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Wildland fire emissions, carbon and climate: Characterizing wildland fuels

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ABSTRACT

Smoke from biomass fires makes up a substantial portion of global greenhouse gas, aerosol, and black carbon (GHG/A/BC) emissions. Understanding how fuel characteristics and conditions affect fire occurrence and extent, combustion dynamics, and fuel consumption is critical for making accurate, reliable estimates of emissions production at local, regional, national, and global scales. The type, amount, characteristics, and condition of wildland fuels affect combustion and emissions during wildland and prescribed fires. Description of fuel elements has focused on those needed for fire spread and fire danger prediction. Knowledge of physical and chemical properties for a limited number of plant species exists. Fuel beds with potential for high impact on smoldering emissions are not described well. An assortment of systems, methods, analytical techniques, and technologies have been used and are being developed to describe, classify, and map wildland fuels for a variety of applications. Older systems do not contain the necessary information to describe realistically the wildland fuel complex. While new tools provide needed detail, cost effectiveness to produce a reliable national fuels inventory has not been demonstrated. Climate change-related effects on vegetation growth and fuel distribution may affect the amount of GHG/A/BC emissions from wildland fires. A fundamental understanding of the relationships between fuel characteristics, fuel conditions, fire occurrence, combustion dynamics, and GHG/A/BC emissions is needed to aid strategy development to mitigate the expected effects of climate change.

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1. Introduction

Total land area of the United States (US) is estimated to be 9,161,966 km^2 (Central Intelligence Agency, 2009). Approximately 65% of the conterminous US (Fry et al., 2011), 74% of Alaska, 55% of Hawaii, and 62% of Puerto Rico is occupied by natural vegetation (Homer et al., 2004). The vegetation types of the US encompass most of the vegetation biomes found in North America, which includes tundra, boreal, temperate, and tropical (Barbour and Billings, 2000; Brown et al., 2000). Within a biome, all species have the potential to burn depending on plant and environmental conditions, although the plant organs burned, the amount and type of plants consumed, and the nature of the combustion process vary widely.

Fire is a global phenomenon that releases the energy stored by plants during photosynthesis. Live and dead vegetation is the fuel source for wildland fires. Consideration of the inter-relationship between vegetation and fuel is, therefore, critical for evaluating likely changes associated with a changing climate. Development of novel climatic conditions in a greenhouse world is likely to affect future fire regimes (McKenzie et al., 2004) and create "no-analog" vegetation communities (Williams and Jackson, 2007), which may affect the biological, physical, and chemical characteristics of fuel sources for wildland fires (Bowman et al., 2009). Open biomass burning is the largest contributor of fine particulate matter ($PM_{2.5}$) and the second largest contributor of black carbon to the atmosphere (US Environmental Protection Agency, 2012), so an understanding of the ecology of vegetation and fuels provides important context for discussions of wildfire and emissions of greenhouse gases, aerosols, and black carbon (GHG/A/BC). Estimates of past, current, and projected future emissions from wildland fires are critical for understanding the carbon cycle, including the effects of carbon emissions on atmospheric processes; measuring and assessing effects on air quality; and producing accurate projections of climate change. The objective of this paper is to synthesize the state of science regarding wildland fuels as they relate to GHG/A/BC emissions. The synthesis will examine the assortment of systems, methods, analytical techniques, and technologies that have been used and are being developed to describe, classify, and map wildland fuels and their characteristics.

For a given wildland fire, the fire size, the amount and type of fuel combusted, and the combustion efficiency determine emissions production and composition. Seiler and Crutzen (1980)

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proposed that the mass of wildland fuels burned annually could be estimated as a function of total area burned, the mass per unit area available for combustion (available fuel) within the burned area, and the fraction of wildland fuel actually consumed during the combustion process. The product of the consumed wildland fuel mass and appropriate emission factors yields an estimate of emissions by pollutant species, including greenhouse gases, aerosols, and black carbon, that can be summed to determine total emissions (French et al., 2011). Emission factors differ with fuel type and combustion phase (i.e., flaming, smoldering, and glowing), so attributing the proportion of total consumption to the different combustion phases is important for accurate estimation of total emissions (Hardy et al., 2001; Ward and Hardy, 1991; Ward and Radke, 1993).

Loading (mass/unit area), fuel consumption (mass/unit area), and emission factor (mass of chemical species produced/mass of fuel burned) are the primary variables tied directly to vegetation characteristics in the process used to estimate emissions production. Substantial error and uncertainty can be introduced to emissions estimates by our current inability to accurately quantify the amount of fuel present and consumed within burned areas and the type and efficiency of combustion of the fuels (flaming, smoldering, or glowing) (French et al., 2011; Mobley et al., 1976; Ottmar et al., 2008; Peterson, 1987). Chemical composition of a wildland fuel and the type and efficiency of combustion determine the composition of the gaseous and particulate emissions produced. It is, therefore, critical to carefully quantify all of the different variables necessary in these calculations to minimize compounding error and generate an accurate estimate of emissions with quantifiable levels of error and uncertainty (French et al., 2004). A full and accurate retrospective accounting is challenging for large areas, long time scales, and complex fuelbeds, when the necessary data are scarce or lacking. Similarly, prospective accounting is challenging in light of uncertainty about future fire pattern, intensity, and frequency coupled with changes in vegetation associated with climate change and elevated carbon dioxide levels (Miller and Urban, 1999; Whitlock et al., 2003).

Shifts in vegetation growth and distribution associated with climate change may alter fuel composition, amount, arrangement, and condition. Climate change-induced increases in area burned (Littell et al., 2009; McKenzie et al., 2004), shifts in vegetation type (Whitlock et al., 2003), and changes in fire severity (Marlon et al., 2006) will likely affect GHG/A/BC emissions from biomass burning. Climate change may also change fire occurrence timing, location, and size; the intensity and severity of prospective fires; the type and amount of fuel consumed; and the characteristics of combustion (Bowman et al., 2009; Hessl, 2011; Sandberg and Dost, 1990). Disturbances other than fire, such as insect outbreaks and severe wind events, also affect fuelbed properties, which can alter the intensity, severity, location, and timing of fire occurrence (Whitlock et al., 2003; Williams and Jackson, 2007), and therefore, the quantity and composition of emissions produced for a given geographic area and time period. The direction, timing, and magnitude of changes in GHG/A/BC emissions will likely vary for a given location or spatial domain and time period (Hessl, 2011).

2. Classification of wildland fuels

Vegetation is grouped into classes or communities based on similarities in species occurrence and abundance. Attributes of the vegetation assemblage may be used to describe fuelbed characteristics for different vegetation classes. It should be noted, however, that, in addition to among-vegetation-class differences in fuelbed characteristics, within-vegetation-class variability is common and often substantial (Hall et al., 2006). Generalized relationships between vegetation communities and fuelbed characteristics that do not account for this variability, and any assessments or inferences made from such generalizations, may be fraught with uncertainty.

2.1. Vegetation

A vegetation classification is developed by grouping similar stands or plots into vegetation, or plant community, types (Tart et al., 2005). Various agencies and groups have used several vegetation classification systems yielding inconsistent systems for describing vegetation nationally in the United States. Examples of vegetation classifications that are based on the current composition of the flora include cover types as defined by the Society of American Foresters (Eyre, 1980) and the Society for Range Management (Shiflet, 1994). Alternatively, potential natural vegetation classification systems attempt to describe a site's biophysical capacity to support different species and species combinations, and are identified based on the composition of the species assemblage that is likely to dominate at the climax of succession in the absence of disturbance (Daubenmire, 1968; Franklin and Dyrness, 1988).

The National Vegetation Classification System (NVCS) was established to address the inconsistent application of different classification systems among agencies and groups (Federal Geographic Data Committee, 1997). Typically for classification systems, each class or type name represents a taxonomic group with defined limits, about which meaningful and reliable statements can be made (Jennings et al., 2009). The structure of the NVCS is based on five diagnostic criteria used to classify vegetation at all levels of the hierarchy: diagnostic species, dominant species, diagnostic growth forms, dominant growth forms, and compositional similarity (Fig. 1). The NVCS formalizes standards for data collection, data analysis, data presentation, and quality control

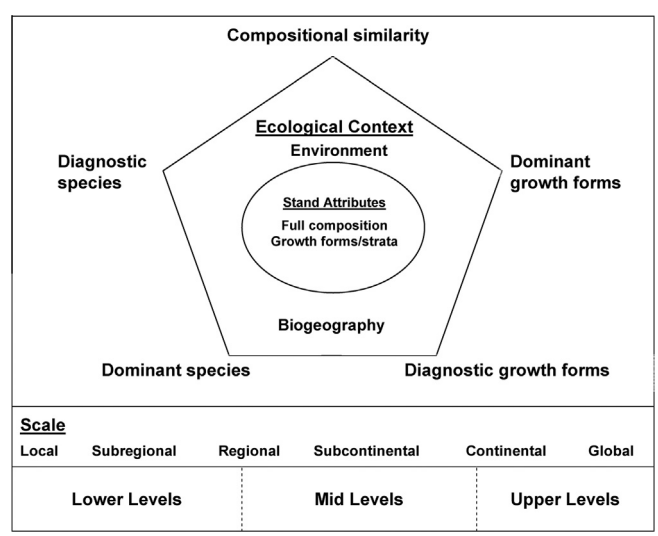

Fig. 1. The pentagon portrays the five vegetation criteria used to classify vegetation at all levels of the NVCS hierarchy. These criteria are arranged from the most fine-scaled on the left to the most broad-scaled on the right. The five criteria are derived from stand attributes or plot data (inside oval) and reflect the ecological context (outside oval) of the stand or plot. The ecological context includes environmental factors and biogeography considered at multiple scales, as well as natural and human disturbance regimes. The upper levels of the NVCS hierarchy are based on dominant and diagnostic growth forms that reflect environment at global to continental scales. The mid levels are based on dominant and diagnostic growth forms and compositional similarity reflecting biogeography and continental to regional environmental factors. The lower levels are based on diagnostic and/or dominant species and compositional similarity reflecting local to regional environmental factors (Fig. 2.1 from (Federal Geographic Data Committee, 2008)).

and assurance. Implementation of the NVCS is intended to produce a data classification system consisting of a hierarchical list of vegetation types and their descriptions. The classification system requires that vegetation types be defined and characterized using appropriate data and consistent standards. Definition of new vegetation types, refinement of existing types, and classification is performed with acquisition and analysis of new data and scientific understanding. The NVCS is part of a proposed International Vegetation Classification (IVC) that currently includes the Canadian National Vegetation Classification and parts of Latin America; the IVC claims integration with classification systems based on Braun-Blanquet approaches (Westhoff and Van der Maarel, 1973). Detailed study of classification systems is beyond the scope of this paper, so it was not possible to determine if the IVC and the NVCS address all of the issues concerning vegetation classification (De Cáceres and Wiser, 2012).

2.2. Fuel

Until recently in the US, fuel characterization and classification approaches have focused on providing inputs for predicting surface and crown fire behavior (Rothermel, 1991, 1972; Van Wagner, 1977) and simulating wildland fire spread (Finney, 1998; Peterson et al., 2009). A set of numerical values called a fuel model describes the physical characteristics of vegetation pertinent to fire spread and energy release. Seventy-three fuel models have been developed for use in fire behavior and fire danger calculations (Albini, 1976; Anderson, 1982; Deeming and Brown, 1975; Scott and Burgan, 2005). Additional fuel models for vegetation not well-represented in the initial 13 Northern Forest Fire Lab models (Albini, 1976; Cohen, 1986; Frandsen, 1983; Hough and Albini, 1978; Weise et al., 2010) are also available. Fuel models tend to include only the fuel elements involved in flaming combustion and progression of a surface fire's flaming front which makes them inadequate for estimating fire effects associated with post-frontal combustion, including GHG/A/BC emissions for several reasons:

(1) Fuel models do not include a full accounting of all fuel particles present in a fuelbed[1]. Fuel particles not involved in flaming combustion and surface fire spread, such as large woody material, ground fuels, and tree canopies, which can be a substantial fraction of the total fuel loading and fuel consumed during combustion, are not included in fire behavior fuel model descriptions.
(2) Fuel models are general representations of fuelbeds based on expected fire behavior and do not necessarily correspond to actual measured fuel characteristics.
(3) Fuel models require developers to adjust characteristics (fuelbed depth, surface area-to-volume ratio, moisture of extinction, fuel loading, etc.) in a circular fashion such that modeled fire behavior meets expectations under different weather and fuel moisture conditions (Sandberg et al., 2007).
(4) Models for predicting fire effects, such as BURNUP, CONSUME, FFE-FVS, and FOFEM, require fuels data, particularly fuel loading, "as measured" and not adjusted to yield expected fire behavior (Albini and Reinhardt, 1997; Prichard et al., 2006; Reinhardt et al., 1997; Reinhardt and Crookston, 2003).
(5) Estimates of carbon pools and fluxes in response to fuel treatments and wildland fire require fuels data as measured (Dicus et al., 2009).
(6) Subtle and even moderate (and sometimes large) differences in fuel characteristics are generally not captured by the limited number of fuel models (Sandberg et al., 2007). For example, fuel loading in conifer-dominated ecosystems can vary by an order of magnitude depending on site, age, and disturbance, but is represented by a limited number of fire behavior or fire danger rating fuel models (Albini, 1976; Anderson, 1982; Scott and Burgan, 2005) with a narrow range of fuel loading in comparison to published information on fuel loading in conifer-dominated ecosystems (Brown and Bevins, 1986; Jenkins et al., 2012; Mobley et al., 1976; Ottmar and Vihnanek, 2000; Ottmar et al., 2003; Page and Jenkins, 2007; Sackett, 1979, 1975; Vihnanek et al., 2009; Wade et al., 1993; Weise et al., 1997; Woodall and Nagel, 2007; Wright et al., 2012). While dynamic fuel models were developed to accommodate the seasonal variability and change over time in fuel characteristics in chaparral and palmetto-gallberry fuel types, they seem to be seldom used (Cohen, 1986; Hough and Albini, 1978; Rothermel and Philpot, 1973). A procedure exists (Burgan and Rothermel, 1984; Burgan, 1987) to create custom fire behavior fuel models (site-specific fuel models) for situations not represented by the original fuel models. Although several custom fuel models have been published (e.g. Freifelder et al., 1998; Knapp et al., 2011; Parresol et al., 2012b; Stephens, 1998), there exists no central repository so the number and reliability of these models is unknown. In some instances, published, potentially useful fuels information representing important fuel types for GHG/A/BC emissions has been lost from memory (e.g. Wendel et al., 1962).

Keane (2013) reviewed methods and systems for describing surface fuelbeds used in the US, Canada, and Australia and noted many of the same limitations of fuel models identified above. References to non-US approaches can be found therein.

Lutes et al. (2009) proposed a framework for evaluating fire effects, including emissions, with what amount to "fire effects fuel models" that they called Fuel Loading Models. The fire effects fuel model approach does not distinguish among different fuelbeds that might produce similar fire effects. For example, fuel types with high woody fuel loading might be considered the same as those with a deep forest floor or organic soil horizon because they exhibit similar soil heating and smoke emissions when burned under dry conditions, when in fact their fuel characteristics are quite different. In the Fuel Loading Models framework, the fire effects used in the classification scheme determine similarity or difference, not the actual fuel characteristics.

The Fuel Characteristic Classification System (Ottmar et al., 2007; Sandberg et al., 2001) (FCCS) is an organizational structure for describing fuels that addresses some of the aforementioned shortcomings of fuel models (and fuel loading models). In the FCCS, data characterizing fuelbeds are organized into six strata: canopy, shrubs, herbs and grasses, dead and down woody debris, litter (includes lichens and mosses) and duff or ground fuels (Fig. 2). Numerous quantities (e.g., coverage, density, height, size, species composition, biomass, etc.) describe modal properties for variables in each stratum for each fuelbed, as appropriate (Riccardi et al., 2007a). Each fuelbed includes a full accounting of all of the combustible material (aboveground only at this point), in contrast to fire behavior, fire danger, and fire effects fuel models, which only characterize a fraction of the fuel present, and may or may not equate with actual measured conditions on the ground. Allometric methods are used to estimate biomass and carbon content for each fuelbed component and stratum (Riccardi et al., 2007b). As well as linking to widely used models for estimating fuel consumption and emissions (i.e., FOFEM and CONSUME), the FCCS incorporates a

[1] Fuelbed is a generic term to describe all fuel particles, regardless of the manner in which they are expected to burn.

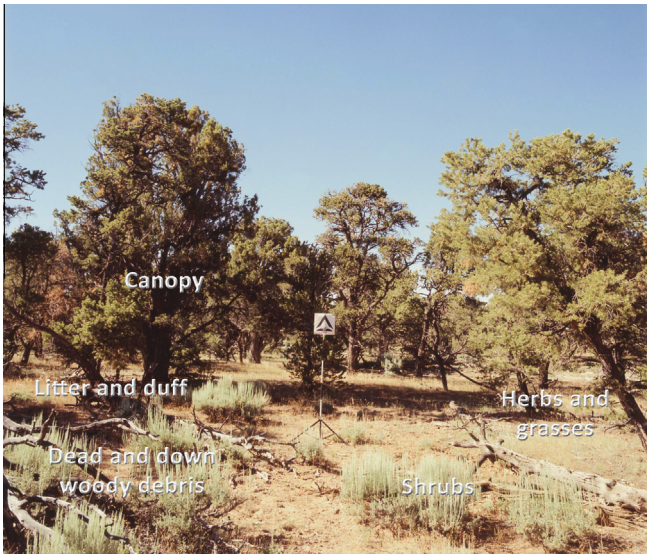

Fig. 2. Natural fuelbeds such as this twoneedle pinyon (*Pinus edulis*) woodland contain different strata.

modified version of the Rothermel (Rothermel, 1972) surface fire behavior algorithm (Sandberg et al., 2007) and a conceptual model for assessing crown fire potential (Schaaf et al., 2007). The FCCS is able to provide a comprehensive accounting of the fuel complex necessary to estimate both GHG/A/BC emissions and fire behavior during wildland fires. FCCS fuelbeds can describe fuels on a continuous scale, allowing the user to resolve and detect differences in fuel characteristics and potential wildland fire emissions among fuel types that are not possible with fuel models which are predominantly static, discrete representations.

3. Characterization and measurement

The physical and chemical properties of fuel particles influence the nature of the combustion process (Byram, 1959; Countryman, 1964; Philpot, 1970) including the amount of fuel likely to be consumed as well as the proportion of combustion that occurs as flaming, smoldering, and glowing (Ward, 2001). Fuelbed properties are highly variable both among (Fig. 3) and within general ecosystem or fuel types (Fig. 4). Accurate estimates of available fuel and the proportion of consumption that occurs in the different combustion phases are important for accurate estimates of GHG/A/BC emissions during wildland fires.

Techniques to describe and quantify vegetation and fuels have a rich history in forestry and ecology (Canfield, 1941; Greig-Smith, 1952; Husch et al., 2003; Mueller-Dombois and Ellenberg, 2002; Van Wagner, 1968). Well-established field and laboratory techniques estimate species composition, mass, height, area, volume, spatial arrangement, chemical composition, and energy content. Techniques range from destructive methods at fine scales (<1 cm) for chemical composition to remotely-sensed methods that cover larger areas at slightly to substantially coarser scales up to 1000 m (Jones and Vaughan, 2010).

3.1. Composition

Wildland fuelbeds are composed of fuel particles derived from the live and dead plant parts of the various species of grass, forb, shrub, and tree species present. Different species produce fuel particles with different properties, including size, shape, mass, density, and chemical composition. The structural and chemical characteristics of individual fuel particles and of fuelbeds (the collection of all fuel particles) and environmental conditions affect the frequency, size, intensity, and season of wildland fires (i.e., the fire regime) and the emissions produced. The elemental composition of plant tissue varies slightly and is often assumed to be approximately 50% carbon, 44% oxygen, and 5% hydrogen on a mass basis (Ward, 2001); these proportions are determined using ultimate analysis and several standard techniques for ultimate analysis have been developed (Jenkins et al., 1998). Reported composition of biomass fuels, which are derived from plant tissue, is 42–54% carbon, 35–45% oxygen, and 5.0–5.9% hydrogen (Demirbas, 2004; Friedl et al., 2005). The relative proportion of cellulose, hemicellulose, and lignin (all complex hydrocarbons) varies within plant structures and among species, and affects combustion processes and products (Yang et al., 2007). Commonly used techniques to determine the relative proportion of cellulose, hemicellulose, and lignin originated in the livestock community (forage analysis) and the wood products community (proximate analysis). Forage analysis is typically used to determine the amount of cellulose and lignin (acid detergent fiber), cellulose, hemicellulose, and lignin (neutral detergent fiber) and lignin alone present in foliage and other dry matter through a series of chemical digestion techniques (Goering and Van Soest, 1970; Undersander et al., 1993). Similar techniques are used for wood (Dore, 1920; Rowell et al., 2005).

The presence of macro- (N, P, S, K, Mg, Ca) and micro- (Fe, Mn, Zn, Cu, Mo, B, Cl), nutrients common to most plants (Bidwell, 1979) can influence the formation and composition of GHG/A/BC emissions (Ward, 2001). Standard analytical techniques such as X-ray fluorescence spectroscopy (Marguí et al., 2005) to determine the elemental composition of plants are available; however, these techniques are not always used to characterize fuels prior to burning. This is particularly true for field emissions studies in which the fuelbed is a mixture of vegetation, so collection of a representative sample of the fuelbed to perform elemental analysis is not trivial. Elemental analysis of single species fuelbeds in laboratory studies has been performed occasionally. The same techniques are used to determine the elemental composition of particulate matter (Chen et al., 2007; Hays et al., 2002).

The physical and chemical traits of fuels affect the timing, location, and final size of individual fires, total annual area burned (Kane et al., 2008; Philpot, 1977; van Wilgen et al., 1990), and therefore GHG/A/BC emissions. Because wood is a valuable and ancient commodity, a great deal of effort has been devoted to the study of its chemical and physical characteristics (Bergman et al., 2010; Fengel and Wegener, 1989). These traits affect its decomposition rate (Keane, 2008; Melin, 1930; Zhang et al., 2008). Traits such as hydrocarbon composition (Mutch, 1970; Ryan and McMahon, 1976) and presence of volatile compounds (Philpot, 1969a) can affect a fuel's flammability (Babrauskas, 2003). Lignin content in foliage differs between hardwood and coniferous foliage, ranging from 5% to 30% (Scott and Binkley, 1997) which affects the decomposition rate of leaf litter, and therefore forest floor fuel levels and accumulation rates. Although the lignin content can be highly variable within life forms, herbs and grasses generally have lower lignin content (5–15%) than woody parts of trees and shrubs (16–33%) (Patton and Gieseker, 1942; Ward, 2001). Fats, terpenes, waxes, oils, and other extractive compounds have higher heat content than cellulose and the other complex carbohydrates that constitute the bulk of vegetation mass, which can affect ignition and combustion (Hough, 1969; Philpot, 1969b). Many of these compounds accumulate in the heartwood of 2- and 3-needled pines of the southern and western US, which results in wood pieces that ignite easily and will burn even during precipitation. The composition of smoke emissions from the burning of this so-called "light wood" or "fat lighter" are only now being described (Akagi et al., 2012).

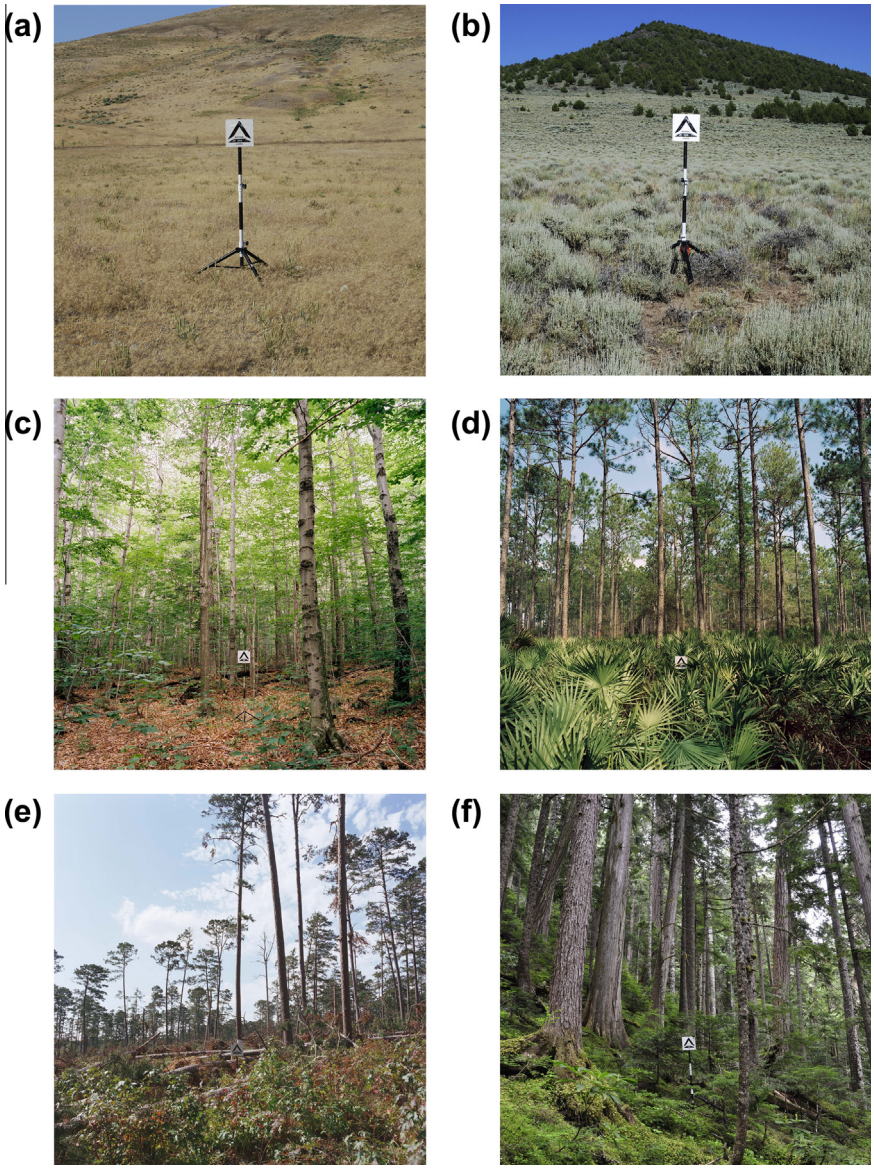

Fig. 3. Fuel properties vary widely among types. For example, fuel loading ranges from (A) 0.7 Mg ha^{-1} in a cheatgrass (*Bromus tectorum*) grassland in eastern Oregon, (B) 5.4 Mg ha^{-1} in big sagebrush (*Artemisia tridentata*) fuels in eastern Oregon, (C) 47.2 Mg ha^{-1} in a mixed hardwood forest in Vermont, (D) 74.1 Mg ha^{-1} in a slash pine (*Pinus elliottii*) forest in Florida, (E) 207.7 Mg ha^{-1} in a shortleaf pine (*P. echinata*) forest with hurricane damage in Texas, and (F) 444.7 Mg ha^{-1} in an old-growth Douglas-fir (*Pseudotsuga menziesii*) forest in western Washington.

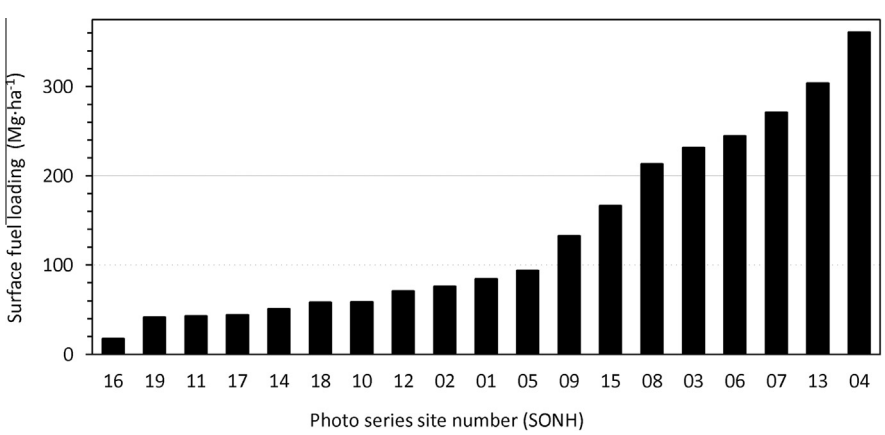

Fig. 4. Fuel properties vary widely within types. Fuel loading ranges from 18 to 361 Mg ha^{-1} in Douglas-fir (*Pseudotsuga menziesii*) forests that are suitable habitat for northern spotted owl nesting in the Pacific Northwest (adapted from Fig. 5 from Wright et al., 2012).

3.2. Physical characteristics

In addition to chemical composition, the size, shape, density, and absorptivity of a fuel particle affects moisture dynamics (Fosberg, 1970; Meentemeyer, 1978), flammability (Anderson, 1970), pyrolysis and devolatilization (Lu et al., 2010), combustion characteristics such as energy release rate and efficiency (Albini and Reinhardt, 1995; Ward, 2001), and, therefore, resulting emission characteristics (e.g., amount, rate, duration, plume rise). Sound woody fuels tend to be cylindrical in shape (Van Wagner, 1968); however, foliage shape is quite variable ranging from cylindrical (needle-like) to elliptical to very complex shapes modeled by fractals (e.g. Wang et al., 2008). The effect of complexity in leaf shape on combustion has tended to be ignored with simplifying assumptions made to describe non-cylindrical foliage (Brown, 1970).

Due to the renewed interest in biomass utilization for energy and fuel production, there are many studies that either measure or model fuel particle size and shape on the processes just mentioned; however, the particles examined are generally very irregular in shape having been produced by grinding, chipping or pulverizing wood. Experimental and modeling results of the combustion of these chipped and ground wood particles may apply to masticated fuels; however, this has not been examined to our knowledge.

A fuelbed with an abundance of thermally thin fuel particles will ignite more readily and experience a higher combustion rate than a fuelbed that lacks these elements (Anderson, 1970). In addition to potentially affecting the total amount of fuel available for combustion, the relative complexity of the fuelbed is also likely to affect the nature of the combustion (and emissions) that occurs by virtue of the diversity of fuel particles with different chemical and physical properties.

3.3. Amount

Fuel amount largely determines the quantity of emissions produced during biomass fires (Brown et al., 1991; Mobley et al., 1976; Wright and Prichard, 2006). Fuel measurement has historically focused on quantifying fuel loading (i.e., the mass of fuel particles of varying type and size), although other metrics, such as fuel volume or surface area (Sandberg et al., 2007) may also be used to describe the amount of fuel present in a fuelbed or at a given location. In complex fuelbeds, especially those with multiple fuelbed strata, such as are found in forested ecosystems, it is important to quantify fuel amount for each stratum individually, as not all strata will necessarily be involved in the combustion process and contribute emissions for all fires.

Well-established methods are used to estimate surface fuel loading at the stand scale (Sikkink and Keane, 2008) including the line and planar intersect methods (Brown, 1971; Lutes et al., 2006), photo-based methods and databases (Keane and Dickinson, 2007; Maxwell and Ward, 1976; Wright et al., 2010), and sampling using fixed or variable-area plots (Kalabokidis and Omi, 1992; Valentine et al., 2001). Remote sensing technologies bridge from measurements at plot and stand scales to larger areas. Well-characterized fuel loading across large spatial domains is critical for estimating and inventorying emissions from wildfires (French et al., 2011).

Tree canopies represent a large potential source of wildland fire emissions in forested fuelbeds. Available fuel loading (i.e., foliage and small twigs), canopy bulk density, and canopy base height are the most commonly reported metrics for quantifying the canopy fuel stratum (Cruz et al., 2003; Sando and Wick, 1972). Studies of tree allometry have traditionally been used to characterize forest crown fuels at the scale of individual trees and combined with forest inventory data to scale individual tree crown fuel estimates to stands and forests. This method assumes that the allometric model being applied is a proper fit for the species, forest type, or location being assessed (Biging and Gill, 1997; Brown, 1978; Mäkelä and Valentine, 2006; Monserud and Marshall, 1999). Traditionally, work modeling crowns has focused on biomass prediction and partitioning into foliage and branches (Brown, 1978; Clark and Taras, 1976; Clark et al., 1985; Jenkins et al., 2004; Loomis et al., 1966; Ter-Mikaelian and Korzukhin, 1997) and foliage distribution within canopies (Aber, 1979; Garber and Maguire, 2005; Maguire and Bennett, 1996; Massman, 1982; Todd et al., 2003; Xu and Harrington, 1998; Zeide, 1998). Allometric models to predict crown fuel mass specifically have been developed primarily for conifer species in the western US (Cruz et al., 2010, 2003; Jorgensen and Jenkins, 2011; Keyser and Smith, 2010; Reinhardt et al., 2006; Tausch, 2009) with considerably less emphasis in the southern US (Agca et al., 2011). This geographic disparity likely reflects the fact that crown fires occur more frequently in western and boreal conifer forests than in southern pine forests. Sand pine (*Pinus clausa*), a southern pine with limited distribution, does occasionally burn in stand-replacement crown fires (Hough, 1973). Allometric work has also occurred in shrub systems prone to fire such as sagebrush, chaparral, and palmetto-gallberry (Brown, 1976; Dickinson and Zenner, 2010; McNab et al., 1978; Parresol et al., 2012a; Reiner et al., 2010; Riccardi et al., 2007b; Riggan et al., 1994; Sah et al., 2004). Several newer methodologies that utilize specialized instruments and ground and aerial remote-sensing have been tested and show promise for quantifying tree and shrub canopy fuel metrics (Erdody and Moskal, 2010; Keane et al., 2005; Skowronski et al., 2007, 2011).

3.4. Arrangement

Within a fuelbed, particle arrangement affects energy and mass transfer and oxygen availability, which can affect fuel conditions and combustion. Arrangement may also affect fuel particle and air temperatures and local humidity depending on shading effects (Byram and Jemison, 1943). Loosely arranged fuel particles provide more void space through which air and energy can flow unimpeded. In contrast, smaller void spaces associated with tightly arranged fuel particles restrict air and energy flow.

Fuel arrangement influences GHG/A/BC emissions through effects on heat transfer among fuel particles in a fuelbed, the instantaneous and overall energy released during combustion, and the efficiency and rate of combustion (Ottmar et al., 2008; Ward, 1979). Traditional metrics for describing fuel arrangement include bulk density (kg m^{-3}), packing ratio (ratio of fuel volume to fuelbed volume) (Countryman and Philpot, 1970), and porosity (ratio of volume of air space to fuelbed volume). Note that the definition of porosity in Countryman and Philpot (1970) is nonstandard and typically not used. The porosity of a fuelbed is a measure of the void space within a fixed volume. In high porosity fuelbeds, air and energy are able to flow in easily altering the individual particles; similarly, air and energy are able to easily flow out of the fuelbed potentially reducing the chances of ignition of fuel particles. Fuelbed arrangement and porosity also affect the impact of precipitation and atmospheric relative humidity on dead fuel particles (Anderson, 1990; Fosberg, 1972; Matthews, 2006). Oxygen is typically more available for combustion in high-porosity fuelbeds, which can change the reactions that occur in the combustion process. Other metrics include horizontal continuity (percent cover) and vertical continuity (gap width). Fuels arranged so that combustion is most efficient will generate the fewest non-CO_2 emissions for each unit mass of fuel consumed (Ward and Hao, 1991). Fuel continuity (both horizontal and vertical) affects the relative ease with which a fire will sustain spread through a fuelbed which

has implications for area burned and resulting quantity of GHG/A/BC emissions.

Fuel amount and arrangement variables important for modeling the amount, source strength, and fate of emissions produced by wildland fires are inputs to physically based fire models such as FIRETEC, the Wildland-urban interface Fire Dynamics Simulator (WFDS), and the coupled fire-atmosphere models WRF-Fire and WRF-SFIRE (Coen et al., 2013; Linn et al., 2002; Mandel et al., 2011; Mell et al., 2007; Parsons et al., 2011). FIRETEC is a coupled fire-atmosphere model that solves governing physical equations to model combustion processes and fire behavior in a three-dimensional spatial domain. WFDS also simulates fire dynamics in a three-dimensional domain by solving governing physical equations, but atmospheric processes are not included. WRF-Fire and WRF-SFIRE couple a meteorological model with the Rothermel (1972) surface fire spread model to provide fire spread predictions. FIRETEC and WFDS have also been applied in fuel types outside of the US (Mell et al., 2007; Pimont et al., 2011). While numerous studies have investigated the effects of vegetation structure and arrangement on air flow in forest, shrub, and grass canopies (Aylor et al., 1993; Baldocchi and Meyers, 1988; Driese and Reiners, 1997; Wang, 2011), Pimont et al. (2011) may be the first to use a coupled fire-atmosphere model. Development of similar physics-based models is an active area of research in Europe and Australia as well; the interested reader is referred to recent reviews by Sullivan (2009a, 2009b, 2009c) for more details on the state of fire behavior modeling. Although they require a more detailed description of the fuel complex than has been performed traditionally, outputs from these types of models can contribute to our understanding of the relationship between fuels and emission impacts from wildland fires.

Terrestrial and aerial laser scanning (Loudermilk et al., 2012, 2009; Morsdorf et al., 2010; Seielstad et al., 2011) and newer methods and models for describing fuel arrangement and architecture show promise (Krivtsov et al., 2009; Parsons et al., 2011; Pimont et al., 2009; Todd et al., 2003). These techniques and tools can produce highly detailed, spatially explicit information about the fuelbed properties required to simulate pyrolysis, combustion, fuel consumption, and fire emissions with physics-based fire models. These modeling approaches are recent and have received limited testing. The resolution of the fuels information used by the aforementioned new generation of fire behavior models differs. The SFIRE component of WRF-SFIRE incorporates the Rothermel model which assumes steady-state fire dynamics so the level of detail in fuels as provided in a fuel model is sufficient and appropriate for WRF-SFIRE. However, FIRETEC and WFDS do not assume steady-state fire dynamics and require fuels data of greater complexity than is embodied in a fuel model.

In addition to affecting surface fuel properties, the arrangement of vegetation also affects airflow within canopies. Unburned vegetation above a wildland fire may affect the nature and quantity of emissions transported into the open air above the canopy. While there are numerous studies examining pollutant transport within canopies and deposition of pollutants from the atmosphere onto plant canopies (e.g. Karl et al., 2010), to our knowledge, there are few, if any, studies examining the filtering effect that plant canopies might have on smoke emissions that are lofted through the canopy. Potential condensation of water on foliage has been hypothesized, which suggests that other aerosols might condense on the canopy and not be lofted into the free air (Martin et al., 1969).

3.5. Moisture content

The proportion of fuel mass that is consumed during wildland fires varies as fuel moisture changes with diurnal, seasonal, and inter-annual fluctuations in environmental conditions and plant biology (Hough, 1978). Dead fuel moisture content varies with environmental conditions (solar radiation, temperature, relative humidity, and rainfall) and is affected by fuel particle size, weathering, and decay status (Anderson, 1985; Fosberg, 1970; Haines and Frost, 1978; Van Wagner, 1979) while live fuel moisture is a function of plant physiology and phenology (Agee et al., 2002; Kramer and Kozlowski, 1979). Nelson (2001) provided a detailed description of water relations in fuels. In fire danger calculations, live fuel moisture content is estimated from large woody fuel moisture content, drought indices, and other slow-responding measures of water content (Burgan, 1988, 1979; Viegas et al., 2001); however, recent work is examining the potential of more physiologically based methods to estimate the water content of living vegetation (Jolly et al., 2005; Thornley, 1996).

The water content of fuels (fuel moisture content) influences combustion dynamics in wildland fire by affecting the time-temperature history of dead and live fuels exposed to heat fluxes (Davis and Martin, 1960; Fletcher et al., 2007; Rothermel, 1972). The time-temperature history determines when moisture evaporates from the surface of the fuel, when pyrolysis begins and ends, when ignition occurs, when charring occurs, and when the burning of the fuel particle is finished. Thus, measures of fuel moisture are important for estimating fire danger (Deeming et al., 1977), fire behavior (Rothermel, 1972), and fuel consumption (Bragg, 1982; Goodrick et al., 2010; Hardy et al., 1996; Hough, 1978; Ottmar, 1983; Sandberg, 1980; Wright and Prichard, 2006). Indices of fuel moisture derived for fire behavior and fire danger estimation have been correlated with fuel consumption (Ottmar, 2014). Small dead fuel particles with a high ratio of surface area-to-volume respond more quickly to changes in relative humidity and precipitation than larger particles. Given sufficient time and lack of precipitation, large, downed logs (also known as coarse woody debris) can reach very low fuel moisture levels and burn, contributing significantly to residual smoldering combustion. Dead fuel moisture content of typical fuel particles can be measured directly by taking the difference between the weight of samples collected under ambient conditions and the weight after oven drying, or by regularly field-weighing voucher specimens (i.e., 10-hr timelag fuel moisture sticks) with known oven-dry weight. While standard techniques to determine moisture content of wood and wildland fuels exist (Countryman and Dean, 1979; D07 Committee, 2007; Norum and Miller, 1984), these techniques are often ignored to the possible detriment of the affected study. In the United States, previously developed statistically-derived models for dead fuel moisture content (Bradshaw et al., 1984) are being replaced gradually in operational systems by the physical model developed by Nelson (2000). Both of these models use daily weather observations as input.

Live fuel moisture content varies by species and season as plants complete their annual cycles of growth and senescence in response to environmental cues. The foliar moisture content of tree crowns and shrubs, in particular, can vary widely throughout the year (Agee et al., 2002; Blackmarr and Flanner, 1975; Chrosciewicz, 1986) and is theorized to affect vertical and horizontal fire initiation and spread (Scott and Reinhardt, 2001; Van Wagner, 1993). Similarly, grass fuels show pronounced seasonal trends in fuel moisture, and the propensity to burn, associated with annual curing as the moisture content of individual leaves and the ratio of live:dead plant parts change. Oven-dried samples collected from a few discrete locations traditionally provide the data to estimate the moisture content of live fuels. Periodic, repeated sampling from the same location over one or more years can be used to establish the timing and variability of seasonal fuel moisture trends (Countryman and Dean, 1979). Methods for analyzing remotely sensed imagery are being developed to estimate live fuel moisture content over large areas. To date these methods are limited by the spatial

resolution of the sensors being used and the strength of the relationship between fuel moisture and vegetation indices or spectral measurements (Dasgupta et al., 2007; Peterson et al., 2008; Schneider et al., 2008). Space-based sensors, such as MODIS and AVHRR, have spatial resolutions of 0.25–1.1 km depending on the spectral band and the sensor (Table 1). Compared to satellite-based instruments, airborne sensors have been shown to be superior for live fuel moisture estimation (Peterson et al., 2008). Airborne sensors can be used to improve the coarser resolution of space-borne instruments, which provide for more extensive spatial coverage (Cheng et al., 2006a; Roberts et al., 2006). Canopy structure affects correlations to estimate water content of live vegetation (Cheng et al., 2006b). Since current fire danger and behavior systems were designed primarily with dead fuels in mind, live fuel moisture information currently functions as an index of fire potential, at best (Alexander and Cruz, 2012; Fernandes and Cruz, 2012; Weise and Saveland, 1996), and the resolution provided by space-borne sensors is probably sufficient for the present.

Depending upon the fuelbed type and burning conditions, live fuels in general, and crown fuels in particular, represent a large emissions source from wildland fires. Should projected changes in climate lead to increases in water balance deficit in more productive ecosystems and shifts in plant distributions, this could lead to reductions in the fuel moisture content of live vegetation and increased combustion and consumption of live fuels, particularly if these areas experience an increase in fire frequency and area burned (Littell and Gwozdz, 2011).

4. Mapping

Recall that wildland fire emissions are determined as a function of the total area burnt over a given time period, the nature of the fuels present within the burnt areas, the fraction of the available fuel that is combusted, and the nature of the combustion. Vegetation, and therefore fuel, composition and characteristics are spatially dependent and influenced by the biophysical setting (e.g., latitude, slope, aspect, elevation, incoming solar radiation, potential evapotranspiration) of a given location. It is, therefore, critical to understand the spatial distribution of available fuel on the earth's surface so that geographically coincident information about area burned and fuels can be used to estimate wildland fire emissions.

Early fuel mapping efforts focused on assessing fire danger (Burgan and Shasby, 1984; Hornby, 1935) and, therefore, characterized only those components thought to be important for fire danger. As these map units do not include a description of many of the fuel elements that combust and contribute GHG/A/BC emissions during smoldering and glowing combustion, their use in emissions estimates will tend to underestimate total emissions and produce questionable results. Fuel model maps are currently limited to either 23 fire danger or 50 fire behavior categories.

4.1. Vegetation

Vegetation mapping is the process of delineating the geographic distribution, extent, and landscape patterns of vegetation types and/or structural characteristics. Consistent mapping of vegetation types requires that a classification be completed first because classification defines the entities to be mapped (Tart et al., 2005). Mapping and field checking vegetation types helps improve the classification concepts, which should facilitate more effective mapping of vegetation at multiple scales. Due to varying scale of vegetation patterns and the resolution of remotely sensed spatial data, map units may often include more than one vegetation type at any given level of the hierarchy. Both vegetation description detail and map unit spatial resolution must be considered.

A number of different remote sensing technologies are used for mapping vegetation types and attributes. Measurement and interpretation of spectral reflectance from vegetation has matured greatly from the initial LANDSAT imagery in the 1970s and is routinely used to identify and map vegetation types (Xie et al., 2008). A variety of satellite sensors that operate in different portions of the electromagnetic spectrum with varying levels of spatial and temporal resolution are commonly used in vegetation mapping (Table 1). Fuel mapping efforts often use remote sensing-based vegetation maps as data sources.

Estimation of available fuel mass is one of the largest sources of error in the estimation of emissions from wildland fire (Ottmar et al., 2008). In addition to classifying vegetation, remote sensing technology has the potential also to estimate biomass. Biomass estimation from remote sensing is still a challenge and a current area of research and development (Lu, 2006). Since biomass estimation involves integration of different sensors, algorithms and variables, an understanding of the sources of uncertainty is critical. As an example, the root mean square error of models associated with a fine resolution biomass map of temperate forest ranged from 14 to 34 Mg ha^{-1} (Zhao et al., 2009).

4.2. Fuels

Fuels have been mapped using remote sensing, biophysical modeling, field reconnaissance, and sampling approaches (Keane et al., 2001). Methods that use a combination of the aforemen-

Table 1
Remote sensing platforms commonly used in vegetation mapping and biomass estimation (adapted from Table 1, Xie et al., 2008).

Sensor	Spatial resolution	Application
Landsat TM	30 m (multispectral) 120 m (thermal IR)	Vegetation community mapping at regional scales
Landsat ETM+	15 m (panchromatic) 30 m (multispectral) 60 m (thermal IR)	Vegetation community and sometimes dominant species mapping at regional scales
SPOT	2.5–20 m (various modes)	Vegetation community and species mapping at regional scales
MODIS	250–1000 m (multispectral)	Land cover type mapping at global and continental scales
AVHRR	1100–5000 m (visible, near IR, thermal IR)	Land cover type mapping at global and continental scales
IKONOS	1 m (panchromatic, multispectral)	Vegetation community and species mapping at local and regional scales
QuickBird	0.6 m (panchromatic) 2.4 m (multispectral)	Vegetation community and species mapping at local and regional scales
ASTER	15 m (near IR) 30 m (short wave IR) 90 m (thermal IR)	Vegetation community and species at regional to continental scales
AVIRIS	Varies from approx. 1–30 m (hyperspectral)	Vegetation community and species at local to regional scales
Hyperion	30 m (hyperspectral)	Vegetation community and species at regional scales

tioned approaches have the highest likelihood of generating the most useful, accurate, and complete spatial characterization of wildland fuels. The most commonly used remote sensing method is to indirectly map fuels by relating fuel characteristics to readily identifiable attributes in the imagery, such as broad vegetation types or land cover classes, so development of technologies and methods for mapping vegetation bear directly on mapping fuels. Vegetation types or classes are often not well correlated with fuelbed properties which may compromise the accuracy and utility of the resulting map product when attempting to relate remotely sensed vegetation attributes to fuel characteristics and conditions (Reich et al., 2004).

Remote sensing can also be used to directly map some fuelbed characteristics (e.g., fuelbed height, leaf area, etc.) and has been commonly used to map foliage moisture content for fire danger and fire behavior purposes (Burgan and Shasby, 1984; Peterson et al., 2008). Not all fuelbed attributes can be resolved with imagery; a full accounting of fuelbed characteristics and conditions is not possible using direct mapping methods. In addition, many fuel characteristics vary over spatial scales that are too small (i.e., <1 m) to be resolved by many satellite-based sensors. Airborne sensors are generally able to provide higher resolution data than satellite sensors (Andersen et al., 2005), and ground-based sensors are able to provide higher resolution than airborne sensors (Loudermilk et al., 2009; Seielstad et al., 2011). In forested systems, remote sensing instruments may be unable to differentiate spectral differences between canopy and surface fuels (Belward et al., 1994; van Leeuwen and Huete, 1996) and tree canopies physically obstruct the sensor's view of fuels in lower strata (Keane et al., 2001). In vegetation types with more open canopies, ground and canopy coverage mapping has been achieved with accuracies >80% (Muñoz-Robles et al., 2012). Newer technologies, such as Light Detection and Ranging (LiDAR) and Synthetic Aperture Radar (SAR) show promise for being able to see through and below tree canopies to improve the measurement resolution of different structural attributes of the fuelbed (Gleason and Im, 2011; Roberts et al., 2007; Saatchi et al., 2007; Seielstad and Queen, 2003; van Leeuwen and Nieuwenhuis, 2010). Saatchi et al. (2007) report that SAR fuel estimates accounted for 70% of variation in field data at plot and stand levels and as much as 85% of the variation when separated into fuel load classes.

Biophysical modeling is another indirect fuel mapping method that relates information about environmental gradients, disturbance history, and ecological processes to vegetation dynamics to predict fuel characteristics (Keane et al., 2001). A number of analytical techniques are employed, including gradient nearest neighbor imputation (Ohmann and Gregory, 2002) and compartment modeling (Hall et al., 2006). A benefit of this approach is that the linkage between biophysical processes and fuel characteristics can be used to dynamically map fuelbeds as climate and disturbance regimes change (Keane et al., 2001).

Field reconnaissance mapping (Hornby, 1936) which involves *in situ* measurements or assignments of fuel characteristics for specific areas based on direct human observation is costly and impractical given modern funding and staffing limits, but it is performed at small spatial scales (<100 m^2) for use in image classification or photo interpretation and accuracy assessment and validation. The aforementioned biophysical modeling parameterizes relationships from spatially referenced plot-level vegetation and fuels data.

The Landscape Fire and Resource Management Planning Tools project (LANDFIRE; Rollins et al., 2004) has used a combination of direct and indirect remote sensing, biophysical modeling, and field sampling to produce a comprehensive, 30 m-resolution national map of different vegetation and fuels classes and attributes (Fig. 5). LANDFIRE fuels products include maps of fuel models (Albini, 1976; Deeming et al., 1977; Scott and Burgan, 2005; Stocks et al., 1989), FCCS fuelbeds (McKenzie et al., 2007; Ottmar et al., 2007), fuel loading models (Lutes et al., 2009), and different canopy fuel characteristics (coverage, height, base height, and bulk density). Integration of multiple data sources and fuel mapping techniques for the LANDFIRE project represents a significant advancement in fuel mapping capabilities; however, its reliance on indirect methods and modeling means that LANDFIRE designations for individual map pixels may not accurately represent existing fuelbed characteristics.

Development of data reduction and analysis techniques for the various sensors, including airborne and terrestrial LiDAR, is an area of active research that could represent the next step forward in fuel characterization. For example, image fusion, a technique that combines airborne LiDAR and advanced image-processing, is able to produce information that cannot be attained from a single sensor and appears to provide improvements in estimates based on LiDAR alone (Erdody and Moskal, 2010; Mutlu et al., 2008). Other types of image fusion using Quickbird imagery have been used with some success in pasture and woody vegetation (Muñoz-Robles et al., 2012). Innovative techniques that integrate repeat imagery, field data, and disturbance history (Meigs et al., 2011; Powell et al., 2010) are also contributing to a more robust understanding of trends in biomass accumulation and therefore potential future fuel loading and GHG/A/BC emissions.

5. Knowledge gaps

Methods for estimating GHG/A/BC emissions from wildland fires rely on accurate characterization of the fuelbeds that burn within the fire perimeter. Although fuels are characterized for many ecosystems, there are still many types that are described insufficiently. There is currently no central repository containing all of the fuels information that has been published in the US and old data are often overlooked by current researchers (Wendel et al., 1962). Fuelbeds in landscapes that are dominated by invasive species such as salt cedar (*Tamarix pentandra*), cheatgrass (*Bromus tectorum*), buffel grass (*Cenchrus ciliaris*), fountaingrass (*Pennisetum setaceum*), Brazilian peppertree (*Schinus terebinthefolius*), and melaleuca (*Melaleuca quinquenervia*) now experience uncharacteristically frequent or intense fire and require additional study (Loope, 2000; Wade et al., 1979; Zouhar et al., 2008). In addition, very little research has been conducted to document fuel characteristics in shortgrass prairies and many wetland ecosystems (Wade et al., 1979; Wendel et al., 1962). Preliminary investigations are underway in manipulated fuelbeds such as those treated with different kinds of mastication equipment (Battaglia et al., 2010; Kane et al., 2009; Sikes and Muir, 2009) and mulches (Manzello et al., 2006; Steward et al., 2003), although more research and development is warranted. In addition, further study is necessary to determine how novel vegetation and fuel assemblages arising under an altered climate regime could affect area burned, combustion efficiency, fuel loading and consumption, and, ultimately, GHG/A/BC emissions.

In addition to a shortage of information for some wetland fuelbed types, some fuelbed components are also quantified poorly. In particular, description of belowground and soil fuel characteristics is not well defined or documented. The belowground component is important from a carbon cycling and accounting perspective, as it has been estimated that 30% or more of the total site biomass is plant roots (Seiler and Crutzen, 1980). Large amounts of biomass with long-duration smoldering potential are found in ecosystems with deep organic soils, such as pocosin shrublands in the Atlantic coastal plain of the US (Blackmarr and Flanner, 1975; Frandsen, 1997; McMahon et al., 1980; Reardon et al., 2007; Wendel et al., 1962) and sphagnum bogs in boreal regions. Our inability to de-

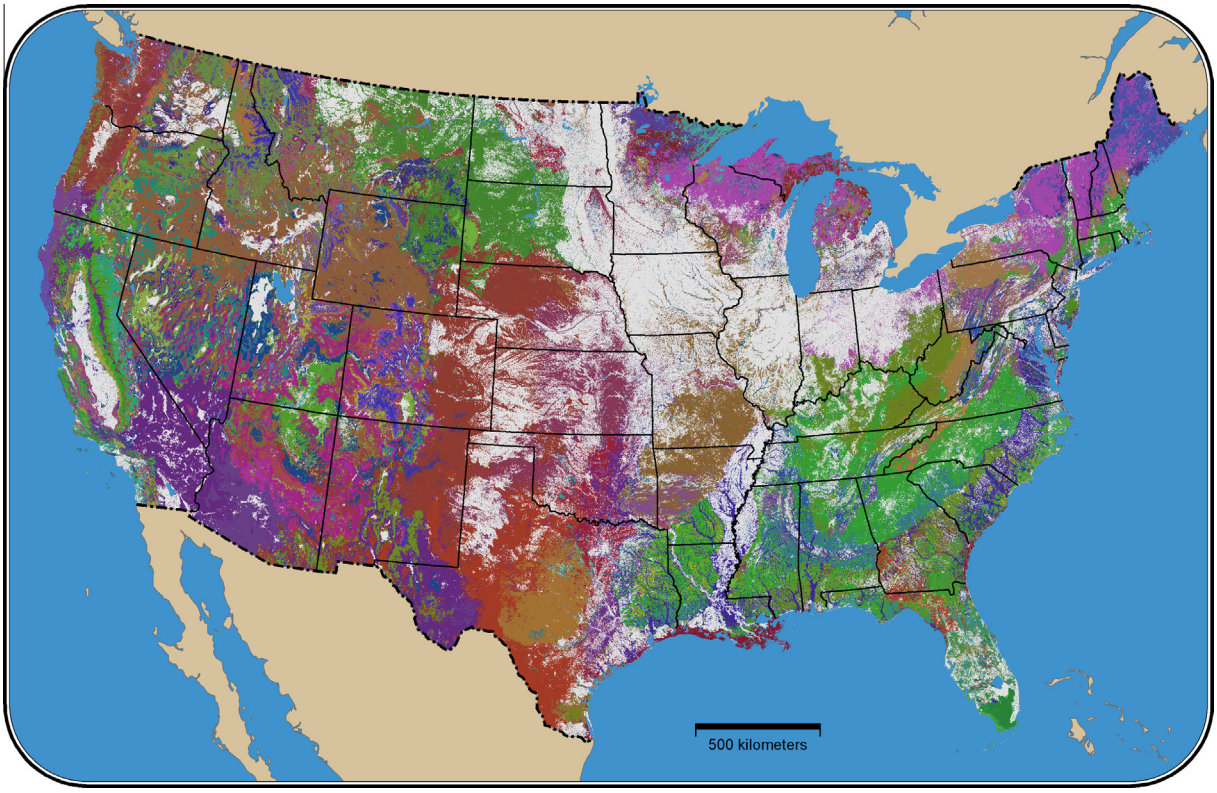

Fig. 5. Fuel Characteristic Classification System (FCCS) fuelbed map (1-km resolution) for the conterminous United States derived from LANDFIRE existing vegetation types. This is an example of a fuel map product developed by using direct and indirect remote sensing, and biophysical modeling.

scribe fully their biogeochemical characteristics (including moisture dynamics) limits our ability to adequately estimate and model fire behavior and effects, including fuel consumption and emissions. Although not typically considered a wildland fuel, with the increasing encroachment of development into the wildlands, structures represent a large potential emission source in some locations. At present there is no method or framework for characterizing houses and other built infrastructure in the context of wildland fire and GHG/A/BC emissions. Between 1990 and 2007, approximately 250–3000 homes burned annually in extreme wildfires (Cohen, 2008); in 2010 alone, the National Fire Protection Association reported 46,300 intentionally set structure fires (http://www.nfpa.org/assets/files/PDF/Latest%20estimates/Latest-EstimatesIntentionalFires.pdf). Given the relatively small number of houses burned by wildland fire and the complexity of materials within such structures, the contribution of these structures to emissions from wildland fire is unknown and may actually be more important in other categories of GHG/A/BC emissions.

The relationship among fuel characteristics, fuel consumption, and emissions is relatively poorly documented and understood for several fuel components, including tree crowns, live shrubs, and belowground biomass. Both FOFEM and CONSUME, software tools for estimating fuel consumption and emissions that currently represent the state of the art, do not include any evidence-based prediction capability for canopy fuel consumption and require a best-guess estimate by the user. FOFEM and CONSUME also have a very limited selection of models for estimating live fuel consumption (Hough, 1978; Wright and Prichard, 2006), although work is ongoing in this area (Goodrick et al., 2010; Reid et al., 2012; Wright, in press-a, in press-b).

The deposition of aerosols on vegetation surfaces in canopies as smoke is lofted through the canopy has not been reported anywhere in the literature to our knowledge. The impact of this "scrubbing" or "filtering" effect on the quantity of emissions introduced into the free air is unknown.

Methods for describing fuel heterogeneity and discontinuity (or connectedness) at all spatial scales require new techniques, methods, and metrics. Heterogeneity and discontinuity have been shown to affect fire spread and intensity, which will ultimately influence emissions production by way of effects on area burned, combustion efficiency, consumption rate and amount of fuel consumed. Related to the concept of developing more sophisticated methods for quantifying spatial properties of the fuelbed, our ability to describe the variability and level of uncertainty in fuel type and amount in fuel maps needs additional attention to refine emissions estimates (French et al., 2011, 2004).

6. Summary

Description and quantification of wildland fuel consumption is a key step in the estimation of emissions produced by wildland fire. Numerous systems and tools have been devised to characterize vegetation and wildland fuels in the United States. Older systems do not contain the necessary information to describe realistically the wildland fuel complex nor do we have adequate tools to provide a cost-effective, reliable inventory of the actual mass of wildland fuel produced and burned annually. There are many promising solutions to these problems, but national implementation will be required.

Several important fuel types are described poorly such as masticated fuels, organic soils, wetland fuelbeds, invasive species, and shortgrass prairie. Fuelbed elements not related to fire spread or fire danger prediction have not been quantified extensively. The relationships among fuel characteristics, fuel consumption, and emissions are poorly documented and understood for several fuel

components including tree crowns, live shrubs, and belowground biomass. Elimination of many of these knowledge gaps should reduce the uncertainty associated with the fuel component of the GHG/A/BC emissions equation.

References

Aber, J.D., 1979. Foliage-height profiles and succession in northern hardwood forests. Ecology 60, 18–23.

Agca, M., Popescu, S.C., Harper, C.W., 2011. Deriving forest canopy fuel parameters for loblolly pine forests in eastern Texas. Can. J. For. Res. 41, 1618–1625.

Agee, J.K., Wright, C.S., Williamson, N., Huff, M.H., 2002. Foliar moisture content of Pacific Northwest vegetation and its relation to wildland fire behavior. For. Ecol. Manage. 167, 57–66.

Akagi, S.K., Yokelson, R.J., Burling, I.R., Meinardi, S., Simpson, I., Blake, D.R., McMeeking, G.R., Sullivan, A., Lee, T., Kreidenweis, S., Urbanski, S., Reardon, J., Griffith, D.W.T., Johnson, T.J., Weise, D.R., 2012. Measurements of reactive trace gases and variable O_3 formation rates in some South Carolina biomass burning plumes. Atmos. Chem. Phys. Discuss. 12, 25255–25328.

Albini, F.A., 1976. Estimating wildfire behavior and effects (General Technical Report No. INT-30). USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Albini, F.A., Reinhardt, E.D., 1995. Modeling ignition and burning rate of large woody natural fuels. Int. J. Wildland Fire 5, 81–91.

Albini, F.A., Reinhardt, E.D., 1997. Improved calibration of a large fuel burnout model. Int. J. Wildland Fire 7, 21–28.

Alexander, M.E., Cruz, M.G., 2012. Assessing the effect of foliar moisture on the spread rate of crown fires. Int. J. Wildland Fire.

Andersen, H., McGaughey, R.J., Reutebuch, S., 2005. Estimating forest canopy fuel parameters using LIDAR data. Remote Sens. Environ. 94, 441–449.

Anderson, H.E., 1970. Forest fuel ignitibility. Fire Technol. 6, 312–319.

Anderson, H.E., 1982. Aids to determining fuel models for estimating fire behavior (General Technical Report No. INT-122). USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Anderson, H.E., 1985. Moisture and fine forest fuel response. In: Proceedings of the Eighth Symposium on Fire and Forest Meteorology. Society of American Foresters, Detroit, MI, pp. 192–199.

Anderson, H.E., 1990. Moisture diffusivity and response time in fine forest fuels. Can. J. For. Res. 20, 315–325.

Aylor, D.E., Wang, Y., Miller, D.R., 1993. Intermittent wind close to the ground within a grass canopy. Bound. Layer Meteorol. 66, 427–448.

Babrauskas, V., 2003. Ignition Handbook: Principles and Applications to Fire Safety Engineering, Fire Investigation, Risk Management and Forensic Science. Fire Science Publishers; Society of Fire Protection Engineers, Issaquah, WA (Bethesda, Md.).

Baldocchi, D.D., Meyers, T.P., 1988. Turbulence structure in a deciduous forest. Bound. Layer Meteorol. 43, 345–364.

Barbour, M.G., Billings, W.D., 2000. North American Terrestrial Vegetation, second ed. Cambridge University Press, Cambridge, UK.

Battaglia, M.A., Rocca, M.E., Rhoades, C.C., Ryan, M.G., 2010. Surface fuel loadings within mulching treatments in Colorado coniferous forests. For. Ecol. Manage. 260, 1557–1566.

Belward, A.S., Kennedy, P.J., Gregoire, J.M., 1994. The limitations and potential of AVHRR GAC data for continental scale fire studies. Int. J. Remote Sens. 15, 2215–2234.

Bergman, R., Cai, Z., Carli, C.G., Clausen, C.A., Dietenberger, M.A., Falk, R.H., Frihart, C.R., Glass, S.V., Hunt, C.G., Ibach, R.E., Kretschmann, D.E., Rammer, D.R., Ross, R.J., Stark, N.M., Wacker, J.P., Wang, X., White, R.H., Wiedenhoeft, A.C., Wiemann, M.C., Zelinka, S.L., 2010. Wood Handbook, Wood as an Engineering Material (General Technical Report No. FPL-GTR-190). USDA Forest Service, Forest Products Laboratory, Madison, WI.

Bidwell, R.G.S., 1979. Plant Physiology. Macmillan, New York.

Biging, G.S., Gill, S.J., 1997. Stochastic models for conifer tree crown profiles. For. Sci. 43, 25–34.

Blackmarr, W.H., Flanner, W.B., 1975. Moisture variation in selected pocosin shrubs of eastern North Carolina (Research Paper No. SE-124). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., DeFries, R.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz, M.A., Prentice, I.C., Roos, C.I., Scott, A.C., Swetnam, T.W., Van der Werf, G.R., Pyne, S.J., 2009. Fire in the Earth system. Science 324, 481–484.

Bradshaw, L.S., Deeming, J.E., Burgan, R.E., Cohen, J.D., 1984. The 1978 National Fire-Danger Rating System: technical documentation (General Technical Report No. INT-169). USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Bragg, T.B., 1982. Seasonal variations in fuel and fuel consumption by fires in a bluestem prairie. Ecology 63, 7–11.

Brown, J.K., 1970. Ratios of surface area to volume for common fine fuels. For. Sci. 16, 101–105.

Brown, J.K., 1971. A planar intersect method for sampling fuel volume and surface area. For. Sci. 17, 96–102.

Brown, J.K., 1976. Estimating shrub biomass from basal stem diameters. Can. J. For. Res. 6, 153–158.

Brown, J.K., 1978. Weight and density of crowns of Rocky Mountain conifers (Research Paper No. INT-197). USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Brown, J.K., Bevins, C.D., 1986. Surface fuel loadings and predicted fire behavior for vegetation types in the northern Rocky Mountains (Research Note No. INT-358). USDA Forest Service, Intermountain Research Station, Ogden, UT.

Brown, J.K., Reinhardt, E.D., Fischer, W.C., 1991. Predicting duff and woody fuel consumption in northern Idaho prescribed fires. For. Sci. 37, 1550–1566.

Brown, J.K., Smith, J.K., Lyon, L.J., 2000. Wildland fire in ecosystems: effects of fire on flora (General Technical Report No. RMRS-GTR-42-vol.2). USDA Forest Service, Rocky Mountain Research Station, Ogden, UT.

Burgan, R.E., 1979. Estimating live fuel moisture for the 1978 National Fire Danger Rating System (Research Paper No. INT-226). USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Burgan, R.E., 1987. Concepts and interpreted examples in advanced fuel modeling (General Technical Report No. INT-238). US Department of Agriculture, Forest Service, Intermountain Research Station, Ogden, UT.

Burgan, R.E., 1988. 1988 Revisions to the 1978 National Fire-Danger Rating System (Research Paper No. SE-273). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Burgan, R.E., Rothermel, R.C., 1984. BEHAVE: Fire Behavior Prediction and Fuel Modeling System–FUEL Subsystem (General Technical Report No. INT-167). USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.

Burgan, R.E., Shasby, M.B., 1984. Mapping broad-area fire potential from digital fuel, terrain, and weather data. J. For. 82, 228–231.

Byram, G.M., 1959. Combustion of forest fuels. In: Forest Fire: Control and Use. McGraw-Hill, Inc. pp. 61–89.

Byram, G.M., Jemison, G.M., 1943. Solar radiation and forest fuel moisture. J. Agric. Res. 67, 149–176.

Canfield, R.H., 1941. Application of the line interception method in sampling range vegetation. J. For. 39, 388–394.

Central Intelligence Agency, 2009. The World Factbook 2009. Central Intelligence Agency, Washington, DC.

Chen, L.-W.A., Moosmüller, H., Arnott, W.P., Chow, J.C., Watson, J.G., Susott, R.A., Babbitt, R.E., Wold, C.E., Lincoln, E.N., Hao, W.M., 2007. Emissions from laboratory combustion of wildland fuels: emission factors and source profiles. Environ. Sci. Technol. 41, 4317–4325.

Cheng, Y., Gamon, J., Fuentes, D., Mao, Z., Sims, D., Qiu, H., Claudio, H., Huete, A., Rahman, A., 2006a. A multi-scale analysis of dynamic optical signals in a southern California chaparral ecosystem: a comparison of field, AVIRIS and MODIS data. Remote Sens. Environ. 103, 369–378.

Cheng, Y.-B., Zarco-Tejada, P.J., Riaño, D., Rueda, C.A., Ustin, S.L., 2006b. Estimating vegetation water content with hyperspectral data for different canopy scenarios: relationships between AVIRIS and MODIS indexes. Remote Sens. Environ. 105, 354–366.

Chrosciewicz, Z., 1986. Foliar moisture content variations in four coniferous tree species of central Alberta. Can. J. For. Res. 16, 157–162.

Clark, A.I., Taras, M.A., 1976. Comparison of aboveground biomasses of the four major southern pines. For. Prod. J. 26, 25–29.

Clark, A.I., Phillips, D.R., Frederick, D.J., 1985. Weight, volume, and physical properties of major hardwood species in the Piedmont (Research Paper No. SE-255). USDA Forest Service Southeastern Forest Experiment Station, Asheville, NC.

Coen, J.L., Cameron, M., Michalakes, J., Patton, E.G., Riggan, P.J., Yedinak, K.M., 2013. WRF-fire: coupled weather-wildland fire modeling with the weather research and forecasting model. J. Appl. Meteorol. Climatol. 52, 16–38.

Cohen, J.D., 1986. Estimating fire behavior with FIRECAST: user's manual (General Technical Report No. PSW-90). USDA Forest Service, Pacific Southwest Research Station, Berkeley, CA.

Cohen, J., 2008. The wildland-urban interface fire problem: a consequence of the fire exclusion paradigm. For. Hist. Today, 20–26.

Countryman, C.M., 1964. Mass fires and fire behavior (Research Paper No. PSW-19). USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

Countryman, C.M., Dean, W.A., 1979. Measuring moisture content in living chaparral: a field user's manual (General Technical Report No. PSW-36). USDA Forest Service, Pacific Southwest Research Station, Berkeley, CA.

Countryman, C.M., Philpot, C.W., 1970. Physical characteristics of chamise as a wildland fuel (Research Paper No. 66). USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

Cruz, M.G., Alexander, M.E., Wakimoto, R.H., 2003. Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. Int. J. Wildland Fire 12, 39–50.

Cruz, M.G., Alexander, M.E., Wakimoto, R.H., 2010. Corrigendum to: Assessing canopy fuel stratum characteristics in crown fire prone fuel types of western North America. Int. J. Wildland Fire 19, iii.

D07 Committee, 2007. Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials (No. ASTM Standard D4442-07). ASTM International, West Conshohocken, PA.

Dasgupta, S., Qu, J., Hao, X., Bhoi, S., 2007. Evaluating remotely sensed live fuel moisture estimations for fire behavior predictions in Georgia, USA. Sens. Environ. 108, 138–150.

Daubenmire, R., 1968. Plant Communities. A Textbook of Plant Synecology. Harper & Row, New York.

Davis, L.S., Martin, R.E., 1960. Time-temperature relationships of test head fires and backfires (Research Notes No. 148). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.
De Cáceres, M., Wiser, S.K., 2012. Towards consistency in vegetation classification. J. Veg. Sci. 23, 387–393.
Deeming, J.E., Brown, J.K., 1975. Fuel models in the national fire-danger rating system. J. For. 73, 347–350.
Deeming, J.E., Burgan, R.E., Cohen, J.D., 1977. The National Fire-danger Rating System – 1978 (General Technical Report No. INT-39). USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.
Demirbas, A., 2004. Combustion characteristics of different biomass fuels. Prog. Energy Combust. Sci. 30, 219–230.
Dickinson, Y.L., Zenner, E.K., 2010. Allometric equations for the aboveground biomass of selected common eastern hardwood understory species. North. J. Appl. For. 27, 160–165.
Dicus, C.A., Delfino, K., Weise, D.R., 2009. Predicted fire behavior and societal benefits in three eastern Sierra Nevada vegetation types. Fire Ecol. 5, 67–78.
Dore, W.H., 1920. The proximate analysis of coniferous woods. Ind. Eng. Chem. 12, 476–479.
Driese, K.L., Reiners, W.A., 1997. Aerodynamic roughness parameters for semi-arid natural shrub communities of Wyoming, USA. Agric. For. Meteorol. 88, 1–14.
Erdody, T.L., Moskal, L.M., 2010. Fusion of LiDAR and imagery for estimating forest canopy fuels. Remote Sens. Environ. 114, 725–737.
Eyre, F.H., 1980. Forest Cover Types of the United States and Canada. Society of American Foresters, Bethesda, MD.
Federal Geographic Data Committee, 1997. Vegetation Classification Standard. FGDC Secretariat, US Geological Survey, Reston, VA.
Federal Geographic Data Committee, 2008. National Vegetation Classification Standard, Version 2. FGDC Secretariat, US Geological Survey, Reston, VA.
Fengel, D., Wegener, G., 1989. Wood: Chemistry, Ultrastructure. Reactions. Walter de Gruyter & Co., Berlin.
Fernandes, P.M., Cruz, M.G., 2012. Plant flammability experiments offer limited insight into vegetation-fire dynamics interactions. New Phytol. 194, 606–609.
Finney, M.A., 1998. FARSITE, Fire Area Simulator–model development and evaluation (Research Paper No. RMRS-RP-4). USDA Forest Service, Rocky Mountain Research Station, Ft. Collins, CO.
Fletcher, T.H., Pickett, B.M., Smith, S.G., Spittle, G.S., Woodhouse, M.M., Haake, E., Weise, D.R., 2007. Effects of moisture on ignition behavior of moist California and Utah leaves. Combust. Sci. Technol. 179, 1183–1203.
Fosberg, M.A., 1970. Drying rates of heartwood below fiber saturation. For. Sci. 16, 57–63.
Fosberg, M.A., 1972. Theory of precipitation effects on dead cylindrical fuels. For. Sci. 18, 98–108.
Frandsen, W.H., 1983. Modeling big sagebrush as a fuel. J. Range Manag. 36, 596–600.
Frandsen, W.H., 1997. Ignition probability of organic soils. Can. J. For. Res. 27, 1471–1477.
Franklin, J.F., Dyrness, C.T., 1988. Natural Vegetation of Oregon and Washington. Oregon State University Press, Corvallis, OR.
Freifelder, R.R., Vitousek, P.M., D'Antonio, C.M., 1998. Microclimate change and effect on fire following forest-grass conversion in seasonally dry tropical woodland. Biotropica 30, 286–297.
French, N.H.F., Goovaerts, P., Kasischke, E.S., 2004. Uncertainty in estimating carbon emissions from boreal forest fires. J. Geophys. Res. 109, D14S08.
French, N.H.F., De Groot, W.J., Jenkins, L.K., Rogers, B.M., Alvarado, E., Amiro, B., De Jong, B., Goetz, S., Hoy, E., Hyer, E., Keane, R., Law, B.E., McKenzie, D., McNulty, S.G., Ottmar, R., Pérez-Salicrup, D.R., Randerson, J., Robertson, K.M., Turetsky, M., 2011. Model comparisons for estimating carbon emissions from North American wildland fire. J. Geophys. Res. 116, G00K05.
Friedl, A., Padouvas, E., Rotter, H., Varmuza, K., 2005. Prediction of heating values of biomass fuel from elemental composition. Anal. Chim. Acta 544, 191–198.
Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., Wickham, J., 2011. Completion of the 2006 national land cover database for the conterminous United States. Photogramm. Eng. Remote Sens. 77, 858–864.
Garber, S.M., Maguire, D.A., 2005. The response of vertical foliage distribution to spacing and species composition in mixed conifer stands in central Oregon. For. Ecol. Manage. 211, 341–355.
Gleason, C.J., Im, J., 2011. A review of remote sensing of forest biomass and biofuel: options for small-area applications. GIScience Remote Sens. 48, 141–170.
Goering, H.K., Van Soest, P.J., 1970. Forage Fiber Analysis (Apparatus, Reagents, Procedures and Some Applications) (Agricultural Handbook No. 379). USDA Agricultural Research Service, Washington, DC.
Goodrick, S.L., Shea, D., Blake, J., 2010. Estimating fuel consumption for the upper coastal plain of South Carolina. S. J. Appl. For. 34, 5–12.
Greig-Smith, P., 1952. The use of random and contiguous quadrats in the study of the structure of plant communities. Ann. Bot. 16, 293–316.
Haines, D.A., Frost, J.S., 1978. Weathering effects on fuel moisture sticks: corrections and recommendations (Research Paper No. NC-154). USDA Forest Service, Northcentral Forest Experiment Station, St. Paul, MN.
Hall, S.A., Burke, I.C., Hobbs, N.T., 2006. Litter and dead wood dynamics in ponderosa pine forests along a 160-year chronosequence. Ecol. Appl. 16, 2344–2355.
Hardy, C.C., Conard, S.G., Regelbrugge, J.C., Teesdale, D.R., 1996. Smoke emissions from prescribed burning of southern California chaparral (Research Paper No. PNW-RP-486). USDA Forest Service, Pacific Northwest Research Station, Portland, OR.
Hardy, C.C., Ottmar, R.D., Peterson, J.L., Core, J.E., Seamon, P., 2001. Smoke Management Guide for Prescribed and Wildland fire, 2001 edition (Report No. PMS-420-2). National Wildfire Coordination Group, Boise, ID.
Hays, M.D., Geron, C.D., Linna, K.J., Smith, N.D., Schauer, J.J., 2002. Speciation of gas-phase and fine particle emissions from burning of foliar fuels. Environ. Sci. Technol. 36, 2281–2295.
Hessl, A.E., 2011. Pathways for climate change effects on fire: models, data, and uncertainties. Prog. Phys. Geog. 35, 393–407.
Homer, C., Huang, C., Yang, L., Wylie, B., Coan, M., 2004. Development of a 2001 national land cover database for the United States. Photogramm. Eng. Remote Sens. 70, 829–840.
Hornby, L.G., 1935. Fuel type mapping in region one. J. For. 33, 67–72.
Hornby, L.G., 1936. Fire control planning in the northern Rocky Mountain region (Progress Report 1). USDA Forest Service, Northern Rocky Mountain Forest and Range Experiment Station, Missoula, MT.
Hough, W.A., 1969. Caloric value of some forest fuels of the southern United States (Research Note No. SE-120). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.
Hough, W.A., 1973. Fuel and weather influence wildfires in sand pine forests (Research Paper No. SE-106). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.
Hough, W.A., 1978. Estimating available fuel weight consumed by prescribed fires in the South (Research Paper No. SE-187). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.
Hough, W.A., Albini, F.A., 1978. Predicting fire behavior in palmetto-gallberry fuel complexes (Research Paper No. SE-174). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.
Husch, B., Beers, T.W., Kershaw Jr., J.A., 2003. Forest Mensuration, fourth ed. J. Wiley, New York.
Jenkins, B., Baxter, L., Miles, T., Miles, T., 1998. Combustion properties of biomass. Fuel Process. Techol. 54, 17–46.
Jenkins, J.C., Chojnacky, D.C., Heath, L.S., Birdsey, R.A., 2004. National-scale biomass estimators for United States tree species. For. Sci. 49, 12–35.
Jenkins, M.J., Page, W.G., Hebertson, E.G., Alexander, M.E., 2012. Fuels and fire behavior dynamics in bark beetle-attacked forests in western North America and implications for fire management. For. Ecol. Manage. 275, 23–34.
Jennings, M.D., Faber-Langendoen, D., Loucks, O.L., Peet, R.K., Roberts, D., 2009. Standards for associations and alliances of the US National Vegetation Classification. Ecol. Monogr. 79, 173–199.
Jolly, W.M., Nemani, R., Running, S.W., 2005. A generalized, bioclimatic index to predict foliar phenology in response to climate. Glob. Change Biol. 11, 619–632.
Jones, H., Vaughan, R., 2010. Remote Sensing of Vegetation: Principles, Techniques, and Applications. Oxford University Press, New York.
Jorgensen, C.A., Jenkins, M.J., 2011. Fuel complex alterations associated with spruce beetle-induced tree mortality in intermountain spruce/fir forests. For. Sci. 57, 232–240.
Kalabokidis, K., Omi, P., 1992. Quadrat analysis of wildland fuel spatial variability. Int. J. Wildland Fire 2, 145–152.
Kane, J.M., Varner, J.M., Hiers, J.K., 2008. The burning characteristics of southeastern oaks: discriminating fire facilitators from fire impeders. For. Ecol. Manage. 256, 2039–2045.
Kane, J.M., Varner, J.M., Knapp, E.E., 2009. Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon, USA. Int. J. Wildland Fire 18, 686–697.
Karl, T., Harley, P., Emmons, L., Thornton, B., Guenther, A., Basu, C., Turnipseed, A., Jardine, K., 2010. Efficient atmospheric cleansing of oxidized organic trace gases by vegetation. Science 330, 816–819.
Keane, R.E., 2008. Biophysical controls on surface fuel litterfall and decomposition in the northern Rocky Mountains, USA. Can. J. For. Res. 38, 1431–1445.
Keane, R.E., 2013. Describing wildland surface fuel loading for fire management: a review of approaches, methods, and systems. Int. J. Wildland Fire 22, 51–62.
Keane, R.E., Dickinson, L.J., 2007. The photoload sampling technique: estimating surface fuel loadings from downward-looking photographs of synthetic fuelbeds (General Technical Report No. RMRS-GTR-190). USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
Keane, R.E., Burgan, R., Van Wagtendonk, J., 2001. Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS, and biophysical modeling. Int. J. Wildland Fire 10, 301–319.
Keane, R.E., Reinhardt, E.D., Scott, J., Gray, K., Reardon, J., 2005. Estimating forest canopy bulk density using six indirect methods. Can. J. For. Res. 35, 724–739.
Keyser, T., Smith, F.W., 2010. Influence of crown biomass estimators and distribution on canopy fuel characteristics in ponderosa pine stands of the Black Hills. For. Sci. 56, 156–165.
Knapp, E.E., Varner, J.M., Busse, M.D., Skinner, C.N., Shestak, C.J., 2011. Behaviour and effects of prescribed fire in masticated fuelbeds. Int. J. Wildland Fire 20, 932.
Kramer, P.J., Kozlowski, T.T., 1979. Physiology of Woody Plants. Academic Press, New York.
Krivtsov, V., Vigy, O., Legg, C., Curt, T., Rigolot, E., Lecomte, I., Jappiot, M., Lampin-Maillet, C., Fernandes, P., Pezzatti, G.B., 2009. Fuel modelling in terrestrial ecosystems: an overview in the context of the development of an object-orientated database for wild fire analysis. Ecol. Model. 220, 2915–2926.
Linn, R., Reisner, J., Colman, J.J., Winterkamp, J., 2002. Studying wildfire behavior using FIRETEC. Int. J. Wildland Fire 11, 233–246.

Littell, J.S., Gwozdz, R.B., 2011. Climatic water balance and regional fire years in the Pacific Northwest, USA: linking regional climate and fire at landscape scales. In: McKenzie, D., Miller, C., Falk, D.A. (Eds.), The Landscape Ecology of Fire. Springer Netherlands, Dordrecht, pp. 117–139.
Littell, J.S., McKenzie, D., Peterson, D.L., Westerling, A.L., 2009. Climate and wildfire area burned in western US ecoprovinces, 1916–2003. Ecol. Appl. 19, 1003–1021.
Loomis, R.M., Phares, R.E., Crosby, J.S., 1966. Estimating foliage and branchwood quantities in shortleaf pine. For. Sci. 12, 30–39.
Loope, L.L., 2000. Vegetation of the Hawaiian Islands, in: North American Terrestrial Vegetation. Cambridge University Press, Cambridge, UK, pp. 661–688.
Loudermilk, E.L., Hiers, J.K., O'Brien, J.J., Mitchell, R.J., Singhania, A., Fernandez, J.C., Cropper, W.P., Slatton, K.C., 2009. Ground-based LIDAR: a novel approach to quantify fine-scale fuelbed characteristics. Int. J. Wildland Fire 18, 676–685.
Loudermilk, E.L., O'Brien, J.J., Mitchell, R.J., Cropper, W.P., Hiers, J.K., Grunwald, S., Grego, J., Fernandez-Diaz, J.C., 2012. Linking complex forest fuel structure and fire behaviour at fine scales. Int. J. Wildland Fire 21, 882–893.
Lu, D., 2006. The potential and challenge of remote sensing-based biomass estimation. Int. J. Remote Sens. 27, 1297–1328.
Lu, H., Ip, E., Scott, J., Foster, P., Vickers, M., Baxter, L.L., 2010. Effects of particle shape and size on devolatilization of biomass particle. Fuel 89, 1156–1168.
Lutes, D.C., Keane, R.E., Caratti, J.F., Key, C.H., Benson, N.C., Sutherland, S., Gangi, L.J., 2006. FIREMON: Fire Effects Monitoring and Inventory System (General Technical Report No. RMRS-GTR-164-CD). USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
Lutes, D.C., Keane, R.E., Caratti, J.F., 2009. A surface fuel classification for estimating fire effects. Int. J. Wildland Fire 18, 802–814.
Maguire, D.A., Bennett, W.S., 1996. Patterns in vertical distribution of foliage in young coastal Douglas-fir. Can. J. For. Res. 26, 1991–2005.
Mäkelä, A., Valentine, H.T., 2006. Crown ratio influences allometric scaling in trees. Ecology 87, 2967–2972.
Mandel, J., Beezley, J.D., Kochanski, A.K., 2011. Coupled atmosphere-wildland fire modeling with WRF 3.3 and SFIRE 2011. Geosci. Model Dev. 4, 591–610.
Manzello, S.L., Cleary, T.G., Shields, J.R., Yang, J.C., 2006. Ignition of mulch and grasses by firebrands in wildland–urban interface fires. Int. J. Wildland Fire 15, 427–431.
Marguí, E., Hidalgo, M., Queralt, I., 2005. Multielemental fast analysis of vegetation samples by wavelength dispersive X-ray fluorescence spectrometry: possibilities and drawbacks. Spectrochim. Acta Part B: At. Spectrosc. 60, 1363–1372.
Marlon, J., Bartlein, P.J., Whitlock, C., 2006. Fire-fuel-climate linkages in the northwestern USA during the Holocene. Holocene 16, 1059–1071.
Martin, R.E., Cushwa, C.T., Miller, R.L., 1969. Fire as a physical factor in wildland management. In: Proceedings of the 9th Tall Timbers Fire Ecology Conference. Tall Timbers Research Station, Tallahassee, FL, pp. 271–288.
Massman, W.J., 1982. Foliage distribution in old-growth coniferous tree canopies. Can. J. For. Res. 12, 10–17.
Matthews, S., 2006. A process-based model of fine fuel moisture. Int. J. Wildland Fire 15, 155–168.
Maxwell, W.G., Ward, F.R., 1976. Photo series for quantifying forest residues in the ponderosa pine type, ponderosa pine and associated species type, lodgepole Pine Type (General Technical Report No. PNW-GTR-52). USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.
McKenzie, D., Gedalof, Z., Peterson, D.L., Mote, P., 2004. Climatic change, wildfire, and conservation. Conserv. Biol. 18, 890–902.
McKenzie, D., Raymond, C.L., Kellogg, L.-K.B., Norheim, R.A., Andreu, A.G., Bayard, A.C., Kopper, K.E., Elman, E., 2007. Mapping fuels at multiple scales: landscape application of the fuel characteristic classification system. Can. J. For. Res. 37, 2421–2437.
McMahon, C.K., Wade, D.D., Tsoukalas, S.N., 1980. Combustion characteristics and emissions from burning organic soils. Presented at the 73rd Annual Meeting of the Air Pollution Control Association, Air Pollution Control Association, Montreal, Quebec.
McNab, W.H., Edwards Jr., M.B., Hough, W.A., 1978. Estimating fuel weights in slash pine-palmetto stands. For. Sci. 24, 345–358.
Meentemeyer, V., 1978. Macroclimate and lignin control of litter decomposition rates. Ecol. 59, 465–472.
Meigs, G.W., Kennedy, R.E., Cohen, W.B., 2011. A Landsat time series approach to characterize bark beetle and defoliator impacts on tree mortality and surface fuels in conifer forests. Remote Sens. Environ. 115, 3707–3718.
Melin, E., 1930. Biological decomposition of some types of litter from North American forests. Ecology 11, 72–101.
Mell, W., Jenkins, M.A., Gould, J., Cheney, P., 2007. A physics-based approach to modelling grassland fires. Int. J. Wildland Fire 16, 1–22.
Miller, C., Urban, D.L., 1999. A model of surface fire, climate and forest pattern in the Sierra Nevada, California. Ecol. Model. 114, 113–135.
Mobley, H.E., Barden, C.R., Crow, A.B., Fender, D.E., Jay, D.M., Winkworth, R.C., 1976. Southern Forestry Smoke Management Guidebook (General Technical Report No. SE-10). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.
Monserud, R.A., Marshall, J.D., 1999. Allometric crown relations in three northern Idaho conifer species. Can. J. For. Res. 29, 521–535.
Morsdorf, F., Mårell, A., Koetz, B., Cassagne, N., Pimont, F., Rigolot, E., Allgöwer, B., 2010. Discrimination of vegetation strata in a multi-layered Mediterranean forest ecosystem using height and intensity information derived from airborne laser scanning. Remote Sens. Environ. 114, 1403–1415.
Mueller-Dombois, D., Ellenberg, H., 2002. Aims and Methods of Vegetation Ecology. Blackburn Press, Caldwell, NJ.
Muñoz-Robles, C., Frazier, P., Tighe, M., Reid, N., Briggs, S.V., Wilson, B., 2012. Assessing ground cover at patch and hillslope scale in semi-arid woody vegetation and pasture using fused Quickbird data. Int. J. Appl. Earth Observation Geoinform. 14, 94–102.
Mutch, R.W., 1970. Wildland fires and ecosystems – a hypothesis. Ecology 51, 1046–1051.
Mutlu, M., Popescu, S., Stripling, C., Spencer, T., 2008. Mapping surface fuel models using lidar and multispectral data fusion for fire behavior. Remote Sens. Environ. 112, 274–285.
Nelson Jr., R.M., 2000. Prediction of diurnal change in 10-h fuel stick moisture content. Can. J. For. Res. 30, 1071–1087.
Nelson, R.M., Jr., 2001. Water relations of forest fuels. In: Johnson, E.A., Miyanishi, K. (Eds.), Forest Fires: Behavior and Ecological Effects. Academic Press, San Diego, CA, pp. 79–143.
Norum, R.A., Miller, M., 1984. Measuring fuel moisture content in Alaska: standard methods and procedures (General Technical Report No. PNW-171). USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.
Ohmann, J.L., Gregory, M.J., 2002. Predictive mapping of forest composition and structure with direct gradient analysis and nearest-neighbor imputation in coastal Oregon, USA. Can. J. For. Res. 32, 725–741.
Ottmar, R.D., 1983. Predicting fuel consumption by fire stages to reduce smoke from slash fires. In: Proceedings of the Northwest Forest Fire Council Annual Meeting, Olympia, WA.
Ottmar, R.D., 2014. Wildland fire emissions, carbon and climate: Modeling fuel consumption. For. Ecol. Manage. 317, 41–50.
Ottmar, R.D., Vihnanek, R.E., 2000. Stereo photo series for quantifying natural fuels. Volume VI: longleaf pine, pocosin, and marshgrass types in the Southeast United States (Report No. PMS-835). National Wildfire Coordination Group, National Interagency Fire Center.
Ottmar, R.D., Vihnanek, R.E., Mathey, J.W., 2003. Stereo photo series for quantifying natural fuels. Volume VIa: sand hill, sand pine scrub, and hardwoods with white pine types in the Southeast United States with supplemental sites for volume VI (Report No. PMS-838). National Wildfire Coordination Group, National Interagency Fire Center.
Ottmar, R.D., Sandberg, D.V., Riccardi, C.L., Prichard, S.J., 2007. An overview of the fuel characteristic classification system – quantifying, classifying, and creating fuelbeds for resource planning. Can. J. For. Res. 37, 2383–2393.
Ottmar, R.D., Miranda, A.I., Sandberg, D.V., 2008. Characterizing sources of emissions from wildland fires. In: Wildland Fires and Air Pollution, Developments in Environmental Science. Elsevier, pp. 61–78.
Page, W.G., Jenkins, M.J., 2007. Mountain pine beetle-induced changes to selected lodgepole pine fuel complexes within the Intermountain region. For. Sci. 53, 507–518.
Parresol, B.R., Blake, J.I., Thompson, A.J., 2012a. Effects of overstory composition and prescribed fire on fuel loading across a heterogeneous managed landscape in the southeastern USA. For. Ecol. Manage. 273, 29–42.
Parresol, B.R., Scott, J.H., Andreu, A., Prichard, S., Kurth, L., 2012b. Developing custom fire behavior fuel models from ecologically complex fuel structures for upper Atlantic Coastal Plain forests. For. Ecol. Manage. 273, 50–57.
Parsons, R.A., Mell, W.E., McCauley, P., 2011. Linking 3D spatial models of fuels and fire: effects of spatial heterogeneity on fire behavior. Ecol. Model. 222, 679–691.
Patton, A.R., Gieseker, L., 1942. Seasonal changes in the lignin and cellulose content of some Montana grasses. J. Animal Sci. 1, 22–26.
Peterson, J.L., 1987. Analysis and Reduction of the Errors of Predicting Prescribed Burn Emissions (Thesis). University of Washington, Seattle, WA.
Peterson, S., Roberts, D., Dennison, P., 2008. Mapping live fuel moisture with MODIS data: a multiple regression approach. Remote Sens. Environ. 112, 4272–4284.
Peterson, S.H., Morais, M.E., Carlson, J.M., Dennison, P.E., Roberts, D.A., Moritz, M.A., Weise, D.R., 2009. Using HFire for spatial modeling of fire in shrublands (Research Paper No. PSW-RP-59). USDA Forest Service, Pacific Southwest Research Station, Albany, CA.
Philpot, C.W., 1969a. Seasonal changes in heat content and ether extractive content of chamise (Research Paper No. INT-61). USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.
Philpot, C.W., 1969b. The effect of reduced extractive content on the burning rate of aspen leaves (Research Note No. INT-92). USDA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.
Philpot, C.W., 1970. Influence of mineral content on the pyrolysis of plant materials. For. Sci. 16, 461–471.
Philpot, C.W., 1977. Vegetative features as determinants of fire frequency and intensity. In: Proceedings of the Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems, (General Technical Report WO-3). USDA Forest Service, Washington, DC. pp. 12–16.
Pimont, F., Dupuy, J.-L., Caraglio, Y., Morvan, D., 2009. Effect of vegetation heterogeneity on radiative transfer in forest fires. Int. J. Wildland Fire 18, 536–553.
Pimont, F., Dupuy, J.-L., Linn, R.R., Dupont, S., 2011. Impacts of tree canopy structure on wind flows and fire propagation simulated with FIRETEC. Ann. For. Sci. 68, 523–530.
Powell, S.L., Cohen, W.B., Healey, S.P., Kennedy, R.E., Moisen, G.G., Pierce, K.B., Ohmann, J.L., 2010. Quantification of live aboveground forest biomass dynamics with Landsat time-series and field inventory data: a comparison of empirical modeling approaches. Remote Sens. Environ. 114, 1053–1068.

Prichard, S.J., Ottmar, R.D., Anderson, G.K., 2006. Consume 3.0 User's Guide. USDA Forest Service, Pacific Northwest Research Station, Seattle, WA.
Reardon, J., Hungerford, R., Ryan, K., 2007. Factors affecting sustained smouldering in organic soils from pocosin and pond pine woodland wetlands. Int. J. Wildland Fire 16, 107–118.
Reich, R.M., Lundquist, J.E., Bravo, V.A., 2004. Spatial models for estimating fuel loads in the Black Hills, South Dakota, USA. Int. J. Wildland Fire 13, 119–129.
Reid, A.M., Robertson, K.M., Hmielowski, T.L., 2012. Predicting litter and live herb fuel consumption during prescribed fires in native and old-field upland pine communities of the southeastern United States. Can. J. For. Res. 42, 1611–1622.
Reiner, A.L., Tausch, R.J., Walker, R.F., 2010. Estimation procedures for understory biomass and fuel loads in sagebrush steppe invaded by woodlands. West. N. Am. Nat. 70, 312–322.
Reinhardt, E.D., Crookston, N.L., 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator (General Technical Report No. RMRS-GTR-116). USDA Forest Service, Rocky Mountain Research Station, Ft. Collins, CO.
Reinhardt, E., Keane, R.E., Brown, J.K., 1997. First Order Fire Effects Model: FOFEM 4.0, User's Guide (General Technical Report No. INT-344). USDA Forest Service, Intermountain Research Station, Ogden, UT.
Reinhardt, E., Scott, J., Gray, K., Keane, R., 2006. Estimating canopy fuel characteristics in five conifer stands in the western United States using tree and stand measurements. Can. J. For. Res. 36, 2803–2814.
Riccardi, C.L., Ottmar, R.D., Sandberg, D.V., Andreu, A., Elman, E., Kopper, K., Long, J., 2007a. The fuelbed: a key element of the fuel characteristic classification system. Can. J. For. Res. 37, 2394–2412.
Riccardi, C.L., Prichard, S.J., Sandberg, D.V., Ottmar, R.D., 2007b. Quantifying physical characteristics of wildland fuels using the fuel characteristic classification system. Can. J. For. Res. 37, 2413–2420.
Riggan, P.J., Franklin, S.E., Brass, J.A., Brooks, F.E., 1994. Perspectives on fire management in Mediterranean ecosystems of southern California. In: Moreno, J.M., Oechel, W.C. (Eds.), The Role of Fire in Mediterranean-type Ecosystems, Ecological Studies. Springer-Verlag, New York, pp. 140-162.
Roberts, D.A., Dennison, P.E., Peterson, S., Sweeney, S., Rechel, J., 2006. Evaluation of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and Moderate Resolution Imaging Spectrometer (MODIS) measures of live fuel moisture and fuel condition in a shrubland ecosystem in southern California. J. Geophys. Res. 111, G04S02.
Roberts, J.W., Tesfamichael, S., Gebreslasie, M., Van Aardt, J., Ahmed, F.B., 2007. Forest structural assessment using remote sensing technologies: an overview of the current state of the art. S. Hemisphere For. J. 69, 183–203.
Rollins, M.G., Keane, R.E., Parsons, R.A., 2004. Mapping fuels and fire regimes using remote sensing, ecosystem simulation, and gradient modeling. Ecol. Appl. 14, 75–95.
Rothermel, R.C., 1972. A mathematical model for predicting fire spread in wildland fuels (Research Paper No. INT-115). US DA Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT.
Rothermel, R.C., 1991. Predicting behavior and size of crown fires in the northern Rocky Mountains (Research Paper No. INT-438). USDA Forest Service, Intermountain Research Station, Ogden, UT.
Rothermel, R.C., Philpot, C.W., 1973. Predicting changes in chaparral flammability. J. For. 71, 640–643.
Rowell, R.M., Pettersen, R., Han, J.S., Rowell, J.S., Tshabalala, M.A., 2005. Cell wall chemistry. In: Handbook of Wood Chemistry and Wood Composites. CRC Press, Boca Raton, FL, pp. 35–74.
Ryan, P.W., McMahon, C.W., 1976. Some chemical and physical characteristics of emissions from forest fires. 69th Annual Meeting of the Air Pollution Control Association, Air Pollution Control Association, Portland, OR.
Saatchi, S., Halligan, K., Despain, D.G., Crabtree, R.L., 2007. Estimation of forest fuel load from radar remote sensing. IEEE Trans. Geosci. Remote Sens. 45, 1726–1740.
Sackett, S.S., 1975. Scheduling prescribed burns for hazard reduction in the Southeast. J. For. 73, 143–147.
Sackett, S.S., 1979. Natural fuel loadings in ponderosa pine and mixed conifer forests of the Southwest (Research Paper No. RM-213). USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO.
Sah, J., Ross, M., Koptur, S., Snyder, J., 2004. Estimating aboveground biomass of broadleaved woody plants in the understory of Florida Keys pine forests. For. Ecol. Manage. 203, 319–329.
Sandberg, D.V., 1980. Duff reduction by prescribed underburning in Douglas-fir (Research Paper No. PNW-272). USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR.
Sandberg, D.V., Dost, F.N., 1990. Effects of prescribed fire on air quality and human health. In: Walstad, J.D., Radosevich, S.R., Sandberg, D.V. (Eds.), Natural and Prescribed Fire in Pacific Northwest Forests. Oreg. State Univ. Press, Corvallis, OR, pp. 191–218.
Sandberg, D.V., Ottmar, R.D., Cushon, G.H., 2001. Characterizing fuels in the 21st Century. Int. J. Wildland Fire 10, 381–387.
Sandberg, D.V., Riccardi, C.L., Schaaf, M.D., 2007. Reformulation of Rothermel's wildland fire behaviour model for heterogeneous fuelbeds. Can. J. For. Res. 37, 2438–2455.
Sando, R.W., Wick, C.H., 1972. A method of evaluating crown fuels in forest stands (Research Paper No. NC-84). USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.
Schaaf, M.D., Sandberg, D.V., Schreuder, M.D., Riccardi, C.L., 2007. A conceptual framework for ranking crown fire potential in wildland fuelbeds. Can. J. For. Res. 37, 2464–2478.
Schneider, P., Roberts, D.A., Kyriakidis, P.C., 2008. A VARI-based relative greenness from MODIS data for computing the Fire Potential Index. Remote Sens. Environ. 112, 1151–1167.
Scott, N.A., Binkley, D., 1997. Foliage litter quality and annual net N mineralization: comparison across North American forest sites. Oecologia 111, 151–159.
Scott, J.H., Burgan, R.E., 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model (General Technical Report No. RMRS-GTR-153). USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
Scott, J.H., Reinhardt, E.D., 2001. Assessing crown fire potential by linking models of surface and crown fire behavior (Research Paper No. RMRS-RP-29). USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.
Seielstad, C.A., Queen, L.P., 2003. Using airborne laser altimetry to determine fuel models for estimating fire behavior. J. For. 101, 10–15.
Seielstad, C., Stonesifer, C., Rowell, E., Queen, L., 2011. Deriving fuel mass by size class in Douglas-fir (*Pseudotsuga menziesii*) using terrestrial laser scanning. Remote Sens. 3, 1691–1709.
Seiler, W., Crutzen, P.J., 1980. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. Clim. Change 2, 207–247.
Shiflet, T.N., 1994. Rangeland cover types of the United States. Society for Range Management.
Sikes, K.G., Muir, P.S., 2009. A comparison of the short-term effects of two fuel treatments on chaparral communities in southwest Oregon. Madroño 56, 8–22.
Sikkink, P.G., Keane, R.E., 2008. A comparison of five sampling techniques to estimate surface fuel loading in montane forests. Int. J. Wildland Fire 17, 363–379.
Skowronski, N., Clark, K., Nelson, R., Hom, J., Patterson, M., 2007. Remotely sensed measurements of forest structure and fuel loads in the pinelands of New Jersey. Remote Sens. Environ. 108, 123–129.
Skowronski, N.S., Clark, K.L., Duveneck, M., Hom, J., 2011. Three-dimensional canopy fuel loading predicted using upward and downward sensing LiDAR systems. Remote Sens. Environ. 115, 703–714.
Stephens, S.L., 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests. For. Ecol. Manage. 105, 21–35.
Steward, L.G., Sydnor, T.D., Bishop, B., 2003. The ease of ignition of 13 landscape mulches. J. Arboric. 29, 317–321.
Stocks, B.J., Lynham, T.J., Lawson, B.D., Alexander, M.E., Van Wagner, C.E., McAlpine, R.S., Dube, D.E., 1989. Canadian forest fire danger rating system: an overview. For. Chron. 65, 258–265.
Sullivan, A.L., 2009a. Wildland surface fire spread modelling, 1990–2007. 1: physical and quasi-physical models. Int. J. Wildland Fire 18, 349–368.
Sullivan, A.L., 2009b. Wildland surface fire spread modelling, 1990–2007. 2: empirical and quasi-empirical models. Int. J. Wildland Fire 18, 369–386.
Sullivan, A.L., 2009c. Wildland surface fire spread modelling, 1990–2007. 3: simulation and mathematical analogue models. Int. J. Wildland Fire 18, 387–403.
Tart, D., Williams, C., Brewer, C., DiBenedetto, J., Schwind, B., 2005. Section 1: existing vegetation classification and mapping framework. In: Brohman, R., Bryant, L. (Eds.), Existing Vegetation Classification and Mapping Technical Guide, (General Technical Report WO-67) USDA Forest Service, Washington, DC.
Tausch, R.J., 2009. A structurally based analytic model for estimation of biomass and fuel loads of woodland trees. Nat. Resour. Model. 22, 463–488.
Ter-Mikaelian, M.T., Korzukhin, M.D., 1997. Biomass equations for sixty-five North American tree species. For. Ecol. Manage. 97, 1–24.
Thornley, J., 1996. Modelling water in crops and plant ecosystems. Ann. Bot. 77, 261–275.
Todd, K.W., Csillag, F., Atkinson, P.M., 2003. Three-dimensional mapping of light transmittance and foliage distribution using lidar. Can. J. Remote Sens. 29, 544–555.
Undersander, D., Mertens, D.R., Thiex, N., 1993. Forage Analyses Procedures. National Forage Testing Association, Omaha, NE.
US Environmental Protection Agency, 2012. Report to Congress on Black Carbon (EPA-450/R-12-001). US Environmental Protection Agency, Washington, DC.
Valentine, H.T., Gove, J.H., Gregoire, T.G., 2001. Monte Carlo approaches to sampling forested tracts with lines or points. Can. J. For. Res. 31, 1410–1424.
van Leeuwen, W.J.D., Huete, A.R., 1996. Effects of standing litter on the biophysical interpretation of plant canopies with spectral indices. Remote Sens. Environ. 55, 123–138.
van Leeuwen, M., Nieuwenhuis, M., 2010. Retrieval of forest structural parameters using LiDAR remote sensing. Eur. J. For. Res. 129, 749–770.
Van Wagner, C.E., 1968. The line intersect method in forest fuel sampling. For. Sci. 14, 20–26.
Van Wagner, C.E., 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7, 23–34.
Van Wagner, C.E., 1979. A laboratory study of weather effects on the drying rate of jack pine litter. Can. J. For. Res. 9, 267–275.
Van Wagner, C.E., 1993. Prediction of crown fire behavior in two stands of jack pine. Can. J. For. Res. 23, 442–449.
Van Wilgen, B.W., Higgins, K.B., Bellstedt, D.U., 1990. The role of vegetation structure and fuel chemistry in excluding fire from forest patches in the fire-prone fynbos shrublands of South Africa. J. Ecol. 78, 210–222.
Viegas, D.X., Pinol, J., Viegas, M.T., Ogaya, R., 2001. Estimating live fine fuels moisture content using meteorologically-based indices. Int. J. Wildland Fire 10, 223–240.

Vihnanek, R.E., Balog, C.S., Wright, C.S., Ottmar, R.D., Kelly, J.W., 2009. Stereo photo series for quantifying natural fuels. Volume XII: post-hurricane fuels in forests of the southeast United States (General Technical Report No. PNW-GTR-803). USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Wade, D., Ewel, J., Hofstetter, R., 1979. Fire in south Florida ecosystems (General Technical Report No. SE-17). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Wade, D.D., Forbus, J.K., Saveland, J.M., 1993. Photo series for estimating post-hurricane residues and fire behavior in southern pine (General Technical Report No. SE-82). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Wang, W., 2011. An analytical model for mean wind profiles in sparse canopies. Bound. Layer Meteorol. 142, 383–399.

Wang, X.-F., Huang, D.-S., Du, J.-X., Xu, H., Heutte, L., 2008. Classification of plant leaf images with complicated background. Appl. Math. Comput. 205, 916–926.

Ward, D.E., 1979. Particulate matter and aromatic hydrocarbon emissions from the controlled combustion of alpha pinene (Dissertation). University of Washington, Seattle, WA.

Ward, D., 2001. Combustion chemistry and smoke. In: Johnson, E.A., Miyanishi, K. (Eds.), Forest Fires: Behavior and Ecological Effects. Academic Press, San Diego, CA, pp. 55-77.

Ward, D.E., Hao, W.M., 1991. Projection of emissions from burning of biomass for use in studies of global climate and atmospheric chemistry. 84th Annual Meeting of the Air and Waste Management Association. Air and Waste Management Association, Vancouver, British Columbia.

Ward, D.E., Hardy, C.C., 1991. Smoke emissions from wildland fires. Environ. Int. 17, 117–134.

Ward, D.E., Radke, L.F., 1993. Emissions measurements from vegetation fires: A comparative evaluation of methods and results. In: Crutzen, P.J., Goldammer, (Eds.), Fire in the Environment: The Ecological, Atmospheric and Climatic Importance of Vegetation Fires. pp. JG53–JG76.

Weise, D.R., Saveland, J.M., 1996. Monitoring live fuel moisture – a task force report. Fire Manage. Notes 56, 12–16.

Weise, D.R., Gelobter, A., Haase, S.M., Sackett, S.S., 1997. Photo series for quantifying fuels and assessing fire risk in giant sequoia groves (General Technical Report No. PSW-GTR-163). USDA Forest Service, Pacific Southwest Research Station, Berkeley, CA.

Weise, D.R., Stephens, S.L., Fujioka, F.M., Moody, T.J., Benoit, J., 2010. Estimation of fire danger in Hawai'i using limited weather data and simulation. Pac. Sci. 64, 199–220.

Wendel, G.W., Storey, T.G., Byram, G.M., 1962. Forest fuels on organic and associated soils in the coastal plain of North Carolina (Station Paper No. 144). USDA Forest Service, Southeastern Forest Experiment Station, Asheville, NC.

Westhoff, V., Van der Maarel, E., 1973. The Braun-Blanquet approach. In: Whittaker, R.H., (Ed.), Handbook of Vegetation Science. Part V. Ordination and Classification of Communities. Junk, The Hague, Netherlands, pp. 617–726.

Whitlock, C., Shafer, S.L., Marlon, J., 2003. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. For. Ecol. Manage. 178, 5–21.

Williams, J.W., Jackson, S.T., 2007. Novel climates, no-analog communities, and ecological surprises. Front. Ecol. Environ. 5, 475–482.

Woodall, C.W., Nagel, L.M., 2007. Downed woody fuel loading dynamics of a large-scale blowdown in northern Minnesota, USA. For. Ecol. Manage. 247, 194–199.

Wright, C.S., in press. Models for predicting fuel consumption in sagebrush-dominated ecosystems. Rangel. Ecol. Manage.

Wright, C.S., in press. Fuel consumption models for pine flatwoods fuel types in the southeastern United States. S. J. Appl. For.

Wright, C.S., Prichard, S.J., 2006. Biomass consumption during prescribed fires in big sagebrush ecosystems. In: Andrews, P.L., Butler, B.W. (Eds.), Fuels Management-How to Measure Success (Proceedings RMRS-P-41). USDA Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, pp. 489–500.

Wright, C.S., Eagle, P.C., Olson, D.L., 2010. A high-quality fuels database of photos and information. Fire Manage. Today 70, 27–31.

Wright, C.S., Vihnanek, R.E., Restaino, J.C., Dvorak, J.E., 2012. Photo series for quantifying natural fuels. Volume xi: eastern oregon sagebrush-steppe and northern spotted owl nesting habitat in the Pacific Northwest. (General Technical Report No. PNW-GTR-878). USDA Forest Service, Pacific Northwest Research Station, Seattle, WA.

Xie, Y., Sha, Z., Yu, M., 2008. Remote sensing imagery in vegetation mapping: a review. J. Plant Ecol. 1, 9–23.

Xu, M., Harrington, T.B., 1998. Foliage biomass distribution of loblolly pine as affected by tree dominance, crown size, and stand characteristics. Can. J. For. Res. 28, 887–892.

Yang, H., Yan, R., Chen, H., Lee, D.H., Zheng, C., 2007. Characteristics of hemicellulose, cellulose and lignin pyrolysis. Fuel 86, 1781–1788.

Zeide, B., 1998. Fractal analysis of foliage distribution in loblolly pine crowns. Can. J. For. Res. 28, 106–114.

Zhang, D., Hui, D., Luo, Y., Zhou, G., 2008. Rates of litter decomposition in terrestrial ecosystems: global patterns and controlling factors. J. Plant Ecol. 1, 85–93.

Zhao, K., Popescu, S., Nelson, R., 2009. Lidar remote sensing of forest biomass: a scale-invariant estimation approach using airborne lasers. Remote Sens. Environ. 113, 182–196.

Zouhar, K., Smith, J.K., Sutherland, S., Brooks, M.L., 2008. Wildland fire in ecosystems: fire and nonnative invasive plants (General Technical Report No. RMRS-GTR-42-vol. 6). USDA Forest Service, Rocky Mountain Research Station, Ogden, UT.