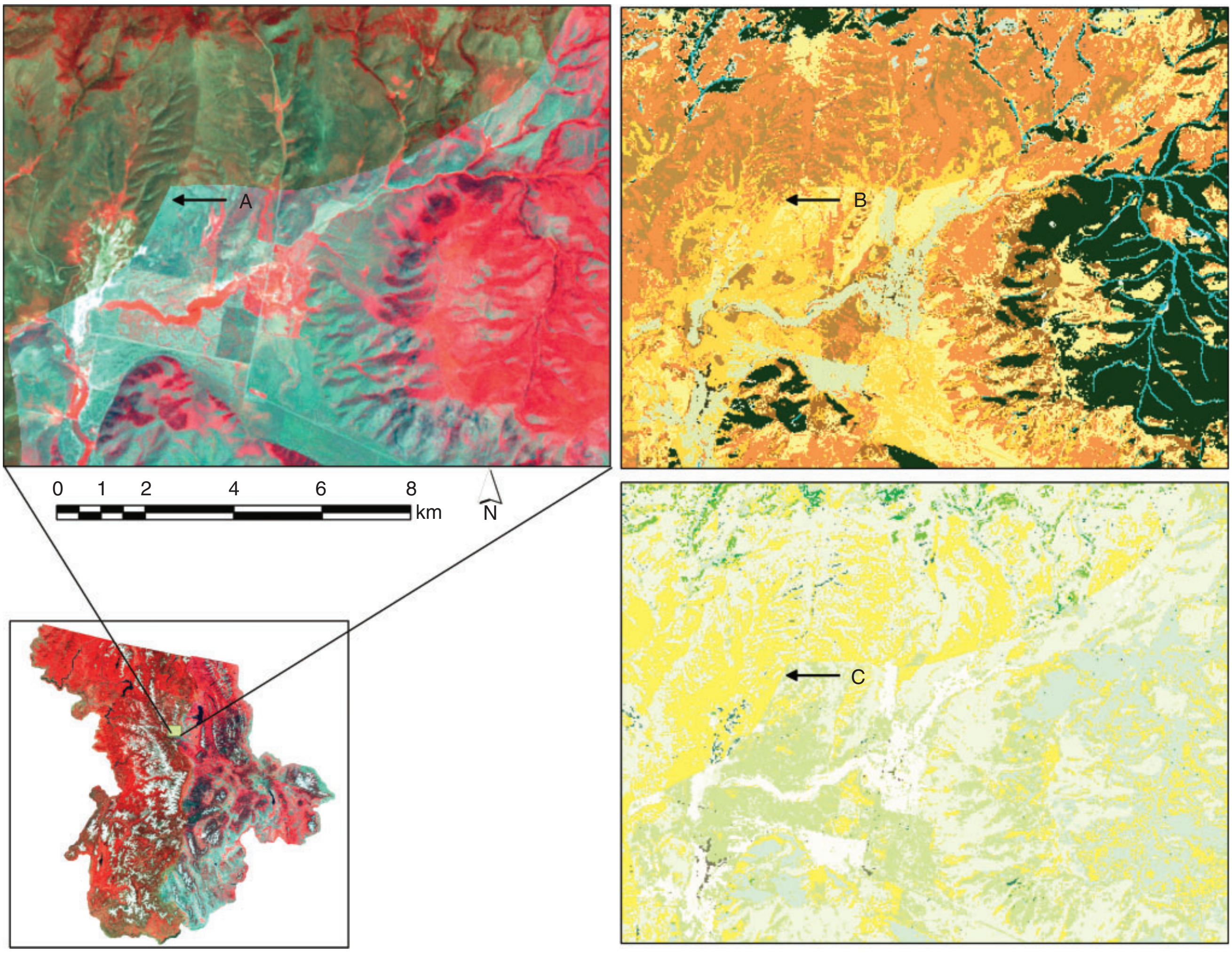

Fig. 6. The effect of seam lines between Enhanced Thematic Mapper (ETM) satellite scenes for the adjacent LANDFIRE mapping zones 10 and 19. Note the propagation of the seam lines from the satellite imagery (A) to the existing vegetation type product (B) and to the surface Fire Behavior Fuel Model (FBFM) products (C).

Rollins 2009). Each scene (overpass) potentially yields different radiometric characteristics owing to phenological differences, sun–sensor–target geometry, or atmospheric distortion from particulate matter (principally water vapor, dust, and pollution). Seam lines in any of the spatial inputs to the fuel mapping process will inevitably yield artificially delineated fuel complexes. Seam lines in the surface FBFM data products could be removed, but this would require specialized attention to each scene, which is beyond the scope of the current national assessment. Future LANDFIRE mapping efforts may have the capacity to provide such detail. The implication of seam lines in the surface FBFM product is that estimated fire behavior could abruptly change with no biophysical justification. Another issue resulting in unexpected fire behavior estimates was the presence of humid-climate fuel models (Scott and Burgan 2005) in western mapping zones.

Some fire behavior experts, during calibration workshops, indicated that expected rates of spread and flame lengths in some arid regions of the western US were best represented using the Scott and Burgan (2005) set of surface FBFMs designed for humid climates, which are characterized by high moisture of extinction at which the fire will not spread. The implication of mapping humid-climate surface FBFMs in arid regions is that simulated fire progression can continue through evening hours, thus potentially overestimating the area and perimeter of a fire. A lack of barriers to fire spread such as water and sparsely vegetated and barren areas in the fuel data products can also lead to overestimates of fire area and perimeter.

The sparsely vegetated and barren categories were originally under-represented in the LANDFIRE fuel data products on relatively steep north-westerly slopes, even when large rock outcrops were readily visible in high resolution aerial photography. The sparse or barren and water classes were inherited from the National Land Cover Dataset (Vogelmann *et al.* 2001; Homer *et al.* 2004). The Landsat satellite imagery used to develop the National Land Cover Dataset product was acquired during a nominal overpass time of ~1030 hours local standard time, a period when shadows are cast in mountainous terrain, making

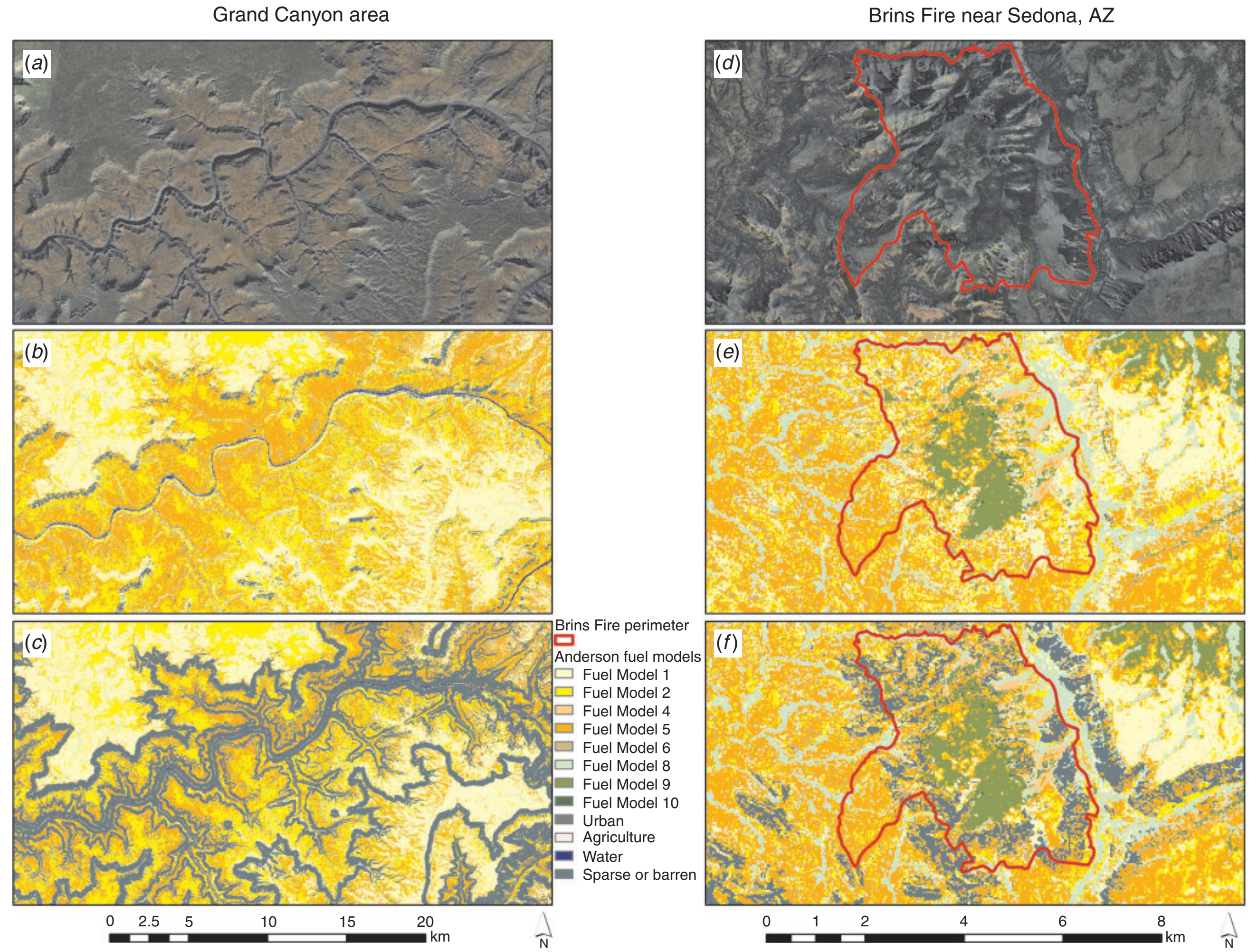

Fig. 7. Results of the sparse or barren remapping process. Portions of the Grand Canyon and Brins Fire near Sedona, Arizona, are shown for comparison purposes. (*a*) and (*d*) show the Enhanced Thematic Mapper (ETM) satellite imagery for these two areas while (*b*) and (*e*) represent the original surface Fire Behavior Fuel Model (FBFM) product containing only minute fractions of the sparse/barren class and (*c*) and (*f*) represent the remapped sparse or barren class.

sparse or barren areas hard to detect. Because of these shadows, fires could be simulated through these areas that should, in fact, act as barriers to fire spread, thus resulting in incorrect fire growth estimates. To help rectify this situation, sparsely vegetated and barren areas were remapped individually using spectral classification and thresholding techniques with special emphasis in steep mountainous terrain. The results of this effort greatly increased the mapped area of sparsely vegetated and barren classes across the landscape. This increase is especially notable in the area near Sedona, Arizona, where the Brins Fire burned in 2006 and Grand Canyon National Park in Northern Arizona (Fig. 7). The current version of the LANDFIRE fuel data products includes the updated sparsely vegetated and barren categories.

Canopy fuels

Important issues regarding canopy fuel products, identified during annual post-fire-season reviews include: (1) CBH values are unreliable and generally too high for accurate simulation of transition from surface to crown fire; (2) CBD values seem too low for simulating active crown fire; and (3) CC values are too high.

CBH values are typically higher than expected, especially at low values of observed CBH (Fig. 8) (Table 3). Table 3 describes model and map accuracy for zones where regression trees were used to predict CBD and CBH. The map accuracy metrics in Table 3 must be interpreted with caution, because we used the same plots for model development and map accuracy assessment, which leads to optimistic bias (Hammond and Verbyla 1996). In addition, Table 3 indicates that CBD is a more reliable product than CBH, which makes sense from a remote sensing perspective, because the red and near-infrared channels of the Enhanced Thematic Mapper and Thematic Mapper sensors are sensitive to chlorophyll content and leaf biomass. Further, CBD is a bulk property of a stand (Reinhardt *et al.* 2006*a*), which is somewhat related to other canopy traits such as leaf area index and canopy cover, both of which have a rich history of measurement and mapping (White *et al.* 2000; Burrows *et al.* 2001;

Cohen *et al*. 2003). In contrast, CBH only represents a theoretical threshold below which transition from surface to crown fire is possible. A CBH estimate should account for ladder fuels, which can include combustibles such as shrubs, lichens, moss, loose bark, dead bole branches, suspended needles, and other fuel particles (Brown and Davis 1973). These attributes are rarely collected in the field. The lack of specific ladder fuel data available for predicting CBH using the *FuelCalc* software (Reinhardt *et al*. 2006*b*) can render CBH values higher than expected. In addition, CBH from *FuelCalc* lacks obvious relationships with any of the predictive variables (such as stand structural attributes) available in the fuels mapping effort (Keane *et al*. 2006*a*) (Table 1). For example, a CBH of 1 m can occur in any forested vegetation type, on any aspect, slope, or elevation. Although height to live crown (not to be confused with CBH as defined here) is influenced by species and stand history (Keane *et al*. 2002*b*), these variables are not available as spatial products across the landscape. Krasnow (2007) reports some success predicting CBH using a regression tree approach ($R^2 = 0.47$, $P < 0.001$) with exceptional relationships reported between CBH and solar radiation. Close examination of the models in Krasnow (2007), however, still reveals prediction errors near 100% across the lower range of CBH values evaluated.

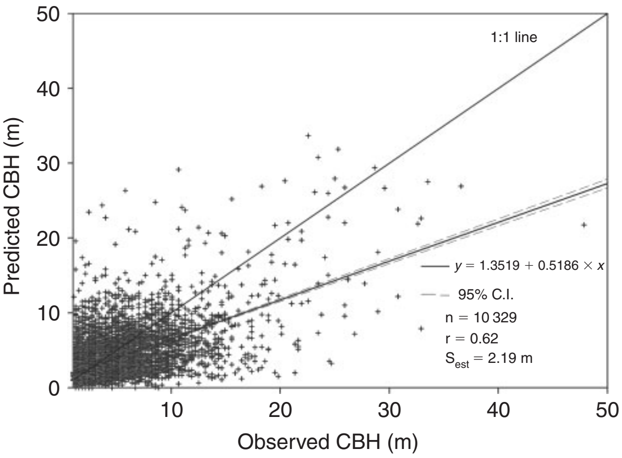

Fig. 8. Predicted and observed canopy base height (CBH) based on cross validation of regression tree models for 15 mapping zones. Biases for the 33rd, 66th and 99th percentiles of the data are as follows: 2.8, 1.8 and −5.5 m. Mean absolute errors for the 33rd, 66th and 99th percentiles are as follows: 3.0, 3.6 and 9.7 m. The percentiles are based on observed CBH values, which for the 33rd and 66th percentiles are 1.2 and 2.7 m, respectively.

The regression trees used to predict CBH across the landscape in the current work were not robust enough to yield sufficiently accurate results (Table 3) owing to poor relationships between CBH estimates and the myriad of predictor variables used in the analysis. As LANDFIRE CBH data are typically higher than expected, simulation of crown fire activity is limited. Users should carefully evaluate if CBH data are appropriate to meet their objectives.

As with CBH, users should also carefully evaluate if the CBD product is appropriate for use in a specific region. Models such as FARSITE (Finney 2004) and NEXUS (Scott 1999) offer different algorithms for predicting whether active crown fire is likely to occur (Scott 2006). Given the disparity between crown fire calculation systems, it is clear that no consensus exists among fire system modelers as to the appropriate methodology by which to estimate CBD for the purpose of fire behavior simulation. Thus, it is difficult to ascertain the efficacy of the LANDFIRE CBD product in meeting its stated objective. Despite this ambiguity, the cross-validation of the regression tree modeling indicates that CBD is more accurately predicted than CBH (Table 3). In addition, CBD exhibits a similar spatial pattern as the CC product. Visual inspection of the CC product reveals a logical spatial connection with satellite imagery and associated LANDFIRE data products (i.e. clear-cuts, riparian areas, herbaceous-dominated areas, and densely timbered stands are visually apparent across all fuel products) (Fig. 5). The CC product typically yields values that are higher than expected. Fig. 9 depicts the bias in the LANDFIRE Forest CC product for mapping zone 19

Table 3. Cross validation statistics from regression tree models and map accuracy estimates for canopy base height (CBH) and canopy bulk density (CBD) for 12 mapping zones

Abbreviations are: r, correlation coefficient; MAE, mean absolute error. Sample size (*n*) is the same for both the CBH and CBD model and map accuracy evaluations

Map zone	CBH (m)							CBD ($kg\,m^{-3}$)					
	Model accuracy			Map accuracy				Model accuracy			Map accuracy		
	r	Bias	MAE	r	Bias	MAE	*n*	r	Bias	MAE	r	Bias	MAE
1	0.40	0.04	0.79	0.20	0.81	2.34	2263	0.57	0.001	0.043	0.55	0.022	0.063
2	0.14	2.55	2.87	0.30	1.29	3.73	939	0.56	0.004	0.041	0.57	0.013	0.057
3	0.14	0.64	0.87	0.14	0.59	1.36	453	0.79	−0.001	0.054	0.53	−0.038	0.110
6	0.10	0.44	0.79	0.10	0.58	1.34	1276	0.70	0.000	0.063	0.49	−0.062	0.120
7	0.33	0.92	1.22	0.26	0.5	2.42	1804	0.76	0.001	0.033	0.69	0.013	0.043
9	0.35	0.58	0.88	0.26	0.74	1.65	623	0.52	0.000	0.027	0.62	0.029	0.049
10	0.30	1.79	2.03	0.33	−0.6	2.72	3328	0.57	−0.002	0.035	0.55	0.006	0.046
15	0.57	0.9	1.05	0.37	1.16	2.48	1143	0.76	0.000	0.030	0.45	0.007	0.046
16	0.54	0.56	0.85	0.33	0.06	1.37	904	0.71	0.001	0.038	0.55	−0.006	0.054
17	0.66	0.11	0.25	0.93	0.21	0.41	126	0.77	−0.008	0.053	0.85	−0.008	0.053
19	0.24	0.78	1.01	0.00	2.2	3.13	2594	0.65	−0.001	0.041	0.49	0.008	0.062
21	0.06	0.85	1.21	0.44	0.38	1.90	1161	0.66	0.000	0.030	0.62	0.016	0.047

with a modal CC value of ~85%, which seems too high when compared with plot-based estimates of canopy cover. Fig. 9 indicates that most stands in zone 19 exhibit canopy cover between ~25 and 55%, which is much lower than the CC product suggests for the same region. Overestimates of canopy cover can lead to slower rates of spread and lower intensities than expected owing to the reduced mid-flame wind speed and reduced solar drying of surface fuels. However, lowering canopy cover values does not necessarily yield the expected commensurate increase in mid-flame wind speed (Albini and Baughman 1979). For example, a stand with 100% canopy cover that is 50 m in height reduces an estimated 6.1-m (20 foot) wind speed by ~94%. A reduction in canopy cover to 50% reduces wind speed measured at 6.1 m (20 foot) by only 91% – a 50% drop in canopy cover for a nearly imperceptible change in estimated mid-flame wind speed. Canopy cover also acts to modulate fuel moistures (Rothermel *et al*. 1986). For example, when all influential factors are held constant, fine dead fuel moisture of 4% is boosted to 5.1 and 8.3% in FlamMap (Finney 2006) by canopy covers at 10 and 100%, respectively. This shading effect and subsequent increase in fuel moisture can significantly alter estimated fire behavior.

Recent application of LANDFIRE fuel data

The LANDFIRE fuel data layers can be used for applications at varying scales, including project-level planning (e.g. <4048 ha (10 000 acres)), particularly where higher-resolution data are lacking. However, LANDFIRE fuel data are exceptionally well suited for comparative analyses within and between larger regions. There are recent examples of successful application of LANDFIRE fuel data for strategic planning, and wildland fire behavior analyses across the landscape (www.landfire.gov/products_applications.php, accessed 22 April 2009). Programs and systems such as Fire Spread Probability (FSPro), Rapid Assessment of Values at Risk (RAVAR) and the Wildland Fire Decision Support System (http://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml, accessed 22 April 2009) all rely on LANDFIRE data products to operate across the US. The Wildland Fire Decision Support System was implemented for the first time in June 2007 to support strategic planning on large wildland fires. The Wildland Fire Decision Support System has three modules: (1) the FSPro module, which is used to estimate spatial fire spread probabilities by simulating fire growth under thousands of potential weather sequences (Fig. 10); (2) the RAVAR module, which is a new fire economics tool that identifies the primary values threatened by large fire events; and (3) the Stratified Cost Index,which is used to characterize the cost of large wildland fires. By September 2007, the Wildland Fire Decision Support System had been used to support 140 fire incidents, with a total of 910 FSPro analyses, 92 RAVAR analyses, and 52 Stratified Cost Index calculations. Analyses of this magnitude are not possible without seamless datasets covering millions of hectares such as those offered by the LANDFIRE Project.

Updating, maintaining and improving LANDFIRE fuel data products

To reduce costs, the LANDFIRE Project was required to produce geospatial products using existing plot data and existing satellite image mosaics. The data used in the LANDFIRE Project were collected for disparate purposes, the likes of which

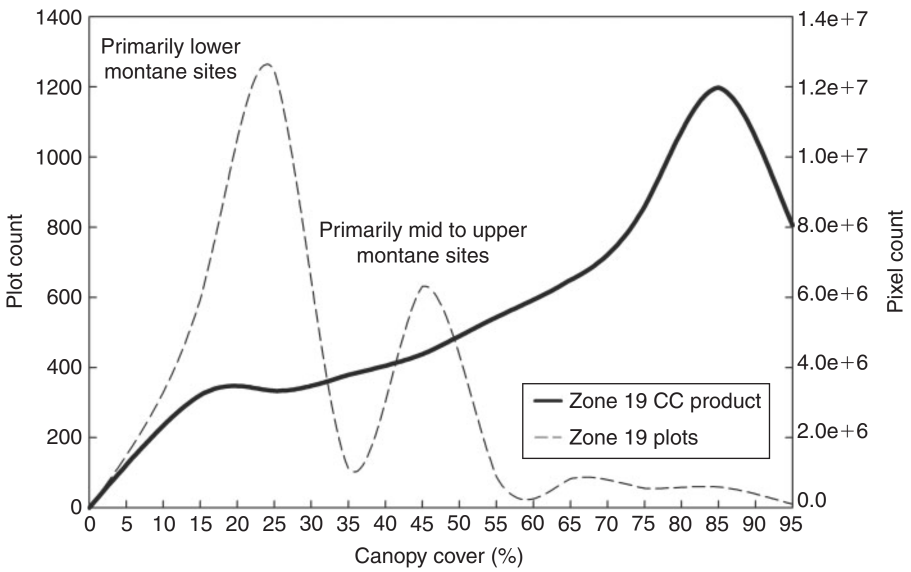

Fig. 9. Comparison of the frequency distribution between field-based estimates of canopy cover and the LANDFIRE Canopy Cover product, inherited from the National Land Cover Dataset (NLCD) project (Vogelmann *et al*. 2001; Homer *et al*. 2004) for mapping Zone 19. The peaks in the canopy cover plot distribution are primarily due to site differences. Lower montane sites in this zone tend to be moisture-limited where shade-intolerant species dominate including ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*). The peak around 45% canopy cover is due to mid to upper montane areas supporting more productive sites often dominated by lodgepole pine (*Pinus contorta* var. *latifolia*), subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*).

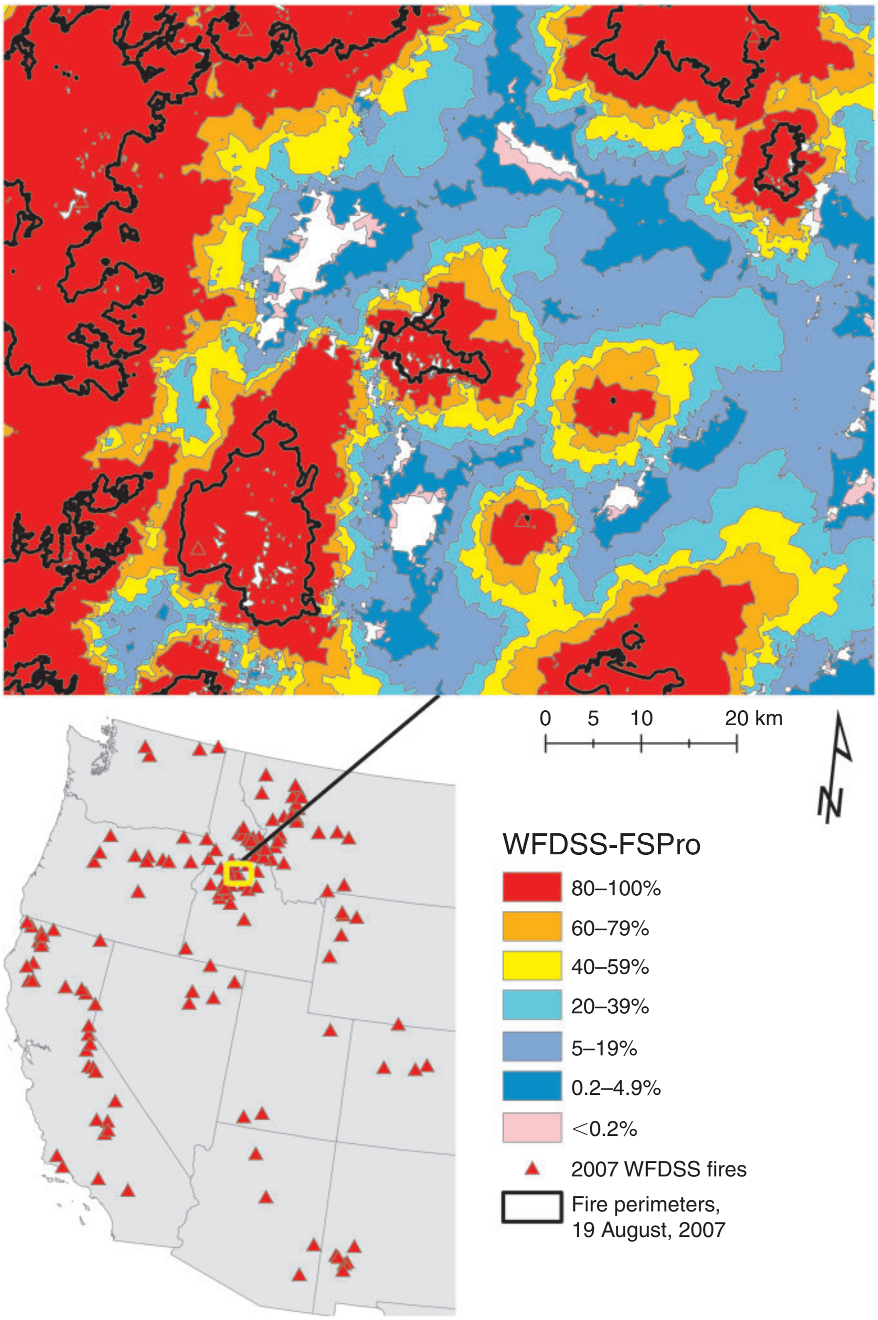

Fig. 10. Wildland Fire Decision Support System Fire Spread Probability program (WFDSS-FSPro) simulation output for large fires during the 2007 fire season in Central Idaho. This simulation covered ~1.6 million ha. In this output of the FSPro simulation, a fire spread probability >80% means that given historic weather conditions, the probability that the fire will burn an area in the coming days is >80%.

rarely focussed on providing training data for a fuel mapping effort. Thus the recommendations for updating and improving LANDFIRE data have one overarching need in common: more high-quality field data collected in a consistent, unbiased manner for the sole purpose of supporting future fuel mapping efforts.

The LANDFIRE fuel data products represent the landscape ~2001 (Multi-Resolution Land Characteristics imagery ranged in date from 1999 to 2003). The implication is that disturbances on the landscape that occurred after 2001 are not well represented in LANDFIRE fuel data products. For improved efficacy, LANDFIRE fuel data products need to be updated to represent current conditions. Several key concepts to aid the updating process were identified during the development and production of the LANDFIRE fuel data products for the US. These include, but are not limited to: (1) frequent updates of surface FBFMs and canopy fuel in response to changing biomass conditions, especially in areas with exotic annual grasses and other natural disturbances such as fire, wind, snow, ice storms, insects and disease; (2) improved CBH estimates and continued development of the CBD product; and (3) improved forest canopy cover estimates focussing first on gathering consistent estimates of true canopy cover. Updating the fuel data products to account for landscape-level changes should be a part of future fuel mapping strategies. Examples of such landscape-level changes include natural disasters such as hurricanes and fires, planned fuel reduction activities, or invasions from exotic species such as *Bromus*, *Tamarisk* and *Melaleuca* spp. If the spatial extent and intensity of these phenomena can be assessed with some certainty, it is conceivable that a monitoring scheme could be devised to update the initial LANDFIRE surface FBFM products to account for these changes across the landscape. The USDA Forest Service's Remote Sensing Applications Center and EROS (Earth Resources Observation and Science) have begun mapping burn severity for the US (http://fsgeodata.fs.fed.us/mtbs/, accessed 22 April 2009). This project will be an important component of the updating process for LANDFIRE fuel data products.

In addition to wildland fires, effects from events such as hurricanes should also be evaluated for changes in fuel across the landscape. In a similar fashion, a monitoring scheme should be devised that tracks the intra- and interannual variability of herbaceous biomass, particularly in the arid south-western US. If, for example, growing season precipitation is higher than normal, it could indicate potential for increased fine-fuel load to propagate fire across otherwise non-burnable landscapes (Swetnam and Betancourt 1990). The Moderate Resolution Imaging Spectroradiometer sensor is well suited for such regional, comparative analyses (Reeves *et al*. 2006*b*) and should be investigated to enhance future fuel mapping efforts. Improving methods for updating surface FBFMs in response to disturbance should be accompanied by improvements in canopy fuel estimates as well.

Recent canopy fuel mapping efforts using Light Detection and Ranging (LIDAR) technology (Riaño *et al*. 2003; Andersen *et al*. 2005) suggest improvement is possible over methods employed here. This is because, unlike optical remote sensing, LIDAR systems can produce a true profile of various canopy strata (Andersen *et al*. 2005). Effective implementation of LIDAR data requires extensive ground-based data collection for calibration and validation. In addition, regression formulae developed to predict CBH from LIDAR data are sensitive to flight and sensor specifications such as flying height, flying speed, sensor swath width and laser pulse density and rate (Andersen *et al*. 2005). LIDAR data are not available for much of the US, although more data are being collected on an annual basis by various entities. Even if it were possible that CBH could be mapped infallibly at the landscape scale, errors in estimated surface fire behavior resulting from incorrect assumptions for weather, wind, surface FBFMs, or fire behavior algorithms would still prevent accurate simulation of crown fire activity much of the time. As a final improvement to mapping canopy fuels, advancements must be made in canopy cover estimates.

A plot-based mapping approach that relies on consistently estimated canopy cover should be devised for future enhancements to the LANDFIRE Forest CC data product. In the absence of such field measurements, which would undoubtedly be quite resource-intensive, one approach to obtaining field-referenced data could be stem-mapping FIA plots (e.g. Gill *et al*. 2000). The advantage of the stem-mapping approach is that actual measurements of canopy cover are not needed. Instead, tree lists, such as those currently collected by the FIA program, can be used. A cover value for each bole in the tree list is estimated, and then all of these canopy cover values are summed over the plot. Canopy cover values estimated using this method can be extrapolated across the landscape using readily available satellite remote sensing data.

Conclusions

The LANDFIRE Project is the first of its kind to develop fuel data products needed for fire behavior simulation seamlessly for the entire US, at 30-m spatial resolution, across all ownerships, using previously collected field datasets and consistent methodologies. The fuel data were produced in tandem, yielding integrated products that make sense in the context of one another. These products are expected to form baseline data for national to regional planning, whereas local datasets, which may cost more and take longer to produce per unit area, may be used in place of, or in addition to, LANDFIRE data products. However, the objective and comprehensive nature of LANDFIRE data has given them a track record of being used for such activities as tactical fire behavior assessment. Despite some difficulties with these data, the spatial patterns usually depict conditions seen across the landscape, except in the case of disturbances that altered the landscape after the image acquisition dates used for the LANDFIRE Project. This comprehensive fuel mapping effort has elucidated the need for a new generation of fire behavior simulation models that use inputs that can be accurately measured in the field. The CBD, CBH and surface FBFM data products cannot be readily measured in the field. This makes modeling and evaluating the accuracy of these products problematic. Despite this difficulty, the LANDFIRE fuels mapping process provides a framework for developing seamless and integrated data for use in fire behavior models.

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