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Wildland fire emissions, carbon, and climate: Modeling fuel consumption

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ABSTRACT

Fuel consumption specifies the amount of vegetative biomass consumed during wildland fire. It is a two-stage process of pyrolysis and combustion that occurs simultaneously and at different rates depending on the characteristics and condition of the fuel, weather, topography, and in the case of prescribed fire, ignition rate and pattern. Fuel consumption is the basic process that leads to heat absorbing emissions called greenhouse gas and other aerosol emissions that can impact atmospheric and ecosystem processes, carbon stocks, and land surface reflectance. It is a critical requirement for greenhouse gas emission inventories. There are several fuel consumption models widely used by scientists and land managers including the First Order Fire Effects Model, Consume, and CanFIRE. However, these models have not been thoroughly evaluated with an independent, quality assured, fuel consumption data set. Furthermore, anecdotal evidence indicates the models have limited ability to predict consumption of specific fuel bed categories such as tree crowns, deep organic layers, and rotten logs that can contribute significantly to greenhouse gases. If we are to move forward in our ability to assess the contribution of wildland fire to greenhouse gas to the atmosphere, our current fuel consumption models must be evaluated and modified to improve their predictive capabilities. Finally, information is lacking on how much black and brown carbon from wildland fire is generated during the combustion process and how much remains on site becoming sequestered in soils, partially offsetting greenhouse gas emissions. This synthesis focuses on the process and modeling of fuel consumption and knowledge gaps that will improve our ability to predict fuel consumption and the resulting greenhouse gas emissions.

1. Introduction

The consumption of fuels during wildland fire is the basic process that leads to emissions and impacts on the atmosphere, ecosystem processes, carbon stocks, and land surface reflectance (Ottmar et al., 2009a; Hardy et al., 2001; Agee, 1993; Ramanathan and Carmichael, 2008; Flanner et al., 2007). Models and systems that provide wildland fire greenhouse gas and aerosol emissions inventories (Heilman et al., 2014) require explicit knowledge of the fuel consumed as shown in Fig. 1 (Ottmar et al., 2009b; Battye and Battye, 2002; Hardy et al., 2001; Levine, 1994; French et al., 2010) along with area burned, fuel characteristics (Weise and Wright, 2014); fire behavior, and emission factors (Urbanski, 2014). Although all inputs for source characterization are important, errors in estimates of fuel consumption input can contribute errors of 30% or more to estimates of greenhouse gas emissions from wildland fires (Peterson, 1987; Peterson and Sandberg, 1988; French et al., 2004). Furthermore, the way that fuel is consumed determines the specific components of fire emissions, including greenhouse gases (GHG), and aerosols such as black carbon (BC) and organic carbon (OC). These aerosols are of concern because they can affect the radiative properties of the atmosphere and the albedo of snow-covered landscapes and sea ice. BC deposited on ice and snow can increase melting while if the aerosols remain in the atmosphere, they may shield the ice and snow from melting (Sand et al. 2013; Ramanathan and Carmichael, 2008; Flanner et al., 2007). Black carbon is also an inert compound that is incorporated into the soil and becomes a source for sequestered carbon that offsets part of the greenhouse gas and aerosol emissions input into the atmosphere (Kuhlbusch et al., 1996; Deluca and Aplet, 2008; Rovira et al., 2009; Brewer et al., 2013).

Fuel consumption is the mass of vegetative matter either live or dead that is pyrolyzed or combusted during a wildland fire. Fuel consumption is generally expressed as mass of biomass consumed per unit area (e.g., t ha^{-1}). In cases where the time it takes to consume a specific amount of fuel is known, consumption rate can be calculated and expressed as mass consumed over time (e.g., g c^{-1} or t min^{-1}). This paper is a synthesis of the current state of knowledge regarding fuel consumption, factors and variables that influence fuel consumption, systems currently available for predicting fuel consumption, and future direction in research to improve

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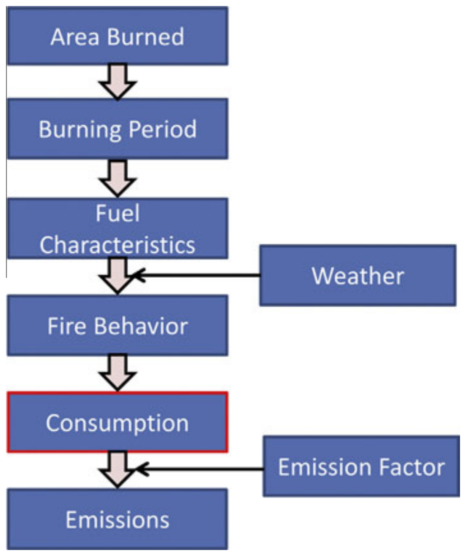

Fig. 1. Inputs required for determining emissions of greenhouse gases from wildland fire.

our knowledge and predictive capabilities for estimating greenhouse gases produced from wildland fire.

2. Background

Fuels are consumed in a complex combustion process that varies widely among wildland fires. In the simplest terms, combustion of vegetative matter (cellulose) is a thermal/chemical reaction whereby plant material is rapidly oxidized producing carbon dioxide, water, and heat. This is the reverse of plant photo synthesis where energy from the sun combines with carbon dioxide and water, producing cellulose. In the real world, the burning process is much more complicated than this. Burning fuels is a two-stage process of pyrolysis and combustion. Although both stages occur nearly simultaneously, pyrolysis occurs first and is the heat-absorbing reaction that converts fuel elements such as cellulose into char, carbon dioxide, carbon monoxide, water vapor, highly combustible vapors and gases, and particulate matter (Debano et al., 1998; Ward, 2001; Parsons et al., in press). Combustion follows as the escaping hydrocarbon vapors released from the surface of the fuels oxidize. Because combustion efficiency is rarely 100% during wildland fires, hundreds of chemical compounds are emitted into the atmosphere, in addition to carbon dioxide and water. Pyrolysis and combustion proceed at many different rates since wildland fuels are often very complex and non-homoge neous (DeBano et al., 1998), and environmental conditions may vary locally and temporally as a function of terrain, wind, vegetation structure, and other factors.

2.1. Fuel bed characteristics

Since fire and the resulting fuel consumption can occur across a range of spatial scales, the characteristics of fuels need to be considered at both fine (individual particles) and landscape scale. At the fine scale such as a particle or collection of particles (e.g., shrub or tree), there are five general fuel bed characteristics which influence how a fuel particle will combust including chemistry, quantity (mass), density, geometry, and continuity. These five characteristics are referred to as the fuels pentagon (Parsons et al., in press). Each characteristic is further described as to its contribution to consumption.

2.1.1. Chemistry

Fuel particles are composed of four broad chemical categories: water, carbohydrates, fats and proteins, and mineral content (Parsons et al., in press). Fractional allocation of a fuel to different categories of chemical compounds varies substantially depending on the type of fuel, whether the fuel is dead or alive, and in the case of dead material, how much decay has occurred.

The water content of a fuel has long been known as a major factor in fuel consumption since the specific heat of water is approximately 4 Jg^{-1} °C, over four times that of any other chemical component of wildland fuels. This requires a tremendous amount of energy to evaporate the moisture in a fuel that could otherwise be used to raise the fuel to ignition temperature and pyrolyze the fuel to support consumption. Many studies have shown that it takes longer to ignite a fuel particle and less fuel is consumed with higher moisture content (Dimitrakopoulos and Papaioannou, 2001; Pellizzaro et al., 2007; Xanthopoulos and Wakimoto, 1993; Sandberg and Ottmar, 1983; Brown et al., 1991). One exception to this rule occurs with decayed fuels such as large rotten logs. Often the material slowly combusts even though the moisture content is extremely high. The variable controlling the combustion was found to be amount and state of decay (Hyde et al., 2011).

Carbohydrates make up a large portion of wildland fuels. These carbon-based compounds provide the primary substrates for the pyrolysis products that contribute to flaming consumption. Fat-based compounds and proteins make up 10% or more of the dry mass of fuels. The fats are generally composed of waxes, oils, resins, and isoprenes; are often highly flammable; and have twice the heat content of any other compound (Merrill and Watt, 1973). Finally, mineral and ash content is the measure of the amount of fuel that is composed of unburnable compounds. Ash content can vary greatly among species, and small changes in the ash content can induce large changes in the combustion of wildland fuels (Broido and Nelson, 1964).

2.1.2. Quantity (mass)

The mass of fuel is a fundamental fuel characteristic important for estimating the amount of fuel that a fire will consume (Prichard et al., 2007; Brown et al., 1991) and is often defined two ways. Total biomass is considered to be the entire amount of combustible material present. Available fuel mass is the amount of total biomass expected to be consumed in a particular situation (Byram, 1959). It is determined by the structural and chemical fuel characteristics; fuel moisture, meteorological influences, and topography; how the fire is burning when it reaches the fuel; and, for prescribed fires, the way fire is applied. Climate and weather conditions, distribution of the fuel bed categories, and properties of the fuel complex will determine the differences in total and available fuel mass. For example, a temperate rain forest fuel bed can contain several hundred Mg ha^{-1} of total biomass. However, only a small portion generally becomes available biomass because of the moist climate and lack of ignition potential (Fig. 2). In a dry forest, total biomass may have only 2 or 3 Mg ha^{-1} of total biomass, but a large portion of that biomass will be available biomass because of dry climate and high potential for ignition.

2.1.3. Density (compactness)

The compactness of a fuel bed influences several processes related to consumption, including heat transfer and oxygen diffusion. For example, pieces of fuel spaced apart such as found in a sparse prairie grass fuel bed will have plenty of oxygen diffusion to support consumption, but the heat transfer will be minimal. However, piled wood may have excellent heat transfer properties for improved combustion but this may be offset by limited oxygen diffusion (Hardy et al., 2001)

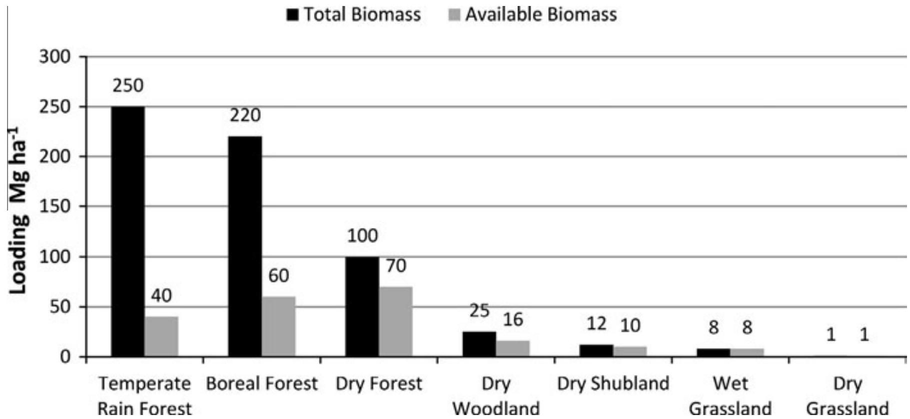

Fig. 2. Total and available biomass for dry and wet biomes determined from the Digital Photo Series (Ottmar et al., 2009b) and Consume using average environmental variables (Prichard et al., 2007).

2.1.4. Geometry

Surface area-to-volume ratio is a fuel property that describes individual particle geometry and strongly influences total fuel consumption, amount of fuel consumed during the flaming and smoldering phases, fuel temperature, and moisture dynamics. Because the combustion zone generally occurs at the surface of the fuel, the size of the fuel and its surface area in relationship to its volume influences the amount of heat required to ignite and burn particles. Small fuels, such as grasses, with large surface areas compared to their volume, require less heat to ignite and combust as compared to larger woody fuels with small surface area-to-volume ratios. Fuels with large surface area-to-volume ratios generally burn during the flaming stage where larger fuels with small surface area-to-volume ratios often burn during the smoldering stage. Furthermore, the geometry determines moisture uptake and release from a fuel particle. Grass particles, for example, with large surface area-to-volume ratios can absorb and release moisture quickly compared to large logs with small surface area-to-volume ratios.

2.1.5. Continuity

Another fuel characteristic with important implications for fuel consumption is continuity, or spacing, of the fuels. At a scale of individual particles, such as a litter bed of leaves and needles, fuels are considered continuous because the size of the gaps are small compared to typical flame lengths (Finney et al., 2010). At larger scales, horizontal and vertical fuel continuity is very important to determining consumption and whether or not fuels are close enough to one another for flames to interact and cause fuel particles to consume. The influence of continuity differs depending on fireline intensity. For example, a twig may not be consumed by a low-energy fire but might be consumed if the fire were hotter.

At the landscape scale, the diversity of fuels makes them difficult to characterize, classify, or describe. There are several strategies for addressing this complexity including the Fuel Characteristic Classification System (FCCS) (Ottmar et al., 2007; Riccardi et al., 2007) and the Fuel Loading Model (FLM) (Lutes et al., 2009). The FCCS describes fuels as a series of fuel bed categories and subcategories, each with their own properties that are used to determine how they will combust and be consumed. The fuel bed is composed of six horizontal strata to represent every fuel element that has a potential to be consumed including the trees, shrubs, herbaceous vegetation, woody dead material, litter, and ground fuels (Fig. 3). The FLM is a classification system for duff, litter, and fine and coarse woody material that can be used to stratify fuel beds into loading classes for estimating fire effects and mapping purposes across large regions.

2.2. Weather variables

Environmental variables of temperature, relative humidity, precipitation, and wind can affect the amount of fuel consumed Air temperature and relative humidity influence the consumption of fuels with high surface area-to-volume ratios (e.g., shrubs, grass, fine woody material, litter, moss, and lichen) more than fuels with a low surface-to-volume ratios such as large, sound logs. Precipitation and wind affect all fuel types. Precipitation decreases consumption while wind increases consumption.

2.3. Pre-ignition and combustion phases

There are four major phases when dead fuel particles burn (Mobley, 1976; Prescribed Fire Working Team, 1985; Lobert and Warnatz, 1993). These phases are: (1) pre-ignition (sometimes referred to the solid phase); (2) flaming (sometimes referred to as the gaseous phase); (3) smoldering; and (4) glowing (Fig. 4). Live fuel consumption by phase is an area of active research and will not be discussed in this paper.

During the pre-ignition phase, fuels ahead of the fire front are heated by radiation and convection, and water vapor is driven to the surface of the fuels and expelled into the atmosphere. As the fuel's internal temperature rises, cellulose (a carbohydrate that forms the main constituent of the cell wall in most plants), hemicellulose (also a type of cellulose found in the cell wall), and lignin (an organic polymer that makes many plants rigid and woody) begin to decompose and release combustible organic gases and vapors (Ryan and McMahon, 1976; Lobert and Warnatz, 1993). This process generally occurs faster if the material contains more cellulose than lignin (Gani and Naruse, 2007). Because these gases and vapors are hotter than the surrounding area, they rise and mix with oxygen in the air, igniting at temperatures between 325 °C and 355 °C and leading to the flaming phase or gas-phase process (DeBano et al., 1998; Lobert and Warnatz, 1993).

In the flaming phase, the fuel temperature rises rapidly. Pyrolysis accelerates and is accompanied by flaming of the combustible gases and vapors. The combustion efficiency (the fraction of burned fuel carbon converted to carbon dioxide (CO_2), see Urbanski, 2014) during the flaming stage is usually relatively high as long as volatile emissions remain in the vicinity of the flames. The predominant products of flaming combustion are CO_2 and water vapor (H_2O). The water vapor is a product of the combustion process and also derives from moisture being driven from the fuel. Temperatures during the flaming (gas) stage can range from 500 °C to 1900 °C (Ryan and McMahon, 1976; Lobert and Warnatz, 1993;

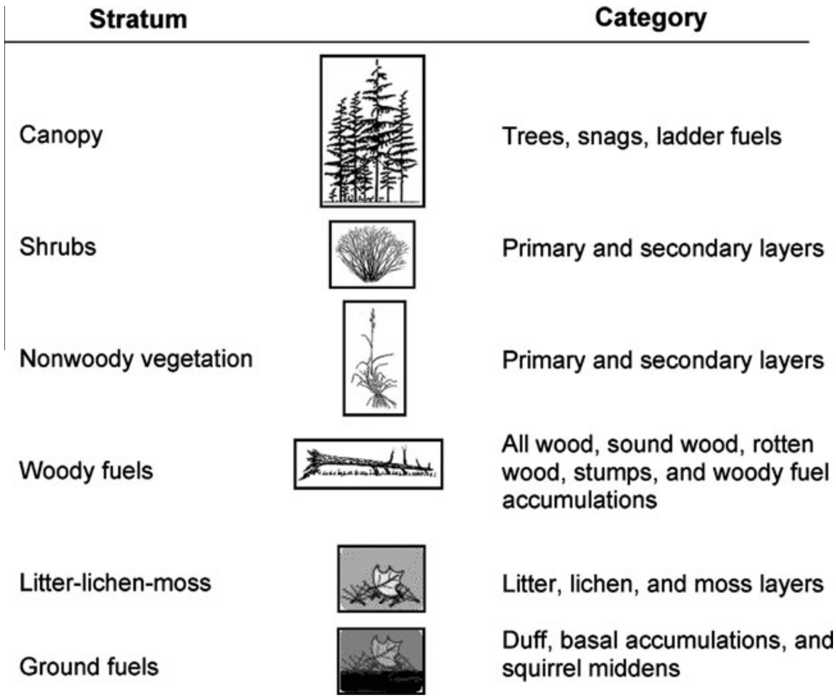

Fig. 3. Horizontal stratification of an FCCS fuel bed by strata and categories.

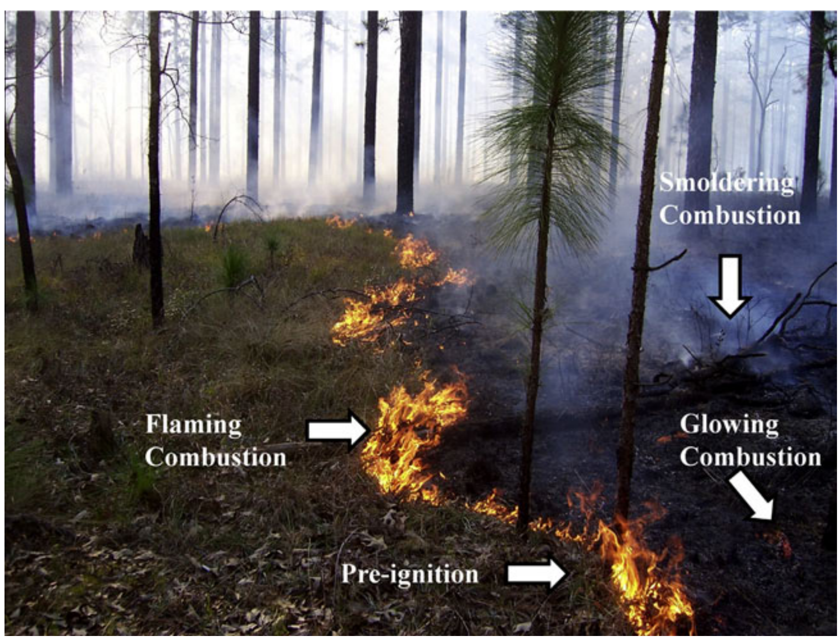

Fig. 4. Pyrolysis and three phases of combustion.

Fristrom, 1995; Sullivan et al., 2003). During the flaming period, the average reduction of exterior diameter of round wood material occurs at a rate of 2.5 cm per 8 min (Anderson, 1969). For example, a dry limb 2.5 cm in diameter would take approximately 8 min to completely consume if flaming combustion was sustained during the entire time period.

During the smoldering phase, emissions of combustible gases and vapors are too low to support flaming combustion (Lobert and Warnatz, 1993). The result is a decreased fire spread rate and a significant drop in combustion temperature. Peak smoldering temperatures have been found to range from 300 °C to 600 °C (Agee, 1993; Rein et al., 2008). The gases and vapors condense more than in the flaming stage, appearing as visible smoke as they escape into the atmosphere. This smoke consists mostly of droplets less than a micrometer in size. The particulate emission factors that represent the phase are often double that represented by the flaming stage (Hardy et al., 2001; Urbanski et al., 2008).

Smoldering combustion is more prevalent in certain fuel types (e.g., duff, organic soils, and rotten logs) due to the lack of oxygen necessary to support flaming combustion and less prevalent in fuels with high surface area-to-volume ratios (e.g., grasses, shrubs, and small diameter woody fuels) (Sandberg and Dost, 1990).

Because heat generated from smoldering combustion is seldom sufficient to sustain a convection column, the smoke often stays near the ground and may concentrate in nearby valley bottoms, com pounding the impact of the fire on air quality. Near the end of the smoldering phase, the pyrolysis process nearly ceases, leaving the fuel that did not completely consume with a layer of black char, high in carbon.

In the glowing phase, most volatile gases have been driven off. Oxygen in the air can now reach the exposed surface of char left from the flaming and smoldering phases, and the remaining fuels begin to glow with the characteristic orange color. Peak temperatures of the burning fuel during the glowing phase are similar to those found in the smoldering phase and range from 300 °C to 600 °C (Lobert and Warnatz, 1993; DeBano et al., 1998; Rein et al., 2008). There is little visible smoke. Carbon dioxide, carbon monoxide, and methane are the principal products of glowing combustion. This phase continues until the temperature of the fuel drops or until only noncombustible, mineral gray ash remains.

The phases described above occur both sequentially and simultaneously as a fire front moves across the landscape. The efficiency of combustion that takes place in each phase is not the same, resulting in a different set of chemical compounds being released at different rates into the atmosphere. Fuel type, fuel moisture content, density of the fuelbed, continuity, moisture content of the surface a fuel is laying on, relative humidity, air temperature, wind speed, and the way the fuels are ignited in the case of prescribed fires or wildfire burnout operations, can affect the total amount of biomass consumed and what is consumed during various combustion stages. The flaming stage has high combustion efficiency; that is, it tends to emit the most CO_2 and BC relative to the mass of fuel consumed but less non-CO_2 emissions such as CO, CH_4, CO, and other gas phase organic compounds relative to the mass of fuel consumed (Lobert and Warnatz, 1993). The smoldering and glowing stages have low combustion efficiencies and produce more non-CO_2 emissions and less BC relative to the mass of fuel consumed (Lobert and Warnatz, 1993). This means that techniques to manage the combustion phase during prescribed fire (which is a typical practice used to reduce smoke and air quality impacts) will not reduce greenhouse gas (GHG) emissions. If the fuel is consumed, it will emit either large amounts of CO_2 and BC during the flaming phase or large amounts of non-CO_2 and other gas phase organics during the smoldering and glowing phases. Unless there is a way to maximize char production during the fire, and then store it in soil, managers can only reduce GHG emissions by reducing the amount of fuel consumed. This can be done by burning when fuel moisture content is higher, burning a smaller area, and by reducing the fuel load through mechanical means.

2.4. Black, organic and brown carbon production

Biomass burning produces a continuum of carbonaceous substances in atmospheric aerosols, where at one end is the strongly light absorbing black carbon (BC) to the thermally reactive and colorless organic substances called organic carbon (OC) (Andreae and Gelencser, 2006; Poschl, 2003). BC is a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths (USEPA, 2012). Although OC are less light absorbing than BC, there is a subset of OC that contain organic substances that absorb in the UV spectrum and give a ''brownish'' hue. These are often referred to brown carbon (BrC). BC, OC, and BrC are formed as a result of the incomplete combustion of fuels (Battye and Battye, 2002; Andreae and Gelencser, 2006). The degree of combustion is related to the fuel type, moisture content, weather conditions, and in the case of prescribed fire, ignition pattern. Generally, elemental BC is formed during the flaming phase and OC and BrC are formed during the smoldering phase (McMeeking et al., 2009; Yokelson et al., 2013). These aerosols are of particular concern in the atmosphere at boreal and polar latitudes because of effects on albedo. If BC, OC, and BrC generated from wildland fire are deposited in snow- and ice-covered regions at the boreal and polar latitudes, only the aerosols deposited on the ice will enhance melting. The BC, OC, and BrC remaining aloft in the atmosphere will absorb sunlight and shield the ice and snow from melting (Sand et al., 2013; Ramanathan and Carmichael, 2008; Flanner et al., 2007). Following wildland fires, charred residues and ash remain as byproducts of incomplete combustion. Carbon in these residues often is elemental black carbon, basically inert, and has a prolonged residence time as it becomes incorporated into the soil. Over time, fires can lead to a net increase in an area's ability to sequester carbon, offsetting a portion of the carbon released into the atmosphere during the fire (Kuhlbusch et al., 1996; Deluca and Aplet, 2008; Rovira et al., 2009; Brewer et al., 2013).

3. Fuel consumption modeling

Consumption of shrubs, grasses, woody fuels, litter, and duff in forests and rangelands in the temperate, tropical, and boreal regions of the world has become better understood in recent years. Studies have collected a large number of comprehensive data sets that include fuel characteristics, fuel moisture, fuel consumption, and environmental variables from both wildfires and prescribed fires (Table 1). These datasets have been used to develop fuel consumption models such as Consume (Prichard et al., 2007), FOFEM (Reinhardt et al., 1997), CanFIRE, and BORFIRE (de Groot et al., 2007, 2009). Although fuel consumption can be predicted from a simple rule based system developed from anecdotal evidence, a set of empirically derived equations developed from field data, or a physics-based models, most fuel consumption software packages use a combination of the three approaches. Consume (Prichard et al., 2007) and the First Order Fire Effects Model (FOFEM) (Reinhardt et al., 1997) are examples of this combination approach. Although great strides have been made in understanding pyrolysis and combustion processes in natural fuels (Gronli and Melaaen, 2000; Costa and Sandberg, 2004; Rostami et al. 2004; Ohlemiller 1985), the models are currently limited to simple fuel beds, do not account for spatially discontinuous fuels, and will need field data to calibrate and modify coefficients to provide a more realistic results (Mell et al., 2007).

As discussed earlier in the paper, each fuel bed category burns and consumes differently due to the characteristics of the fuel and to environmental factors, and has to be considered when modeling. Recent work in the western and southeastern United States by Wright, 2013; Wright (in press), and Wright and Prichard (2006) has shown that shrub consumption is best modeled as a function of fuel amount, fuel condition (i.e., dead fuel moisture content) and environment (i.e., season, wind speed, and slope). Studies conducted across the United States found that fuel consumption of grass, herbaceous material, small dead woody fuels (<7.62 cm in diameter), and litter is dependent upon total load and fuel moisture content, with generally 80% consumption occurring during the flaming phase with the remaining consuming during the smoldering stage (Prichard et al., 2007; Brown et al., 1991). Large dead woody fuel consumption (>7.65 cm) also depends on moisture content of the woody fuel and loading, but only 50% of the consumption occurs during the flaming phase (Prichard et al., 2007; Brown et al., 1991). Duff consumption during wildland fires in the west, south, and boreal regions of the United States depends on the depth and moisture content of duff, and the duration of fire in the woody fuels (Van Wagner, 1972; Sacket, 1980; Sandberg, 1980; Harrington, 1987; Brown et al., 1991; Prichard et al., 2007; Ottmar and Baker, 2007) and occurs primarily during the

Table 1
Partial list of studies on fuel consumption by region and fuel bed category.

Citation	Region	Fuel bed category
Hough (1968)	Southeastern United States	Shrub, grass, woody, litter, duff
Van Wagner, 1972	Canada	Duff
Hough, 1978	Southeastern United States	Shrub, grass, woody, litter, duff
Sandberg, 1980	Western United States	Duff
Sandberg and Ottmar, 1983	Western United States	Shrub, grass, woody, litter, duff
Ottmar, 1984	Pacific Northwest, United States	Shrub, grass, woody, litter, duff
Brown et al., 1985	Western United States	Shrub, grass, woody, litter, duff
Ottmar et al., 1985	Western United States	Duff
Little et al., 1986	Western United States	Duff
Frandsen, 1987	Western United States	Duff
Harrington, 1987	Western United States	Woody, litter, duff
Stocks, 1987	Canada	Shrub, grass, woody, litter, duff
Ottmar, 1987	Pacific Northwest	Shrub, grass, woody, litter, duff
Brown et al., 1991	Western United States	Shrub, grass, woody, litter, duff
Ottmar et al., 1993	Western United States	Shrub, grass, woody, litter, duff
Albini and Reinhardt, 1997	Western United States	Shrub, grass, woody, litter, duff
Carvalho et al., 2001	Brazil	Woody
Carvalho et al., 2002	Brazil	Woody
Stocks et al., 2004	Canada	Crown, shrub, grass, woody, litter, moss, duff
Rabelo et al., 2004	Brazil	Woody
Ottmar et al., 2006	United states	Shrubs, grass, woody, litter, duff
Wright and Prichard, 2006	Western United States	Shrubs
Ottmar and Baker, 2007	Alaska, United States	Litter, moss, duff
Prichard et al., 2007	United States	Shrub, grass, woody, litter, duff
Reardon et al., 2007	Southeastern United States	Duff
de Groot et al., 2009	Canada	Litter, moss, duff
Russell-Smith et al., 2009	Australia	Grass
Hollis et al., 2010	Australia	Woody
Hyde et al., 2011	United States	Woody
Wright, 2011	Western United States	Piled wood
Wright et al., in press	Southeastern United States	Shrubs
Wright et al., 2013	Western United States	Shrubs

smoldering stage. Consumption of tree crowns in forests, shrub crowns in shrublands, large rotten logs, and fuel beds with deep peat layers such as in wetland (pocosin) region of the southeastern United States is poorly understood and additional research is needed (Wright, 2013; Wright, in press; Wright and Prichard, 2006; Reardon et al., 2007, 2009; Hyde et al., 2011).

Because consumption during the flaming phase is more efficient than during the smoldering phase, and different emission factors are applied depending on the chemical compound of interest, separate calculations of flaming consumption and smoldering consumption are required for assessment of total black carbon and greenhouse gas and aerosol emissions. Equations for predicting biomass consumption by combustion phase for major fuel types in the United States are widely available in two major software packages including Consume (Prichard et al., 2007; Consume, 2012) and FOFEM (Reinhardt and Keane, 2000; Reinhardt, 2003; Reinhardt et al., 1997). Consume predicts fuel consumption in a variety of fuel types including logging slash, piled woody debris, or natural forest, shrub, and grass fuels using a mix of empirical, theoretical, and rule-based models. Variables include the amount of fuel, woody fuel and duff moisture content, and meteorological data. The system also predicts loading of piled wood and assumes 90% consumption (Hardy, 1996; Wright et al., 2010a; Wright et al., 2010b). Consume is linked to the Fuel Characteristic Classification System (Ottmar et al., 2007) for assigning default fuel loadings. It also incorporates features that allow users to reduce modeled fuel loads where fuel reduction techniques have been implemented. A list of fuel consumption equations currently available in Consume are presented in Appendix A (Prichard et al., 2007). These models are being modified as new data is acquired and old data reanalyzed.

The First Order Fire Effects Model (FOFEM) estimates fuel consumption for different regions of the country by fuel bed category using empirically derived equations, rules of thumb, and the BURNUP model (Albini, 1994; Albini and Reinhardt, 1995, 1997; Albini et al., 1995; Lutes, 2013; First Order Fire Effects Model 2012). BURNUP is a mechanistic woody fuel consumption model that considers heat transfer and burning rate of woody fuel particles as they interact over the duration of a burn (Lutes, 2013). Consumption of canopy fuels is not predicted in FOFEM and requires the user to enter the proportion of the canopy that will consume. Shrub consumption is modeled with rules developed from anecdotal evidence (Reinhardt et al., 1997). All grasses and herbaceous fuels are assumed to consume unless the season is spring where 90% consumption is assigned. The consumption of litter is calculated by BURNUP. Generally 100% of the litter is consumed. Duff consumption is assumed to be constant and is calculated using a number of algorithms from Hough, 1978; Brown et al., 1985, 1991; Harrington, 1987; and Hungerford, 1996. A list of fuel consumption equations by fuel bed category and region currently used by the First Order Fire Effects Model (FOFEM) are presented in Appendix B (Reinhardt et al., 1997; Brown et al., 1985; First Order Fire Effects Model 2012).

The availability of a validation data set for fuel consumption models is limited, and therefore the models have not been validated. . This is changing, however. A 2011 study collected a fuel consumption dataset, including pre- and post-burn fuel characteristics and day-of-burn environmental variables to help in determining Consume and FOFEM uncertainties, biases, and application limits in the eastern United States (Ottmar and Dickinson, 2011). Consume and FOFEM performed well in predicting the consumption of the shrub, grass, 1-h, 10-h, and 100-h woody fuel components in southern pine fires. However, both performed poorly in predicting 1-h, 10-h, and 100-h woody fuel consumption in mixed hardwood sites. Although Consume more accurately predicted large woody fuel consumption in both the pine and mixed hardwoods, both models poorly predicted litter consumption. In 2012, the Prescribed Fire Combustion Atmospheric Dynamics

Research Experiment (RxCADRE) acquired one of the largest fire data sets in the world (Prescribed Fire Combustion Atmospheric Dynamics Research Experiment [RxCADRE], 2012). This data set will be available to all interested scientists for fuel consumption model development, testing and evaluation.

Consume and FOFEM have their limitations, as do all models. Both are limited by the range of data that went into building the models. Consequently, care must be taken if these models are applied to fuel bed types or under environmental conditions outside these ranges. For example, Consume does not work well in the hardwood fuel bed types of the northeastern United States and does not account for windy conditions.

Consume and FOFEM are updated on a regular basis as new consumption models are developed and evaluated, and as new computer applications become available. Consume, for example, has been reprogrammed into a distinct, maintainable module and integrated into the Fire and Fuels Application system (FFA). It includes the natural fuels digital photo series (Ottmar et al., 2009b), FCCS (Ottmar et al., 2007), and Fire and Emissions Production Simulator (FEPS) (Anderson et al., 2004). It has been integrated into the Interagency Fuels Treatment Decision Support System (IFT-DSS) sponsored by the Joint Fire Science Program (JFSP, 2012).

Woody debris that either accumulates naturally in a forest or is left over from a timber harvest is often piled by hand or by machinery and later burned to reduce fuel loads and, consequently, fire hazard. The Pile Calculator (Wright et al., 2010a,b) is a web-based application that uses formulas for different geometric shapes to estimate the volume of biomass that has been piled, and empirically derives relationships between volume and biomass to estimate pile weight for different pile types (machine vs. hand) composed of different material (different types of coniferous vs. hardwood/shrub material). These relationships were derived by Hardy (1996) and Wright et al. (2010a) from pile measurements collected throughout the western United States. The system assumes 90% consumption, but the user may enter a different value where more or less consumption is expected. Studies are currently ongoing to develop a pile consumption model (Wright, 2011). Additional pile research is needed in other fuel bed types and in determining how much of the biomass consumes.

Much of the research on fuels and fuel consumption has required extensive ground-based sampling over the past 30 years and the resulting fuel consumption models are now being joined with remote sensing applications to improve our ability to estimate greenhouse gases and aerosols emissions. The remote sensing applications provide the size of the area burned while the fuel consumption models provide the amount of biomass consumed. Coupled with emission factors, estimates of total greenhouse gas emissions and carbon can be made. There are several systems that have integrated remote sensing with fuel consumption models. The Wildland Fire Emissions Information System (WFEIS) (French et al., 2009) is one such model that is based on (1) remote sensing technology to acquire the size of the area burned, (2) the Fuel Characteristic Classification System (Ottmar et al., 2007; Weise and Wright, 2014) to provide fuel characteristics, and (3) Consume (Prichard et al., 2007) to provide fuel consumption and emissions data. A comparison of several systems including FOFEM (Reinhardt, 2003), Consume (Prichard et al., 2007), WFEIS (French et al., 2009), the Canadian Forest Service's CanFIRE (de Groot, 2010), and the Global Fire Emissions Database (GFED) (van der Werf et al., 2010) to estimate the movement of carbon released during wildfires from the terrestrial biosphere to the atmosphere was made by (French et al., 2011). The results between systems often did not agree and variations were attributed to differences in model assumptions and methods including changes in fuel moisture and in accounting for biomass consumed in the canopy of forests.

4. Wildfire vs. prescribed fire

Generally two to four times more fuel is consumed during a wildfire than a prescribed fire, leading to more greenhouse gas emissions (Ottmar, 1992; Huff et al., 1995; Brown and Bradshaw, 2004). There are three main reasons for this. First, fuels are generally drier in a wildfire, so more of the larger woody material and forest floor consumes. Second, tree crowns are often involved, increasing the fuel consumption even more. Third, wildfire may occur during very windy periods, increasing both the consumption of fuel and size of the fire.

Prescribed fires, on the other hand, are planned and can be ignited under fuels and weather conditions to meet specific objectives such as reducing the mass of small fuels or eliminating unwanted species. Most often, prescribed fires are ignited when fuel moistures are high in the large woody fuels and forest floor, reducing the availability of those fuels to consume. If the fuel bed is composed mostly of grass, prescribed fire will consume about the same amount of fuel as wildfire because most prescriptions call for fuel moisture conditions that will allow a majority of the grass to consume. It is only when tree crowns, shrubs, large woody fuels, and duff are present that there is a potential for more fuel consumed during wildfires than during prescribed fires because the prescribed fire prescription does not call for a majority of the heavy material to consume.

5. Knowledge gaps

Although fuel consumption modeling has improved over the past 30 years, studies targeting specific fuel bed categories are needed where data are limited, such as live tree and shrub branches and canopies, deep organic layers, and large rotten logs. There is a lack of quality-controlled, integrated fuel consumption data sets to continue development and evaluation of fuel consumption models. Furthermore, fuel moisture prediction models, an important variable for predicting fuel consumption, are poor, especially for the large woody fuels and organic soils. As we move forward with advanced remote sensing techniques, large scale estimates of greenhouse gas emissions will not improve unless we find ways to better connect fuels and consumption to remote sensing data. This may include sensing of wildland fire severity and relating that to fuel consumption, or interpreting both physical and moisture attributes. Finally, additional research is needed to better understand the (1) charred residues and ash remaining after fires, (2) how much of that material becomes sequestered carbon to offset the emissions of greenhouse gases, and (3) how much BC, OC, and BrC is generated and will be dispersed into the atmosphere and deposited at higher latitudes potentially increasing snow melt.

6. Conclusion

The combustion of vegetation during wildland fire has the potential to generate large amounts of GHGs and other aerosol emissions. To assess the contribution of wildland fires to these emissions, a common understanding of how fuel consumes is needed. Over the past 30 years we have made great strides in our ability to predict fuel consumption as evidenced by several models widely used by scientists and land managers in the United States and Canada. These include the First Order Fire Effects Model, Consume, and CanFIRE. Although these software systems are in use today, evaluations of the models with independent data sets is lacking, restricting our ability to ascertain the true contribution of wildland fire to the GHG and aerosol emissions. Furthermore, information is limited on the production and sequestration of BC into the soils following wildland fire that may serve as a partial offset of GHG and aerosol emitted into the atmosphere.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2013.06.010.

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