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Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling

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Abstract. Fuel maps are essential for computing spatial fire hazard and risk and simulating fire growth and intensity across a landscape. However, fuel mapping is an extremely difficult and complex process requiring expertise in remotely sensed image classification, fire behavior, fuels modeling, ecology, and geographical information systems (GIS). This paper first presents the challenges of mapping fuels: canopy concealment, fuelbed complexity, fuel type diversity, fuel variability, and fuel model generalization. Then, four approaches to mapping fuels are discussed with examples provided from the literature: (1) field reconnaissance; (2) direct mapping methods; (3) indirect mapping methods; and (4) gradient modeling. A fuel mapping method is proposed that uses current remote sensing and image processing technology. Future fuel mapping needs are also discussed which include better field data and fuel models, accurate GIS reference layers, improved satellite imagery, and comprehensive ecosystem models.

Keywords: Fuel mapping, fire simulation, remote sensing, fuel modeling, gradient modeling

Introduction

Wildland fuels are critical elements in many wildland fire planning and management activities. Fuels represent the organic matter available for fire ignition and combustion, and they represent the one factor relating to fire that humans can control (Rothermel 1972; Albini 1976; Salas and Chuvieco 1994). Fire managers need to spatially describe fuel characteristics across many spatial scales to aid in fire management decision-making (Mutch *et al.* 1993; Covington *et al*. 1994; Ferry *et al.* 1995; Leenhouts 1998). Effective fire suppression during the last 60–70 years has increased surface and crown fuel loadings in many forests and woodlands settings, and such high accumulations could foster large, intense, and severe wildland fires that were historically rare (Ferry *et al.* 1995; Mutch 1995). These fires could result in the loss of human life or property as people continue to settle in wildland settings. Never before have so many people been threatened by the adverse consequences of severe fires in the western United States. Accurate, spatially explicit fuels data have become increasingly important as land management agencies embrace prescribed fire as a viable treatment alternative to reduce the potential for severe fires over large land areas. A spatial description of fuels is fundamental to assessing fire hazard and risk across a landscape so management projects can be prioritized and designed (Chuvieco and Congalton 1989; Hawkes *et al.* 1995). Despite these growing risks, many natural resource agencies do not have adequate maps of fuels to manage wildland fire. Most do not even collect fuels information during field inventories.

Fuels are defined as the physical characteristics, such as loading (weight per unit area), size (particle diameter), and bulk density (weight per unit volume), of the live and dead biomass that contribute to the spread, intensity, and severity of wildland fire (Anderson 1982; Burgan and Rothermel 1984) (Table 1). Surface fuels are the dead organic matter deposited on the ground from surrounding vegetation, or they are the live vegetation, such as trees, shrubs and grass, growing very close to the ground (Brown and See 1981). Crown fuels are aerial live and dead biomass suspended within vegetation canopies (van Wagner 1977; Rothermel

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Table 1. Categories of fuel types that can comprise a fuel model

Fuel type	Size (particle diameter)	Description
Crown fuels		
Crown foliage	Any	Living and dead crown foliage including needles and leaves
Crown branchwood	0–3 cm	Live and dead crown branchwood
Arboreal lichens and mosses	Any	Epiphytic mosses and lichens hanging from live and dead branches and foliage
Surface fuels		
Shrub, live	Any	Live shrub fuels including trees, shrubs
Shrub, dead	Any	Dead shrubby material suspended above ground
Herb, live	Any	Live herbaceous plants including grasses, sedges, forbs, ferns, and lichen
Herb, dead	Any	Dead herbaceous plant parts suspended above ground
Litter	< 1 cm	Recently cast needles, leaves, cones, bark, buds, etc.
Duff	None	Partially decomposed litter
Downed dead woody	0–1 cm	1 h timelag woody twigs and branches
	1–3 cm	10 h timelag woody twigs and branches
	3–8 cm	100 h timelag woody branches
	8–23 cm	1000 h timelag branches and logs
	23–50 cm	10000 h timelag logs; coarse woody debris
	50+ cm	10000+ h timelag logs; coarse woody debris

1991). Downed dead woody surface fuels are separated into diameter size classes defined by their rate of drying (Fosberg 1970) (Table 1). Remaining dead organic matter on the ground is classified into litter and duff depending on the degree of decomposition. Duff fuels generally do not contribute to the propagation of the flaming front, but duff can smolder for long periods, thereby heating soil to temperatures that are lethal to soil biota (Hungerford *et al.* 1991). Live fuel moisture contents typically exceed dead fuel moisture contents because living plants extract moisture from the soil for photosynthesis and growth, thereby maintaining high plant moistures, except during extended drought.

Because it is difficult to describe all physical characteristics for all fuels in an area, a generalized description of fuel properties, called a **fuel model**, is often created. A fuel model is a set of average fuel characteristics—usually loading and surface area-to-volume ratios for fire behavior fuel models—for selected fuel types, depending on the application of the fuel model. The most commonly used fuel models were constructed for fire behavior prediction (the 13 standard fire behavior fuel models of Anderson 1982) and fire danger rating (the 20 National Fire Danger Rating System (NFDRS) models of Deeming *et al.* 1978). These fuel models are limited to the *prediction* of fire behavior because they do not quantify fuel characteristics needed for other applications such as fire effects calculations. Large logs, duff, and crown fuels, for example, are missing from most fire behavior fuel models. Fuel models useful for ecosystem description and fire effects prediction could be obtained from fuel photo series, a photographic depiction of fuels for typical forest types for many parts of the western United States (e.g. Fischer 1981), but these photo series lack vital information needed for crown fire simulation (van Wagner 1993). Hardy *et al.* (2001) created a fuel model database where many fuel characteristics are assigned to cover type and stand structure categories. Sandberg *et al.* (2001) describe new advances in fuel description and modeling that will be useful for the entire gamut of fire management concerns from fire behavior prediction to fire effects simulation to ecosystem simulation modeling.

Fuel maps are essential to fire management at many spatial and temporal scales (Table 2). Coarse scale fuel maps are integral to global, national, and regional fire danger assessment to more effectively plan, allocate, and mobilize suppression resources at weekly, monthly and yearly evaluation intervals (Werth *et al.* 1985; Chuvieco and Martin 1994; Simard 1996; Burgan *et al.* 1998; Klaver *et al.* 1998; de Vasconcelos *et al.* 1998). Broad area fuel maps are also useful as inputs for simulating regional carbon dynamics, smoke scenarios, and biogeochemical cycles (Running *et al.* 1989; Kasischke *et al.* 1998; Leenhouts 1998; Lenihan *et al.* 1998). Mid-scale or regional-level digital fuel maps are important in (1) rating ecosystem health; (2) locating and rating fuel treatments; (3) evaluating fire hazard and risk for land management planning; and (4) aiding in environmental assessments and fire danger programs (Pala and Taylor 1989; Ottmar *et al.* 1994; Salas and Chuvieco 1994; Wilson *et al.* 1994; Hawkes *et al.* 1995; Cohen *et al.* 1996; Sapsis *et al.* 1996; Chuvieco *et al.* 1997). Fine scale or landscape-level fuel maps are essential for local fire management because they also describe fire potential for planning and prioritizing specific burn projects (Chuvieco and Congalton 1989; Pala *et al.* 1990; Maselli *et al.* 1996). More importantly, such maps can be used as inputs to spatially explicit fire growth

Table 2. Description of fuel map development across three scales
AVHRR, Advanced Very High Resolution Radiometer; AVIRIS, Airborne Visible and Infrared Imaging Spectrometer; MODIS, Moderate-Resolution Imaging Spectroradiometer; MSS; Multispectral Scanner; TM; Thematic Mapper, SPOT, Le Système Pour l'Observation de la Terre; IKONOS, the first commercial high-resolution satellite, and aerial photos

Fuel maps	Spatial scale		
	Coarse	Mid	Fine
Primary application	Fire danger	Fire risk and hazard	Fire growth
Fire uses	Plan and allocate resources	Locate and prioritize treatment areas	Simulate fire behavior, predict fire effects
Other possible uses	Global carbon budgets	Forest health assessment, EIS	Simulate ecosystem and fire dynamics
Most probable mapping approach	Indirect, gradient model	Direct, indirect, gradient model	Field reconnaissance, direct, gradient model
Mapping entities	Land use types	Fuel models	Fuel models, fuel loadings
Possible pixel sizes	500 m–5 km	30–500 m	5–30 m
Imagery	AVHRR, MODIS	MODIS, MSS, TM	TM, SPOT, AVIRIS, IKONOS, aerial photos

models to simulate planned and unplanned fires to more effectively manage or fight them (Stow *et al.* 1993; Hardwick *et al.* 1996; Gouma and Chronopoulou-Sereli 1998; Grupe 1998; Keane *et al.* 1998*b*).

Recent advances in computer software and hardware have enabled development of spatially explicit fire growth models, thereby revolutionizing fire management decision support systems at the landscape level (Sanderlin and Sunderson 1975; Andrews 1989; Richards 1990; Ball and Guertin 1992). These computer models allow managers to better simulate spatial characteristics of fire growth and intensities, enabling improved fire management that could save many lives and homes (Finney 1998). However, these models require detailed, high resolution digital maps of surface and crown fuel characteristics to generate accurate and consistent fire behavior predictions (Pala *et al.* 1990; Finney 1998; Grupe 1998). FARSITE, for example, requires three topographic and five fuels layers to simulate surface and crown fire growth and intensity (Finney 1998). Unfortunately, these fuels layers are quite costly and difficult to build because they require abundant field data and extensive expertise in remote sensing, geographical information systems (GIS), fire and fuel modeling, image processing, and vegetation mapping (Mark *et al.* 1995; Grupe 1998; Keane *et al.* 1998*b*).

This paper summarizes past, present, and future approaches for mapping fuels for fire management at multiple scales. We discuss challenges involved in mapping fuels, review historical fuel mapping approaches, propose current methodologies, and describe technologies and protocols needed in the future to prepare accurate digital fuels maps. This paper does not discuss the mapping of vegetation (e.g. Bobbe *et al.* 2001), of actual fires, or of fire hazard, unless they pertain directly to creating fuels maps.

Fuel mapping methods

Challenges

There are several reasons why mapping fuels from remotely sensed data is inherently difficult and costly. First and most important, many of the remotely sensed data used in mapping, such as aerial photos and satellite images, are unable to detect surface fuels because the ground is often obscured by the forest canopy (Elvidge 1988; Lachowski *et al.* 1995). Overstory plant leaf cover will prevent most remote sensors from capturing the spatial complexity of the surface fuel layer. Obviously, this problem is most prevalent in forested ecosystems and less important in rangelands (Merrill *et al.* 1993; Chladil and Nunez 1995). A companion problem created by the forest canopy is that, even if sensors were able to view the ground as in stands with open crowns, it is often difficult to distinguish between the fuels on the ground and the fuels suspended in the canopy (Keane *et al.* 1994). Even if the canopy were removed, it is doubtful that reflected electromagnetic energy would correlate well with surface fuel characteristics needed for fire management.

Perhaps the most noteworthy fuel property that confounds accurate fuel mapping is the high variability of fuels across time and space (Brown and See 1981; Harmon *et al.* 1986; Agee and Huff 1987). Fuel variability within a stand can often equal the variability of fuels across the landscape (Jeske and Bevins 1979; Brown and Bevins 1986). A single wind event or wet snow incident can instantly double or triple dead, downed fuel loadings and change the entire structure of the fuelbed in the immediate area. Moreover, discarded leaf and twig material are often deposited in uneven or clumped distributions under canopies (Hirabuki 1991). Fuel accumulation and decomposition are scale-dependent processes that depend on the interaction of the existing vegetation, fuel size, bulk density, and disturbance regime with the environment. Two ecosystem characteristics important to fuel dynamics, plant species morphology and decomposition, are often highly correlated with the biophysical setting (Daubenmire 1966; Fogel and Cromack 1977; Harmon *et al.* 1986).

Stand history is perhaps the single most important factor dictating fuel bed characteristics. Brown and Bevins (1986) found few statistically significant differences in fuel loadings between cover types and site types because of vast differences in stand histories across plots in similar environments. Fuel loadings were different because recent underburns might have consumed most woody fuel but left the canopy intact, or historical and current insect, disease, harvesting, and climatic events may have created high fuel loads (Habeck 1976; Brown and See 1981). Olsen (1981) recognized the inverse relationship of fire frequency to fuel loadings. Moreover, trees killed by fire or other disturbances tend to deposit fuels differently than healthy, living trees. Accumulation rates tend to be abrupt with disturbance mortality but more gradual without disturbance (Hirabuki 1991). Tree or plant longevity will also dictate fuel dynamics; short-lived species often deposit fuel faster because of higher mortality levels (Bazzaz 1979; Minore 1979). As a result, fuel characteristics will be quite variable across the resolution of most remotely sensed imagery and any generalized representation of the fuelbed is sure to be difficult to apply to the entire area of a mapped polygon. It is precisely this spatial fuel property that makes collecting field data for accuracy assessments of fuel maps so difficult and enigmatic.

Derivation of the fuel models used to describe fuels is another reason fuel mapping is so demanding. The often-used fuel models of Anderson (1982) are not so much a quantitative description of fuel characteristics, but rather a set of manipulated inputs to compute expected fire behavior. The inherent complexity of the mechanistic fire behavior models of Rothermel (1972) and Albini (1976) make it difficult to predict realistic fire behavior from actual fuel loadings (Burgan and Rothermel 1984; Burgan 1987). As a result, a somewhat complicated procedure must be followed each time a fire manager wishes to create a new fuel model for a local situation. This procedure involves altering measured fuel characteristics to reflect the actual fire behavior that would be observed for the new situation (Burgan and Rothermel 1984). Analysts who have little experience in fire or fuels modeling find it difficult to create new fuel models accurately and consistently (Burgan and Rothermel 1984; Root *et al.* 1985; Hardwick *et al.* 1996). The identification of fuel models in the field is quite subjective because it is based on an individual's perception of fire behavior rather than on actual measurements of fuel loadings. Many people find it difficult to identify fuel models on the ground because it requires 1) knowledge of the fuel characteristics important to fire behavior, 2) expertise in estimating fire behavior in the field, and 3) familiarity with the fire behavior models. Often, veteran fire managers cannot agree on an Anderson (1982) fuel model for one stand because this assessment is more an art than a science (Burgan and Rothermel 1984; Keane *et al.* 1998*b*). Finally, fire behavior fuel models do not quantify *all* dead and live biomass pools at a stand-level, thus they are not useful for other fire applications such as smoke computation and carbon cycling simulation (Keane *et al.* 1998*a*; Leenhouts 1998).

Another difficulty in mapping fuels from remotely sensed imagery concerns the adequate discrimination of the many fuel types that comprise the fuel bed. The fuel complex is composed of many types (live and dead woody and herbaceous) and sizes (1, 10, 100, and 1000 hour) of fuels (see Table 1). Each fuel type is important to at least one, but not all, facets of fire management. Surface fire behavior prediction needs only the litter, 1, 10, and 100 hour woody fuels, whereas smoke prediction would also require quantification of log, duff, and crown fuels (Rothermel 1972; Reinhardt *et al.* 1997). It is often difficult to distinguish between the various fuel types using most remotely sensed imagery products because of the disparity between particle size and image resolution; fine fuels important for fire spread are too small to be detected accurately by imagery and are often hidden by undergrowth vegetation and logs. Also, fine fuels are typically too variable and too small to be mapped using most commercial imagery resolutions (Finney 1998). In addition, it is difficult to detect if the fine fuels are in standing trees or are on the ground.

Fuel types or characteristics (e.g. surface fuel model, crown fuels, stand height) cannot be mapped independently or illogical combinations will inevitably result (Keane *et al.* 1998*a*). All fuel layers must be developed and mapped in parallel so they are spatially congruent and consistent. This means that crown height for a stand must not be taller than the stand height, for example. This is difficult to accomplish using only remotely sensed data because the spectral and spatial resolution of most imagery is not responsive to all fuel categories simultaneously, and most image classification techniques cannot concurrently classify more than one attribute. For example, independent, supervised classifications of the Thematic Mapper (TM) imagery to map cover type and tree crown closure in New Mexico created many conflicting pixels across the two maps, such as rangeland cover types assigned 30% tree canopy cover (Keane *et al.* 2000).

Fuels maps must be developed at fine resolutions to obtain realistic simulations of spatial fire growth and behavior. Coarse spatial resolutions where a single fuel model is assigned to large polygons (i.e. stands) may not produce reliable fire spread predictions because the homogeneous conditions assumed by the single fuel model do not reflect actual fuel variability across the large area (Finney 1998). This is important because most fuel layers are created from vegetation or stand maps with large polygons of similar overstory vegetation conditions. Within-stand variation of fuel characteristics is often lost as fuel maps increase in grain and extent, especially if these maps are created from vegetation-based maps. As a result, intra-stand variation in fire behavior will not be simulated and this may eventually cause inaccurate fire growth calculations. Ironically, maps with small polygon sizes (less than 0.5 ha) are too detailed for use in most land management projects.

Since fuels and vegetation mapping can be expensive and time-consuming, it would be especially cost-effective if fuels data layers were developed so that other maps, applicable to other resource management concerns, were also created at the same time (Keane *et al.* 1998*b*). For example, a vegetation map might have attributes that quantify both hiding cover for wildlife along with the necessary fuels attributes for FARSITE. It would also be extremely efficient if other data layers needed for fire management analyses were developed in conjunction with the fuel layers so the resulting suite of layers form a comprehensive spatial data set for all land management decision support systems. For example, a better description of crown biomass and duff loadings could be used to predict fuel consumption and the amount, timing and direction of smoke from simulated fires (Reinhardt *et al.* 1997). Moreover, fuel field sampling efforts could sample other ecological attributes to increase the scope of the mapping effort.

Many research and management fuel mapping projects are currently in progress or have been completed for the western United States (e.g. Root *et al.* 1985; Grupe 1998; Keane *et al.* 1998*b*, 2000). These projects use diverse methodologies and various remotely sensed products to create the desired fuels layers for their areas of concern (see next section). A distinct disadvantage to this uncoordinated approach is that maps of adjacent areas may be incompatible, or there may be areas missing critical fuel assignments when maps are merged. Wildland fire growth is seldom confined to land ownership boundaries, so it is essential that fuel layers used to predict fire spread in models like FARSITE be seamlessly merged so the entire fire can be modeled without a break in data quality or consistency. However, developing standardized methods for creating fuels layers is difficult because of the diverse number of existing vegetation data layers, the wide variety of remotely sensed data products, and the paucity of field data available in each land management organization. Therefore, it seems imperative to standardize fuel sampling procedures, fuels layer development methods, and fuels classifications so that compatible fuels layers for fire prediction are created.

Approaches

There are four general strategies used to map fuels at multiple scales: (1) field reconnaissance, (2) direct mapping with remote sensing, (3) indirect mapping with remote sensing, and (4) biophysical modeling (Table 3). **Field reconnaissance** involves traversing a landscape on the ground and recording the extent of similar fuel conditions in notebooks or on paper maps. Few remotely sensed products

Table 3. A comparison of fuel mapping approaches listing the top three advantages and disadvantages for each approach

Advantages	Disadvantages
Field reconnaissance	
Mapping actual observations	Costly, time-consuming
Minimal analysis error	Somewhat subjective
Limited number of steps	Bias towards mountainous terrain
Direct remote sensing	
Simple, direct image classification	Canopy obstruction in forests
Limited number of steps in development	Classifying vegetation rather than fuels
Ground reference simple	Difficult to classify all fuel characteristics
Indirect remote sensing	
Many classifications and data available	Errors assigning fuels to vegetation categories
Mapped objects discriminated well by imagery	Polygons too large for accurate fire growth predictions
Robust maps useful for other applications	Vegetation categories too broad or fine
Biophysical modeling	
Scale-independent	Describes potential rather than existing
Provide ecological context to interpret fuels	Requires abundant data, models, analysis
Can simulate fuel changes over time	Complex, difficult to understand

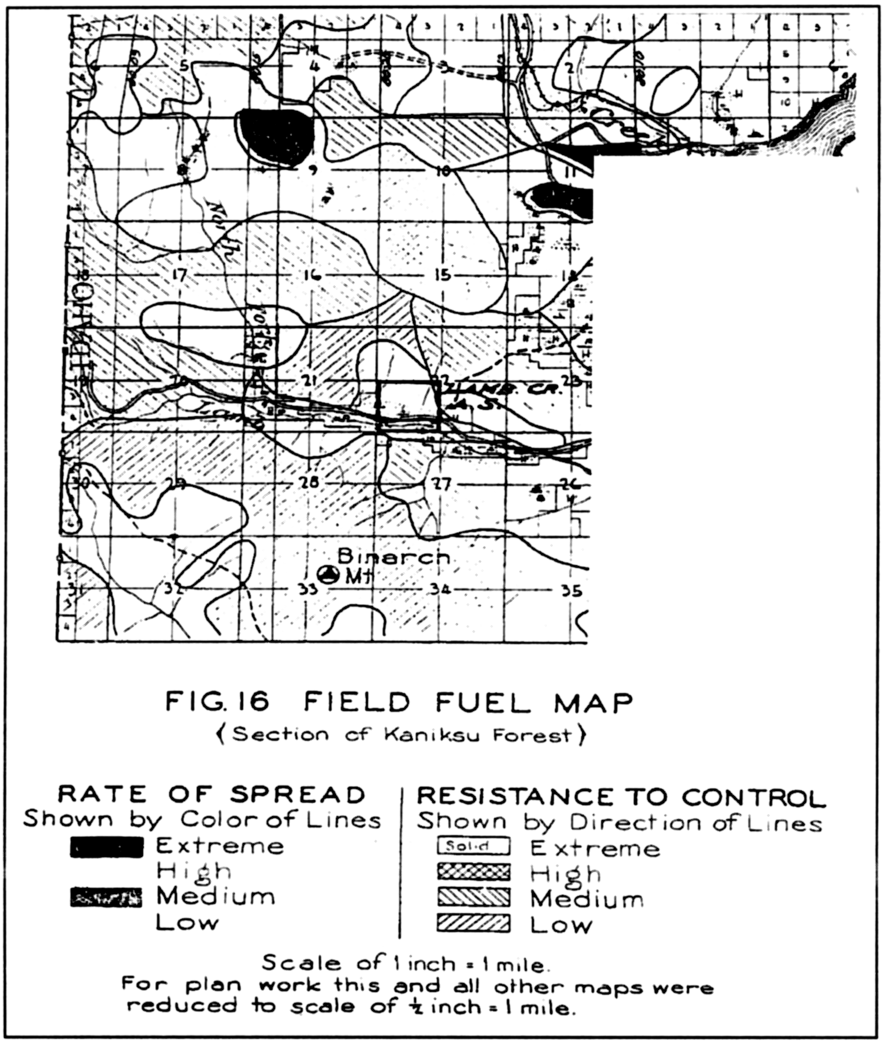

Fig. 1. Example of Hornby's (1935) fuel maps created using the field reconnaissance approach. Note that the fuel models are actually quantifications of fire behavior and risk.

are used in this process except for perhaps aerial photographs for navigation. Remarkably, Hornby (1936) mapped more than 6 million ha in the northern Rocky Mountains using over 90 Civilian Conservation Corps (CCC) workers who walked, rode, or drove through national forest lands and described fuel conditions by coloring polygons on maps with crayons (for example, see Fig. 1). Instead of descriptions of actual fuels loadings, Hornby's (1935) crews mapped two factors that defined what he called a fuel type: (1) resistance to control and (2) rate of fire spread (Fig. 1). Hornby's work stands out because of its enormous scope and human effort. It is, by far, the most comprehensive field reconnaissance mapping venture in the literature. The fuel classification used by Hornby (1936) was ahead of its time because it linked fire behavior with fuel characteristics, but it was useful for only one fire management purpose, suppressing wildfires. We believe that the reconnaissance approach was used by many land management agencies, but it was difficult to find documentation of their methods.

The primary advantage of the reconnaissance strategy is that fuels are mapped from actual conditions observed on the ground (Hornby 1935) (Table 3). Mapping error is limited to erroneous fuel type assessments or improper stand delineations on paper maps. The amount of human effort needed for this type of mapping, however, would probably be impossible today. Hornby (1936) suggested that each person could map about 1000–2000 ha per day at a cost of $US 0.01 per ha. Today it would probably cost 10–40 times as much to map at that intensity. Another drawback is the sampling bias towards mountainous terrain. Most mapping was done from observation points on high, burned-over vistas, so areas not directly seen from these mountain lookouts were probably mapped with less accuracy. Moreover, resultant maps would not be especially useful for other fire management concerns unless other attributes were specifically sampled and mapped. This approach would be more appropriate if it were used to create the field reference datasets (i.e. ground-truth) to validate maps created from remotely sensed data products.

Direct fuel mapping using remote sensing refers to the direct assignment of fuel characteristics to the results of image classification or photo interpretation (Verbyla 1995). This approach has the highest success when estimating total living and dead biomass in grasslands and shrublands (Friedl *et al.* 1994; Millington *et al.* 1994; Chladil and Nunez 1995) but has limited use for assessing surface fuels in forested ecosystems because of the canopy obstruction problem (Elvidge 1988). At a coarse scale, principal components and NDVI calculated from AVHRR (Advanced Very High Resolution Radiometer) imagery composites of the western United States were classified directly to fuel classes that were based on vegetation for input to an Initial Attack Management System (McKinley *et al.* 1985) (Table 2). The three images generated from the tasseled cap transformation on TM multispectral data have been used to classify chaparral shrub fuel characteristics across mid-scale landscapes in California (Cohen 1989; Stow *et al.* 1993). Merrill *et al.* (1993) estimated living grassland biomass in Yellowstone National Park using regression models on bands 4, 6, and 7 from Landsat Multi-Spectral Scanner (MSS) imagery. Crown biomass can be computed from Leaf Area Index (LAI) using the specific leaf area (kg m^{-2}) (Waring and Running 1998) and several studies have had varied success estimating LAI from Landsat TM and MSS imagery (Running *et al.* 1989; Running 1990).

Salas and Chuvieco (1994) classified TM imagery directly to 11 of Anderson's (1982) fuel models, then assigned vegetation categories to each fuel model to compute fire risk on a large landscape in Spain. An Anderson (1982) fuel model map was classified directly from TM imagery of Camp Lejeune, North Carolina, for simulating prescribed fires with FARSITE (Campbell *et al.* 1995). A special kriging technique called isarithmic analysis was used to interpolate sagebrush fuel loadings across a small Colorado landscape from field data (Kalabokidis and Omi 1995). Large-scale aerial photography and aerial sketch mapping have been used successfully to estimate natural and slash fuel distributions in a variety of forested settings in Canada (Morris 1970; Muraro 1970; Dendron Resource Surveys 1981; Belfort 1988).

A Landsat 5 TM image was used to map fuels for Yosemite National Park (van Wagtendonk 1999). NDVI values were computed and classified into 30 unique categories using a clustering routine. A GIS was used to assign an Anderson (1982) fuel model to each category based on existing vegetation, topography, and hydrography data layers using information gained from field surveys. Personal experience, field surveys, and historical plot data were used to verify the final map. In some cases, custom fuel models had to be developed. Another approach used analysis of multi-temporal TM imagery to map fuel conditions (Root and van Wagtendonk 1999). Five spectral bands on six ortho-corrected and registered TM scenes representing approximately 1-month intervals during the growing season are being analysed to identify fuel types based on seasonal changes in plant phenology.

The advantage of the direct approach is its simplicity. By classifying fuels directly from imagery, compounding errors from biomass calculations, translation errors from vegetation classifications, and image processing steps are minimized. The primary disadvantage is that it is difficult to quantify the entire array of fuel characteristics in a way meaningful to fire management in many forested ecosystems. For example, two independent image classifications of surface and crown fuel models would be required for most fire growth applications, and there is a high probability that these two classifications will not be spatially congruent or consistent. Convolved surface and crown spectra are difficult to decouple. Also, it is difficult to train spectral classifications to discriminate between surface and crown fuel types in forests because the sensor cannot see the forest floor (Belward *et al.* 1994). As a result, image classifications often differentiate vegetation characteristics rather than fuel attributes. Another disadvantage is that few fuel classifications integrate all fuel components into one model. Robust fuel models and classifications that will be useful to many mapping efforts are badly needed for comprehensive fuel mapping activities.

Indirect mapping remote sensing approaches recognize the limitations of imagery to directly map fuel characteristics so other, more easily mapped, ecosystem characteristics are used as surrogates for fuels. This approach assumes that biophysical or biological properties can be accurately classified from remotely sensed imagery, and that these attributes, most often related to the vegetation, correlate well with fuel characteristics or fuel models. Although this appears to be the most commonly used approach for mapping fuels, its applicability and success are highly scale- and ecosystem-dependent. Coarse scale imagery such as AVHRR are often used to discriminate broad vegetation types or land cover classes, and these classes correlate well with fuels because vegetation categories are so broad that they generally have unique fuel characteristics (Table 2). Burgan *et al.* (1998) used Omernik's (1987) ecoregions and the Loveland *et al.* (1991) AVHRR land cover classification to develop an NFDRS fuel model map of the conterminous United States. An NFDRS fuel map of California and surrounding areas was developed from vegetation types from the North American Land Characteristics database (Loveland *et al.* 1993), the Omernik (1987) ecoregion map, and many field plots (Klaver *et al.* 1998). A knowledge-based system of neural networks was used to search for unique fuel patterns on a large landscape in Portugal from land-use, vegetation, satellite imagery, and elevation information (de Vasconcelos *et al.* 1998). Landsat imagery was used to map vegetation on 100 million ha in Alaska, and then fuel models, developed by Mallot (1984), were assigned to each vegetation category (Willis 1985). Ottmar *et al.* (1994) assigned a wide variety of fuels characteristics to combinations of vegetation cover and structure types for the Interior Columbia Basin Ecosystem Management Project (Quigley *et al.* 1996).

Many variations of this indirect approach have been used for mid to fine scale fuel mapping projects. Jain *et al.* (1996) intensively sampled fuels for all categories of a forest type map created from Linear Image Self Scanning (LISS II) imagery to create a fuel map for Rajaji National Park in India. Dead and live carbon pools were assigned to TM-classified vegetation types on a 1.2 million ha landscape in the Oregon Cascades as inputs to forest ecosystem models (Cohen *et al.* 1996). Fire fuel model maps of the North Cascades National Park were developed by Root *et al.* (1985) from plant community maps created from 1979 Landsat MSS imagery and environmental relationships. They assigned both the NFDRS (Deeming *et al.* 1978) and the Anderson (1982) fuel models to each classified vegetation type. Miller and Johnston (1985) used a similar approach where they assigned NFDRS fuel models to vegetation maps created from classifications of MSS and AVHRR imagery. Mark *et al.* (1995) assigned Anderson (1982) fuel models to combinations of timber size class, stocking level, crown density, crown texture, and vegetation type categories assessed from aerial photography in their timber stand atlas. In Canada, Canadian Forest Fire Behaviour Prediction System (FBP, Forestry Canada Fire Danger Group 1992) fuel types were assigned to vegetation categories on maps created from Landsat MSS data for Wood Buffalo National Park (Wilson *et al.* 1994), Quebec (Kourtz 1977), and Manitoba (Dixon *et al.* 1985). Hawkes *et al.* (1995) used a rigorous expert systems approach to assign FBP fuel types to combinations of stand structure and composition information obtained from forest surveys. AVIRIS (Airborne Visible and Infrared Imaging Spectrometer) imagery coupled with spectral mixture analysis was used to classify vegetation fraction, cover, and water content in California, which were then related to fuel loadings directly sampled on the ground (Roberts *et al.* 1998). Yool *et al.* (1985) used MSS imagery to describe brushy fuels in southern California, while Hardwick *et al.* (1996) assigned Anderson (1982) fuel models to vegetation categories from the TM-derived CALVEG vegetation map to create a fuel map for the Lassen National Forest.

The indirect approach is often used for many reasons. First, there are many vegetation classifications available to name spectral clusters or describe training areas (Anderson *et al.* 1998; Grossman *et al.* 1998), and most people can consistently identify vegetation types in the field with little trouble (Eyre 1980). Moreover, there are many existing vegetation maps and field data sets that can be used to augment fuel mapping. Most satellite imagery and other remotely sensed products are better suited for differentiating between vegetation types than fuel types. Vegetation maps created from this approach can be used for other land management applications. For instance, ecological attributes, such as forage value, can also be assigned to vegetation or land use categories to create other useful maps. For example, an effort in the Interior Columbia Basin Ecosystem Management Project assigned wildlife habitat levels to the coarse scale cover type map to estimate historical to current declines in habitat value (Quigley *et al.* 1996). Next, fuels maps can easily be updated as additional field data are collected or as new vegetation maps are produced. Finally, vegetation maps often provide a context for interpreting fuel distributions across a landscape. For example, it is helpful to know that a polygon was assigned a fuel model 9 (needle litter) because it was a ponderosa pine stand.

The major disadvantage of the indirect approach is that fuels are not always correlated with vegetation characteristics or land-use categories. As mentioned, stand history, biophysical setting, and vegetation structure are also significant factors governing fuel characteristics, so they should be incorporated into the fuel model assignment protocols. Keane *et al.* (1998*b*, 2000) found that polygons with identical composition, structure, and site conditions could have as many as four different fuel models. Another disadvantage is that vegetation layers are often composed of stands or polygons that may be too coarse for fine scale fire spread simulation. Homogenization of the fine scale fuel mosaic may result in smoothed fire spread predictions that may not be realistic (Finney 1998). Furthermore, vegetation classification categories may be too broad to represent unique fuel characteristics accurately. Keane *et al.* (2000) sampled at least 3, and up to 10, different Anderson (1982) fuel models for 30% of identical vegetation classification categories while mapping fuels on the Gila National Forest in New Mexico, USA.

The last approach uses **environmental gradients** and **biophysical modeling** to create fuel maps. Environmental gradients are those biogeochemical phenomena, such as climate, topography, and disturbance, that directly influence vegetation and fuel dynamics, and biophysical modeling is using mechanistic ecosystem dynamics models to quantify those gradients across a landscape. Relationships between biophysical processes and organic matter accumulation and decomposition can be used to predict fuel characteristics (Gosz 1992; Muller 1998; Ohmann and Spies 1998). Gradients can be topographical (e.g. elevation, aspect, slope), biological (e.g. successional stages), geological (e.g. soils, landform), or biogeochemical (i.e. evapotranspiration, productivity, nutrient availability). Kessell (1976, 1979) used seven gradients based on topography and vegetation to predict fuel models and loadings in Glacier National Park, Montana. Habeck (1976) sampled fuels and vegetation in the Selway–Bitterroot Wilderness Area of Idaho and related fuel loadings to stand age and moisture–temperature gradients. Potential and existing vegetation were mapped from topographic, soils, and climate layers (Davis and Goetz 1990; Twery *et al.* 1991; Brzeziecki *et al.* 1993). Keane *et al.* (1997, 2000) developed a protocol for mapping fuels from several biogeochemical and biophysical variables using an extensive network of field plots. Kessell and Catellino (1978) used a form of gradient modeling to predict chaparral fuels in California. Ohmann and Spies (1998) included simulated temperature and precipitation layers in predicting plant species in Oregon forests.

The value of this approach is that gradients provide an ecological context in which to understand, explore, and predict fuel dynamics. Low fuel loadings in a stand, for example, may be explained by low precipitation, high evapotranspiration, and shallow soils. Furthermore, environmental gradients can describe those important ecosystem processes that correlate with fuels, such as biogeochemical cycling, to provide a temporal and spatial framework for creating dynamic fuels maps. For example, climate change effects on spatial fuel loadings can be computed easily by evaluating changes in environmental gradients under the new climate (Keane *et al.* 1996*b*). Most environmental gradients are scale-independent, meaning the same gradients may be used to predict fuel characteristics across many spatial scales, but the range and distributions might change.

One problem with this approach is that biophysical gradients do not provide a complete description of existing biotic conditions, and remotely sensed data are often needed to spatially portray vegetation-based gradients such as succession classes or cover types. Gradient information is best used to describe the potential of a landscape or stand to support a fuel model or set of models (Kessell 1979; Keane *et al.* 1997). Another disadvantage is that this approach requires abundant field data, complex ecosystem models, and intensive statistical analysis requiring extensive expertise in ecological sampling, simulation modeling, and statistical examination. But, once a gradient framework is established with continuous calibration of key variables, it can be used by all land management agencies.

Some fuel and vegetation mapping projects used combinations of the above four approaches to improve fuel mapping for their land areas. Keane *et al.* (1998*b*, 2000) used terrain modeling to differentiate potential vegetation types using topographical gradients that were then used to stratify satellite imagery classification and create FARSITE fuel maps for several areas in the Rocky Mountains. Many of the mid-scale, indirect mapping studies mentioned above used digital elevation models (DEMs) to impose elevational restrictions on classified cover type distributions (e.g. Root *et al.* 1985). Twery *et al.* (1991) used artificial intelligence technology merged with GIS to predict species composition from topography. A fuel mapping project in Yosemite National Park combined satellite imagery (Root and van Wagtendonk 1999; van Wagtendonk 1999) with aerial photography and field data.

None of the four fuel mapping approaches presented here appear superior. All approaches require extensive field sampling to construct accurate maps and broad expertise in fire and fuels modeling, image processing, and GIS techniques. More importantly, no approach appeared to create the most accurate maps. This is primarily because (1) most studies did not perform or report accuracy assessments for their final fuels maps; (2) inadequate field data sets were used in estimating accuracy; or (3) accuracy assessment methods were not consistent across studies. Interestingly, when assessments were reported, they usually ranged between 40 and 85% correct, regardless of fuel mapping approach. This may indicate that higher accuracies with today's technology may be difficult to achieve due to the inherent variability in ecological systems across natural landscapes and scale problems in extrapolating plot data to an entire polygon. Certain approaches were better for some situations than others. For example, the direct approach is better for grassland fuels but the indirect approach was better for forest fuels.

Fuels mapping strategies

Strategies using current technology

Synthesizing the literature and experience, we advocate an integrated approach that merges extensive field sampling with image classification of vegetation characteristics and biophysical gradient modeling. At a minimum, we suggest using the base vegetation classifications of (1) biophysical settings; (2) species composition; and (3) vertical stand structure, (termed the vegetation triplet) to map fuels across multiple scales (Keane *et al.* 1998*b*, 2000). Fuel characteristics can then be assigned to biophysical and vegetation category combinations to create robust and flexible maps for fire growth prediction. This approach, detailed in Fig. 2, has been used to quantify a number of other ecological attributes in past succession and ecological research and management projects (Arno *et al.* 1985; Fischer and Bradley 1987; Steele and Geier-Hayes 1989; Quigley *et al.* 1996; Taylor *et al.* 1998; Menakis *et al.* 2001).

Biophysical setting is the general term used to describe the important environmental factors that govern fuel and vegetation dynamics, thereby providing a context in which to interpret, constrain, or stratify spatial fuel differences (Keane *et al.* 1997; Lunetta *et al.* 1998). Site-related ecological processes, such as productivity, decomposition, and fire regime, often dictate fuel dynamics and describe fuel

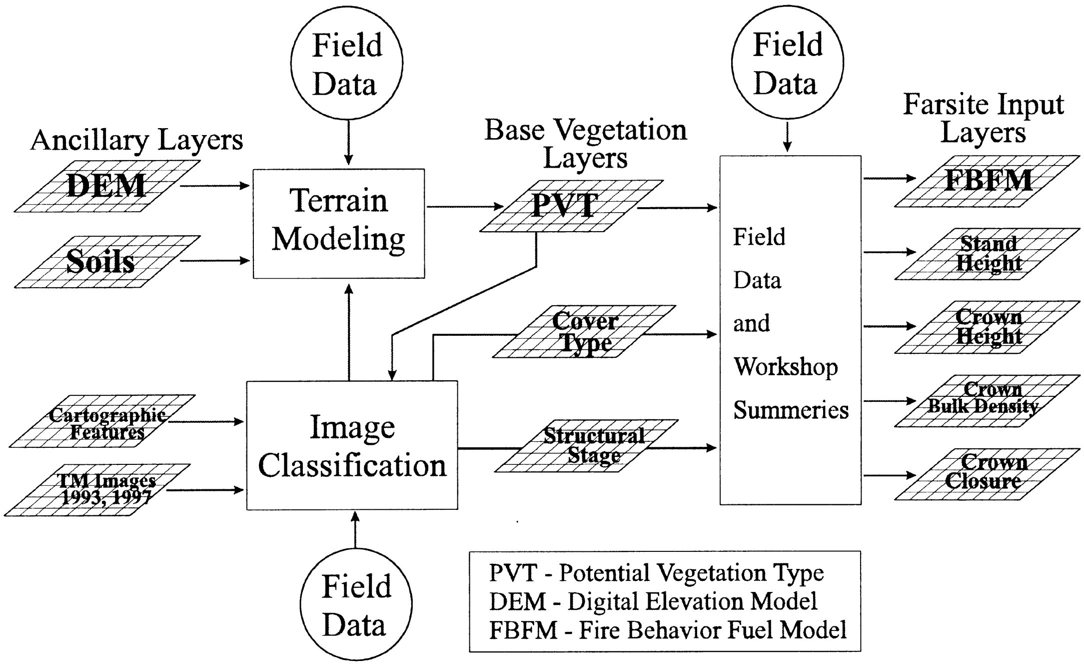

Fig. 2. Proposed method of mapping fuels using the vegetation triplet of biophysical settings (i.e. potential vegetation type or PVT), species composition (i.e. cover type), and stand structure (i.e. structural stage).

potential in many ecosystems (Brown and Bevins 1986; Waring and Running 1998). Biophysical setting classifications can be as simple as specifying elevational limits for a cover type or fuel model (Burgan and Shasby 1984; Root *et al.* 1985; Keane *et al.* 1998*a*), or as complex as spatially simulating biogeochemical processes using mechanistic ecological process models (Thornton and White 1996; Keane *et al.* 1997). Simulated environmental gradients can be used to describe unique properties of the fuel bed and also to aid in vegetation image classification (Burgan *et al.* 1998; Keane *et al.* 2000).

However, gradient simulation models need extensive input layers describing soils, vegetation ecophysiology, and climate. Simple biophysical settings maps developed from topographic rule-based terrain models are best used when field data are scarce. Terrain models are somewhat easy to create because all that is needed is a DEM, but they often are inconsistent and inaccurate over large land areas because of the highly variable relationship between climate, topography, and fuels (Brown and Bevins 1986). An ideal biophysical settings layer would directly integrate several environmental processes such as climate, hydrology, biogeochemical cycles, and soils to spatially predict the distribution of fuel types.

Biophysical settings are inherently difficult to map because they represent the complex integration of long-term climatic interactions with vegetation, soils, fauna, and disturbance (Habeck 1976; Barrett and Arno 1993; Keane *et al.* 1996*b*). Moreover, identification of those biophysical processes critical to fuel dynamics is difficult because most are unknown or unquantifiable, and they are difficult to identify in the field because of their temporal aspect. One would need to place a weather station within each mapped polygon for several years to identify appropriate biophysical settings categories described by climate. So, a vegetation-based classification is often needed to identify biophysical settings on the ground. The biophysical classification can then be cross-referenced to the vegetation-based site classification to identify biophysical settings from a plant key indirectly.

Potential vegetation type (PVT) classifications provide an ideal linkage between biophysical settings and vegetation (Daubenmire 1966; Pfister *et al.* 1977). These classifications assume the plant community that would eventually inhabit a site in the absence of disturbance uniquely describes environmental conditions. PVT classifications include habitat types at fine scales (e.g. Pfister *et al.* 1977), fire groups at mid-scales (Fischer and Bradley 1987), and temperature-moisture classes at coarse scales (Reid *et al.* 1995; Quigley *et al.* 1996). Terrain modeling is often used to map potential vegetation types from ranges of elevation, slope, aspect, and soils (Deitschman 1973; Shasby *et al.* 1981; Barrett and Arno 1993; Keane *et al.* 1998*b*) (Fig. 2).

Vegetation composition and stand structure are probably the two most important ecosystem characteristics useful to fuel mapping. Composition is important because the plant species that dominate a community have unique morphology, branch fall, and litterfall properties that tend to create distinctive fuelbed characteristics (Brown and See 1981; Brown and Bevins 1986). Stand structure is critical because it describes the vertical arrangement of live and dead biomass above the surface (O'Hara *et al.* 1996). Cover types can be used to classify species composition, but the classification categories must match the scale of application (Eyre 1980). Many structural stage classifications are available to define stand structure, but process-based structural stages that describe stand developmental processes often work best for spatial applications in diverse landscapes (Oliver and Larson 1990; O'Hara *et al.* 1996). Satellite imagery, aerial photo interpretation, or field reconnaissance can be used to map cover types and structural stages across a region (Hessberg *et al.* 1998; Keane *et al.* 1998*b*; e.g. Bobbe *et al.* 2001) (Fig. 2). However, most remotely sensed imagery products are unable to accurately discriminate stand structure and composition to the detail or resolution useful in resource management (Redmond and Prather 1996). Accuracies can be significantly improved if biophysical settings are used to stratify or aid cover type and structural stage image classification and mapping (Keane *et al.* 1998*b*; Menakis *et al.* 2001). Efforts should be made to comply with national standards for both vegetation and structural classifications systems (Grossman *et al.* 1998).

Creating robust, comprehensive, and flexible vegetation classifications can be one of the most demanding tasks of any mapping project because they are the heart of the fuel mapping procedure. The resolution of vegetation classification categories needs to match the resolution of fuel mapping categories to produce the best fuel maps. For example, cover type classifications need to be detailed enough to identify major changes in surface and crown fuel characteristics at a 30 m pixel resolution, but broad enough to minimize classification and sampling complexity for fire behavior prediction. Broad categories smooth the spatial distribution of fuels, while many fine categories overwhelm the satellite image classification process and require inordinately large field data sets (Schowengerdt 1983; Jensen 1998). Vegetation classification categories also need to be designed to be useful to other facets of land management besides fire planning and simulation (Verbyla 1995). This is difficult because the cover type classification categories commonly used in land management are difficult to accurately discriminate using only satellite imagery (Kalliola and Syrjanen 1991; Lachowski *et al.* 1995; Jakubauskas 1996; Keane *et al.* 1998*b*). Conversely, the vegetation-based categories often assigned to spectral clusters from unsupervised classifications are difficult to apply in many management analyses because they described differences in spectra rather than differences in vegetation. As a result, they rarely contain sufficient resolution to uniquely identify existing fuel conditions. Vegetation map categories need to be structured hierarchically to enable aggregation so they can be linked across spatial scales (Kalliola and Syrjanen 1991).

Fuel maps may then be created by assigning desired fuel characteristics, such as fuel model, crown height, and crown cover, to all combinations of the cover type, structural stage, and biophysical settings (i.e. PVT) categories (Keane *et al.* 1998*a*, 1998*b*, 2000) (see Fig. 2). Summarized field data are used as reference for fuel model assignments, but local knowledge can be used when there is a shortage of field data. Keane *et al.* (1998*a*, 2000) convened several workshops where local fire experts assigned fuel models to all combinations of potential vegetation type, cover type, and structural stage based on their past observations, but they found that these assignments need to be assessed for accuracy and consistency.

There are many advantages of using this vegetation triplet approach to map fuels.

- The concept can be used across many spatial scales because the classification categories can be scaled to the appropriate level of application. For instance, a cover type category at a coarse scale may be 'needleleaf conifer' whereas the same cover type at a mid- or fine-scale might be 'ponderosa pine'.
- Resource professionals already use some form of these classifications to formally or informally describe stands or landscapes (Pfister *et al.* 1977).
- There is a large body of research available on these types of classifications and their mapping (Eyre 1980; Shiflet 1994; Lachowski *et al.* 1995).
- This vegetation triplet provides an ecological context in which to interpret fuels maps. For example, it is useful to know that a stand received a closed timber model (fuel model 8) because it is a high elevation, north-facing site dominated by spruce-fir in the pole stage. These layers can also be used to map many other ecosystem characteristics such as hiding cover, coarse woody debris, and erosion potential, which are useful to wildlife, fuels, and hydrology management issues. This mapping triplet has been used successfully to describe fuels and ecosystem characteristics at coarse- (Keane *et al.* 1996*a*; Quigley *et al.* 1996), mid- (Ottmar *et al.* 1994; Hardy *et al.* 2001), and fine-scales (Arno *et al.* 1985; Steele and Geier-Hayes 1989; Shao *et al.* 1996).
- Lastly, the fuels layers can be easily updated as additional field data are obtained or as vegetation and fuel model classifications change in the future.

Field sampling

The collection of field data is the most critical task in the mapping of fuels, and it is often the most costly and time-consuming part of any mapping effort (Wilson *et al.* 1994; de Vasconcelos *et al.* 1998; Keane *et al.* 1998*b*). Georeferenced plot data are the only source available to describe actual fuelbed characteristics because important fuels, such as fine woody fuels, are hidden by the canopy or are too small to detect with imagery used for reference mapping such as videography and large-scale aerial photographs (Burgan and Hardy 1994). Ground-based fuel sampling is literally the only way to accurately describe fuel characteristics for fire modeling and map creation. It would be unwise to attempt to map fuels without extensive field sampling. However, the high variability of fuel characteristics in space and time requires fuel sampling methods that match the map objectives, scale, and legend. For example, a fuel model estimate might be the only field requirement for coarse scale maps or FARSITE input fuel maps, but fuel loadings by size class may be needed for fine-scale maps to produce smoke estimates.

Georeferenced field data are important for many reasons. First, field data provide important ground-reference or an accurate description of what is being remotely sensed. This means that sampled polygons can be used as training areas in supervised classifications or that they can be used for cluster labeling in unsupervised classifications (Verbyla 1995; Jensen 1998). Field data also provide a means for quantifying accuracy and precision of developed spatial classifications. Plot data are critical for designing and improving keys for the vegetation and fuels classifications being mapped with imagery. But, most importantly, field data provide a means for interpreting image classifications of fuels. Reasons for inaccuracies or inconsistencies in an image classification can be explored using detailed plot data. For example, an inaccurately mapped shrub–herb category can often be improved if the cover of bare soil and rock was sampled at each plot.

Perhaps the single biggest barrier for fuels mapping projects on public lands is the lack of dependable, georeferenced field data describing existing fuels conditions. Few historical ecosystem or timber inventory efforts included an adequate quantification of fuels. For those projects where fuels were actually measured, inadequate training in fuel model assessment and fuel measurement techniques resulted in questionable field estimates (Keane *et al.* 1998*a*). Many historical fuels data sets are not useful because they lack accurate geographical location. Merging fuel data sets is difficult because fuel characteristics were often estimated using different sampling methodologies. Since quality fuel data are so rare, it is imperative that fuels be consistently sampled with standardized protocols to maximize usefulness of field data sets (Jensen *et al.* 1993). Moreover, it is important that fuels sampling be integrated with national and local ecosystem inventory projects to maximize sampling efficiency.

Map accuracies

Quantitative accuracy assessments are essential for interpreting map quality and subsequent fire model output (Congalton and Green 1999). Fire growth predictions should, for example, identify those fuel types that generate high fire intensities but are mapped inaccurately. Moreover, accuracy assessments should indicate if additional sampling or fuel type aggregation is needed for the fuel types mapped with a low level of reliability (Congalton 1991). Accuracy assessments are even more critical in fuel mapping because most projects use indirect techniques where the fuel bed is not the mapped entity. Therefore, accuracy assessment protocols should be explicitly built into any standardized fuel mapping approach.

Low map accuracies do not always mean that the fuel map is worthless, considering the high variability and complexity of fuels. Mapping consistency may be just as important as accuracy. Moreover, low accuracies could also be a result of inherent sampling and analysis errors such as (1) scale differences in field data and mapped elements; (2) improper georegistration; (3) erroneous field identification of a mapped attribute: (4) improper use of vegetation or fuels classifications; (5) mistakes in field data entry; or (6) differences in sampling error of fuel components (see Table 1). Keane *et al.* (2000) hierarchically assessed accuracy of vegetation and fuel maps by quantifying error in the field data, vegetation and fuel classifications, and resultant maps so that major sources of error could be identified and controlled. They found that over 20% of map error resulted from the inherent variability of ecological attributes sampled at the stand-level.

Future strategies

Tomorrow's successful fuel mapping projects will integrate extensive field databases, comprehensive GIS data sources, state-of-the-art satellite and airborne imagery, and biophysical simulation models to create comprehensive and accurate fuel maps. An extensive, hierarchical field database will always be essential in the construction of fuels layers, regardless of the technology used in mapping fuels. Future GIS data layers will provide important spatial data for social, transportational, and ecological systems to be used as references to characterize local to regional fuel differences. The next generation of satellite and airborne imagery will provide multi-scale, hyperspectral, and fine resolution spatial data for the classification of fuels or the mapping of those ecosystem characteristics important to fuel dynamics. Mechanistic ecosystem process models will provide quantitative descriptions of the influence of biophysical processes on fuel dynamics across a temporal domain (Waring and Running 1998). Limitations of current technologies must be recognized and corrected if used in fuel layer construction, and new technologies must be developed to improve upon the limitations of current GIS products, remote sensors, and computer simulation packages.

Because field sampling is often the most costly phase of any mapping project, it seems logical to standardize sampling methods and databases to create a comprehensive ground-truth database for multi-scale mapping projects. A national, standardized fuels GIS database containing all collected georeferenced field data should be created so that spatially explicit fuels data can be accessible to everyone. These data should be quality checked, georeferenced, and summarized for only those essential attributes describing fuels (Sandberg *et al.* 2001). In addition, a meta-database should be created describing the source, reliability, and protocols used for each data set included in the database. Standardized methodologies should be prepared and posted to the Internet so that all government and private organizations can collect fuels data in the same manner. Then, a comprehensive user interface should be developed for the same Web site to allow entry and analysis of collected data. As a first step, the GLOBE (Global Learning and Observations to Benefit the Environment) project sponsored by NASA has recently added comprehensive fuel sampling protocols to their system that is a valuable fuel data source for mapping (http://www.globe.gov).

Comprehensive fuel models must be developed to meet the diverse demands of all land management activities (Hardy *et al.* 2000; Sandberg *et al.* 2001). These fuel models should quantify a myriad of fuel characteristics, such as loading, size, bulk densities, for all biomass compartments at a stand level (Table 3) so that their application is greater than just fire behavior prediction. These new models should be easily, accurately, and consistently keyed in the field and linked to other standardized vegetation and biophysical classifications. Moreover, the classification structure of these models must allow hierarchical aggregation and division so that fuel models can be tailored to the scale of applications. A link to historical and current fuel models should also be created so that past mapping efforts can be updated and refined. In addition, there must be a process and a protocol for creating new fuel models for local conditions when deemed necessary by management. Last, these models should be posted to the Internet so the data are available to all. Sandberg *et al.* (2001) are creating extensive fuel models for the United States.

Multiple scale, hierarchically nested, ecologically based, standardized land classification systems must be integrated with GIS technology to produce detailed maps useful to fuel modeling and mapping (Anderson *et al.* 1998; Grossman *et al.* 1998). First, a comprehensive GIS layer should be developed to document all past fuel mapping projects detailing the extent, approach, and accuracy of each. Extensive soils maps must be created or refined to account for edaphic properties integral to fuel conditions and ecosystem simulation (Soil Conservation Service 1991). Vegetation layers should be created across multiple scales using standardized hierarchical classifications (Loveland *et al.* 1993). Map chronosequences describing ecosystem characteristics, such as LAI, and created from updated satellite imagery will be important in quantifying biomass available for burning and parameterizing various ecosystem models (Running *et al.* 1989; Keane *et al.* 1996*b*; Thornton and White 1996). Climate layers that integrate long-term weather into quantitative descriptions germane to fuel and vegetation mapping will also be valuable in the future (Thornton 1998).

New technology for satellite or airborne imagery and image classification techniques is badly needed to accurately and consistently map fuels in the future. First, hyperspectral remotely sensed products might be needed to facilitate the unmixing of spectrally similar pixels (Ambrosia *et al.* 1992; Roberts *et al.* 1998). Hyperspectral imagery from AVIRIS sensors can possibly separate the canopy reflectance from the litter or ground signal (Cohen 1991; Ustin *et al.* 1991; Asner 1998; Root and van Wagtendonk 1999). Next, a sensor is needed that peers through the forested canopy and directly senses the complexity of the forest floor and the structure of the canopy. Active remote sensors such as Synthetic Aperture Radar (SAR) and Lidar that propagate pulses of electromagnetic radiation and detect the reflective backscatter show promise for achieving these ends (Bufton 1989; Dubayah *et al.* 1997; Bergen and Dobson 1999).

These sensors have been successfully used to estimate biomass, stand volume, and canopy height (Rignot *et al.* 1994; Weltz *et al.* 1994; Naesset 1997), and they should be useful for estimating surface fuel models, crown bulk densities, and canopy dimensions (Nelson *et al.* 1988; Nelson 1997). Higher resolution scanners (smaller than 30 m pixel size) are also needed for fine-scale, high profile fuel mapping projects to capture fine scale fuel distributions for accurate fire growth projections. Finer spatial resolutions may not, however, increase map accuracies or improve map quality, especially for large landscapes with diverse ecosystems, and may only complicate the mapping process by overwhelming computer resources and sampling efforts. Davis *et al.* (1991) mention that better image processing, GIS, and statistical software technology is needed to facilitate research and management activities in mapping ecological characteristics.

But, this advanced remote sensing technology will come at a price. New analysis techniques are needed to synthesize these detailed remotely sensed data for mapping. Then, new software packages will need to be designed to automate image processing analysis, and this means the image processing experts will need to be trained in these new techniques. Coordinated research funding and integrated institutional frameworks are essential for the development of these promising remote sensing technologies.

The merger of ecosystem models with remote sensing to map environmental gradients important to fuel characteristics will be vital to accurate and robust fuel mapping. Mechanistic ecosystem simulation models have improved over the last two decades and there are a wide variety of models for application at coarse mid- (e.g. FOREST-BGC and BIOME-BGC, Running and Coughlan 1988; Running and Gower 1991; Running and Hunt 1993; Thornton 1998), and fine-scales (e.g. Fire-BGC, Keane *et al.* 1996*b*). These models can be used to spatially simulate those ecosystem processes known to govern fuel dynamics and these processes can then be used to predict fuel characteristics. Weather simulation and extrapolation programs are essential for generating fine scale predictions of temperature, humidity, radiation, and precipitation across many temporal scales (Hungerford *et al.* 1989; Thornton *et al.* 1997). Keane *et al.* (1997) developed a prototype system to link remote sensing, gradient modeling, and ecosystem simulation into a package for mapping those characteristics important to land management. Thornton and White (1996) created a series of process-based maps of the Interior Columbia River Basin to aid in land classification. Mechanistic models can also be used to update fuels maps by simulating accumulation and decomposition processes to see how the fuels have changed over the life of the map.

Summary

Maps depicting fuel characteristics are essential to fire and land management at many scales because they can be used to compute fire hazard, risk, behavior, and effects for planning and real time applications. Fuel maps are difficult to create because of the obstruction of the forest canopy, limitations of remote sensing products, high variability of fuels, and construction of fuel models. Four approaches have been used to map fuels but none appear highly accurate or consistent. A possible strategy for mapping fuels with current technology involves assigning fuel models to combinations of three classifications that describe biophysical setting, species composition, and stand structure. Future technologies for mapping fuels need to meld all approaches to create the most useful maps, but other remote sensing technologies are still needed. Sensor technology that penetrates the forest canopy and senses ground complexity is needed for accurate mapping of crown and surface fuels. Ecosystem simulation modeling will play an important role in quantifying those gradients responsible for fuel distributions to aid in image classification, ecological understanding, and fuels map revision and refinement.

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