Chapter 12

Mapping Wildland Fuel across Large Regions for the LANDFIRE Prototype Project

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Introduction

The Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, required that the entire array of wildland fuel characteristics be mapped to provide fire and landscape managers with consistent baseline geo-spatial information to plan projects for hazardous fuel mitigation and to improve public and firefighter safety. Fuel maps were some of the core deliverables of the LANDFIRE Prototype Project. The LANDFIRE approach for mapping fuel combined information from the LANDFIRE reference database (LFRDB) (Caratti and others, Ch. 4), biophysical gradient layers (Holsinger and others, Ch. 5), maps of potential vegetation (Frescino and Rollins, Ch. 7), and maps of vegetation composition and vegetation structure (Zhu and others, Ch. 8) to produce the entire suite of geo-spatial data for predicting the behavior and effects of wildland fires across the United States.

The fuel layers developed for the LANDFIRE effort were selected on the basis that they provide input to software commonly used in fire management planning. All LANDFIRE fuel layers can be directly used in one or more fire analysis tools, including the FARSITE fire growth model (Finney 1998). Moreover, these fuel layers may also be used for many other applications. Surface fuel layers provide comprehensive inventories of dead biomass that can be used to calculate carbon pools for estimating particulate production and modeling smoke dispersal. Canopy fuel layers provide important information on canopy characteristics that can be used to calculate leaf area index (LAI), shading, rain and snowfall interception, and surface roughness for ecosystem and hydrological modeling. Still other layers provide data on critical stand characteristics that may be used to quantify hiding and thermal cover for wildlife.

Background

Fuel is defined for the LANDFIRE Prototype as any material that can burn in a wildland fire. More specifically, wildland fuel is defined by characteristics of live and dead biomass pools that contribute to the spread, intensity, and severity of wildland fire (Burgan and Rothermel 1984). The primary characteristic used to describe fuel is "loading," which is defined as mass per unit area, or more specifically, the dry weight of a fuel component per unit area (kg m^{-2}). Other characteristics include particle density, surface area-to-volume ratio, packing ratio, and heat content. Fine fuel, such as twigs, grass, and foliage, primarily contributes to the spread of wildland fire, whereas coarse fuel, such as branches and logs, contributes mostly to post-frontal combustion and fire intensity.

Perhaps the most confounding property of fuel is its high variability in space and time (Brown and Bevins 1986). Fuel tends to have a clumped distribution within a stand that is related to the interaction between exogenous disturbance factors, such as windthrow, snowbreak, and

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insects, and the endogenous stand characteristics, such as tree distribution, density, and tree species. Moreover, the spatial distribution of fuel can vary by fuel size class and fuel type (grass, shrub, or woody, for example). Fine fuel (such as foliage or small twigs) tends to fall and accumulate uniformly over time, but the coarser fuel, such as branches and logs, tends to accumulate after episodic events such as windstorms, spring snowfalls, and insect epidemics. These factors contribute to the difficulty in describing, modeling, and mapping fuel (Keane and others 2001).

Two major categories of fuel were mapped in the LANDFIRE Prototype Project: surface fuel and canopy fuel. Surface fuel is composed of those dead and live biomass components that occur on the ground (under 2 m) and is the fuel that contributes to the spread and intensity of surface fire. This type of fuel is typically described by the following fuel components: herbaceous (live or dead), shrub (live or dead), downed/dead woody, litter, and duff. There were five size classes of downed/dead woody fuel used in the LANDFIRE Prototype: 1-, 10-, 100-, 1000-, and 10,000-hour fuel (1-, 2.5-, 8-, and 50-cm upper diameter thresholds). Litter is freshly fallen organic material, and duff is the decomposed organic material. For most fire behavior and effects applications, surface fuel is represented by a set of characteristics, with fuel loading being the most dynamic over time and space. Other characteristics include surface area-to-volume ratios, bulk density, and heat content (Albini 1976; Anderson 1982; Rothermel 1972). Because of the high diversity and variability of surface fuel components (Brown and Bevins 1986), surface fuel characteristics are usually quantified using "fuel models" that are composed of summaries of fuel loading by fuel component for unique ecological or fire behavior conditions (see Anderson 1982 for examples). For LANDFIRE purposes, all surface fuel is represented by fuel models that classify fuel loading by component. For example, a fuel model, as used in this paper, might represent the actual loading of each fuel component (such as litter, duff, and canopy fuel), or a fuel model might represent loadings by fuel component calculated to achieve a desired outcome when simulating fire behavior or effects.

Canopy fuel comprises those aerial biomass components higher than 2 m above the ground that can carry a crown fire and is typically consumed in the crown fire. This fuel is usually the foliage and small branchwood (<2.5 cm diameter) in a tree's crown (Scott and Reinhardt 2002). Unlike surface fuel, which is often described using categorical variables such as fuel component, canopy fuel was described in the LANDFIRE Prototype by four continuous variables: bulk density (kg m^{-3}), canopy cover (%), canopy height (m), and canopy base height (m). These four characteristics are essential for modeling crown fire initiation and propagation in the various fire management software tools (Finney 1998; Scott 1999).

We developed eight layers to describe both surface and canopy fuel for the LANDFIRE Prototype. As mentioned above, these layers were selected because they are essential for predicting fire behavior and effects so that fire hazard analyses and fire management planning may be performed in a spatial domain (Salas and Chevico 1994). These eight layers are:

- Anderson's (1982) 13 fire behavior fuel models (FBFM13).
- Scott's and Burgan's (2005) 40 fire behavior fuel models (FBFM40)
- Fuel characterization classes (FCCs) (Sandberg and Ottmar 2001)
- Fuel loading models (FLM) (Lutes and others, in preparation)
- Canopy bulk density (CBD)
- Canopy cover (CC)
- Canopy height (CH)
- Canopy base height (CBH)

Each classification or continuous variable that was mapped for each layer will be described in detail in the following sections.

The development of the LANDFIFRE fuel spatial data layers was a complex task that required the integration of diverse spatial analyses. For example, the surface fuel maps were created using a classification or rule-based approach, whereas the canopy layers were created using an integration of statistical modeling, classification, and ecosystem simulation. We have therefore stratified the sections of this chapter by surface fuel and canopy fuel for simplicity.

Surface Fuel Layers

In the LANDFIRE Prototype, we mapped four surface fuel model classifications to represent the gamut of surface fuel inputs needed to run commonly used models that simulate both fire behavior and effects. Two of these fuel classifications (fire behavior fuel models) are used to calculate fire behavior variables, such as fire intensity and spread rate, and the remaining two (fire effects fuel models) are used for computing fire effects, such as fuel consumption and smoke production. For the LANDFIRE Prototype, two new classifications describing fire behavior and effects were developed to complement two existing classifications and to match the scale and resolution of the LANDFIRE process. In this chapter, the term "fuel model" is used to represent a unique category in the fuel classification. These categories are unique sets of fuel characteristics (primarily amount of biomass) by fuel component that are linked to vegetation composition and structure. For example, an open ponderosa pine stand would likely be assigned an FBFM13 model 2 and a dense spruce-fir stand would be assigned an FBFM13 model 10.

Fire behavior fuel models—Eleven of the 13 fire behavior fuel models (FBFM13) were originally developed by Rothermel (1972) as input into his spread model for predicting fire behavior (spread and intensity) (table 1). Albini (1976) added two other models to this classification (dormant brush and southern rough) to create the standard 13 fire models used in fire management today (see Rothermel 1983). Anderson (1982) provided vegetation descriptions, stylized pictures, and a key to aid managers in determining fire behavior fuel models. These 13 fire behavior fuel models represent distinct distributions of fuel loading among surface fuel types (live and dead), size classes, and fuel components. They are described by the fuel type or carrier (grass, brush, litter, or slash) most commonly responsible for fire spread and are represented by a variety of characteristics, including biomass loading, surface area-to-volume ratio by size class and component, fuelbed depth, and moisture of extinction. Extensive early fire modeling research revealed that prediction of fire behavior with real-world fuel loading is problematic (Albini and Anderson 1982; Andrews 1980; Rothermel 1983). Therefore, fire scientists

Table 1—The 13 standard fire behavior fuel models developed by Rothermel (1972) and Albini (1976) and described by Anderson (1982).

Fuel Model	Group	Description
1	Grass	Surface fires that burn fine herbaceous fuels, cured and curing fuels, little shrub or timber present, primarily grasslands and savanna
2	Grass	Burns fine, herbaceous fuels, stand is curing or dead, may produce fire brands in oak or pine stands
3	Grass	Most intense fire of grass group, spreads quickly with wind, one third of stand dead or cured, stands average 3 ft tall
4	Shrub	Fast spreading fire, continuous overstory, flammable foliage and dead woody material, deep litter layer can inhibit suppression
5	Shrub	Low intensity fires, young, green shrubs with little dead material, fuels consist of litter from understory
6	Shrub	Broad range of shrubs, fire requires moderate winds to maintain flame at shrub height, or will drop to the ground with low winds
7	Shrub	Foliage highly flammable, allowing fire to reach shrub strata levels, shrubs generally 2 to 6 feet high
8	Timber	Slow, ground burning fires, closed canopy stands with short needle conifers or hardwoods, litter consist mainly of needles and leaves, with little undergrowth, occasional flares with concentrated fuels
9	Timber	Longer flames, quicker surface fires, closed canopy stands of long-needles or hardwoods, rolling leaves in fall can cause spotting, dead-down material can cause occasional crowning
10	Timber	Surface and ground fire more intense, dead-down fuels more abundant, frequent crowning and spotting causing fire control to be more difficult
11	Logging Slash	Fairly active fire, fuels consist of slash and herbaceous materials, slash originates from light partial cuts or thinning projects, fire is limited by spacing of fuel load and shade from overstory
12	Logging Slash	Rapid spreading and high intensity fires, dominated by slash resulting from heavy thinning projects and clearcuts, slash is mostly 3 inches or less in diameter, fire is usually sustained until there is a fuel break or a change in fuel type
13	Logging Slash	Fire spreads quickly through smaller material and intensity builds slowly as large material ignites, continuous layer of slash larger than 3 inches in diameter predominates, resulting from clearcuts and heavy partial cuts, active flames sustained for long periods of time, fire i susceptible to spotting and weather conditions

created synthetic representations of wildland fuel that, when input into the fire model, would simulate realistic fire behavior under known temperature, moisture, and wind conditions. Although the fuel loading used in these models did not represent actual amounts measured in the field, the simulated fire behavior using these artificial amounts was found to approximate reality, especially with respect to the resolution of the fire behavior model. Since their development, FBFM13 have served as the foundation for fire behavior prediction (Andrews and Bevins 1999).

Despite FBFM13's advantages, the resolution of these 13 fuel model categories is so coarse that subtle changes in fuelbed conditions, such as those incurred by fuel treatment activities, often cannot be detected using the FBFM13 categories. In addition, since the FBFM13 models were developed for application during severe fire weather (Anderson 1982), they had limited abilities to predict fire behavior for purposes of prescribed fire and wildland fire use. Additionally, these models had limited abilities for simulating and comparing different fuel treatments' effects on fire behavior. Many fuel treatments do not produce sufficient fuel modification by which to reclassify a stand to a different FBFM13 fuel model category. Scott and Burgan (2005) also mention that new fuel models were needed to better represent fuel types in high humidity areas and forests with litter, grass, and shrub understories. We therefore determined that a finer resolution fire behavior fuel model would be necessary for guiding fuel treatments at a national scale (Keane and Rollins, Chapter 3).

In 2003, the LANDFIRE Prototype Project funded an extensive fuel modeling study, led by the Fire Behavior Research Unit (RWU-4401) of the Rocky Mountain Research Station and Systems for Environmental Management, to create the next generation of fire behavior fuel models. In 2005, Scott and Burgan created a new set of 40 fire behavior fuel models (FBFM40) that are hierarchically organized by fuel strata and fuel loading (table 2). This set of fuel models provides a better tool for fire behavior prediction because it balances the resolution of fuel conditions with the algorithms contained in widely accepted fire behavior models. These 40 fire behavior fuel models have already been implemented in the BehavePlus fire modeling system (Andrews 1986; Andrews and Bevins 1999; Andrews and others 2003) and the FARSITE fire growth model (Finney 1998). Unlike Anderson's (1982) FBFM13 descriptions, subtle modifications in vegetation composition and structure resulting from fuel treatment activities may be detected using FBFM40 under most circumstances.

One limitation of fire behavior fuel model classifications relates to the difficultly in accurately and consistently determining which fire behavior fuel model best describes fuel conditions in a particular stand. Since fire behavior fuel models are assigned according to expected fire behavior, extensive experience in evaluating potential fire behavior under particular fuel conditions is required to assign fire behavior fuel models. Even the most experienced fire modeling specialists have difficulty agreeing on a common fuel model for certain stand and weather conditions. This limitation is exacerbated by the high variability of fuel by component across spatial scales (Keane and others 2001). It is therefore common for a stand to be described by two or more fire behavior fuel models. As a consequence, spatially explicit field data containing estimates of fire behavior fuel models are rare. Another limitation of fire behavior fuel models is that they do not quantify all dead and live biomass pools at a stand level, thus they are not useful for other fire applications such as predicting smoke production and vegetation mortality (Keane and others 1998a; Leenhouts 1998).

Fire effects fuel models—The many fire effects prediction models, such as FOFEM (Reinhardt and Keane 1998; Reinhardt and others 1997) and CONSUME (Ottmar and others 1993), require actual fuel loading estimates by fuel component to simulate fire effects-related processes, such as fuel consumption and smoke generation. However, because fuel loadings for the FBFM13 and FBFM40 classifications were modified to predict realistic fire behavior, the fire behavior fuel models are not useful for computing fire effects. Simulation of fire effects requires classifications of fuel loading across all biomass components that accurately describe real fuel across large landscapes.

There are two main fire effects fuel model classification systems used in the LANDFIRE Prototype mapping effort. The first, called the Fuel Characterization Classification System (FCCS), was developed by Sandberg and others (2001). This system summarizes fuel loading by component using canopy, shrub, surface, and ground fuel stratifications (www.fs.fed.us/pnw/fera/research). Several fuelbed categories that describe unique combustion environments form the foundation of FCCS. These categories were selected based on general characteristics, such as region, stand structure, and stand history. Fuel component loadings for these fuelbeds were summarized into a set of fuel models referred to as the "national default fuelbeds," which we will refer to here as default fuel characterization classes, or FCCs for brevity. These default FCCs can then be modified using specialized

Table 2—Description of the 40 fire behavior fuel models developed by Scott and Burgan (2005).

Fuel Model Number	Fuel Model Code	Name	Description
GRASS			
101	GR1	Short, sparse dry climate grass	Grass is short naturally or heavy grazing, predicted rate of fire spread and flame length is low
102	GR2	Low load, dry climate grass	Primarily grass with some small amounts of fine, dead fuel, any shrubs do not affect fire behavior
103	GR3	Low load, very coarse, humid climate grass	Continuous, coarse humid climate grass, any shrubs do not affect fire behavior
104	GR4	Moderate load, dry climate grass	Continuous, dry climate grass, fuelbed depth about 2 feet
105	GR5	Low load, humid climate grass	Humid climate grass, fuelbed depth is about 1-2 feet
106	GR6	Moderate load, humid climate grass	Continuous humid climate grass, not so coarse as GR5
107	GR7	High load, dry climate grass	Continuous dry climate grass, grass is about 3 feet high
108	GR8	High load, very coarse, humid climate grass	Continuous, coarse humid climate grass, spread rate and flame length may be extreme if grass is fully cured
109	GR9	Very high load, humid climate grass	Dense, tall, humid climate grass, about 6 feet tall, spread rate and flame length can be extreme if grass is fully cured
GRASS-SHRUB			
121	GS1	Low load, dry climate grass-shrub	Shrubs are about 1 foot high, grass load is low, spread rate moderate and flame length is low
122	GS2	Moderate load, dry climate grass-shrub	Shrubs are 1-3 feet high, grass load is moderate, spread rate high and flame length is moderate
123	GS3	Moderate load, humid climate grass-shrub	Moderate grass/shrub load, grass/shrub depth is less than 2 feet, spread rate is high and flame length is moderate
124	GS4	High load, humid climate grass-shrub	Heavy grass/shrub load, depth is greater than 2 feet, spread rate is high and flame length very high
SHRUB			
141	SH1	Low load dry climate shrub	Woody shrubs and shrub litter, fuelbed depth about 1 foot, may be some grass, spread rate and flame low
142	SH2	Moderate load dry climate shrub	Woody shrubs and shrub litter, fuelbed depth about 1 foot, n grass, spread rate and flame low
143	SH3	Moderate load, humid climate shrub	Woody shrubs and shrub litter, possible pine overstory, fuelbed depth 2-3 feet, spread rate and flame low
144	SH4	Low load, humid climate timber shrub	Woody shrubs and shrub litter, low to moderate load, possible pine overstory, fuelbed depth about 3 feet, spread rate high and flame moderate
145	SH5	High load, humid climate grass-shrub	Grass and shrubs combined, heavy load with depth greater than 2 feet, spread rate and flame very high
146	SH6	Low load, humid climate shrub	Woody shrubs and shrub litter, dense shrubs, little or no herbaceous fuel, depth about 2 feet, spread rate and flame high
147	SH7	Very high load, dry climate shrub	Woody shrubs and shrub litter, very heavy shrub load, depth 4-6 feet, spread rate somewhat lower than SH6 and flame very high

(continued)

Table 2 (Continued)

Fuel Model Number	Fuel Model Code	Name	Description
SHRUB			
148	SH8	High load, humid climate shrub	Woody shrubs and shrub litter, dense shrubs, little or no herbaceous fuel, depth about 3 feet, spread rate and flame high
149	SH9	Very high load, humid climate shrub	Woody shrubs and shrub litter, dense finely branched shrubs with fine dead fuel, 4-6 feet tall, herbaceous may be present, spread rate and flame high
TIMBER-UNDERSTORY			
161	TU1	Low load dry climate timber grass shrub	Low load of grass and/or shrub with litter, spread rate and flame low
162	TU2	Moderate load, humid climate timber-shrub	Moderate litter load with some shrub, spread rate moderate and flame low
163	TU3	Moderate load, humid climate timber grass shrub	Moderate forest litter with some grass and shrub, spread rate high and flame moderate
164	TU4	Dwarf conifer with understory	Short conifer trees with grass or moss understory, spread rate and flame moderate
165	TU5	Very high load, dry climate shrub	Heavy forest litter with shrub or small tree understory, spread rate and flame moderate
TIMBER LITTER			
181	TL1	Low load compact conifer litter	Compact forest litter, light to moderate load, 1-2 inches deep, may represent a recent burn, spread rate and flame low
182	TL2	Low load broadleaf litter	Broadleaf, hardwood litter, spread rate and flame low
183	TL3	Moderate load conifer litter	Moderate load conifer litter, light load of coarse fuels, spread rate and flame low
184	TL4	Small downed logs	Moderate load of fine litter and coarse fuels, small diameter downed logs, spread rate and flame low
185	TL5	High load conifer litter	High load conifer litter, light slash or dead fuel, spread rate and flame low
186	TL6	Moderate load broadleaf litter	Moderate load broadleaf litter, spread rate and flame moderate
187	TL7	Large downed logs	Heavy load forest litter, larger diameter downed logs, spread rate and flame low
188	TL8	Long needle litter	Moderate load long needle pine litter, may have small amounts of herbaceous fuel, spread rate moderate and flame low
189	TL9	Very high load broadleaf litter	Very high load fluffy broadleaf litter, may be heavy needle drape, spread rate and flame moderate
SLASH-BLOWDOWN			
201	SB1	Low load activity fuel	Light dead and down activity fuel, fine fuel is 10-20 t/ac, 1-3 inches in diameter, depth less than 1 foot, spread rate moderate and flame low
202	SB2	Moderate load activity fuel or low load blowdown	Moderate dead down activity fuel or light blowdown, 7-12 t/ac, 0-3 inch diameter class, depth about 1 foot, blowdown scattered with many still standing, spread rate and flame low
203	SB3	High load activity fuel or moderate load blowdown	Heavy dead down activity fuel or moderate blowdown, 7-12t/ac, 0-.25 inch diameter class, depth greater than 1 foot, blowdown moderate, spread rate and flame high
204	SB4	High load blowdown	Heavy blowdown fuel, blowdown total, foliage and fine fuel still attached to blowdown, spread rate and flame very high

software (see http://www.fs.fed.us/pnw/fera/research/ for details) to create new, finer-scale FCCs to represent local conditions. In the LANDFIRE Prototype, we mapped the default FCCs, allowing managers to then, through the software, modify these default FCCs to reflect finer-scale, local fuel conditions for project-level fuel treatment planning. Over 200 default FCCs were used in the LANDFIRE prototype effort, thus a table describing each would be prohibitively long and not appropriate for this report.

The default FCCs can be keyed only from vegetation characteristics observed in the field or from variables contained in existing databases. However, there is often a low degree of fidelity between FCCs and LANDFIRE vegetation classes (Long and others, Ch. 6) because of the high variability in fuel loadings within and between fuel components (Keane and others 2001). There are no key criteria in the FCCS that use fuelbed characteristics to uniquely identify default FCCs; that is, it is difficult, if not impossible, to consistently determine FCCs based on fuel data alone.

The high fuel loading variability and large number of default FCCs presented a special scale problem in the LANDFIRE Prototype. We found the default FCCs to be useful at fine spatial scales, but it was difficult to accurately map the default FCCs across large regions with diverse ecosystems because the classification resolution of the FCCS did not match the resolution needed to describe fuel across entire regions. For example, there was an insufficient number of default FCCs in the FCCS to link to all the vegetation conditions quantified by the LANDFIRE mapping process. We therefore created a second, companion fire effects fuel model classification that accounted for the high variability across fuel components and matched the resolution of LANDFIRE mapping process as well as the resolution of the models used to predict fire effects.

The fuel loading model (FLM) classification was developed for the LANDFIRE Prototype by Lutes and others (in preparation) to specifically match the scale of LANDFIRE mapping with the scale of fire effects modeling. They developed a broad classification of fuelbeds based on fuel loading by component that accounts for the high variability of loading within and between fuel components. Instead of assigning fire effects fuel models to vegetation characteristics, Lutes and others (in preparation) analyzed the loading of seven surface fuel components in over 4,000 fuelbeds measured in the field and grouped them using an unsupervised agglomerative clustering approach based on component loading. They then calculated the fire effects of smoke production and soil temperature for each fuelbed and used these outputs in a cluster analysis to obtain an FLM classification, which accounts for the variability of fuel loading and related potential fire effects across the seven surface fuel components. Moreover, a rule set was developed in addition to the FLM classification that can be used to determine the appropriate FLM in the field or from existing field databases containing fuel information. A comprehensive description of each FLM is detailed in Lutes and others (in preparation) and is summarized in table 3.

Table 3—Fuel loading models (FLMs) are combinations of duff/litter and coarse woody debris (CWD) biomass that lead to unique fire effects, as measured by soil heating and PM2.5 emissions. Multiple combinations of duff/litter and CWD may point to one FLM.

	Fuel combination 1		Fuel combination 2		Fuel combination 3		
FLM	Duff/litter	CWD	Duff/litter	CWD	Duff/litter	CWD	Associated cover types
	Tons/acre						
1	<8	<13	>5, <8	<13			Herb and shrub
2	>8, <15	<13					Shrub, woodland
4	>20, <40	<13	<8	>17, <35			Tall shrub, low – mid density forest
5	>8, <20	>13, <35					Low – mid density forest
6	>40, <60	<35					Mid – high density forest
7	>20, <40	>13, <35	<40	>35, <90			Mid – high density forest
8	>60, <80	<35	>40, <80	>35	<40	>90	High density forest, large trees
99							Agricultural, barren, unburnable

Canopy Fuel Layers

The spatial representation of canopy fuel is important for assessing the probability and simulating the characteristics of crown fire across forested landscapes (Chuvieco and Congalton 1989; Finney 1998; Keane and others 1998a; Keane and others 2001). Four main variables describing canopy fuel characteristics are commonly applied in wildland fire simulation and fire management planning; these include canopy bulk density (CBD, kg m^{-3}), canopy base height (CBH, m), canopy height (CH, m), and canopy cover (CC, percent).

Canopy bulk density (CBD) describes the mass of available canopy fuel per unit volume of canopy in a stand (Scott and Reinhardt 2005); it is the dry weight of available canopy fuel per unit volume of the canopy including the spaces between the tree crowns (Scott and Reinhardt 2001). Canopy fuel is typically defined by all foliage and branchwood material less than 1 cm in diameter because this is the fuel that is typically consumed in a crown fire (Keane and others 2005). The bulk density of the canopy determines the initiation of a crown fire and the subsequent rate at which a fire spreads through the canopy (Cruz and others 2003; Finney 1998; Van Wagner 1977; Van Wagner 1993).

Canopy base height (CBH) describes the level above the ground at which there is enough aerial fuel to carry the fire vertically into the canopy. This measurement is commonly thought of as the height from the ground to the bottom of the live canopy (Scott and Reinhardt 2001) but may also include dense, dead crown material that can carry a fire. The CBH determines the likelihood of a crown fire and the interaction between the ground, surface, and canopy fuel layers (Cruz and others 2003).

Canopy height (CH) is the height of the top of the canopy, and canopy cover (CC) is the vertically projected percent cover of the live canopy layer for a specific area. Spatially explicit canopy information combined with topographic and weather data are used to determine when and where the transition from a surface fire to a crown fire may occur (Finney 1998).

Maps of these four canopy characteristics, in conjunction with maps of elevation, aspect, slope, and fire behavior fuel models, are required as input to the FARSITE model to simulate fire growth under various weather and wind scenarios (Finney 1998). FARSITE is currently used by many fire managers to plan prescribed burns and to manage wildland fires. It is designed to model fire behavior over a continuous surface at fine time-steps. These canopy characteristics can also be used in NEXUS to calculate the critical wind threshold for propagating a crown fire (Scott 1999).

The CH and CC map layers were mapped by the USGS Center for Earth Resources Observation and Science (EROS) using field-referenced data, satellite imagery, and statistical modeling (Zhu and others, Ch. 8); however, we describe only the development of the CBD and CBH canopy fuel layers in this chapter. These layers were mapped at the USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory (MFSL) in Missoula, Montana using a complex statistical modeling procedure that employs biophysical gradients and satellite imagery to predict these variables across landscapes.

Fuel Mapping

Because of recent advances in fire modeling software and GIS analysis packages, maps of wildland fuel have become essential in wildland fire management and in planning and implementing fuel treatments (Finney 1998; Keane and others 2001). As mentioned, these spatial layers provide critical input to the numerous fire models currently available for fire management (see www.frames.nbii.gov). However, the mapping of wildland fuel is a difficult and costly task for two main reasons.

First, many of the remotely sensed data used in mapping, such as aerial photos and satellite images, are unable to detect surface fuel because the ground is often obscured by the forest canopy (Asner 1998; Elvidge 1988; Lachowski and others 1995). Even if sensors were able to view the ground, the resolution of the imagery makes it difficult to distinguish between fuel components on the ground and between surface fuel and fuel suspended in the canopy (Keane and others 2001). Second, high variability in fuel loading and other vegetation characteristics across time and space is a confounding property of fuel that prevents it from being accurately mapped (Agee and Huff 1987; Brown and See 1981; Harmon and others 1986). Fuel variability within a stand can often equal or be greater than the variability of fuel across the landscape (Brown and Bevins 1986; Brown and See 1981; Jeske and Bevins 1979). Brown and Bevins (1986) found few statistically significant differences in fuel loadings between vegetation types and biophysical settings because of the vast differences in stand histories between areas with similar environments. This finding indicates that fuel is not always related to mapped vegetation categories. Keane and others (2001) summarized four general strategies commonly used to map fuel: 1) field reconnaissance, 2) indirect mapping with remote sensing, 3) direct mapping with remote sensing, and 4) biophysical gradient modeling. The indirect mapping with remote sensing approach recognizes the inability of imagery to directly map fuel; thus, other, more easily mapped ecosystem characteristics are used instead as surrogates for fuel. This approach assumes certain biological properties can be accurately classified from remotely sensed imagery, and these attributes, most often related to the vegetation, correlate well with fuel characteristics or fuel models. Field reconnaissance methods map fuel through direct observation, whereas remote sensing methods assign fuel characteristics using imagery data. (Verbyla 1995). Lastly, the biophysical gradient modeling approach uses environmental gradients and biophysical modeling to create fuel maps. Environmental gradients are those biogeochemical processes, such as climate, topography, and disturbance that directly influence vegetation and fuel dynamics. In the LANDFIRE Prototype fuel mapping effort, we integrated the indirect remote sensing approach with the biophysical gradient modeling approach to map surface fuel, and integrated the direct remote sensing mapping approach with the biophysical gradient modeling approach to map canopy fuel.

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on the procedure followed in developing maps of surface and canopy fuel characteristics, which served as important core products of the LANDFIRE Prototype Project.

Creating the LANDFIRE Fuel Database

The LANDFIRE fuel database was derived from the LANDFIRE reference database (LFRDB) (Caratti, Ch. 4) and compiled so that fuel layers could be directly created based on other LANDFIRE vegetation and biophysical data layers – specifically, the potential vegetation type (PVT) layer (Frescino and Rollins, Ch. 7), the cover type (CT) layer, and the structural stage (SS) layer (Zhu and others, Ch. 8). This database was designed such that each PVT-CT-SS combination was assigned a set of fuel attributes. These fuel attributes were quantified in the following order of priority: 1) from field data, 2) from published literature, and 3) from estimates of experienced wildland fuel professionals.

The LANDFIRE fuel database was used for several purposes: First, it was used to create the surface fuel layers that did not have field data represented in the LFRDB. For example, the FBFM13 and FBFM40 values were rarely recorded in the LFRDB, so these layers were impossible to create using standard mapping and spatial modeling procedures. We had to therefore assign fuel model classification categories to each PVT-CT-SS combination using the myriad of variables describing vegetation composition and condition contained in the LANDFIRE fuel database. This fuel database was also used to assign values to the map where mapping models were in error. Moreover, it could also be used as a quasi-validation or data-check to ensure map consistency. And lastly, it could be used as a reference and guide to step down LANDFIRE fuel assignments to local applications. For example, managers may decide to change assigned fuel models to reflect local conditions.

The database was designed with the following fields:

1. Mapping zone – EROS mapping zone identification number
2. PVT – Potential vegetation type code
3. SCLASS – Succession class code, which represents a combination of cover type and structural stage
4. FBFM13 – Albini (1976) standard 13 fire behavior fuel models (see Anderson 1982) including additional models for water and rock
5. FBFM40 – Scott and Burgan (2005) 40 fire behavior fuel models
6. Default FCCs – Default fuel characterization classes from Sandberg and others (2001)
7. FLMs – Fuel loading models from Lutes and others (in preparation)
8. Canopy height (m) – Uppermost height of the canopy layer
9. Canopy base height (m) — Height at which crown bulk density exceeds 0.011 kg m^{-3}
10. Canopy cover (%) – Percentage of vertically projected tree cover
11. Canopy bulk density (kg m^{-3}) – Maximum bulk density of all vertical layers comprising the forest canopy

Creating Maps of Surface Fuel

The methods used to develop the surface fuel layers were distinctly different from the approach used for the canopy layers. We used a classification or rule-based approach in which fuel model categories from each classification (FBFM13, FBFM40, default FCCs, and FLMs) were assigned to combinations of mapped attributes from other LANDFIRE products using generalized rule sets. A rule set is a hierarchically nested set of rules that assigns surface fuel models to combinations of LANDFIRE data layers using information from the LANDFIRE fuel database (see appendix 12-A). This approach has been used successfully in several recent fuel mapping efforts and fit the design criteria for the LANDFIRE Prototype (Keane and others 1998a; Keane and others 1998b; Keane and Rollins, Ch. 3; Menakis and others 2000). The procedure for the surface fuel mapping process is detailed in Ch. 2: appendix 2-A.

For the LANDFIRE Prototype, the rule-based approach to the mapping of surface fuel was the only available technique for two main reasons: First, statistical modeling approaches could not be used because only a small fraction of the LFRDB contained information about fuel models. This meant that we could not use the classification and regression tree (CART) (Breiman and others 1984) analysis techniques that were applied in other LANDFIRE mapping tasks because there were insufficient reference data to build the statistical functions for spatially predicting surface fuel models. This lack of data was especially a problem in the case of the two new fuel classifications developed during the LANDFIRE Prototype – FBFM40 and FLMs – because they had never been used in the field. Second, there were no existing field and database keys with which to consistently identify fuel models from variables commonly included in field reference databases, such as canopy cover, vegetation type, fuel loading, and tree density. Efforts are currently underway to create field and database keys for each fuel model classification so that fuel models can be assigned to individual plots.

All surface fuel maps were created using rule sets where, in the most simple cases, surface fuel models were assigned to solely PVT-CT-SS combinations (Ch. 2: appendix 2-A). This rule-based approach also allowed for the inclusion of additional data when surface fuel models could not be uniquely described by a PVT-CT-SS combination. In these cases, the PVT-CT-SS stratification was augmented with other data that determine the distribution of surface fuel across landscapes, such as topography or geographic location. For example, a rule set might assign a FBFM13 fuel model to a PVT-CT-SS combination on slopes greater than 50 percent in the northern part of a mapping zone.

We gave confidence rankings to each of the default FCC assignments based on which attributes from the FCCS fuelbed database (Sandberg and Ottmar 2001) were applied. We gave the highest ranking (1) to fuelbeds that had species lists identical to the LANDFIRE PVT and CT species lists. We assigned a confidence ranking of 2 if we needed to associate fuelbeds with unique vegetation classes based on vegetation characteristics and actual and inferred (through expert knowledge) site characteristics. In other words, the default FCCs' vegetation description was similar to but not exactly the same as the LANDFIRE vegetation map units. Finally, using expert knowledge, we assigned a confidence ranking of 3 to the remaining fuelbeds where the information in the FCCs' vegetation description was not represented by the LANDFIRE vegetation map units. For fuelbeds given a confidence ranking of 3, we determined the most appropriate fuelbed based on species composition and structure. In certain cases, we were unable to associate some of the fuelbeds with a unique vegetation class combination because there was not an appropriate fuelbed to represent this situation, even with an expanded definition.

Creating Maps of Canopy Fuel

We developed the two canopy fuel maps (CBD, CBH) for the forested lands of Zone 16 and Zone 19 using a predictive landscape modeling approach (Franklin 1995). This approach integrates remote sensing, biophysical gradients, and field-referenced data to generate maps of canopy bulk density and canopy base height. These canopy fuel characteristics were calculated for numerous plots in the LFRDB and then augmented with a set of mapped predictor variables in a classification and regression tree (CART) approach to predict crown fuel attributes across the two prototype mapping zones.

Calculating canopy fuel characteristics—The first step was to calculate CBD and CBH using FUELCALC, a prototype program developed by Reinhardt and Crookston (2003). FUELCALC computed several canopy fuel characteristics for each field reference plot from the LFRDB based on allometric equations relating individual tree size, canopy, and species characteristics to crown biomass. The canopy characteristics for a stand are computed from a list that specifies the tree species, density (trees per unit area), diameter at breast height (DBH), height, crown base height, and crown class. FUELCALC computes vertical canopy fuel distribution using algorithms that evenly distribute crown biomass over the live crown for each tree. For each plot, the program then divides the canopy into horizontal layers of a user-specified width and reports the CBD value of the layer with the greatest bulk density. The CBH value for each plot is reported as the height of the lowest layer of the canopy that has a bulk density value greater than 0.011 kg m^{-3}. FUELCALC estimates for CH and CC were not used in the mapping process since these maps were created by Zhu and others (Ch. 8).

For the LANDFIRE Prototype FUELCALC canopy fuel calculations we used the Forest Inventory and Analysis (FIA; Gillespie 1999) data from the LFRDB because they provided consistent information and FUELCALC input values across both prototype zones. There were a total of 1,806 FIA plots that fell within the Zone 16 boundary. This included over 32,000 individual tree records. Zone 19 encompassed a total of 1,988 FIA forested plots with over 44,600 individual tree records. We derived crown depth (a FUELCALC input) from the FIA compacted crown ratio attribute, defined as the percentage of the total height of a tree that supports live foliage (Miles and others 2001). We did not attempt to deconstruct the live crown ratio.

Mapped predictor data—Our hypothesis was that plot-level estimates of canopy fuel are correlated with spectral (from satellite imagery) and biophysical (from LANDFIRE computer models) gradients. As a basis for developing a database of mapped predictor variables, we used data from a leaf-on (June 2000) Landsat image and a leaf-off (October 2000) Landsat image. We included three visible bands, three infrared bands, a thermal band, three tasseled-cap transformation bands (brightness, greenness, and wetness) (Huang and others 2001), and a normalized difference vegetation index for each image – totaling 22 variables derived from spectral information (table 4).

The database of mapped predictor variables also included a suite of biophysical gradient layers that were created using WXFIRE, an ecosystem simulation model (Keane and Holsinger 2006; Keane and Rollins, Ch. 3), and four topographic gradient layers. The WXFIRE model integrates DAYMET (Running and Thornton 1996; Thornton and others 1997; Thornton and others 2000) climate data with landscape data and site specific parameters (such as soils and topography) and interpolates 1-km grid DAYMET climate variables to a 30-m grid cell resolution, thereby generating spatially explicit maps of climate and ecosystem variables at fine spatial resolutions. WXFIRE outputs a total of 33 variables (See Holsinger and others, Ch. 5 for detailed information about WXFIRE and biophysical gradient modeling in the LANDFIRE Prototype). However, this exhaustive list was reduced (winnowed) to 16 variables for Zone 16 (table 5) and 18 variables for Zone 19 (table 6) using exploratory analyses of principle components and correlation matrices.

The topographic gradients included four variables derived from the National Elevation Dataset (NED): elevation, percent slope, classified aspect, and a topographic position index. The topographic position index is a metric scaled from 0 to 1 defining the position on a slope, with 0 being the bottom of a valley and 1 the top of a ridge (table 7). In addition to the mapped predictor variables described above, we included four LANDFIRE products as additional predictors: maps of CT, SS, CH, and CC (Long and others Chapter 6; Zhu and others, Chapter 8).

Table 4—Zone 16 and Zone 19 satellite imagery predictor layers for canopy bulk density and canopy base height models.

Variable	Description
onb1	Landsat Leaf-on – band 1 (visible blue)
onb2	Landsat Leaf-on – band 2 (visible green)
onb3	Landsat Leaf-on – band 3 (visible red)
onb4	Landsat Leaf-on – band 4 (near infrared)
onb5	Landsat Leaf-on – band 5 (mid infrared)
onb6	Landsat Leaf-on – band 7 (mid infrared)
onb9	Landsat Leaf-on – band 9 (thermal)
onndvi	Landsat Leaf-on – normalized difference vegetation index
offb1	Landsat Leaf-off – band 1 (visible blue)
offb2	Landsat Leaf-off – band 2 (visible green)
offb3	Landsat Leaf-off – band 3 (visible red)
offb4	Landsat Leaf-off – band 4 (near infrared)
offb5	Landsat Leaf-off – band 5 (mid infrared)
offb6	Landsat Leaf-off – band 7 (mid infrared)
offb9	Landsat Leaf-off – band 9 (thermal)
offtc1	Landsat Leaf-off – tassel-cap transformation (brightness)
offtc2	Landsat Leaf-off – tassel-cap transformation (greenness)
offtc3	Landsat Leaf-off – tassel-cap transformation (wetness)
offndvi	Landsat Leaf-off – normalized difference vegetation index

Table 5—Zone 16 biophysical gradient predictor layers, produced using the WXFIRE model, for canopy bulk density and canopy base height regression tree models.

Variable	Units	Description
aet	kgH20/yr	Actual evapotranspiration
dday	degree C	Degree-days
dsr	days	Days since last rain
evap	kgH20 m^{-2} day^{-1}	Evaporation
gc_sh	s m^{-1}	Canopy conductance to sensible heat
gl_sh	s m^{-1}	Leaf-scale stomatal conductance
outflow	kgH20m^{-2} day^{-1}	Soil water lost to runoff and ground
pet	kgH20 yr^{-1}	Potential evapotranspiration
ppt	cm	Precipitation
psi	-Mpa	Water potential of soil and leaves
rh	%	Relative humidity
snow	cm	Amount of snowfall
srad.fg	w m^{-2}	Shortwave radiation for the site
tmin	degree C	Minimum daily temperature
trans	kgH20 m^{-2} day^{-1}	Soil water transpired by canopy
vmc	scalar	Volumetric water content

Table 6—Zone 19 biophysical gradient predictor layers, produced using the WXFIRE model, for canopy bulk density and canopy base height regression tree models.

Variable	Units	Description
aet	kgH20 yr^{-1}	Actual evapotranspiration
dday	degree C	Degree-days
dsr	days	Days since last rain
evap	kgH20 m^{-2} day^{-1}	Evaporation
gc_sh	s m^{-1}	Canopy conductance to sensible heat
outflow	kgH20 m^{-2} day^{-1}	Soil water lost to runoff and ground
pet	kgH20 yr^{-1}	Potential evapotranspiration
ppfd	umol m^{-2}	Photon flux density
ppt	cm	Precipitation
psi	-Mpa	Water potential of soil and leaves
rh	%	Relative humidity
snow	cm	Amount of snowfall
srad.fg	w m^{-2}	Shortwave radiation for the site
swf	dimension	Soil water fraction
tave	degree C	Average daily temperature
tmin	degree C	Minimum daily temperature
trans	kgH20 m^{-2} day^{-1}	Soil water transpired by canopy
vmc	scalar	Volumetric water content

Table 7—Zone 16 and Zone 19 topographic gradient predictor layers for canopy bulk density and canopy base height regression tree models.

Variable	Units	Description
elev	meters	Elevation
asp	8 classes	Aspect class
slp	%	Slope
posidx	index (0-1)	Topographic position index

Classification and regression trees (CART)—As in the mapping of PVT, CT, and SS (Frescino and Rollins, Chapter 7; Zhu and others, Chapter 8), we used regression trees (Breiman and others 1984) to model and map canopy fuel across zones 16 and 19. Regression tree models are rule-based predictive models in which continuous data values are recursively divided into smaller subsets based on a set of rules. The rules are constructed from available training data in which observations are delineated into smaller subsets of more homogenous classes. For every possible split of each predictor variable, the within-cluster sum of squares about the mean of the cluster on the response variable (the theme being mapped) is calculated. The predictor defines a split at the point that yields the smallest overall within-cluster sum of squares (Breiman and others 1984). For a detailed description of the use of CART in the LANDFIRE Prototype, see Frescino and Rollins, Chapter 7. We tried other statistical approaches, such as nearest neighbor, discriminant analysis, and generalized linear modeling but decided to employ the regression tree approach because it consistently generated valid models that created realistic maps.

The regression trees for modeling canopy fuel were generated using the commercially available machine-learning algorithm, Cubist (Quinlan 1986; Quinlan 1993; Rulequest Research 2004). Cubist offers a fast and efficient means for building regression tree models and applying these models to large areas (Homer and others 2002; Huang and others 2001; Moisen and others 2004; Xian and others 2002; Yang and others 2003). Cubist generates rule-based models with one or more rules defining the conditions in which a linear regression model is established. Cubist can also build "composite models," where a rule-based model is combined with an instance-based (nearest-neighbor) model (Quinlan 1993).

Other features of Cubist include 1) generation of committee models, 2) simplification of (pruning) the models, and 3) extrapolation of the model predictions. First, the committee models are made up of multiple rule-based models where each model "learns" from the prediction errors of the previously built model. The final model's predictions are an average of the predictions of the previously built models. Second, to simplify or prune a model in Cubist, you can specify the percentage of cases that meet the conditions of a rule or explicitly define the maximum number of rules allowed. Third, the extrapolation feature defines the percentage factor in which model predictions can occur outside the range of values determined by the training data (Rulequest Research 2004).

Although not fully automated, the process for modeling and mapping canopy fuel was simplified using a suite of tools developed by Earth Satellite Corporation (2003) in support of the National Land Cover Database (NLCD) project (Vogelmann and others 2001). These tools were developed to integrate the Rulequest Cubist software package (Rulequest Research 2004) with ERDAS Imagine image-processing software (ERDAS, Inc. 2001). We used the NLCD Sampling Tool to set up the input files needed to build the models in Cubist and the NLCD Classifier Tool to generate the final map. The Sampling Tool allows a user to input a spatially explicit layer of field-referenced training data as a dependent variable and multiple spatially explicit gradient layers as independent variables; the tool then outputs the files needed to execute Cubist. The Classifier Tool applies the regression tree model output from Cubist across the specified spatial extent or a specified masked extent.

To meet the input requirements of the NLCD mapping tool and to improve the efficiency of the modeling process, we followed three pre-processing rules: 1) all layers must be ERDAS Imagine images, 2) all layers must have the same number of rows and columns, and 3) all layers must be scaled to size 16-bit or smaller and have positive values. The output from the Sampling Tool includes a data text file, which contains values from the model response and the corresponding value of the model predictor layers for each georeferenced training site, and a file identifying the model input names and data types. We built multiple Cubist models for CBD and CBH for each prototype mapping zone – exploring the different features of Cubist – and selected the model having the lowest error as the model to use for prediction. The final maps of both CBD and CBH were created using the Classifier Tool based on the predictor variables listed in table 8.

Performing QA/QC Procedures

The LANDFIRE fuel layers (both crown and surface fuel) needed to be not only congruent across all fuel layers, but also consistent with all other LANDFIRE layers. It was essential that all pixels in the LANDFIRE data layers have logical combinations of vegetation, fuel, fire, and biophysical parameters. The process used to ensure that pixels across layers were assigned logical map categories was called the LANDFIRE Quality Assurance/Quality Control (QA/QC) procedure. This process was designed for the Zone 16 and Zone 19 fuel maps but not implemented because of administrative problems. In addition, late completion of other LANDFIRE tasks precluded a comprehensive comparison with the fuel

Table 8—Zone 16 and Zone 19 modeled predictor layers for canopy bulk density and canopy base height regression tree models.

Variable	Units	Description
evtr	class	Forest - cover type (rectified)
ssr	class	Forest - structure stage (rectified)
forht	m	Forest - average dominant height
forcov	%	Forest - canopy cover

layers. The LANDFIRE Prototype effort performed only minor logic checks and data scans for inconsistent or abnormal data values. A more comprehensive QA/QC procedure is currently being implemented for LANDFIRE National.

Performing the Accuracy Assessment

Surface fuel layers—Accuracy assessment of the mapped fire behavior fuel models (FBFM13 and FBFM40) proved problematic in the LANDFIRE Prototype for two reasons: 1) there can be more than one correct FBFM assignment in the field and 2) a lack of sufficient geo-referenced field data where FBFM13 and FBFM40 categories were recorded in the field. The FBFM maps were developed to serve as inputs to the fire behavior prediction software (BEHAVE and FARSITE); however, there are numerous other weather, wind, and fuel moisture variables that influence fire behavior simulations. Consequently, more than one FBFM can lead to the same fire behavior characteristics if other environmental variables are adjusted. Accuracy can only be truly tested during specific wildland fires because the primary purpose of the FBFM is to predict fire behavior, not describe fuel characteristics. In such cases, the expected fire behavior can be compared to the observed behavior and the accuracy assessed for that specific situation. The lack of comprehensive field-referenced data prevented a conventional accuracy assessment of all the surface fuel layers. The FBFM40 data were new and therefore hadn't yet been used by field personnel.

The surface fire behavior fuel models (FBFMs), fuel loading models (FLMs), and default FCCS fuelbeds were mapped based on rule sets that were used to link FCCs to unique combinations of PVT, CT, and SS. To test the accuracy of the rule sets, we assigned surface fuel attributes to the PVT-CT-SS combinations for each plot in the LFRDB using the map rule sets. We then compared the assigned surface fuel attribute value of the plot to the corresponding pixel location for that plot on the fuel model maps. We assumed the plot assignment was correct and determined our accuracy based on this surface fuel attribute value.

Canopy fuel layers—We randomly withheld a percentage of the total number of training sites from the LFRDB for each mapping zone for independent accuracy assessment of the final maps. For Zone 16, we withheld 20 percent of the total plots, leaving 1,304 plots for modeling CBD and 325 plots for assessing the accuracy of CBD predictions; we had 1,098 for modeling CBH and 275 for assessing the accuracy of CBH predictions (table 9). Regression trees were pruned and modified based on the cross-validation accuracy assessment.

After analyzing error distribution for Zone 16, we determined for Zone 19 that a subset of only 10 percent of the total plots would be sufficient for assessing accuracy, and the consequent increase in the number of plots used for modeling improved the performance of the model. This resulted in 1,768 plots for modeling CBD, 184 plots for testing CBD predictions, 674 plots for modeling CBH, and 198 for testing CBH predictions (table 9). The data distributions of the model data sets for CBD and CBH (zones 16 and 19) are shown in figure 1. The test data sets had identical distributions.

Table 9—Number of plots used for modeling and accuracy assessment. Error estimates for canopy bulk density (CBD) are in kg m^{-3} and for canopy base height (CBH) in meters.

Zone	Model	Model plots	Test plots	Average error	Relative error	Correlation coefficient
Z16	CBD	1304	325	0.03	0.55	0.76
	CBH	1098	275	1.9	0.65	0.63
Z19	CBD	1768	184	0.05	0.72	0.66
	CBH	1674	198	1.9	0.91	0.38

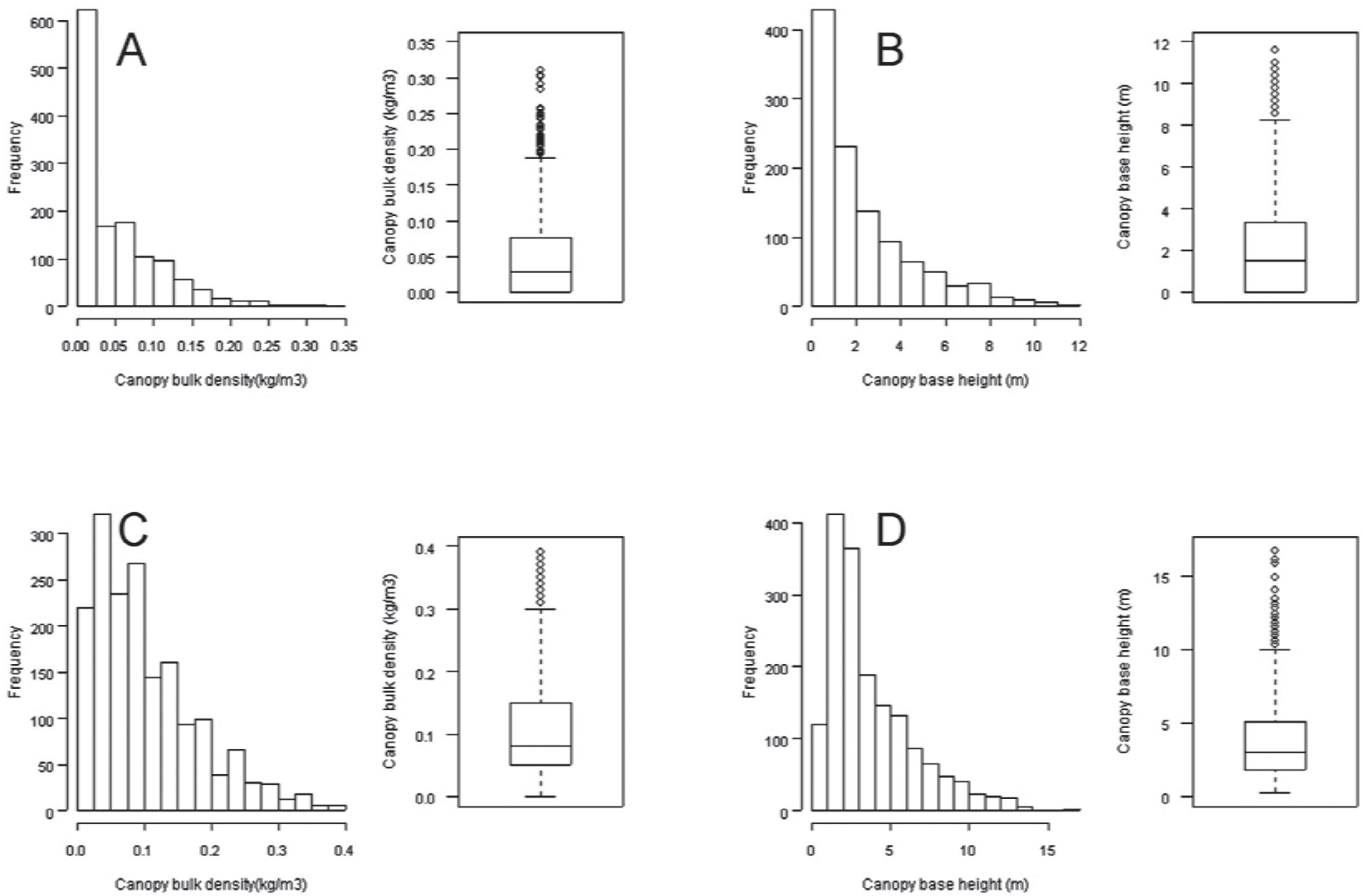


Figure 1—Distribution of plots (frequency) across canopy bulk density (CBD) and canopy base height (CBH) values across the two prototype zones. They are arranged in the following order a) CBD model data set for Zone 16, b) CBH model data set for Zone 16, c) CBD model data set for Zone 19, and d) CBH model data set for Zone 19. The test data sets for CBD and CBH used to validate and assess accuracy of the statistical models had identical distributions for both zones.

Cubist automatically tests the model predictions at each test site and outputs three measures of error: an average error, a relative error, and a correlation coefficient. The average error represents the magnitude of the errors defined by the predicted value compared to the actual value. The relative error is the ratio of the average error to the error that would result from always predicting the mean value. The correlation coefficient measures the agreement between the predicted values and the actual values. Cubist also outputs a scatter plot of the predicted values against the actual values. This is used for visual evaluation of the regression models (Rulequest Research 2004).

Results

Surface Fuel

The FBFM40 and FLM classifications were not completed in time for the mapping of surface fuel models for Zone 16, so only maps of FBFM13 and default FCCs are presented in figure 2. These classifications were completed prior to the mapping of Zone 19, but, unfortunately, the FCCS fuelbeds for this region were unavailable. Therefore, only three surface fuel maps are shown in figure 3 for Zone 19. A summary of the area in each mapping zone by the four fuel classifications is shown in table 10.

Canopy Fuel

Mapping Zone 16—The maps of CBD and CBH for Zone 16 are shown in figure 4. We selected a Cubist model built using a composite model as the best model for predicting CBD across the zone. This model was produced by combining a rule-based model with an instance-based model and adjusting the results based on the seven nearest (most similar) neighbors. Five committee models were built to improve the predictive ability of the model. We set the minimum rule cover at one percent, under the premise that that the conditions associated with any rule should be satisfied by at least one percent of the training cases, and we allowed a ten percent extrapolation of values across the total range of values. Main predictor layers are shown in table 8.

A comparison of the predicted values with our independent test set for Zone 16 revealed an average error of 0.026 kg m^{-3}, a relative error of 0.55 kg m^{-3}, and a correlation coefficient of 0.76 (table 9). The scatter plot is displayed in figure 5a. For CBH, the model selected as having the best predictive power was also built using a composite model. This model was produced by a rule-based model adjusted by six nearest neighbors and four committee models. According to our accuracy measures, the average error was 0.39 m, the relative error was 0.65 m, and the correlation coefficient was 0.63 (table 9). The corresponding scatter plot is shown in figure 5b.

The CBD model included imagery variables that are typical for distinguishing vegetative characteristics (Campbell 1987), biophysical gradients that explain vegetation-water interactions, and topographic gradients explaining the local variation across the zone. The CBH model included transformed imagery variables (offtc1, onb3, and onb5 in table 4), water-related biophysical gradients (aet, pet, ppt, and psi in table 5), and elevation (table 7). The inclusion of transformed imagery variables in the CBH model suggests that there are no direct relationships between CBH and any one band signature. The inclusion of spectral and biophysical gradients as relevant predictors in the models indicates a strong correlation between canopy fuel characteristics and both vegetation and ecological site characteristics.

Mapping Zone 19—The maps of CBD and CBH for Zone 19 are shown in figure 6. For CBD, we created ten committee models, set the minimum rule cover to four percent of the training cases, and allowed ten percent extrapolation. For CBH, we created seven committee models, set a four percent minimum rule, and allowed extrapolation of ten percent.

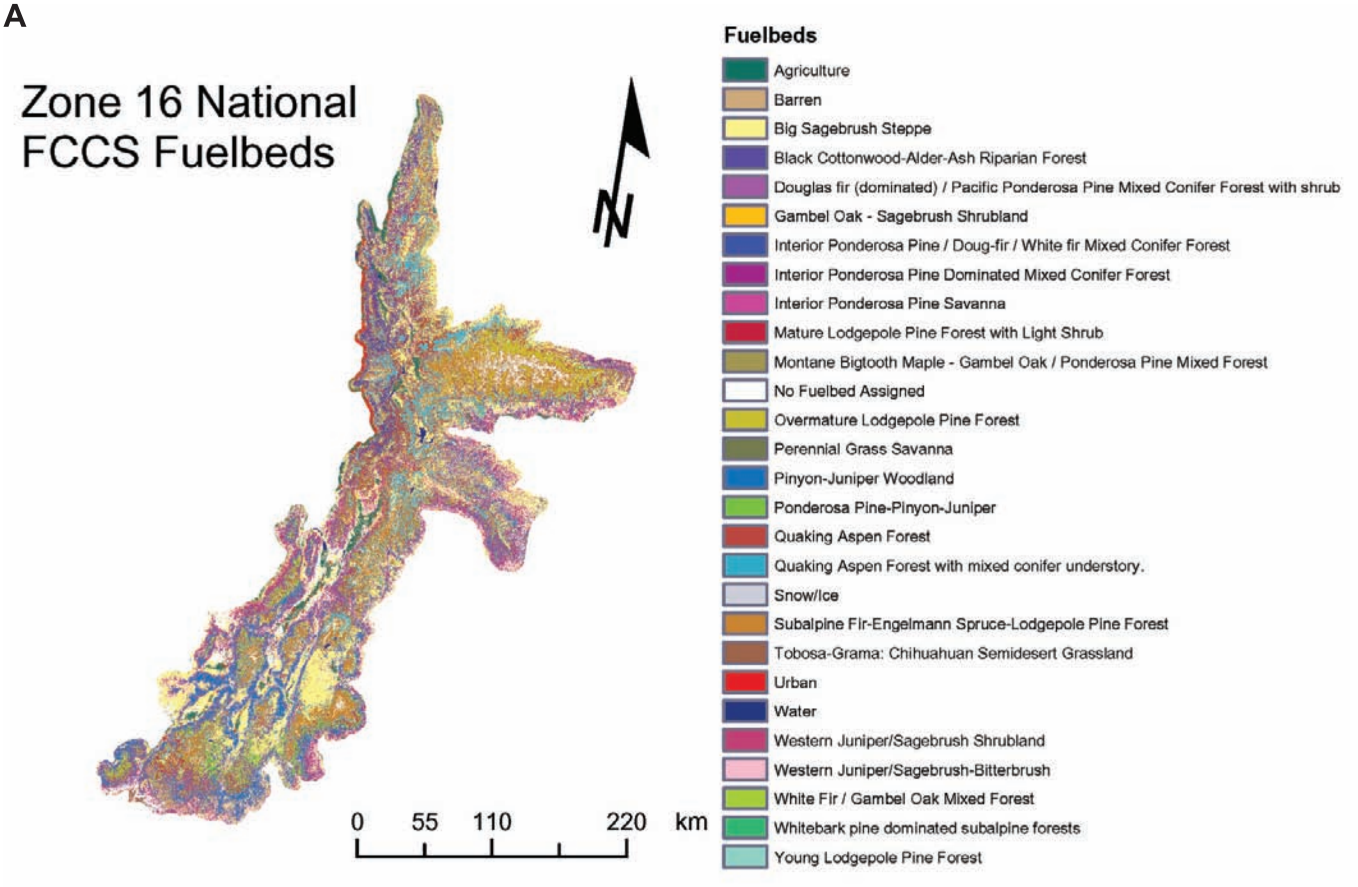
The accuracy assessment for the CBD model revealed a 0.05 kg m^{-3} average error, a 0.72 kg m^{-3} relative error, and a correlation coefficient of 0.66. For CBH, the errors were quite low, with an average error of 1.9 m, a relative error of 0.91 m, and a correlation coefficient of 0.38 (table 9). The relative error of 0.91 suggests that the model for predicting CBH in Zone 19 did not achieve accuracy any higher than the pure mapping of a mean CBH across the zone. The scatter plot of predicted versus real values, shown in figures 5c and 5d, demonstrates that the model over-predicted low values of CBH and under-predicted high values of CBH.

The set of variables that were important for CBD and CBH discrimination showed patterns similar to those in Zone 16. Imagery variables of onb3, onb5, and offtc1 (table 6) were the prominent variables that defined the splits for the canopy bulk density model; followed by biophysical gradients of pet, ppt, dsr, tmin, rh, elev, and posidx (table 7); and modeled variables of evtr and forht. For Zone 19 CBH, the imagery transformations of offtc1 and offtc2 were prominent again,; with gradients of dday, ppt, evap, srad_fg, dsr, elev, and slp; and modeled variables of evtr and forth (table 7).

Table 10—A summary of the area (km^2) within Zone 16 and Zone 19 occupied by the ten most frequent fuel models from each of the four fuel model classifications stratified by potential vegetation type (PVT). The acronyms are defined as follows: FBFM13 = Anderson (1982) 13 standard fire behavior fuel models; FBFM40 = Scott and Burgan (2005) 40 fire behavior fuel models; Default FCCs = default fuel characterization classes (Sandberg and others 2001); and FLMs = fuel loading models by Lutes and others (in preparation). Note: default FCCs were not mapped for Zone 19 because of an insufficient number of fuelbeds and FLMs and FBFM40 were not mapped for Zone 16 because the classifications were not finished in time to map fuel models for that zone.

FBFM13		FBFM40		Default FCCs		FLM	
Model	**km^2**	**Model**	**km^2**	**Classes**	**km^2**	**Model**	**km^2**
				Zone 16			
		- - Not Available - -				- - Not Available - -	
6	25,333.79			Big Sagebrush Steppe	9,403.89		
8	15,088.17			Pinyon-Juniper Woodland	7,001.88		
5	12,374.84			Western Juniper/Sagebrush Shrubland	6,731.48		
2	6,047.90			Subalpine Fir-Engelmann Spruce-Lodgepole Pine Forest	5,979.98		
10	4,012.47			No Fuelbed Assigned	5,498.27		
Barren	1,944.02			Quaking Aspen Forest with mixed conifer understory	5,434.58		
Agriculture	1,877.33			Quaking Aspen Forest	3,764.33		
1	1,345.12			Big Sagebrush Steppe	3,433.29		
Urban	923.55			Western Juniper/Sagebrush-Bitterbrush	3,196.28		
9	439.63			Montane Bigtooth Maple - Gambel Oak / Ponderosa Pine Mixed Forest	2,304.40		
Water	348.17			Douglas fir (dominated) / Pacific Ponderosa Pine Mixed Conifer Forest w/ shrub	2,130.99		
3	219.84			White Fir / Gambel Oak Mixed Forest	1,966.02		
Snow/Ice	1.54			Barren	1,944.02		
				Black Cottonwood-Alder-Ash Riparian Forest	1,932.22		
				Agriculture	1,877.33		
				Overmature Lodgepole Pine Forest	1,721.88		
				Ponderosa Pine-Pinyon-Juniper	1,191.20		
				Perennial Grass Savanna	975.75		
				Urban	923.55		
				Gambel Oak - Sagebrush Shrubland	852.86		
				Zone 19			
				- - - - - - - - - - - - Not Available - - - - - - - - - - - -			
8	39,958.60	TL3	36,098.67			1	46,296.11
2	28,087.17	GS2	21,196.08			7	25,019.09
1	13,458.08	SH2	12,136.64			4	10,935.65
5	13,209.15	TU5	7,466.23			No Fuel	10,415.65
Agriculture	7,397.57	NB3	7,397.57			2	9,276.64
6	6,359.86	GR4	7,306.96			8	7,435.80
10	1,884.77	GR2	6,528.90			5	3,622.28
Barren	1,456.84	TL1	2,795.22			6	1,159.58
Water	1,184.94	GR1	2,786.51				
9	787.52	GS1	2,746.44				
Urban	362.41	TU1	2,573.01				
Snow/Ice	13.88	NB9	1,456.84				
		NB8	1,184.94				
		SH7	701.63				
		TL6	670.30				
		NB1	362.41				
		TL9	354.45				
		SH1	277.55				
		TL2	106.46				
		NB2	13.88				

A



B

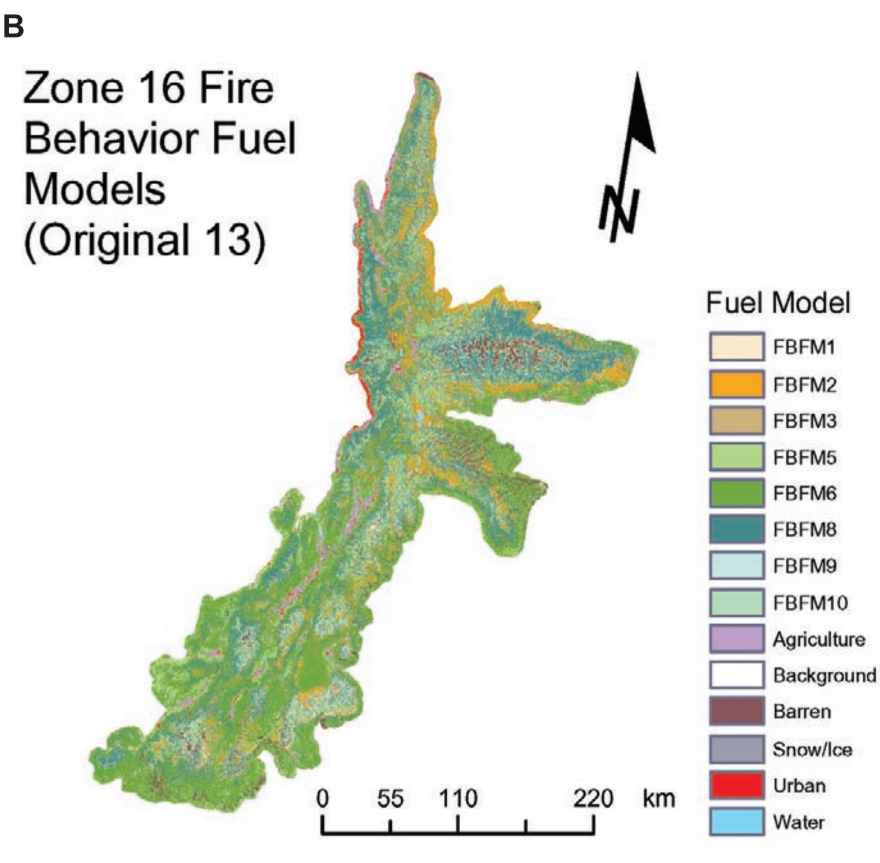


Figure 2—Zone 16 surface fuel maps. Surface fuel model maps for a) the Anderson (1982) 13 standard fire behavior fuel models (FBFM13) and the b) default fuel characterization classes (FCCs). The fuel loading model and 40 fire behavior fuel model classifications were not developed when fuel for Zone 16 was mapped.

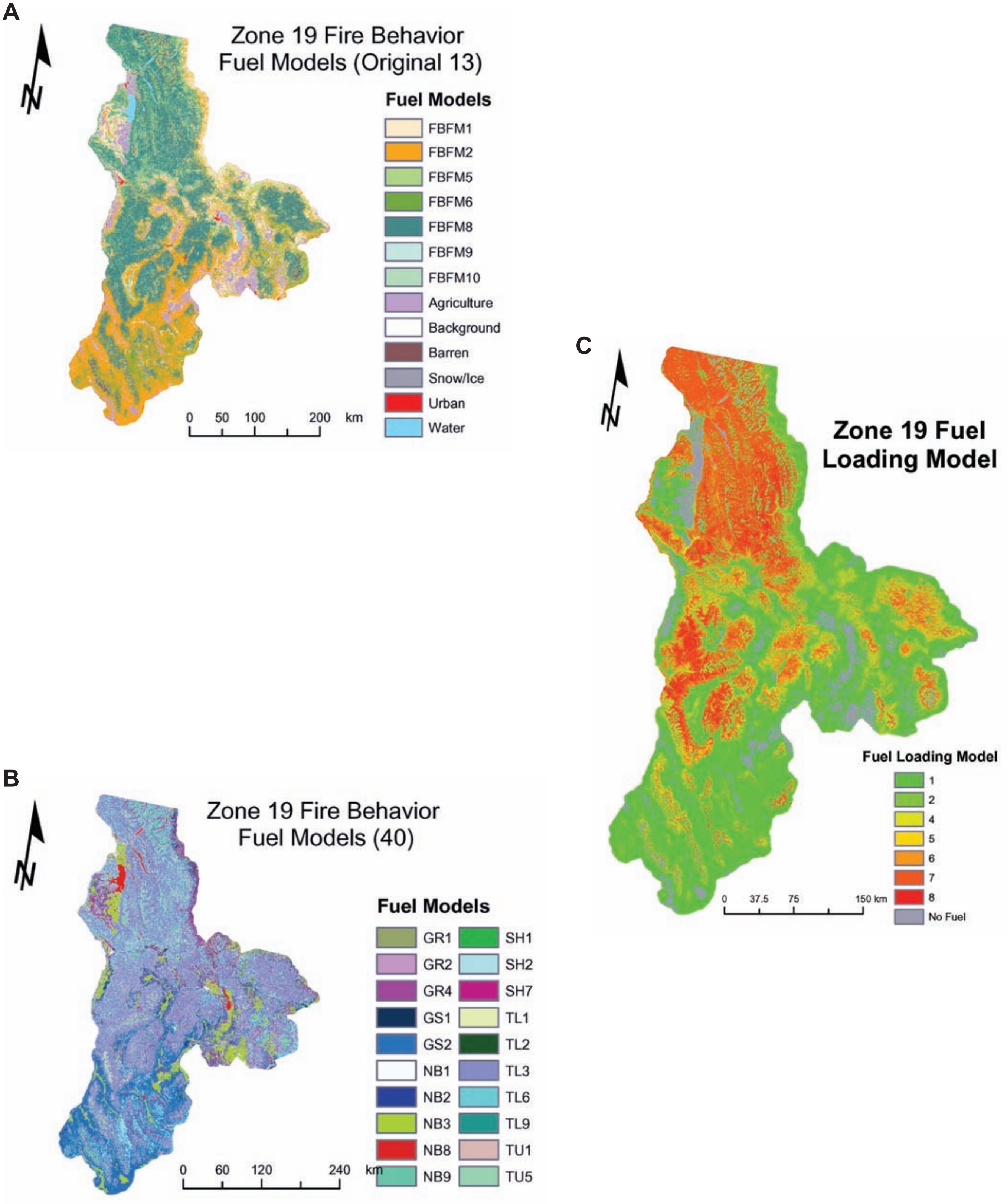


Figure 3—Zone 19 surface fuel maps. Surface fuel model maps for a) the Anderson (1982) 13 standard fire behavior fuel models (FBFM13), b) Scott and Burgan (2005) 40 fire behavior fuel models (FBFM40), and c) the default fuel characterization classes (default FCCs).

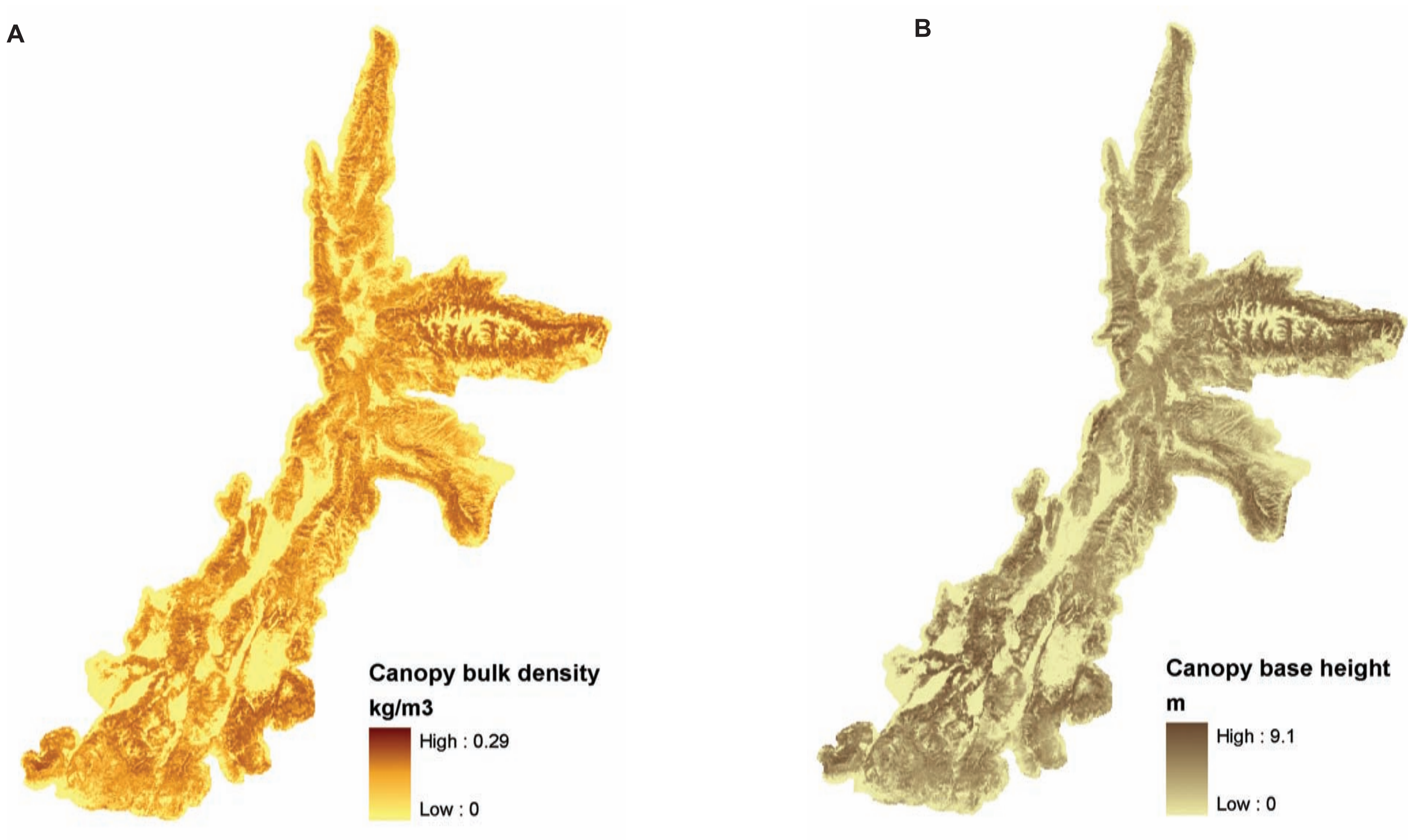


Figure 4—Zone 16 canopy fuel layers. Shown are maps of a) canopy bulk density (CBD) and b) canopy base height (CBH) for Zone 16.

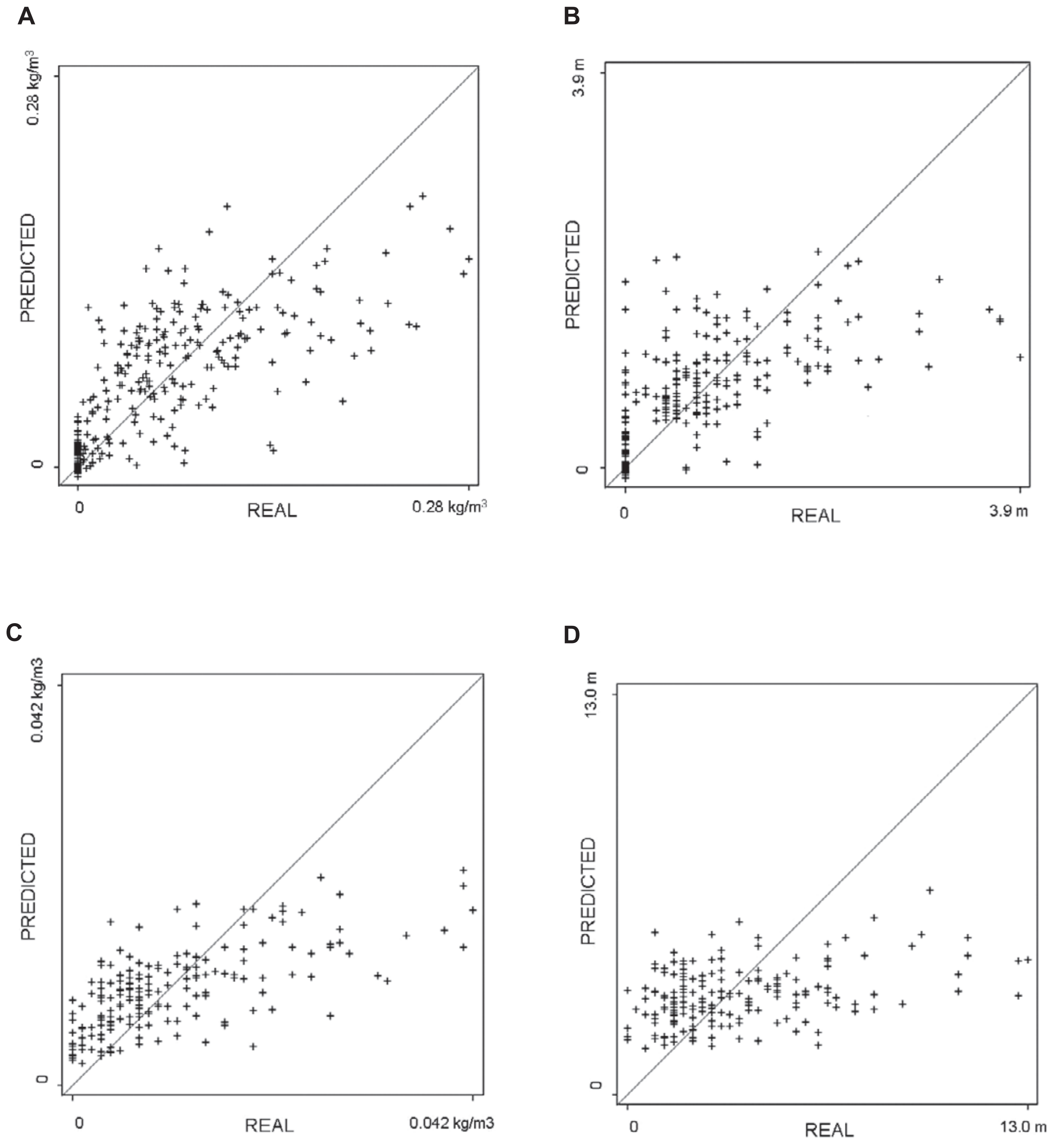


Figure 5—Accuracy assessment of the predicted versus real (observed) values for canopy bulk density (CBD) and canopy base height (CBH) for both mapping zones. The diagonal line indicates full agreement between the model and field data. The scatterplots are: a) Zone 16 canopy bulk density, b) Zone 16 canopy base height, c) Zone 19 canopy bulk density, and d) Zone 19 canopy base height.

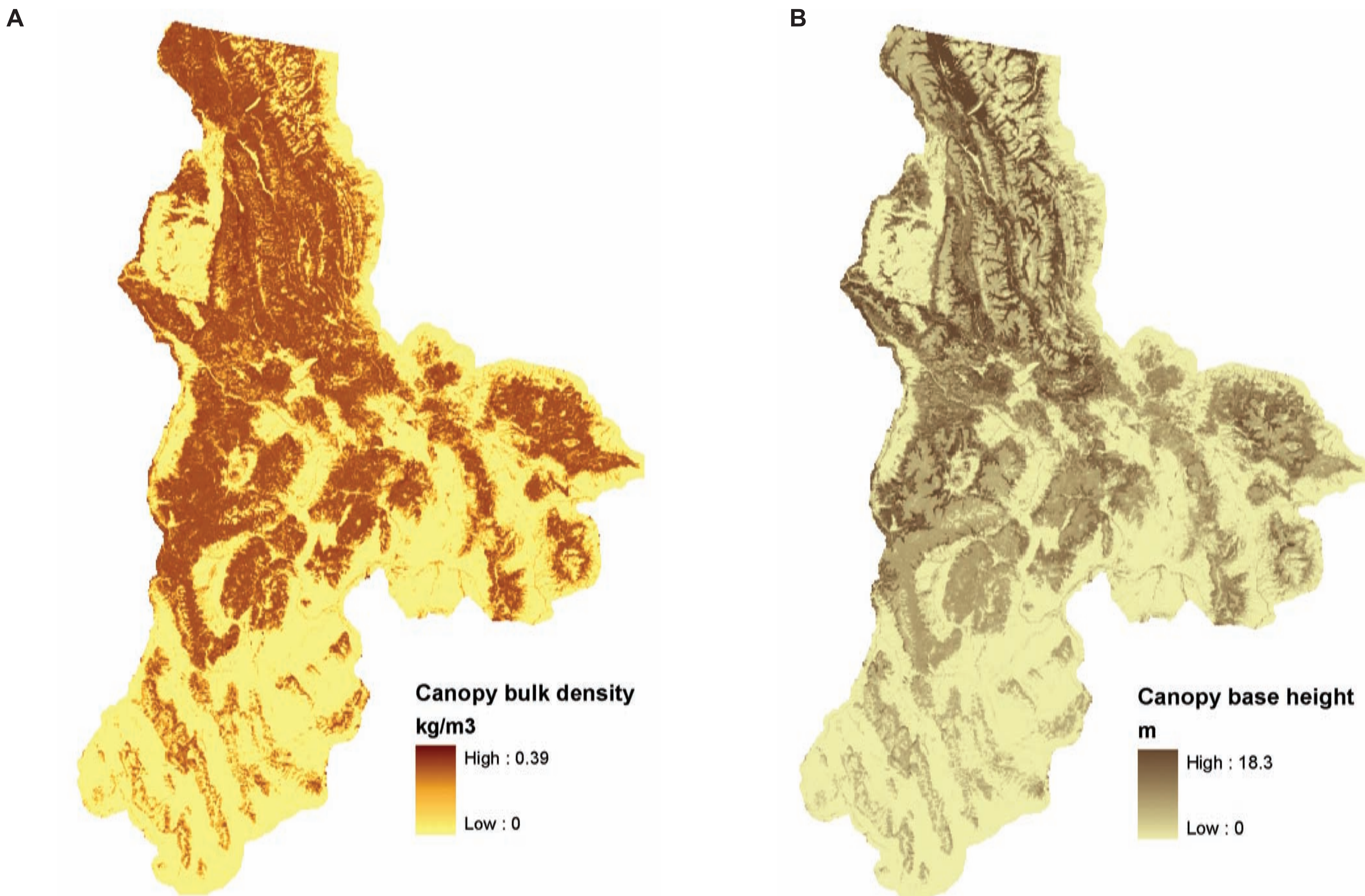


Figure 6—Zone 19 canopy fuel layers. Shown are maps of a) canopy bulk density (CBD) and b) canopy base height (CBH) for Zone 19.

Discussion

Surface Fuel Maps

Rule-based approach to fuel mapping—In the LANDFIRE Prototype, we used the classification or rule-based approach to assign fuel models to combinations of vegetation and biophysical settings. Despite limitations, this approach was the most appropriate given the project guidelines, design criteria, and available data (Keane and Rollins, Ch. 3). The fuel maps described in this chapter are important products of the LANDFIRE Prototype Project because they provide critical inputs to fire behavior and effects models commonly used to explore alternative management strategies for implementation of the National Fire Plan. However, it would have been preferable to use the same gradient-based predictive landscape modeling approaches to surface fuel mapping as those used for the mapping of vegetation and canopy fuel (see Frescino and Rollins, Ch. 7 and Zhu and others, Ch. 8) because:

1) the mapping resolution (30 m pixel) would more closely match the resolution of fuel variability as compared with the mapping resolution of PVT-CT-SS combinations (usually mapped as groups of pixels), and this would eventually result in more accurate fire behavior predictions;
2) the resolution of the fuel model classification categories would more closely match the spatial resolution than the PVT-CT-SS resolution (for example, you could have more than one fuel model within a PVT-CT-SS combination using the gradient approach); and
3) the fuel models would be mapped based on the ecological processes and gradients, such as productivity, species composition, and decomposition, that govern the distribution and condition of wildland fuel across landscapes.

Overall, the lack of consistent and accurate field data on fuel in the LANDFIRE Prototype prevented a statistical modeling strategy for fuel mapping. Therefore, if possible, a comprehensive empirical approach should be employed, as in other LANDFIRE tasks, for fuel mapping in the national implementation of LANDFIRE.

The LANDFIRE Prototype did not deliver all surface fuel map products for a number of reasons. First, the fuel classifications (FBFM40, default FCCs, and FLMs) were not completed in time for the LANDFIRE Prototype mapping effort. For Zone 16, we mapped the default national fuelbeds provided to us by the Fire and Environmental Effects Research Team (FERA) in December of 2003. However, these default FCCs were still in draft format. We found that while the default fuelbed set seemed to apply to a wide variety of vegetation and fuel types throughout Zone 16, over 20 percent of the map area – especially the herbaceous and shrub types – was not well-represented by the default FCCS categories. In addition, we found that the fuelbed list was also missing detailed information for large sections of the country. The default FCCs provided with the FCCS software were developed to represent major fuelbeds of concern to fire managers. Many of these defaults were selected through workshops held throughout the country by fire managers and ecologists who were focusing on the problem fuel types in their respective areas. Less hazardous vegetation and fuel types were not emphasized in the development of the FCCS. However, the LANDFIRE Prototype needed to map all vegetation and fuel conditions found within the mapping zones. We anticipated a new and more comprehensive version of the default FCCs prior to mapping Zone 19 since more than a year had passed since the release of the previous version. Unfortunately, we did not receive the new set in time to map Zone 19. However, during this time we determined through discussions with the FERA team that a better way to create a LANDFIRE fuelbed map would be to modify the default fuelbeds to reflect the vegetation and fuel conditions described in the LFRDB, thereby creating custom LANDFIRE fuelbed classes. These would be more meaningful to the LANDFIRE National Project, and custom development is encouraged by FERA. This approach is currently being evaluated for national LANDFIRE implementation. Lastly, because the FLM classification was not completed in time, it was not extensively tested and validated in the LANDFIRE Prototype effort.

Canopy Fuel Maps

Again, training data were the main limiting factor for the statistical regression tree modeling approached used to map CBH and CBD across both zones. However, this limitation was not as severe as during the surface fuel modeling phase. Low accuracies may also have resulted from the quality of the training data used to build and test the models because regression tree performance depends greatly on the quality of the field data used. We conducted our analysis under the assumption that the data perfectly represented ground conditions; however, the fuel database used to estimate canopy fuel may not have been free of errors. The accuracy of the CBD and CBH calculations is dependent upon the accuracy of the tree measurements on the ground as well as the accuracy of the allometric equations used to derive CBD and CBH. Another assumption was that the positional accuracy of the training data was within spatial tolerances (Vogelmann and others, Ch. 13). In other words, each georeferenced location was assumed to match the corresponding pixel value of each predictor. Another source of error in the fuel database was that the FIA tree data crown dimensions were sampled by visually compacting the crown length to eliminate gaps in the canopy, which subjectively and falsely raises the tree crown base height and results in overestimations of CBH. Lastly, the variable plot sampling used in FIA inventory may tend to oversimplify canopy conditions because not all trees that contribute to canopy fuel are measured in the same area.

Another possible reason for the fuel maps' low accuracies were the scale and resolution difficulties encountered when computing CBD and CBH at the plot level using the FUELCALC program; both values are difficult to assess at a stand or pixel level because they have highly variable distributions in the horizontal and vertical dimensions (Keane and others 2005). The limited information gathered for each tree requires that several assumptions be made in order to compute CBD and CBH at the stand level. For example, the CBH was computed as the lowest layer with greater than 0.037 kg m^{-3} bulk density. This layer's bulk density might have been based on data from only one tree or from a seedling/sapling layer that is well below the overstory canopy. Moreover, the threshold of 0.037 kg m^{-3} is a somewhat arbitrary number suggested by Alexander (1988).

The FUELCALC program served as a critical tool in the calculation of canopy characteristics, but this software presented some major limitations. We used a beta version of the program that contained crown biomass algorithms and crown fuel adjustment factors for only 14 Rocky Mountain conifer species. However, this program was preferable over other biomass calculation software packages, such as BIOPAK (Means and others 1994), because it computes crown biomass by fuel component and integrates the results of an extensive canopy fuel sampling effort into biomass components (Scott and Reinhardt 2002, 2005). More tree species must be included in the software so it can be applied to other ecosystems in the U.S. This program needs to be revised to incorporate a user-friendly interface and an extensive users' manual so that it can be used to compare and contrast LANDFIRE map values at local scales. Lastly, FUELCALC output has not been compared with measured canopy characteristics in many areas of the United States and subsequently refined. This model refinement must be completed to ensure credible canopy fuel estimates are being calculated.

Low accuracies of the CBD and CBH regression tree models posed a major problem in canopy fuel mapping. These low accuracies may indicate that plot-level estimates of canopy fuel are not directly or closely correlated with spectral imagery information and gradients of biophysical and topographic characteristics, resulting primarily from the fact that CBH and CBD are canopy characteristics that are hidden from view. Canopy base height is nearly impossible to detect using passive sensors such as Landsat because it is at the bottom of an obstructing canopy. Only active remote sensing techniques, such as Lidar or Radar, have the ability to detect vertical canopy dimensions (Keane and others 2001). Since the passive sensors do not detect canopy depth, it is difficult to determine which canopy layer has the greatest CBD. This is the main reason our statistical models underestimate both CBD and CBH (figs. 5a and 5c).

The difficulty we experienced predicting canopy fuel characteristics indicates that we may have had an inappropriate or insufficient number of predictor gradients. Satellite imagery is an excellent source for describing vegetation patterns but is limited to dominant overstory features. The modeling of forest structure attributes, particularly that of CBH, requires additional predictors to discriminate patterns. Outputs from the BGC process model (Holsinger and others, Ch. 5), which spatially represents the rates of the hydrologic, carbon, and nitrogen cycles, were not available for the LANDFIRE Prototype and were therefore not included in the models. These ecophysiological gradients have proven to be highly useful in discriminating vegetation characteristics (Keane and others 2001; Rollins and others 2004). It should also be noted that the methods for generating the biophysical gradient layers were still under development during the LANDFIRE Prototype and met with limited success (Holsinger and others, Ch. 5). In the national implementation of LANDFIRE, refined, consistent methods for generating these layers will maximize their utility for all LANDFIRE mapping tasks.

Lastly, we encountered a problem upon combining the surface and canopy fuel layers into the landscape format required by the FARSITE model (Finney 1998). We found many inconsistencies between CBD, CBH, CC, and CH values that should have been detected during the analysis and QA/QC phase. For example, canopy height values were lower than canopy base height values for the same pixel. In addition, many CBD estimates were too low to be useful for FARSITE simulation. These inconsistencies were not errors, but rather resulted from problems with the way canopy characteristics were computed in FUELCALC and the way they were independently mapped using biophysical statistical modeling. A more comprehensive QA/QC procedure for these layers will correct many – but not all – of these inconsistencies. To fix these problems in the LANDFIRE Prototype, we directly assigned CBD and CBH values from the LANDFIRE fuel reference database for each PVT-CT-SS combination.

Recommendations for National Implementation

Above all, we recommend obtaining and/or collecting as many georeferenced field fuel and tree data as possible across the nation to create the six fuel layers for the LANDFIRE National effort. It would be beneficial if these data contained assessments of surface fuel model categories for each plot, but fuel loading data can also be used once the field keys for all fuel model classifications have been developed. These data are critical for all modeling, mapping, accuracy assessment, and parameterization tasks in the LANDFIRE Project (Keane and Rollins, Ch. 3). In addition, the field keys, essential for assessing fuel model categories in the field, must be comprehensive, consistent, and accurate. We highly recommend that simple, easy-to-use field keys be created for all surface fuel model classifications. These keys must be tested and validated before they are released for nationwide use.

We also recommend the implementation of extensive QA/QC procedures that rigorously test the fuel layers to detect any inconsistencies and errors, especially in the context of other LANDFIRE digital maps. This procedure should include all LANDFIRE layers and extensive evaluation based on data contained in the LFRDB. This procedure should be flexible so that it can be adjusted according to the specific vegetation types and fire management strategies of the various mapping zones across different regions of the United States.

In addition, we recommend employing the regression tree-based process described above for creating the canopy fuel layers. The efficiency and nonparametric flexibility make regression trees the optimal model for the national implementation of LANDFIRE. The NLCD mapping tool and Cubist software facilitate the implementation of the trees and offer several features for developing the best model. Moreover, the regression tree model's performance will improve with refined predictor layers and training data, which involves the refinement and integration of the BGC and WXFIRE simulation models.

The LANDFIRE vegetation mapping processes must be integrated so that maps combine logically with regard to vegetation ecology and fuel characteristics. In Zone 16's forested areas, for example, approximately 2.6 percent of the total pixels had a predicted CBH value of greater than or equal to the predicted value of CH (fig. 6). Although this percentage is fairly low, some rectification must occur before these layers are used effectively in programs such as FARSITE. If there is no rectification process for "fixing" these pixels, an alternative method will be necessary.

Furthermore, we strongly recommend that all surface and canopy fuel layers be reviewed by local experts to ensure realistic, accurate mapping products. This includes a review of the LANDFIRE fuel database and the rule set used to assign surface fuel model categories to PVT-CT-SS combinations to identify inconsistencies and errors. In addition, a comprehensive documentation of layer properties in the LANDFIRE metadata record will be critical to a thorough technical review of the fuel layers.

Conclusion

In conclusion, the fuel mapping effort described in this chapter was the last in a series of complex tasks performed in the LANDFIRE Prototype effort. As a result, the time allotted to fuel map development and implementation was much less than that allotted to all other tasks. The resulting fuel map products are only first approximations and do not contain the level of detail and investigation incorporated in the other LANDFIRE Prototype products. The results reported here are therefore not as extensive and conclusive as in most of the other LANDFIRE chapters. We plan to fully investigate and explore the process and products of the fuel mapping effort as LANDFIRE National proceeds.

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

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Appendix 12-A

Vegetation combination assignment rule set for Mapping Zone 16 fire behavior fuel models (FBFMs) (Anderson 1982). See Long and others, Ch. 6 for descriptions of cover types, life forms, and structural stages

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If cover type is an Herbaceous life form, then the primary fire carrier is grass.

If cover type is Wetland Herbaceous, then FBFM 1; else
If Low Height, then FBFM 1

If High Height, then FBFM 3

If cover type is a Shrubland life form and structural stage is a Shrubland type, then the primary fire carrier is grass or shrub.

If cover type is Blackbrush, then FBFM 6

If cover type is Desert Shrub, then FBFM 6

If cover type is Dry Deciduous Shrub and High Cover, Low Height and the

If PVT is a Forest type (except Riparian Hardwood cover types) then FBFM 5

If cover type is Dry Deciduous Shrub and PVT is Riparian Hardwood or a non-forest type,
then FBFM 6

If cover type is Dwarf Sagebrush Complex, then FBFM 6

If cover type is Mtn. Deciduous Shrub where Gambel oak is not the dominant shrub and the structural stage is a Shrubland type, then FBFM 6

If cover type is Mtn. Big Sagebrush, then FBFM 2

If cover type is Montane Evergreen Shrub where mountain mahogany is the dominant shrub and is High Cover, High Height, then FBFM 6 else Montane Evergreen Shrub is FBFM 5.

If cover type is Rabbitbrush, then FBFM 6

If cover type is Riparian Shrub, then FBFM 6

If cover type is Salt Desert Shrub, then FBFM 6

If cover type is Wyoming – Basin Big Sagebrush Complex and Low Cover, then FBFM 5

If cover type is Wyoming – Basin Big Sagebrush Complex and High Cover, then FBFM 6

If cover type is a Woodland life form or structural stage is a Woodland type, then the primary fire carrier is grass, shrub, or timber litter.

If cover type is Pinyon – Juniper or Juniper and Low Height, then FBFM 6

Appendix 12-A — (Continued)

If cover type is Pinyon – Juniper or Juniper and High Cover, High Height, then FBFM 8

If cover type is Pinyon – Juniper or Juniper and Low Cover, High Height, then FBFM 2

If cover type is Mtn. Deciduous Shrub where Gambel oak is the dominant shrub and Low Height, then FBFM 6

If cover type is Mtn. Deciduous Shrub where Gambel oak is the dominant shrub and High Height, then FBFM 4

If cover type is a Forest life form, then primary fire carrier is grass, shrub, or timber litter.

If any Forest type and Low Cover, High Height, then FBFM 2

If conifer and Low Cover, Low Height, then FBFM 2

If hardwood and Low Cover, Low Height, then check early growth form.

If bushy or sprouter, then FBFM 6
If single stem, then FBFM 2

If long needle conifer and High Cover, High Height and PVT is moderate/dry, then FBFM 9; (optional) If moist PVT, then FBFM 10

If short needle conifer and High Cover, High Height and PVT is moderate/dry, then FBFM 8; (optional) If moist PVT, then FBFM 10

If hardwood and High Cover, High Height, then FBFM 8

If cover type is Grand Fir or Spruce – Fir and High Cover, Low Height and PVT is moist, then FBFM 8

If cover type is Ponderosa Pine, Lodgepole Pine, Douglas-fir, or Timberline Pine and High Cover, Low Height, then FBFM 6

If hardwood and High Cover, Low Height, then check young growth form.

If bushy or sprouter, then FBFM 6
If single stem, then FBFM 8

Assuming non-drought conditions, we adjusted the rules above after the look-up-table was created based on the logic for modeling fire at the low fuel loading levels found in the Utah Forest Vegetation Simulator – Fire Fuels Extension (FVS-FFE) variant in Reinhardt and Crookston (2003). For example, we adjusted some of the juniper cover types from FBFM 6 to FBFM 5. For mixed-conifer cover types (such as Douglas-fir and Grand Fir – White Fir) we assumed that Low Height meant a stand density >1000 stems/acre.

A moist forest PVT was considered a subalpine forest type and included all Spruce – Fir and Lodgepole Pine PVTs. A moderate/dry forest PVT was considered a montane forest type and included all Grand Fir, Douglas-fir, Timberline Pine, and Ponderosa Pine PVTs.