CSIRO Publishing

International Journal of Wildland Fire

Scientific Journal of IAWF

Volume 10, 2001

Address manuscripts and editorial enquiries to:
International Journal of Wildland Fire
Editor in Chief
Dr Gwynfor Richards
Department of Mathematics and Computer Science
Brandon University
Brandon, Manitoba, Canada R7A 6A9
Telephone: +1 204 727 7362
Fax: +1 204 728 7346
Email: richards@brandonu.ca

International Association of Wildland Fire

Address subscription enquiries to:
CSIRO PUBLISHING
PO Box 1139 (150 Oxford St)
Collingwood, Vic. 3066
Australia
Telephone: +61 3 9662 7644
Fax: +61 3 9662 7611
Email: ijwf@publish.csiro.au

C I
PUBLISHING

Published by CSIRO Publishing
for the International Association of Wildland Fire

www.publish.csiro.au/journals/ijwf

International Journal of Wildland Fire, 2001, **10**, 301–319

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

Robert E. Keane[A], *Robert Burgan*[A] *and Jan van Wagtendonk*[B]

[A]USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, PO Box 8089, Missoula, MT 59807, USA. Telephone: +1 406 329 4846; fax: +1 406 329 4877; email: rkeane@fs.fed.us
[B]US Geological Survey, Western Ecological Research Center Field Station, El Portal, CA 95318, USA. Telephone: +1 209 379 1885; fax: +1 202 379 1886; email: jan_van_wagtendonk@usgs.gov

This paper was presented at the conference 'Integrating spatial technologies and ecological principles for a new age in fire management', Boise, Idaho, USA, June 1999

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

10.1071/WF01028 1049-8001/01/030301

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

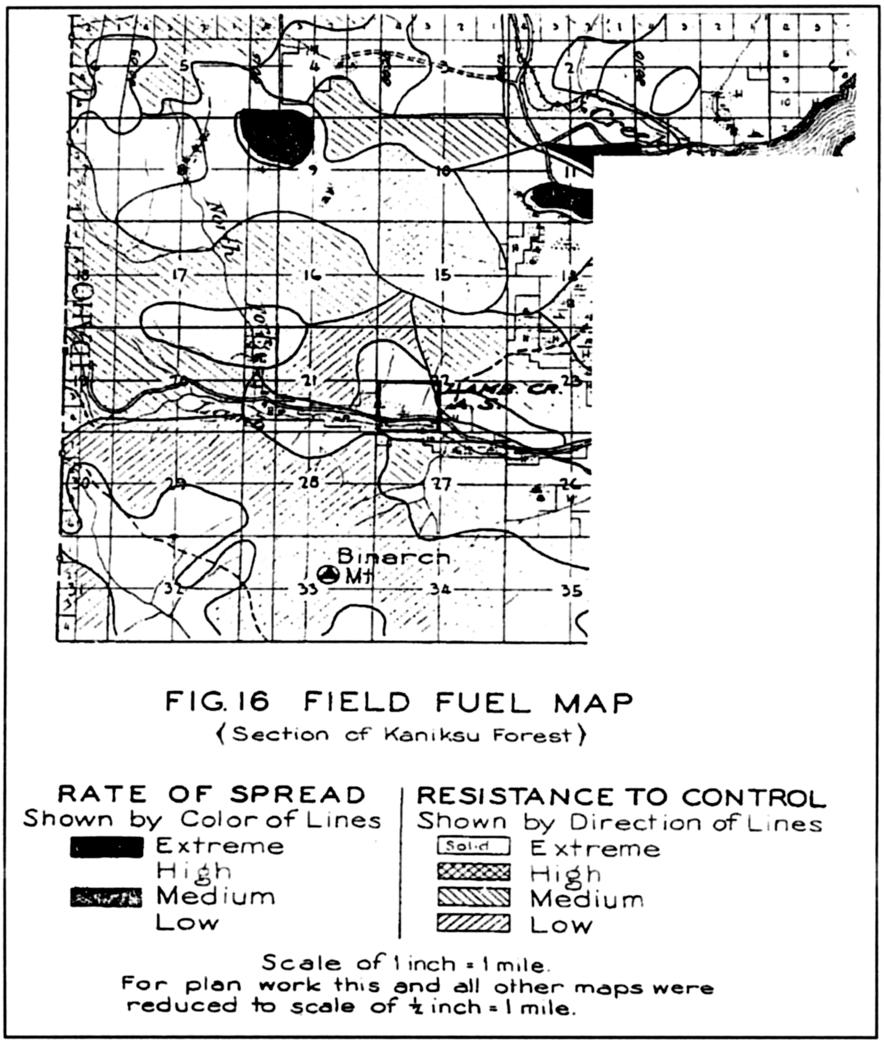

Fig. 1. Example of Hornby's (1935) fuel maps created using the field reconnaissance approach. Note that the fuel models are actually quantifications of fire behavior and risk.

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

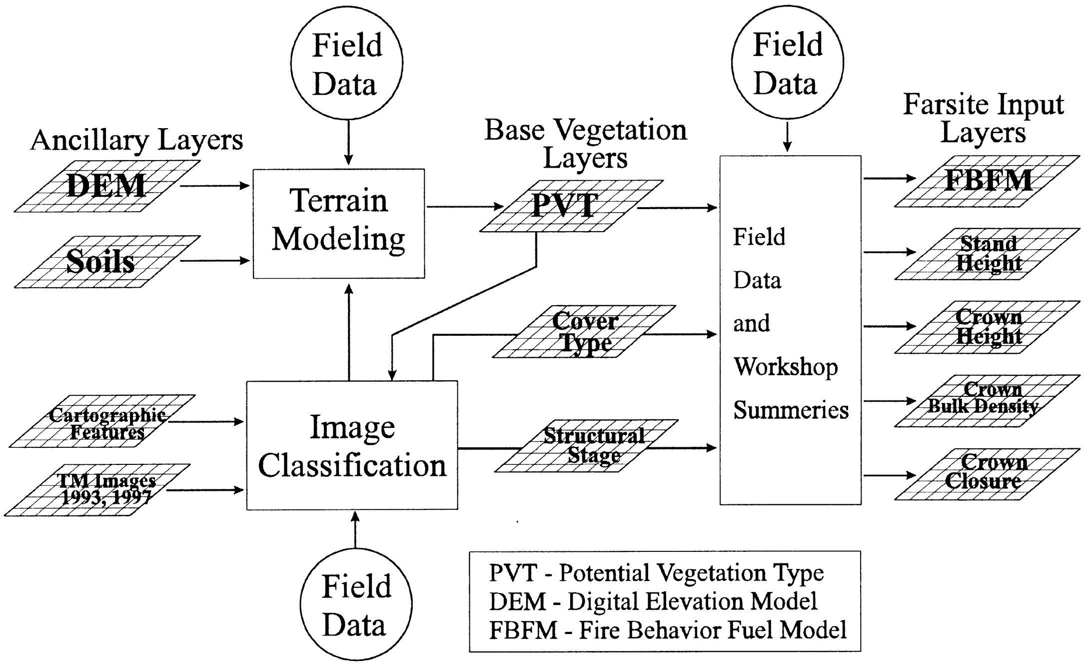

Fig. 2. Proposed method of mapping fuels using the vegetation triplet of biophysical settings (i.e. potential vegetation type or PVT), species composition (i.e. cover type), and stand structure (i.e. structural stage).

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.

Acknowledgements

We thank Kevin Ryan, USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory; Brad Hawkes, Canadian Forest Service, Pacific Forestry Centre; Paul Gessler, College of Forestry, Wildlife and Range Sciences, University of Idaho; Matt Rollins, Tree Ring Laboratory, and Steve Yool, Department of Geography, University of Arizona, for review comments and NASA (NRA-2B-OES-03) for partial funding.

References

Agee JK, Huff MH (1987) Fuel succession in a western hemlock/ Douglas-fir forest. *Canadian Journal of Forest Research* **17**(7), 697-704.

Albini FA (1976) Estimating wildfire behavior and effects. USDA Forest Service General Technical Report INT-30. 23 pp.

Ambrosia VG, Windham L, Wolf D (1992) Forest species and structure analysis using a hyperspectral scanner (AVIRIS) and terrain normalization algorithms. In 'Proceedings of the 4th Forest Service remote sensing applications conference, Orlando Florida'. (Ed. J Greer) pp. 181–189. (American Society of Photogrammetry and Remote Sensing: Bethesda, MD)

Anderson HE (1982) Aids to determining fuel models for estimating fire behavior. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-122. Ogden, UT. 22 pp.

Anderson M, Bourgeron P, Bryer MT, Crawford R, Engelking L, Faber-Langendoen D, Gallyoun M, Goodin K, Grossman DH, Landaal S, Metzler K, Patterson KD, Pyne M, Reid M, Sneddon L, Weakley AS (1998) International classification of ecological communities: Terrestrial vegetation of the United States. Volume II. The National Vegetation Classification System: list of types. (The Nature Conservancy: Arlington, VA)

Andrews PL (1989) Application of fire growth simulation models in fire management. In '10th Conference on fire and forest meteorology, October 26-28, Ottawa'. (Eds DC Maciver, H Auld, and RA Whitewood) pp. 317–321.

Arno SF, Simmerman DG, Keane RE (1985) Characterizing succession within a forest habitat type —an approach designed for resource managers. USDA Forest Service Research Note INT-357. 8 pp.

Asner GP (1998) Biophysical and biochemical sources of variability in canopy reflectance. *Remote Sensing of the Environment* **64**(3), 234–253.

Ball GL, Guertin DP (1992) Advances in fire spread simulation. In 'Proceedings on the 3rd Forest Service remote sensing applications conference—Protecting natural resources with remote sensing', 9–13 April, Tucson, Arizona. pp. 241–249. (American Society of Photogrammetry and Remote Sensing: Bethesda, MD)

Barrett SW, Arno SF (1993) Classifying fire regimes and defining their topographic controls in the Selway–Bitterroot Wilderness. In 'Proceedings of the 11th conference on fire and forest meteorology'. (Eds PL Andrews and DF Potts) pp. 299–307. (Society of American Foresters: Bethesda, MD)

Bazzaz FA (1979) The physiological ecology of plant succession. *Annual Review of Ecology and Systematics* **10**, 351–371.

Belfort W (1988) Controlled-scale aerial sampling photography: Development and implications for multiresource inventory. *Journal of Forestry* **86**(11), 21–28.

Belward AS, Kennedy PJ, Gregoire JM (1994) The limitations and potential of AVHRR GAC data for continental scale fire studies. *International Journal of Remote Sensing* **15**(11), 2215–2234.

Bergen K, Dobson C (1999) Monitoring forest biomass, harvest, and ANPP using SAR. In 'Proceedings of the Society of American Foresters 1998 national convention'. pp. 88–97. (Society of American Foresters: Bethesda, MD)

Bobbe T, Lachowski H, Maus P, Greer J, C. Dull C (2001) A primer on mapping vegetation using remote sensing. *International Journal of Wildland Fire* **10**, 277–287.

Brown JK (1970) A method for inventorying downed woody fuel. USDA Forest Service General Technical Report INT-16. 24 pp.

Brown JK, Bevins CD (1986) Surface fuel loadings and predicted fire behavior for vegetation types in the northern Rocky Mountains. USDA Forest Service, Intermountain Forest and Range Experiment Station Research Note INT-358. Ogden, UT. 9 pp.

Brown JK, See TE (1981) Downed dead woody fuel and biomass in the northern Rocky Mountains. USDA Forest Service, Intermountain Forest and Range Experiment Station General Technical Report INT-117. Ogden, UT. 48 pp.

Brzeziecki B, Kienast F, Wildi O (1993) A simulated map of the potential natural forest vegetation of Switzerland. *Journal of Vegetation Science* **4**, 499–508.

Bufton JL (1989) Laser altimetry measurements from aircraft and spacecraft. *Proceedings of the IEEE* **77**, 463–477.

Burgan RE (1987) Concepts and interpreted examples in advanced fuel modeling. USDA Forest Service General Technical Report INT-238. 40 pp.

Burgan RE, Hardy CC (1994) Ground truthing a national AVHRR based vegetation fuels map. In 'Proceedings of the 12th conference on fire and forest meteorology'. pp. 428–436. (Society of American Foresters: Bethesda, MD)

Burgan RE, Klaver RW, Klaver JM (1998) Fuel models and fire potential from satellite and surface observations. *International Journal of Wildland Fire* **8**(3), 159–170.

Burgan RE, Rothermal RC (1984) BEHAVE: fire behavior prediction and fuel modeling system–FUEL subsystem. USDA Forest Service General Technical Report INT-167. 126 pp.

Burgan RE, Shasby MB (1984) Mapping broad area fire potential from digital fuel, terrain, and weather data. *Journal of Forestry* **82**, 228–231.

Campbell J, Weinstein D, Finney M (1995) Forest fire behavior modeling integrating GIS and BEHAVE. In 'Analysis in support of ecosystem management'. (Compiler JE Thompson) pp. 184–192. USDA Forest Service Ecosystem Management Center Report, Washington D.C.

Chladil MA, Nunez M (1995) Assessing grassland moisture and biomass in Tasmania. The application of remote sensing and empirical models for a cloudy environment. *International Journal of Wildland Fire* **5**(3), 165–171.

Chuvieco E, Congalton RG (1989) Application of remote sensing and geographic information systems to forest fire hazard mapping. *Remote Sensing of the Environment* **29**, 147–159.

Chuvieco E, Martin MP (1994) Global fire mapping and fire danger estimation using AVHRR images. *Photogrammetric Engineering and Remote Sensing* **60**(5), 563–570.

Chuvieco E, Salas J, Vega C (1997) Remote sensing and GIS for long-term fire risk mapping. In 'A review of remote sensing methods for the study of large wildland fires'. (Ed. E Chuvieco) pp. 91–108. Megafires Project ENV-CT96-0256. Alcala de Henares, Spain.

Cohen WB (1989) Potential utility of the TM tasseled cap multispectral data transformation for crown fire hazard assessment. In 'ASPRS/ ACSM annual convention proceedings: Agenda for the 90s'. Volume 3, pp. 118–127. (Baltimore Maryland)

Cohen WB (1991) Chaparral vegetation reflectance and its potential utility for assessment of fire hazard. *Photogrammetric Engineering and Remote Sensing* **57**(2), 203–207.

Cohen WB, Harmon ME, Wallin DO, Fiorella M (1996) Two decades of carbon flux from forests of the Pacific Northwest: estimates from a new modeling strategy. *Bioscience* **46**(11), 836–844.

Congalton RG (1991) A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of the Environment* **37**, 35–46.

Congalton RG, Green K (1999) 'Assessing the accuracy of remotely sensed data: Principles and practices.' (Lewis Publishers, CRC Press: Boca Raton) 137 pp.

Covington WW, Everett RL, Steele R, Irwin LL, Daer TA, Auclair AND (1994) Historical and anticipated changes in forest ecosystems of the Inland West of the United States. *Journal of Sustainable Forestry* **2**(1/2), 13–63.

Daubenmire R (1966) Vegetation: identification of typal communities. *Science* **151**, 291–298.

Davis FW, Goetz S (1990) Modeling vegetation pattern using digital terrain data. *Landscape Ecology* **4**(1), 69–80.

Davis FW, Quattrochi DA *et al.* (1991) Environmental analysis using integrated GIS and remotely sensed data: Some research needs and priorities. *Photogrammetric Engineering and Remote Sensing* **57**(6), 689–697.

Deeming JE, Burgan RE, Cohen JD (1978) The National Fire Danger Rating System. USDA Forest Service General Technical Report.

Deitschman GH (1973) Mapping of habitat types throughout a national forest. USDA Forest Service General Technical Report INT-11. 14 pp.

Dendron Resource Surveys (1981) Logging residue survey and the line transect method: A comparison of field and photo methods. Special Report SR-16, ENFOR Project P-28, Forest Engineering Research Institute Canada, Ottawa, Ontario. 19 pp.

de Vasconcelos JJP, Paul JCU, Silva S, Pereira JMC, Caetono MS, Catry FX, Oliveira TM (1998) Regional fuel mapping using a knowledge based system approach. In 'Proceedings: III international conference on forest fire research and 14th conference on fire and forest meteorology'. Vol. II, pp. 2111–2123.

Dixon R, Shipley W, Briggs A (1985) Landsat—a tool for mapping fuel types in the boreal forest of Manitoba: A pilot study. In 'Proceedings of the Pecora X symposium'. pp. 392–393. (American Society for Photogrammetry and Remote Sensing: Falls Church, VA)

Dubayah R *et al.* (1997) The vegetation canopy Lidar mission. ASPRS conference: Land Satellite Information in the Next Decade. 12 pp.

Elvidge CD (1988) Thermal infrared reflectance of dry plant materials: 2.5-20.0 micrometers. *Remote Sensing of Environment* **26**, 265–285.

Eyre FH (1980) 'Forest cover types of the United States and Canada.' (Society of American Foresters: Washington, D.C.) 147 pp.

Ferry GW, Clark RG, Montgomery RE, Mutch RW, Leenhouts WP, Zimmerman GT (1995) Altered fire regimes within fire-adapted ecosystems. 'Our Living Resources: a report to the nation on the distribution, abundance, and health of U.S. plants animals, and ecosystems.' pp. 222–224. (USDI National Biological Survey: Washington, D.C.)

Finney MA (1998) FARSITE users guide and technical documentation. USDA Forest Service Research Paper RMRS-RP-4. 47 pp.

Fischer WC (1981) Photo guide for appraising downed woody fuels in Montana forests: Interior ponderosa pine, ponderosa pine–larch–Douglas-fir, larch–Douglas-fir, and Interior Douglas-fir cover types. USDA Forest Service General Technical Report INT-97. 133 pp.

Fischer WC, Bradley AF (1987) Fire ecology of western Montana forest habitat types. USDA Forest Service General Technical Report INT-223. 95 pp.

Fogel R, Cromack K (1977) Effect of habitat and substrate quality on Douglas-fir litter decomposition in western Oregon. *Canadian Journal of Botany* **55**, 1632–1640.

Forestry Canada Fire Danger Group (1992) 'Development and structure of the Canadian Forest Fire Behavior Prediction System.' Ontario Information Report ST-X-3. (Forestry Canada, Science for Sustainable Development: Ottawa) 12 pp.

Fosberg MA (1970) Drying rates of heartwood below fiber saturation. *Forest Science* **16**, 57–63.

Friedl MA, Michaelsen J, Davis FW, Walker H, Schimel DS (1994) Estimating grassland biomass and leaf area index using ground and satellite data. *International Journal of Remote Sensing* **15**(7), 1401–1420.

Gosz JR (1992) Gradient analysis of ecological change in time and space: Implications for forest management. *Ecological Applications* **2**(3), 248–261.

Gouma V, Chronopoulou-Sereli A (1998) Wildland fire danger zoning—a methodology. *International Journal of Wildland Fire* **8**(1), 37–43.

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

Grupe MA (1998) Assessing the applicability of the Terrestrial Ecosystem Survey for FARSITE. Master's Thesis, University of New Mexico, Albuquerque, New Mexico, 95 pp.

Habeck JR (1976) Forests, fuels, and fire in the Selway–Bitterroot Wilderness, Idaho. *Tall Timbers Fire Ecology Conference* **14**, 305–353.

Hardwick PE, Lachowski H, Forbes J, Olson R, Roby K, Fites J (1996) Fuel loading and risk assessment for Lassen National Forest. In 'Proceedings of the seventh Forest Service remote sensing applications conference. Nassau Bay, Texas, 6–10 April 1998'. (Ed. JD Greer) pp. 328–339. (American Society for Photogrammetry and Remote Sensing: Bethesda, MD)

Hardy CC, Burgan RE, Ottmar RD (2000) A database for spatial assessments of fire characteristics, fuel profiles, and PM10 emissions. *Journal of Sustainable Forestry* **11** (1/2), 229–245.

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Cummins KW (1986) Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* **15**, 133–302.

Hawkes B, Niemann O, Goodenough D, Lawson B, Thomson A, Sahle W, Fuglem P, Beck J, Bell B, Symington P (1995) Forest fire fuel type mapping using GIS and remote sensing in British Columbia. In 'Proceedings of the symposium GIS Applications in Natural Resources 2—The 9th symposium on Geographic Information Systems, Vancouver, British Columbia'. (Eds M Heit, HD Parker and A Shortreid) pp. 290–299.

Hessberg PF, Smith BG, Kreiter SG *et al.* (1998) Historical and current forest and range landscapes in the Interior Columbia River Basin and portions of the Klamath and Great Basins. Part I: Linking vegetation patterns and landscape vulnerability to potential insect and pathogen disturbances. USDA Forest Service General Technical Report PNW-GTR-558. 357 pp.

Hirabuki Y (1991) Heterogeneous dispersal of tree litterfall corresponding with patchy canopy structure in a temperate mixed forest. *Vegetatio* **94**, 69–79.

Hornby, L.G. (1935) Fuel type mapping in Region One. *Journal of Forestry* **33**(1), 67–72.

Hornby LG (1936) Fire control planning in the northern Rocky Mountain region. Northern Rocky Mountain Forest and Range Experiment Station Progress Report Number 1. Missoula, MT. 180 pp.

Hungerford RD, Harrington MG, Frandsen WH, Ryan KC, Niehoff GJ (1991) Influence of fire on factors that affect site productivity. In 'Proceedings of the symposium on management and productivity of western-montane forest soils'. pp. 32–50. USDA Forest Service General Technical Report INT-280.

Hungerford RD, Nemani RR, Running SW, Coughlan JC (1989) MTCLIM: A mountain microclimate simulation model. USDA Forest Service Research Paper INT-414. 52 pp.

Jain A, Ravan SA, Singh RK, Das KK, Roy PS (1996) Forest fire risk modelling using remote sensing and geographic information systems. *Current Science* **70**(10), 928–933.

Jakubauskas ME (1996) Thematic mapper characterization of lodgepole pine seral stages in Yellowstone National Park, USA. *Remote Sensing of Environment* **56**, 118–132.

Jensen JR (1998) 'Introductory digital image processing.' (Prentice-Hall: Englewood Cliffs, New Jersey) 379 pp.

Jensen ME, Hann W, Keane RE, Caratti J, Bourgeron PS (1993) ECODATA—A multiresource data base and analysis system for ecosystem description and evaluation. In 'Eastside forest ecosystem health assessment. Volume II. Ecosystem management: Principles and applications'. (Eds ME Jensen and PS Bourgeron) pp. 249–265. U.S. Department of Agriculture, Forest Service, National Forest System Information Report.

Jeske BW, Bevins CD (1979) Spatial and temporal distribution of natural fuels in Glacier Park. In 'Proceedings of the 1st conference on scientific research in National Parks. Volume II. USDI National Park'. (Ed. RM Linn) Transactions and Proceedings Number 5, pp. 1219–1224.

Kalabokidis KD, Omi PN (1995) Isarithmic analysis of forest fire fuelbed arrays. *Ecological Modelling* **80**, 47–55.

Kalliola R, Syrjanen K (1991) To what extent are vegetation types visible in satellite imagery. *Annales Botanici Fennici* **28**,45–57.

Kasischke ES, French NFH, Bourgeau-Chavez LL, Ustin SL, Christensen NL (1998) Estimating the release of carbon from forest fires in Alaska using satellite remote sensing data. http://cstars.ucdavis.edu/papers/sustin/carbon/paper.html

Keane RE, Garner JL, Schmidt KM, Long DG, Menakis JP, Finney MA (1998*a*) Development of the input data Layers for the FARSITE fire growth model for the Selway–Bitterroot Wilderness Complex, USA. USDA Forest Service General Technical Report RMRS-GTR-3. 121 pp.

Keane RE, Long DG, Schmidt KM, Mincemoyer S, Garner JL (1998*b*) Mapping fuels for spatial fire simulations using remote sensing and biophysical modeling. In 'Proceedings of the seventh Forest Service remote sensing applications conference. Nassau Bay, Texas, 6–10 April 1998'. (Ed. JD Greer) pp. 301–316. (American Society for Photogrammetry and Remote Sensing: Bethesda, MD)

Keane RE, McNicoll CH, Schmidt KM, Garner JL (1997) Spatially explicit ecological inventories for ecosystem management planning using gradient modeling and remote sensing. In 'Proceedings of the sixth Forest Service remote sensing applications conference—Remote sensing; people in partnership with technology'. pp. 135–146. (American Society of Photogrammetry and Remote Sensing: Bethesda, MD) 448 pp.

Keane RE, Menakis JP, Long D, Hann WJ, Bevins C (1996*a*) Simulating coarse scale vegetation dynamics with the Columbia River Basin Succession Model—CRBSUM. USDA Forest Service General Technical Report INT-340. 50 pp.

Keane RE, Mincemoyer SA, Schmidt KA, Long DG, Garner JL (2000) Mapping vegetation and fuels for fire management on the Gila National Forest Complex, New Mexico. USDA Forest Service General Technical Report RMRS-GTR-46-CD.

Keane RE, Morgan P, Menakis JP (1994) Landscape assessment of the decline of whitebark pine (*Pinus albicaulis*) in the Bob Marshall Wilderness Complex, Montana, USA. *Northwest Science* **68**(3), 213–229.

Keane RE, Morgan P, Running SW (1996*b*) Fire-BGC—a mechanistic ecological process model for simulating fire succession on coniferous forest landscapes of the Northern Rocky Mountains. USDA Forest Service Research Paper INT-RP-484. Ogden, UT. 122 pp.

Kessell SR (1976) Gradient modeling: A new approach to fire modeling and wilderness resource management. *Environmental Management* **1**(1), 39–48.

Kessell SR (1979) 'Gradient modeling: resource and fire management.' (Springer-Verlag: New York) 432 pp.

Kessell SR, Cattelino PJ (1978) Evaluation of a fire behavior integration system for southern California chaparral wildlands. *Environmental Management* **2**(2), 135–159.

Klaver JM, Klaver RW, Burgan RE (1998) Using GIS to assess forest fire hazard in the Mediterranean region of the United States. http://www.esri.com/library/userconf/proc97/PROC97/TO300/PAP286/P286.HTM. 12 pp.

Kourtz PH (1977) An application of Landsat digital technology to forest fire fuel mapping. In 'Fire ecology in resource management: A workshop'. (Ed. DE Dube) pp. 79–81. (Northern Forest Research Centre: Edmonton, Alberta) Information Report NOR-X-21.

Lachowski H, Maus P, Golden M, Johnson J, Landrum V, Powell J, Varner V, Wirth T, Gonzales J, S. Bain S (1995) 'Guidelines for the use of digital imagery for vegetation mapping.' USDA Forest Service Engineering Staff EM-7140-25. 168 pp.

Leenhouts B (1998) Assessment of biomass burning in the conterminous United States. *Conservation Biology (Online)* **2**(1), 1–24. http://www.consecol.org/vol2/iss1/art1

Lenihan JM, Daly C, Bachelet D, Neilson RP (1998) Simulating broad-scale fire severity in a dynamic global vegetation model. *Northwest Science* **72**(4), 91–101.

Loveland TR, Merchant JW, Ohlen DO, Brown JF (1991) Development of a land-cover characteristics database for the conterminous U.S. *Photogrammetric Engineering and Remote Sensing* **57**(11), 1453–1463.

Loveland TR, Ohlen DO, Brown JF, Reed BC, Merchant JW (1993) Prototype 1990 conterminous United States land cover characteristics data set CD-ROM. EROS Data Center, US Geological Survey CD-ROM 9307. 1 disk.

Lunetta RS, Lyon JG, Guindon B, Elvidge CD (1998) North American landscape characterization dataset development and data fusion issues. *Photogrammetric Engineering and Remote Sensing* **64**(8), 821–829.

Mallot N (1984) Alaska fuels fact sheet summary. S-390 Immediate Fire Behavior, State of Alaska, Department of Natural Resources, Division of Forestry Special Report No. 3. 3 pp.

Mark CA, Bushey CL, Smetanka W (1995) Fuel model identification and mapping for fire behavior prediction in the Absaroka–Beartooth Wilderness, Montana and Wyoming. In 'Proceedings: symposium on fire in wilderness and park management'. (Technical coordinators JK Brown, RW Mutch, CW Spoon and RH Wakimoto) pp. 227–229. USDA Forest Service General Technical Report INT-GTR-320.

Maselli F, Rodolfi A, Bottai L, Conese C (1996) Evaluation of forest fire risk by the analysis of environmental data and TM images. *International Journal of Remote Sensing* **17**(7), 1417–1423.

McKinley RA, Chine EP, Werth LF (1985) Operational fire fuels mapping with NOAA-AVHRR data. Pecora X symposium proceedings, pp. 295–304. (American Society for Photogrammetry and Remote Sensing: Falls Church, VA)

Menakis JP, Keane RE, Long DG (2001) Mapping ecological attributes using an integrated vegetation classification approach. *Journal of Sustainable Forestry* **11** (1/2), 245–265.

Merrill EH, Bramble-Brodahl MK, Marrs RW, Boyce MS (1993) Estimation of green herbaceous phytomass from Landsat MSS data in Yellowstone National Park. *Journal of Range Management* **46**, 151–157.

Miller W, Johnston D (1985) Comparison of fire fuel maps produced using MSS and AVHRR data. Pecora X symposium, pp. 305–314. (American Society for Photogrammetry and Remote Sensing: Falls Church, VA)

Millington AC, Critchley RW, Douglas TD, Ryan P (1994) 'Estimating woody biomass in sub-Saharan Africa.' (The World Bank: Washington, D.C.) 191 pp.

Minore D (1979) Comparative autecological characteristics of northwestern tree species: a literature review. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-87 Portland, OR. 28 pp.

Morris WG (1970) Photo inventory of fine logging slash. *Photogrammetric Engineering* **36**, 1252–1256.

Muller F (1998) Gradients in ecological systems. *Ecological Modelling* **108**, 3–21.

Muraro SJ (1970) Slash fuel inventories from 70 mm low-level photography. Canadian Forest Service Publication 1268. (Canadian Forest Service : Ottawa, Ontario) 63 pp.

Mutch RW (1995) Restoring forest health: do we have the will to apply science findings. In 'Proceedings of the conference Forest Health and fire danger in Inland Western Forests'. pp. 18–22. (American Forests: Washington D.C.)

Mutch RW, Arno SF, Brown JK, Carlson CE, Ottmar RD, Peterson JL (1993) Forest health in the Blue Mountains: A management strategy for fire-adapted ecosystems. USDA Forest Service General Technical Report PNW-GTR-310. 14 pp.

Naesset E (1997) Estimating timber volume of forest stands using airborne laser scanner data. *Remote Sensing of Environment* **61**, 246–253.

Nelson R (1997) Modeling forest canopy heights: the effects of canopy shape. *Remote Sensing of Environment* **60**, 327–334.

Nelson R, Swift R, Krabill W (1988) Using airborne lasers to estimate forest canopy and stand characteristics. *Journal of Forestry* **86**, 31–38.

O'Hara K, Latham P, Hessburg P, Smith B (1996) Development of a forest stand structural stage classification for the Interior Columbia River Basin. *Western Journal of Applied Forestry* **11**(3), 97–102.

Ohmann JL, T.A. Spies TA (1998) Regional gradient analysis and spatial pattern of woody plant communities of Oregon forests. *Ecological Monographs* **68**(2), 151–182.

Oliver CD, Larson BC (1990) 'Forest stand dynamics.' (McGraw Hill: New York) 467 pp.

Olsen J (1981) Carbon balance in relation to fire regimes. In 'Proceedings of the conference fire regimes and ecosystem properties'. (Technical Coordinators HA Mooney, TM Bonnicksen, NL Christensen, JE Lotan and WA Reiners) pp. 327–378. USDA Forest Service General Technical Report WO-26.

Omernik JM (1987) Ecoregions of the conterminous United States. *Annals of the Association of American Geographers* **77**(1), 118–125.

Ottmar RD, Vihnanek R, Alvarado E (1994) Forest health assessment: Air quality tradeoffs. In 'Proceedings of the 12th international conference on fire and forest Meteorology, 26–28 October 1993, Jekyll Island, Georgia'. pp. 47–62. (Society of American Foresters: Bethesda, MD)

Pala, S, Taylor D (1989) The foundation for province-wide forest fuel mapping. Proceedings, 12th Canadian symposium on remote sensing, Vancouver, B.C., July 1989.

Pala S, Taylor D, Holder G (1990) Integrating satellite-derived forest fuel data into fire management decision support models. Proceedings, 2nd National GIS conference, Ottawa, 5–8 March 1990.

Pfister RD, Kovalchik BL, Arno SF, Presby RC (1977) Forest habitat types of Montana. USDA Forest Service, Intermountain Forest and

Range Experiment Station General Technical Report INT-34. Ogden, UT. 174 pp..

Quigley TM, Graham RT, R.W. Haynes RW (1996) An integrated scientific assessment for ecosystem management in the Interior Columbia River Basin and portions of the Klamath and Great Basins. USDA Forest Service, Pacific Northwest Research Station General Technical Report PNW-GTR-382. Portland OR. 126 pp.

Redmond RL, Prather ML (1996) Mapping existing vegetation and land cover across western Montana and north Idaho. Report on file at: USDA Forest Service, Northern Region, Ecosystem Management. PO Box 7669, Missoula, MT. Contract 53-0343-4-000012. 211 pp.

Reid M, Bourgeron P, Humphries H, Jensen M (1995) Documentation of the modeling of potential vegetation at three spatial scales using biophysical settings in the Columbia River Basin. Report on file at Northern Region Ecosystem Management Project for completion of contract 53-04H1-6890.

Reinhardt ED, Keane RE, Brown JK (1997) First order fire effects model: FOFEM 4.0, User's Guide. USDA Forest Service General Technical Report INT-GTR-344. 65 pp.

Richards GD (1990) An elliptical growth model of forest-fire fronts and its numerical solution. *International Journal of Numerical Methods in Engineering* **30**, 1163–1179.

Rignot E, Way J, Williams C, Viereck L (1994) Radar estimates of aboveground biomass in boreal forests of interior Alaska. *IEEE Transactions on Geoscience and Remote Sensing* **32**(5), 1117–1124.

Roberts D, Gardner M, Regelbrugge J, Pedreros D, Ustin S (1998) Mapping the distribution of wildfire fuels using AVIRIS in the Santa Monica Mountains. http://cstars.ucdavis.edu/nasa-essp/smm-fires/paper.html. 6 pp.

Root RR, Stitt SCF, Nyquist MO, Waggoner GS, Agee JK (1985) Vegetation and fire fuel models mapping of North Cascades National Park. *ACSM-ASPRS Annual Convention Technical Paper* **3**, 78–85.

Root RR, van Wagtendonk JW (1999) Hyperspectral analysis of multi-temporal Landsat TM data for mapping fuels in Yosemite National Park. In 'Annual ASPRS Conference, Portland, OR, 17-21 May 1999'. (Society of American Photogrammeters: Bethesda, MD) pp. 399–408.

Rothermel RC (1972) A mathematical model for predicting fire spread in wildand fuels. USDA Forest Service Research Paper INT-115.

Rothermel RC (1991) Predicting behavior and size of crown fires in the northern Rocky Mountains. USDA Forest Service Research Paper INT-438. 46 pp.

Running SW (1990) Estimating terrestrial primary productivity by combining remote sensing and ecosystem simulation. In 'Remote sensing of biosphere functioning'. (Eds RJ Hobbs and HA Mooney) pp. 65–85. (Springer-Verlag: New York)

Running SW, Coughlan JC (1988) A general model of forest ecosystem processes for regional applications. I. Hydrologic balance, canopy gas exchange and primary production processes. *Ecological Modelling* **42**,125–154.

Running SW, Gower ST (1991) FOREST-BGC, a general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets. *Tree Physiology* **9**, 147–160.

Running SW, Hunt ER (1993) Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. In 'Scaling physiological processes: leaf to globe'. pp. 141–157. (Academic Press: New York)

Running SW, Nemani RR, Peterson DL, Band LE, Potts DF, Pierce LL, Spanner MA (1989) Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. *Ecology* **70**(4), 1090–1101.

Salas J, Chuvieco E (1994) Geographic information systems for wildland fire risk mapping. *Wildfire* **3**(2), 7–13.

Sandberg DV, Ottmar RD, Cushon GH (2001) Characterizing fuels in the 21st Century. *International Journal of Wildland Fire* **10**, 381–387.

Sanderlin JC, Sunderson JM (1975) A simulation for wildland fire management planning support (FIREMAN). In 'Prototype models for FIREMAN (Part II): Campaign fire evaluation'. Volume II. Mission Research Corp. Contract No. 231-343, Spec. 222, 249 pp.

Sapsis D, Bahro B, Spreo J, Gabriel J, Jones R, Greenwood G (1996) An assessment of current risks, fuels, and potential fire behavior in the Sierra Nevada. Sierra Nevada Ecosystem Project Final Report to Congress: Status of the Sierra Nevada Volume II, Assessment and scientific basis for management options. Centers for Water and Wildland Resources Report 37, pp. 759–785. (University of California: Davis)

Schowengerdt RA (1983) 'Techniques for image processing and classification in remote sensing.' (Academic Press: New York) 289 pp.

Shao, Guofan, Zhao G, Shidong S, Shugart H, Wang S, Schaller J (1996) Forest cover types derived from Landsat Thematic Mapper imagery for Changbai Mountain area of China. *Canadian Journal of Forest Research* **26**, 206–216.

Shasby MB, Burgan RE, Johnson RR (1981) Broad area forest fuels and topography mapping using digital Landsat and terrain data. In 'Proceedings of the 7th international symposium on machine processing of remotely sensed data, West LaFayette, LO'. pp. 529–537.

Shiflet TN (Ed.). (1994) 'Rangeland cover types of the United States.' (Society of Range Management: Denver, CO) 151 pp.

Simard AJ (1996) Fire severity, changing scales, and how things hang together. *International Journal of Wildland Fire* **1**(1), 23–34.

Soil Conservation Service (SCS) (1991) 'State soil geographic data base (STATSGO): Data user's guide.' U.S. Department of Agriculture, Soil Conservation Service Misc. Publication No. 1492. 123 pp.

Steele, R, Geier-Hayes K (1989) The Douglas-fir/ninebark habitat type in central Idaho: Succession and management. USDA Forest Service, Intermountain Research Station General Technical Report INT-252. 65 pp.

Stow D, Hope A, McKinsey D, Pray H (1993) Deriving dynamic information on fire fuel distributions in southern Californian chaparral from remotely sensed data. *Landscape and Urban Planning* **24**, 113–127.

Taylor SW, Baxter GJ, Hawkes BC (1998) Modeling the effects of forest succession on fire behavior potential in southeastern BC. In 'Proceedings of the 14th Conference on fire and forest meteorology and 3rd international conference on forest fire research, 16–20 November 1998, Luso, Portugal'. pp. 2059–2071.

Thornton PE (1998) Regional ecosystem simulation: Combining surface- and satellite-based observations to study linkages between terrestrial energy and mass budgets. PhD Dissertation, University of Montana, Missoula, MT. 280 pp.

Thornton PE, Running SW, White MA (1997) Generating surfaces of daily meteorological variables over large regions of complex terrain. *Journal of Hydrology* **190**(3/4), 214–251.

Thornton PE, White JD (1996) Biogeochemical characterization of the Columbia River Basin using the BGC model: Model description, ecophysiological inputs and landscape description. Final Report on file at Fire Sciences Laboratory, Missoula, MT. 61 pp.

Twery MJ, Elmes GA, Yuill CB (1991) Scientific exploration with an Intelligent GIS: Predicting species composition from topography. *AI Applications* **5**(2), 45–55.

Ustin SL, Wessman CA, Curtiss B, Kasischke E, Way J, Vanderbilt VC (1991) Opportunities for using the EOS imaging spectrometers and synthetic aperture radar in ecological models. *Ecology* **72**(6), 1934–1945.

Van Wagner CE (1977) Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research* **7**, 23–24.

Van Wagner CE (1993) Prediction of crown fire behavior in two stands of jack pine. *Canadian Journal of Forest Research* **23**, 442–449.

van Wagtendonk JW (1999) Use of Thematic Mapper imagery to map fuel models. In 'Proceedings of the 13th Conference on fire and forest meteorology. Lorne, Australia'.

Verbyla DL (1995) 'Satellite remote sensing of natural resources.' (Lewis Publishers, CRC Press: Boca Raton). 198 pp.

Waring RH, Running SW (1998) 'Forest ecosystems: Analysis at multiple scales.' 2nd edn. (Acedemic Press: San Diego) 370 pp.

Weltz MA, Ritchie JC,. Fox HD (1994) Comparison of laser and field measurements of vegetation height and canopy cover. *Water Resources Research* **30**, 1311–1319.

Werth LF, McKinley RA, Chine EP (1985) The use of wildland fire fuel maps produced with NOAA AVHRR scanner data. In 'Proceedings of the Pecora X symposium'. pp. 326–331. (American Society for Photogrammetry and Remote Sensing: Falls Church, VA)

Willis JM (1985) Applications of Landsat imagery for fire fuels mapping projects covering large geographic areas. In 'Proceedings of the Pecora X symposium'. pp. 394–395. (American Society for Photogrammetry and Remote Sensing: Falls Church, VA)

Wilson BA, Ow CFY, Heathcott M, Milne D, McCaffrey TM, Ghitter G, Franklin SE (1994) Landsat MSS classification of fire fuel types in Wood Buffalo National Park. *Global Ecology and Biogeography Letters* **4**, 33–39.

Yool SR, Eckhardt DW, Estes JE, Cosentino MJ (1985) Describing the brushfire hazard in Southern California. *Annals of the Association of American Geographers* **75**, 417–430.