Forest Ecology and Management 317 (2014) 41–50

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

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

Roger D. Ottmar *

U.S. Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, 400 North 34th Street, Suite 201, Seattle, WA, USA

ARTICLE INFO

Article history:
Available online 17 July 2013

Keywords:
Fuel consumption
Wildland fire emissions
Carbon emissions

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.

Published by Elsevier B.V.

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

* Tel.: +1 206 732 7826.
E-mail address: rottmar@fs.fed.us

0378-1127/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.foreco.2013.06.010

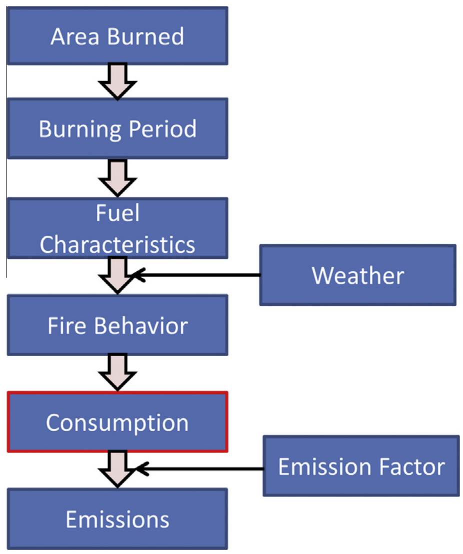

Fig. 1. Inputs required for determining emissions of greenhouse gases from wildland fire.

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)