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# Chapter 3

# Characterizing Sources of Emissions from Wildland Fires

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## Abstract

Smoke emissions from wildland fire can be harmful to human health and welfare, impair visibility, and contribute to greenhouse gas emissions. The generation of emissions and heat release need to be characterized to estimate the potential impacts of wildland fire smoke. This requires explicit knowledge of the source, including size of the area burned, burn period, characteristics and condition of the fuels, amount of fuel consumed, and emission factors for specific pollutants. Although errors and uncertainties arise in the process of estimating emissions, the largest errors are related to the characteristics of the fuels and amount of fuel consumed during the combustion phase. We describe the process of characterizing emissions and review the knowledge and predictive models currently available for performing the calculations. The information can be used by scientists, regulators, and land managers to improve the approach needed to define the emissions source strength for improved air quality and impact assessments.

### 3.1. Introduction

All wildland fires release various amounts of carbon dioxide ($CO_2$), carbon monoxide (CO), methane ($CH_4$), nitrogen oxides ($NO_X$), ammonia ($NH_3$), particulate matter (PM), nonmethane hydrocarbons (NMHC), sulfur dioxide ($SO_2$), and other chemical species into the atmosphere (Crutzen & Andreae, 1990; Holzinger et al., 1999; Yokelson et al., 1996). These particulates and gaseous compounds can be hazardous to human health, threaten human welfare and ecosystems, degrade

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visibility, affect biogeochemical cycles, and contribute to greenhouse gas emissions (Battye & Battye, 2002; Bertschi et al., 2003; Hardy et al., 2001; Miranda et al., 1993, 2005a; Miranda & Borrego, 2002; Sandberg & Dost, 1990; Sandberg et al., 1999, 2002). The impacts are related to chemical reactions, and to transport and deposition processes, and can occur at both global and local scales (Borrego et al., 1999; Crutzen & Andreae, 1990; Crutzen & Carmichael, 1993; Miranda, 1998; Miranda et al., 1994; Reinhardt et al., 2001; Valente et al., 2005; Ward & Radke, 1993).

To acquire a better understanding of the potential impacts of these combustion by-products, the heat release rate and emissions generated by the fire must be characterized (Pouliot et al., 2005). This requires explicit knowledge of the source, including area burned, burning period, fuel characteristics, fire behavior, fuel consumption, and pollutant-specific emission factors (Battye & Battye, 2002; Hardy et al., 2001; Peterson, 1987; Peterson & Sandberg, 1988; Sandberg et al., 2002). Although errors and uncertainties arise during each step of the process of estimating emissions, the largest errors are related to the characteristics of the fuels and fuel consumption (Fig. 3.1) (Hardy et al., 2001; Peterson, 1987; Peterson & Sandberg, 1988), providing the area burned reported is area actually blackened and not total area within the perimeter of the fire.

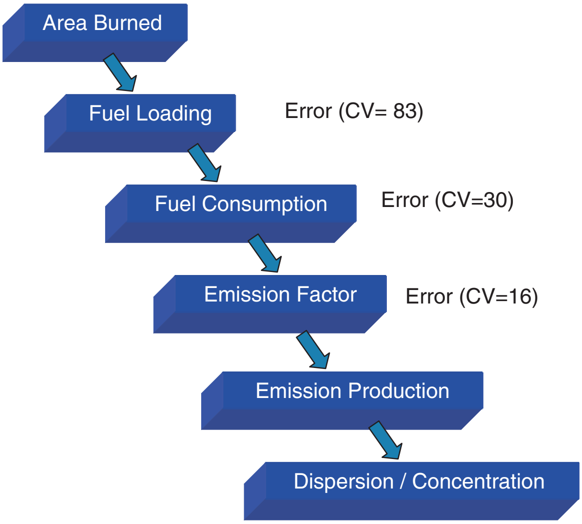

*Figure 3.1.* Information required for estimating emission production. The largest errors are associated with fuel loading and fuel consumption inputs (Peterson, 1987) unless the area burned is total acres within the perimeter of the fire. (CV = coefficients of variation.)

If this is the case, the area burned input value could have the largest uncertainty (Peterson, 1987). This chapter presents the process of characterizing emissions, source strength, and heat release from wildland fires and discusses several of the current models and approaches available to calculate these data.

### 3.2. Area burned

The area burned by a wildland fire is one of the more difficult parameters to accurately obtain when calculating fire emissions (Battye & Battye, 2002). At first glance, the amount of area burned seems relatively easy to determine. However, large systematic errors may exist depending on the quality of the reporting system (Peterson, 1987). Individual estimates of fire size tend to be exaggerated and fires are frequently double-counted in inventories (Sandberg et al., 2002). For example, the entire landscape within a fire perimeter is often reported burned although nonuniform fuels, geographic barriers, or changes in the weather can cause a fire to burn in a mosaic pattern with unburned patches. In other instances, poor reporting systems may miss a large number of fires, thus underestimating the number of acres burned. Although large-scale inventories of area burned are often derived from remotely sensed data, the technique has limited precision and is inadequate in landscapes with variable slope and fuel characteristics (Crutzen & Andreae, 1990; French et al., 2004; Levine, 1994; Sandberg et al., 2002).

Burned area measurements can be obtained from three sources: wildfire reports, prescribed fire or smoke management reports, and aerial or satellite imagery data (Battye & Battye, 2002). All three procedures have problems associated with the information. For example, wildfire reports are often difficult to obtain, fire location and vegetation data associated with the fire may be incorrect, and the daily perimeter growth is rarely included. Prescribed fire and smoke management reports often provide correct project size; however, the fuel loading and actual area burned may be incorrect. Aerial and satellite imagery are expected to provide improved temporal and spatial resolution in the near future, but procedures need further refinement and the imagery often lacks the ability to detect fire under canopies.

### 3.3. Burning period

The burn period (minute) is the length of time combustion is occurring for a particular area and is required for calculating emission source strength (g $\text{min}^{-1}$) and heat release rate (J $t^{-1}$). Source strength and heat release rate are critical inputs to dispersion models for assessing air quality impacts (Hardy et al., 2001; Sandberg et al., 2002).

The burn period for a wildland fire event may extend for several minutes or several months. It will often include periods of large, high intensity fire growth interspersed with periods of low intensity, slow growth. The periods may be marked with well-developed convection columns that entrain emissions and heat from large areas interspersed with periods with low, buoyant smoke with little or no spatial organization. The burn area is seldom all combusting at one time, but rather is an ever-changing perimeter that experiences successive ignitions, flaming spread, and smoldering/residual smoldering combustion periods. Although it is often convenient to characterize a wildland fire as a uniform event having a constant fire behavior and source strength for the entire period, such characterization overlooks the extreme spatial and temporal variation that normally exists over a burn area.

Burn period is not directly entered into wildfire or prescribed fire reports, but can be estimated based on known ignition time and information that indicates when consumption ceased. Satellite or aerial imagery over time could be assessed and used to estimate burning period.

### 3.4. Fuel characteristics

Fuel characteristics can vary widely across regions (Fig. 3.2). For instance, fuel loads can range from less than 0.6 t $\text{ha}^{-1}$ for a perennial grassland in the central part of the United States with no rotten woody material or duff (organic material that includes Oe horizon and Oa horizon), to 35 t $\text{ha}^{-1}$ in a cerrado denso woodland in central Brazil with a grass and shrub understory and a litter layer, to 195 t $\text{ha}^{-1}$ in a mixed-conifer forest with insect and disease mortality in the U.S. Rocky Mountains that has dead and down sound and rotten woody material, snags, litter and duff, and to 381 t $\text{ha}^{-1}$ in a black spruce (*Picea mariana*) forest of northern Canada with a deep moss and organic forest floor layer (Hardy et al., 2001; Ottmar & Vihnanek, 1998, 1999; Ottmar et al., 1998a, 2001, 2007; Sandberg et al., 2002). Human activities have also created an impressive mosaic of forest, shrublands, and grasslands across Occidental Europe also. Fuel loads can range from 2 t $\text{ha}^{-1}$ within a Mediterranean community of *Rosmarinus officinalis* garrigue to 160 t $\text{ha}^{-1}$ within a temperate beech forest of *Fagus silvatica* (Trabaud et al., 1993). The large variation in fuel loading across regions can contribute up to 80% of the error associated with estimating emissions (Peterson, 1987; Peterson & Sandberg, 1988).

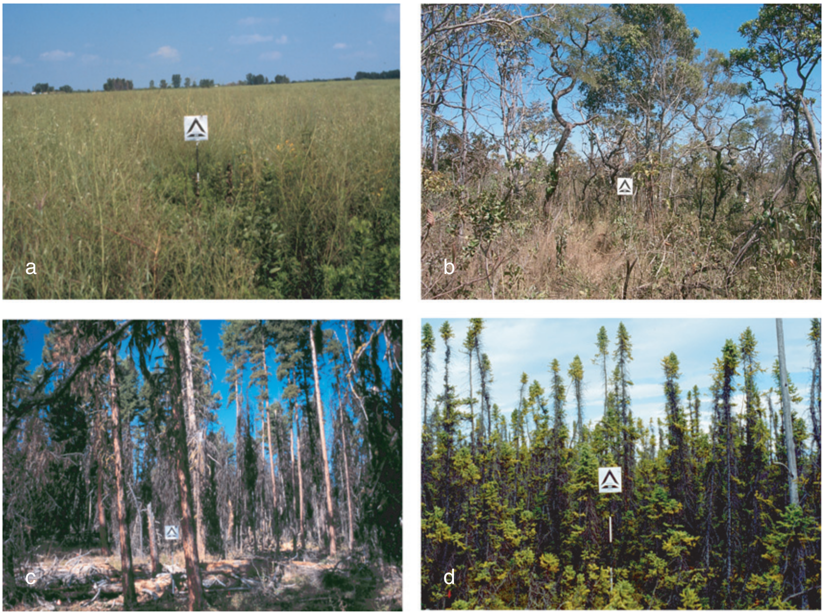

*Figure 3.2.* Fuelbed types and fuel loads can vary widely ranging from (a) grasslands in the midwestern United States (0.6 t ha$^{-1}$), (b) cerrado denso (woodland) in Brazil (35 t ha$^{-1}$), (c) mixed-conifer forest with insect mortality in the Rocky Mountain region of the United States (195 t ha$^{-1}$), and (d) black spruce forest with a deep organic layer in Canada (381 t ha$^{-1}$).

It would be prohibitively difficult to inventory loadings for all fuelbeds every time an assessment of emissions or management decision was necessary (Ottmar et al., 2004; Sandberg et al., 2001). Attempts have been made during the past 30 years to develop systems to construct and classify fuelbeds for loading in several countries with various degrees of success. These include the original and standard Fire Behavior Fuel Models (U.S.) (Anderson, 1982; Andrews & Chase, 1989; Scott & Burgan, 2005), National Fire Danger Rating System Fuel Models (U.S.) (Deeming et al., 1977), Fuel Condition Class System fuelbeds (U.S.) (Ottmar et al., 1998b; Schaaf, 1996), First Order Fire Effects Model (FOFEM) fuelbeds (U.S.) (Reinhardt et al., 1997; Reinhardt & Crookston, 2003), Canadian Fire Danger Rating System (Canada) (Hirsch, 1996), Australian Fire Danger Rating System fuel models (Australia) (Cheney & Sullivan, 1997; Cheney et al., 1990); Photo Series (U.S.) (Ottmar et al., 2004), the Fuel Load Models (U.S.) (Keane, 2005, Landscape Fire and Resource Management Planning Tools Project (LANDFIRE), 2005), and the

European Fire Management Information System (PROMETHEUS) (PROMETHEUS, 1999). Many of these systems were designed for specific software applications and therefore include only the fuelbed components required by the program they were designed to support. Consequently, the systems did not capture all fuel components required to estimate air pollutants (Ottmar et al., 2007; Sandberg et al., 2001). Although progress has been made in assessing fuel characteristics using Light Detection and Ranging (LIDAR) and other remote sensing techniques, large errors are evident when fuel loading is inferred from vegetation type when deriving biomass emissions from remotely sensed data (Crutzen & Andreae, 1990; Levine, 1994; Molina et al., 2006).

The Fuel Characteristic Classification System (FCCS) is a tool that is applicable worldwide, although the current fuelbed database contained in the system is robust only for the United States. The tool enables users to create and catalogue fuelbeds. Fuelbed characteristics from this tool will provide inputs to current and future wildland fire emission production models. The FCCS contains a set of fuelbeds representing the United States that were compiled from scientific literature, fuels photo series, fuels data sets, and expert opinion. The system enables modification and enhancement of these fuelbeds to represent a particular scale of interest. The FCCS then reports assigned and calculated fuel characteristics for each existing fuelbed stratum including the canopy, shrubs, nonwoody, woody, litter/lichen/moss, and duff (Fig. 3.3; Riccardi et al., 2007). FCCS outputs have been used to generate a fuelbed map for the United States, and these data are being used in a national wildland fire emissions inventory (Fig. 3.4; McKenzie et al., 2007) and in the development of fuelbed, fire hazard, and treatment effectiveness maps on several national forests.

The LANDFIRE Project (Rollins & Frame, 2006) will develop digital maps of wildland fuel loadings to be applied across the entire United States at a 30 m spatial resolution. The project will also map FCCS fuelbeds, thus allowing additional fuelbed characteristics to be available for improved estimation of emissions from wildland fires.

In addition, the Euro-Mediterranean Wildland Fire Laboratory European Commission Project (www.eufirelab.org) compiled and listed (Allgower et al., 2006) the different systems used to estimate and map fuelbeds across Europe.

### 3.5. Fire behavior

Fire behavior is defined as the reaction of fine fuels available for burning (Debano et al., 1998) and is dependent on fuelbed type, condition and

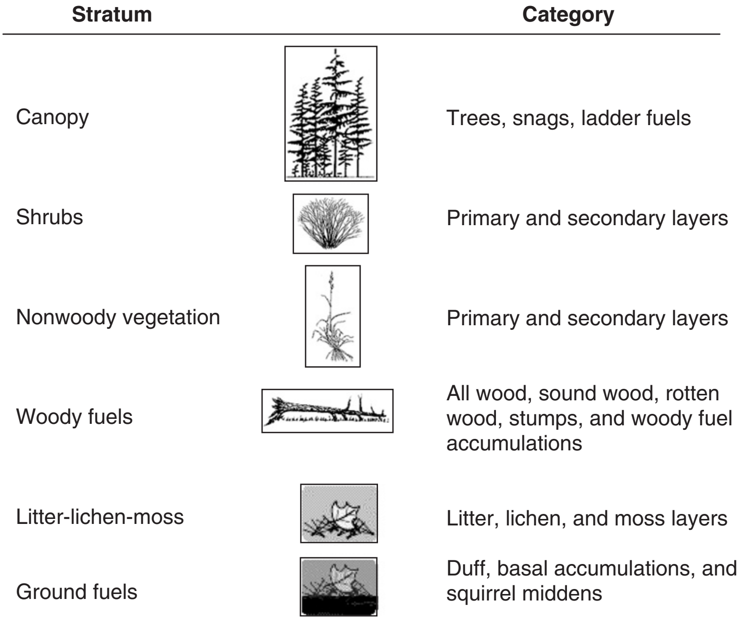

*Figure 3.3.* Horizontal stratification of an FCCS fuelbed by strata and categories in the United States.

arrangement of the fuels, local weather conditions, topography, and in the case of prescribed fire, ignition period and pattern. Important aspects of fire related to the production of emissions include fire intensity ($\mathrm{J\,m^{-2}}$), rate of spread ($\mathrm{m\,min^{-1}}$), and residence time (minute) in the flaming, smoldering, and residual stages of combustion (Sandberg et al., 2002). These aspects of fire behavior influence the combustion efficiency of burning fuels and the resulting pollutant chemistry and emission strength.

The Fire Emissions Production Simulator (FEPS) (Fire and Environmental Research Applications Team, 2006) and a fire growth simulator called FARSITE (Finney, 1998) take into account fire behavior and ignition period and pattern to estimate emission production rates. Both tools model the flaming and smoldering combustion and duration in down woody fuels and duff, although FEPS is better parameterized to predict flaming versus smoldering (Sandberg et al., 2004).

### 3.6. Fuel consumption

Fuel consumption ($\mathrm{t\,ha^{-1}}$) is the amount of biomass consumed during a fire and is another critical component for estimating the amount and

*Figure 3.4.* A 1 km resolution map of FCCS fuelbeds for the contiguous 48 states in the United States.

source strength of emissions and the rate of heat release generated from wildland fire. Fuels are consumed in a complex combustion process that varies widely among fires and is dependent on fuel type, arrangement of the fuel, condition of the fuel, and in the case of prescribed fires, the way the fire is applied. As with fuel loading, extreme variations associated with fuel consumption and the data can contribute errors of 30% or more when emissions are estimated for wildland fires (Peterson, 1987; Peterson & Sandberg, 1988).

Equations for predicting consumption by combustion phase are widely available in two major software packages, Consume 3.0 (Ottmar et al., 2005) and the FOFEM (Reinhardt, 2003; Reinhardt et al., 1997). Consume 3.0 uses a set of theoretical models based on empirical data to predict the amount of fuel consumption from all material that can potentially burn in a fuelbed, including tree crowns, shrubs, grasses, woody fuels, moss, lichen, litter, and duff. The model also separates the consumption into flaming, smoldering, and residual phases. Input variables include the amount of fuel, moisture content of woody fuel and duff, length of ignition, and meteorological data. The system incorporates the FCCS for assigning default fuel loadings. FOFEM 5.0 relies on Burnup, a theoretical model of fuel consumption (Reinhardt et al., 1997). The software computes duff and woody fuel consumption for many forests and rangeland systems of the United States. Both Consume 3.0 and FOFEM 5.0 are updated on a regular basis as new consumption models are developed.

### 3.7. Emission factors

An emission factor ($\mathrm{g\,kg^{-1}}$) for a particular pollutant of interest is defined as the mass of pollutant produced per mass of fuel consumed. Emission factors vary depending on type of pollutant, type and arrangement of fuel, and combustion efficiency (combustion phase). The average emission factors for the flaming and smoldering period of a fire have a relatively small range and contribute to about 16% of the total error associated with predicting emissions (Peterson, 1987; Peterson & Sandberg, 1988). The important distinction between fires is the ratio of flaming to smoldering/residual consumption. This is governed by the fuel characteristics in the burn area and the fuel condition during the burn period. Fires that burn primarily in smoldering combustion can produce several times the mass of pollutants (not including carbon dioxide) as compared to a fire in which a majority of the fuel is consumed during the flaming phase.

Emissions from wildland fires have been measured extensively by researchers since about 1970. The result is a relatively complete set of emission factors for criteria pollutants and many hazardous air pollutants for most important fuel types in the United States (Andreae & Merlot, 2001; Battye & Battye, 2002; Environmental Protection Agency, 1996; Hardy et al., 2001; Ward et al., 1989). Miranda (2004) and Miranda et al. (2005a) present a selection of emission factors to be applied to south-European forest conditions. Less complete compilations of emission factors are available for PM size class distribution, elemental and organic carbon fractions, particulate hazardous air pollutants, methane, ammonia, aldehydes, compounds of nitrogen, volatile organic compounds, and volatile hazardous air pollutants (Battye & Battye, 2002; Goode et al., 1999, 2000; Lobert et al., 1991; McKenzie et al., 1994; Sandberg et al., 2002; Yokelson et al., 1996).

### 3.8. Total emissions, source strength, and heat release

Total emissions from wildland fires can be calculated by the equation

$$\text{Total emissions (g)} = \text{fuel consumed (kg ha}^{-1}) \times \text{emission factor (g kg}^{-1}) \\ \times \text{area burned (ha)}$$

However, much better estimates of emissions can be made if the amount of fuel consumption in the flaming and smoldering/residual combustion periods is known. The fuels consumed during the flaming and smoldering stages are multiplied by the appropriate flaming and smoldering emission factor for an average fuelbed. Consume 3.0 (Ottmar et al., 2005) and FOFEM 5.0 (Reinhardt, 2003; Reinhardt et al., 1997) use this approach to improve the estimates of total emissions produced from wildland fire, as compared with using a fire average fuel consumption and emission factor. Currently, both fuel consumption models provide fuel consumption by fuelbed component, although emission factors by fuelbed component are not available at this time. Emission factor research is ongoing to fill in this gap (Hao, 1998; Ottmar, 2003).

Source strength is the rate of air pollutant emissions in mass per unit of time or in mass per unit of time per unit area and is the product of rate of biomass consumption and emission factor for the pollutant of interest. Source strength can be calculated by the equation

$$\text{Source strength (g min}^{-1}) = \text{fuel consumption (kg ha}^{-1}) \\ \times \text{emission factor (g kg}^{-1}) \\ \times \text{rate of area burned (ha min}^{-1})$$

The consumption of biomass produces thermal energy, and this energy creates buoyancy to lift smoke particles and other pollutants above the fire. Heat release rate is the amount of thermal energy generated per unit of time or per unit of time per unit area. It can be calculated by the equation

$$\begin{aligned}\text{Heat release rate (J min}^{-1}) = {} & \text{fuel consumption (t ha}^{-1}) \\ & \times \text{heat output (J t}^{-1}) \\ & \times \text{rate of area burned (ha min}^{-1})\end{aligned}$$

Both source strength and heat release rate are required by most sophisticated smoke dispersion models (Breyfogle & Ferguson, 1996; Miranda, 2004).

FEPS (Fire and Environmental Research Applications Team, 2006) predicts hourly emissions, heat release, and plume rise values for wildland fires. The program requires area burned, ignition period, fuel characteristics, and fuel moisture conditions as input variables. Fuel consumption may be added as an input or calculated internally. Although the system provides default input values for fuel characteristics, fuel condition, and ignition period to calculate source strength, heat release rate, and plume rise, FEPS can also import consumption and emissions data from Consume 3.0 and FOFEM. FEPS can be used for any forest, shrub, and grassland or piled-fuel types throughout the world.

### 3.9. Implementation

Several large-scale wildland fire emissions inventories and assessments have been conducted over the past several years using variations of the protocols discussed in this chapter. Peterson and Ward (1993) addressed historic emissions in 1989 for the United States using fire reports and expert opinion to determine burned area, fuelbed type, and fuel consumption. Fire average emissions factors were assigned to the fuelbeds and emissions calculated. In 1995, the Grand Canyon Visibility Transport Commission began a more comprehensive emission inventory for 10 states in the western United States. Reports were used to determine area burned; however, the FCC fuelbeds and Consume were used to determine fuel characteristics, fuel consumption, and emissions (Grand Canyon Visibility Transport Commission, 1996). During the Interior Columbia Basin Ecosystem Management Project (Quigley & Arbelbide, 1997) modeled smoke production was compared for recent historical and current time periods based on vegetative attributes determined from aerial photographs (Ottmar et al., 1998b). The vegetation type was assigned an FCC fuelbed, and Consume was used to calculate the emissions for each time period.

The European Commission Project called SPREAD estimated forest fire emissions for the year 2001 in southern Europe. Two approaches were used. The first approach acquired fire reports to determine area burned and used a European variation of the National Fire Danger Rating System to estimate emissions. The second approach also used fire reports to determine area burned but applied the model called EMISPREAD (Miranda et al., 2005b) to calculate emissions. The study found that of the southern European countries, Portugal was the major contributor of wildland fire emissions in 2001 (Miranda, 2005a, 2005b). It was also determined that the emissions from each approach were in reasonable agreement.

The approach to emissions calculations has improved over the years as new research and better models have made been created. Considering current available knowledge and models, a relatively accurate estimate of emissions can be generated (Fig. 3.5). Additional improvements

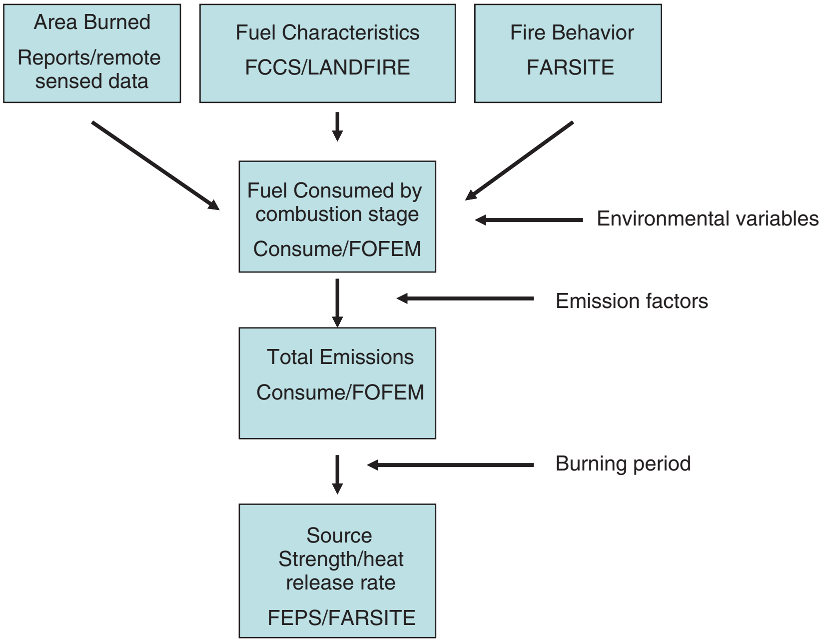

*Figure 3.5.* Flow diagram of one approach to estimating emissions.

in estimating smoke emissions will require better fire reporting or remote sensing of fire perimeters and period of burning; improved ability to assign fuelbed characteristics to the landscape, and development of more robust fuel consumption models that account individually for all combustion phases and all fuelbed components that have a potential to burn. Unless there are important hazardous compounds that do not have emission factors associated with them, additional emission factor research is not the most important science effort to pursue (Hardy et al., 2001; Peterson, 1987). There are well-accepted emission factor numbers (Hardy et al., 2001) available at this time, and the values do not vary greatly by fuelbed type (Sandberg et al., 2002), but rather primarily by the combustion efficiency and the fuel consumption by combustion stage.

The uncertainity associated with the approach described in this chapter to estimate emissions from wildland fire may change in the future. New and improved reporting and sensing methodologies will provide improved burned area data reducing the uncertainty associated with this estimation. Climate change may also cause fuelbed components to be more or less complex and consume differently, increasing or decreasing the associated uncertainty. For example, an increasing temperature and drought climatic pattern for a region may result in a less complex fuelbed, reducing uncertainty. However, the fuelbed will be drier, increasing the amount of fuel available to consume and changing the ratio of flaming and smoldering combustion by fuelbed component. This may result in an increase in uncertainty of this variable.

Although research characterizing fuels and modeling fuel consumption has progressed over the past 20 years (Brown et al., 1991; Ottmar et al., 2005), more studies are needed, especially as climate changes. Future emission production research would be best served by concentrating efforts in the area of burn area assessment, fuelbed characterization, and fuel consumption modeling.

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## REFERENCES

Allgower, B., Calogine, D., Camia, A., Cuiñas, P., Fernandes, P., Francesetti, A., Hernando, C., Koetz, B., Koutsias, N., Lindberg, H., Marzano, R., Molina, D., Morsdorf, F., Ribeiro, L.M., Rigolot, E., and Séro-Guillaume, O. 2006. Methods for wildland fuel description and modeling: Final version of the state-of-the art. Deliverable D-02-06, EUFIRELAB Project EVR1-CT-2002-40028, 57 pp.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. General Technical Report, GTR-INT-122. USDA Forest Service, Intermountain Forest and Range Experiment Station. Ogden, UT.

Andreae, M.O., and Merlot, P. 2001. Emissions of trace gases and aerosols from biomass burning. Global Biogeochem. Cycles 15, 955–966, 2000GB001382.

Andrews, P.L., and Chase, C.H. 1989. BEHAVE: Fire behavior prediction and fuel modeling system–BURN subsystem, part 2. General Technical Report, GTR-INT-122. USDA Forest Service, Intermountain Forest and Range Experiment Station. Ogden, UT.

Battye, W.B., and Battye, R. 2002. Development of emissions inventory methods for wildland fire. Prepared for Thompson G. Pace, D205-01 of the U. S. Environmental Protection Agency, Final report. www.epa.gov/ttn/chief/ap42/ch13/related/firerept.pdf

Bertschi, I.T., Yokelson, R.J., Ward, D.E., Babbitt, R.E., Susott, R.A., Goode, J.G., and Hao, W.M. 2003. Trace gas and particle emissions from fires in large diameter and below ground biomass fuels. J. Geophys. Res. 108(D13), 8472, doi: 10.1029/2002J?oo2100.

Borrego, C., Miranda, A.I., Carvalho, A.C., and Carvalho, A. 1999. Forest fires and air pollution: A local and global perspective. In: Brebbia, C., Jacobson, M., and Power, H., eds. Proceedings of the 7th International Conference on Air Pollution. WIT Press, Southampton, Boston, 741–750.

Breyfogle, S., and Ferguson, S. 1996. User assessment of smoke dispersion models for wildland biomass burning. General Technical Report, PNW-GTR-379. USDA Forest Service, Pacific Northwest Research Station. Portland, OR, 30 pp.

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

Cheney, N.P., and Sullivan, A. 1997. Grassfires fuel, weather and fire behavior. CSIRO Publishing, Collingwood, Australia.

Cheney, N.P., Wilson, A.A.G., and McCaw, L. 1990. Development of an Australian fire danger rating system. RIRDC Project No. CSF-35A Report (unpublished), 24 pp.

Crutzen, P.J., and Andreae, M.O. 1990. Biomass burning in the tropics: Impacts on atmospheric chemistry and biogeochemical cycles. Science 250(4988), 1669–1678.

Crutzen, P.J., and Carmichael, G.R. 1993. Modeling the influence of fires on atmospheric chemistry. In: Crutzen, P.J., and Goldammer, J.G., eds. Fire in the environment: The ecological, atmospheric, and climatic importance of vegetation fires. Wiley, Chichester, England, pp. 90–105.

Debano, L.F., Neary, D., and Folliott, P.F. 1998. Fire's effects on ecosystems. Wiley, New York, 333 pp.

Deeming, J.E., Burgan, R.E., and Cohen, J.D. 1977. The national fire-danger rating system—1978. General Technical Report, GTR-INT-39. USDA Forest Service, Intermountain Forest and Range Experiment Station. Ogden, UT.

Environmental Protection Agency. 1996. Wildfire and prescribes fire emissions. AP-42. U.S. Environmental Protection Agence, Research Triangle Park, NC. 13.1.1-14.

Finney, M.A. 1998. FARSITE: Fire area simulator-model development and evaluation. Research Paper, RMRS-RP-4. USDA Forest Service, Rocky Mountain Research Station. Ft. Collins, CO, 47 pp.

Fire and Environmental Research Applications Team. 2006. Fire emission production simulator web page. www.fs.fed.us/pnw/fera/feps

French, N.H.F., Goovaerts, P., and Kasischke, E.S. 2004. Uncertainty in estimating carbon emissions from boreal forest fires. J. Geophys. Res. 09, D14S08, doi:10.1029/2003J?003635.

Goode, J.G., Yokelson, R.J., Susott, R.A., Babbitt, R.E., Ward, D.E., Davies, M.A., and Hao, W.M. 2000. Measurement of excess $O_3$, $CO_2$, CO, $CH_4$, $C_2H_4$, $C_2H_2$, HCN, NO, $NH_3$, HCOOH, $CH_3COOH$, HCHO, and $CH_3OH$ in 1997 Alaskan biomass burning plumes by airborne Fourier transform infrared spectroscopy (AFTIR). J. Geophys. Res. 105, 22,147.

Goode, J.G., Yokelson, R.J., Susott, R.A., and Ward, D.E. 1999. Trace gas emissions from laboratory biomass fires measured by open-path Fourier transformation infrared spectroscopy: Fires in grass and surface fuels. J. Geophys. Res. 104, 21,237–21,245.

Grand Canyon Visibility Transport Commission. 1996. Report of the Grand Canyon Visibility Transport Commission to the United States Environmental Protection Agency (1996). Western Governors' Association, Denver, CO, 85 pp.

Hao, W.M. 1998. Smoke produced from residual combustion. Ongoing project, Joint Fire Science Progam, National Interagency Fire Center, Boise, ID. http://jfsp.nifc.gov/JFSP_Active_Projects_1.htm

Hardy, C.C., Ottmar, R.D., Peterson, J.L., Core, J.E., and Seamon, P. 2001. Smoke management guide for prescribed and wildland fire: 2001 edition. PMS 420-2. National Wildfire Coordinating Group, Boise, ID, 226 pp.

Hirsch, K.J. 1996. Canadian forest fire behavior prediction (FBP) system: User's guide. Special Report 7. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta.

Holzinger, R., Warneke, C., Hansel, A., Jordan, A., Lindinger, D.H., Scharfe, G., Schade, G., and Crutzen, P.J. 1999. Biomass burning as a source of formaldehyde, acetaldehyde, methanal, acetone, acetonitrile, and hydrogen cyanide. Geophys. Res. Lett. 26, 1161–1164.

Keane, R. 2005. Fuel loading models. www.landfire.gov/National/ProductDescriptions18.php

Landscape Fire and Resource Management Planning Tools Project (LANDFIRE). 2005. Landfire. www.landfire.gov.

Levine, J.S. 1994. Biomass burning and the production of greenhouse gases. In: Zepp, R.G., ed. Climate-biosphere interactions: Biogenic emissions and environmental effects of climate change. Wiley, New York, pp. 139–160.

Lobert, J.M., Scharffe, D.H., Hao, W.M., Kuhlbusch, T.A., Sweuwen, R., Warnesk, P., and Crutzen, P.J. 1991. Experimental evaluation of biomass burning emissions: Nitrogen carbon containing compounds. In: Levin, J.S., ed. Global biomass burning: Atmospheric, climatic, and biospheric Implications. MIT Press, Cambridge, 569 pp.

McKenzie, L., Hao, W.M., Richards, G., and Ward, D. 1994. Quantification of major components emitted from smoldering combustion of wood. Atmos. Environ. 28(20), 3285–3292.

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 FCCS. Can. J. For. Res. 37(12), 2421–2437.

Miranda, A.I. 1998. Forest fire effects on the air quality. Ph.D. Thesis (in Portuguese only). Department of Environmental and Planning, University of Aveiro, Portugal. 213 pp.

Miranda, A.I. 2004. An integrated numerical system to estimate air quality effects of forest fires. Int. J. Wild. Fire 13, 1–10.

Miranda, A.I., and Borrego, C. 2002. Air quality measurements during prescribed fires. In: Viegas, D.X., ed. Forest Fire Research and Wildland Fire Safety: Proceedings of IV International Conference on Forest Fire Research 2002 Wildland Fire Safety Summit, Luso, Coimbra, Portugal, 18–23 November 2002. Millpress Science Publishers, Rotterdam, 205.

Miranda, A.I., Borrego, C., and Viegas, D. 1994. Forest fire effects on air quality. In: Baldasano, J., Brebbia, C., Power, H., and Zannetti, P., eds. Proceedings of the 2nd International Conference on Air Pollution, Vol. 1: Computer simulation. Computacional Mechanics Publications, Southampton, pp. 191–199.

Miranda, A.I., Coutinho, M., and Borrego, C. 1993. Forest fire emissions in Portugal: A contribution to global warming? Environ. Pollut. 83(1,2), 121–123.

Miranda, A.I., Ferreira, J., Valente, J., Santos, P., Amorim, J.H., and Borrego, C. 2005. Smoke measurements during Gestosa-2002 experimental fires. Int. J. Wild. Fire 14, 107–116.

Miranda, A., Borrego, C., Valente, J., Sousa, M., Santos, P., and Carvalho, A. 2005a. Smoke production report. Deliverable D254 of the European Commission Project SPREAD (Forest fire spread prevention and mitigation). EVG1-CT-2001-0043. AMB-QA-10/2005. 43 pp.

Miranda, A., Borrego, C., Sousa, M., Valente, J., Barbosa, P., and Carvalho, A. 2005b. Model of forest fire emission to the atmosphere. Deliverable D252 of the European Commission Project SPREAD (Forest fire spread prevention and mitigation), EVG1-CT-2001-0043. AMB-QA-07/2005, 48 pp.

Molina, M., Alvarez, A., Allgower, B., Kotz, B., Koutsias, N., Fernandes, P., Loureiro, C., Hernando, C., Cohen, M., Rigolot, E., Vigy, O., and Valette, J.C. 2006. Characteristics of wildland fuel bed. EUFIRELAB Project EVR1-CT-2002-40028, Deliverable D-02-04, 52 pp.

Ottmar, R.D. 2003. Forest floor consumption and smoke characterization in boreal forest fuelbed types of Alaska. Ongoing project, Joint Fire Science Progam, National Interagency Fire Center, Boise, ID. jfsp.nifc.gov/JFSP_Active_Projects_3.htm

Ottmar, R.D., Alvarado, E., and Hessburg, P.F. 1998b. Linking recent historical and current forest vegetation patterns to smoke and crown fire in the Interior Columbia River basin. In: Proceedings of 13th Fire and Forest Meteorology Conference. International Association of Wildland Fire, Moran, WY, 523–533.

Ottmar, R.D., Prichard, S.J., and Anderson, G.A. 2005. Consume 3.0. www.fs.fed.us/pnw/fera

Ottmar, R.D., Sandberg, D.V., Riccardi, C.L., and Prichard, S.J. 2007. An overview of the fuel characteristic classification system (FCCS)—quantifying, classifying, and creating fuelbeds for resource planning. Can. J. For. Res. 37, 1–11.

Ottmar, R.D., and Vihnanek, R.E. 1998. Stereo photo series for quantifying natural fuels. Volume II: Black spruce and white spruce types in Alaska. PMS 831. National Wildfire Coordinating Group, National Interagency Fire Center, Boise, ID, 65 pp.

Ottmar, R.D., and Vihnanek, R.E. 1999. Stereo photo series for quantifying natural fuels. Volume V: Midwest red and white pine, northern tallgrass prairie, and mixed oak types in the Central and Lake States. PMS 834. National Wildfire Coordinating Group, National Interagency Fire Center, Boise, ID, 99 pp.

Ottmar, R.D., Vihnanek, R.E., and Wright, C.S. 1998a. Stereo photo series for quantifying natural fuels. Volume I: mixed-conifer with mortality, western juniper, sagebrush, and grassland types in the interior Pacific Northwest. PMS 830. National Wildfire Coordinating Group, National Interagency Fire Center, Boise, ID, 73 pp.

Ottmar, R.D., Vihnanek, R.E., Miranda, H.S., Sato, M.N., and Andrade, S.M.A. 2001. Stereo photo series for quantifying cerrado fuels in central Brazil—Volume I. General Techical Report PNW-GTR-519. USDA Forest Service, Pacific Northwest Research Station. Portland, OR.

Ottmar, R.D., Vihnanek, R.E., Wright, C.S., and Olson, D.L. 2004. Stereo photo series for quantifying natural fuels. Volume VII: Oregon white oak, California deciduous oak, and mixed-conifer with shrub types in the Western United States. National Wildfire Coordinating Group, National Interagency Fire Center, Boise, ID.

Peterson, J.L. 1987. Analysis and reduction of the errors of predicting prescribed burn emissions. Thesis. University of Washington, Seattle, 70 pp.

Peterson, J.L., and Sandberg, D.V. 1988. A national PM10 emissions inventory approach for wildland fires and prescribed fires. In: Mathai, C.V., and Stonefield, D.H., eds. Transactions PM-10 Implementation of Standards: An APCA/EPA international specialty conference. Air Pollution Control Association, Pittsburgh, pp. 353–371.

Peterson, J., and Ward, D. 1993. An inventory of particulate matter and air toxic emissions from prescribed fire in the United States for 1989. Final report. IAG-DW 12934736-01-1989. Prepared by the USDA Forest Service for the U.S. EPA Office of Air Quality Programs and Standards.

Pouliot, G., Pierce, T., Benjey, W., O'Neill, S.M., and Ferguson, S.A. 2005. Wildfire emission modeling: Integrating BlueSky and SMOKE. www.epa.gov/ttn/chief/conference/ei14/session12/pouliot.pdf

PROMETHEUS S.V. Project. 1999. Management techniques for optimization of suppression and minimization of wildfire effects. System validation. European Commission, Contract number ENV4-CT98-0716. http://cardis.europa.eu/data/PROJ_ENV/ACTIONeqDndSESSIONeq8548200595ndDOCeqgndTBLeqEN_PROJ.htm

Quigley, T.M., and Arbelbide, S.J. 1997. An assessment of ecosystem components in the interior Columbia Basin and portfolios of the Klamath and Great Basins. General Technical Report PNW-GTR-405. USDA Forest Service, Pacific Northwest Research Station. Portland, OR.

Reinhardt, E.D. 2003. Using FOFEM 5.0 to estimate tree mortality, fuel consumption, smoke production and soil heating from wildland fire. In: Proceedings of the Second International Wildland Fire Ecology and Fire Management Congress. P5.2. ams.confex.com/ams/FIRE2003/techprogram/paper_65232.htm

Reinhardt, E.D., and Crookston, N.L. 2003. The fire and fuels extension to the forest vegetation simulator. General Technical Report RMRS-GTR-116. USDA Forest Service, Rocky Mountain Research Station, Ft. Collins, CO.

Reinhardt, E.D., Keane, R.E., and Brown, J.K. 1997. First order fire effects model: FOFEM 4.0, user's guide. General Technical Report INT-GTR-344. USDA Forest Service, Intermountain Research Station. Ogden, UT.

Reinhardt, T.E., Ottmar, R., and Castilla, C. 2001. Smoke impacts from agricultrual burning in a rural Brazilian town. J. Air Waste Ma., 51, 443–450.

Riccardi, C.L., Ottmar, R.D., Sandberg, D.V., Andreu, A.G., Elman, E., Kopper, K., and Long, J. 2007. The fuelbed: A key element of the fuel characteristic classification system. Can. J. For. Res. 37(12), 2394–2412.

Rollins, M.G., and Frame, C.K. Tech., eds. 2006. The LANDFIRE prototype project: Nationally consistent and locally relevant geospatial data for wildland fire management. General Technical Report RMRS-GTR-177. USDA Forest Service, Rocky Mountain Research Station, 416 pp.

Sandberg, D.V., and Dost, F.N. 1990. Effects of prescribed fire on air quality and human health. In: Walstad, J.W., Radosevich, S.R., and Sandberg, D.V., eds. Natural and prescribed fire in the Pacific Northwest Forests. Oregon State University Press, Corvallis, pp. 191–218.

Sandberg, D.V., Anderson, G.K., and Norheim, R.A. 2004. Fire emission production simulator [software] ver. 1.1. www.fs.fed.us/pnw/fera/feps/index.shtml

Sandberg, D.V., Hardy, C.C., Ottmar, R.D., Snell, J.A.K., Acheson, A., Peterson, J.L., Seamon, P., Lahm, P., and Wade, D. 1999. National strategic plan: modeling and data systems for wildland fire and air quality. General Technical Report PNW-GTR-450. USDA Forest Service, Pacific Northwest Research Station. Portland, OR, 60 pp.

Sandberg, D.V., Ottmar, R.D., and Cushon, G.H. 2001. Characterizing fuels in the 21st century. Int. J. Wildland Fire 10(4), 381–387.

Sandberg, D.V., Ottmar, R.D., Peterson, J.L., and Core, J. 2002. Wildland fire on ecosystems: Effects of fire on air. General Technical Report RMRS-GTR-42-vol. 5. USDA Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, 79 pp.

Schaaf, M.D. 1996. Development of the fire emissions tradeoff model (FETM) and application to the Grande Ronde River Basin, Oregon. Final report. Contract 53-82FT-03-2 for USDA Forest Service, Pacific Northwest Region, Portland, OR.

Scott, J.H., and Burgan, R.E. 2005. Standard fire behavior fuel models: A comprehensive set for use with Rothermel's surface fire spread model. General Technical Report, RMRS-GTR-153. USDA Forest Service, Rocky Mountain Research Station. Ft. Collins, CO.

Trabaud, L., Christensen, N., and Gill, A. 1993. Historical biogeography of fire in temperate and Mediterranean ecosystems. In: Crutzen, P., and Goldammer, J., eds. Fire in the environment: The ecological, atmospheric, and climatic importance of vegetation fires. Wiley, pp. 277–295.

Valente, J., Miranda, A.I., Lopes, A.G., Borrego, C., and Viegas, X. 2005. A local-scale modelling system to simulate smoke dispersion. The Joint Meeting of the Sixth Symposium on Fire and Forest Meteorology and the 19th Interior West Fire Council Meeting, 25–27 October, Canmore, Canada. Proceedings on CD-ROM.

Ward, D.E., Hardy, C.C., Sandberg, D.V., and Reinhardt, T.E. 1989. Part III-emissions characterization. In: Sandberg, D.V., Ward, D.E., and Ottmar, R.D., comp., eds. Mitigation of Prescribed Fire Atmospheric Pollution through Increased Utilization of Hardwoods, Piled Residues, And Long-Needled Conifers. Final report. U.S. DOE, EPA. USDA Forest Service, Pacific Northwest Research Station. Seattle.

Ward, D., and Radke, L. 1993. Emissions measurements from vegetation fires: A comparative evaluation of methods and results. In: Crutzen, P., and Goldammer, J., eds. Fire in the environment: The ecological, atmospheric and climatic importance of vegetation fires. Wiley, Chichester, England.

Yokelson, R.J., Griffith, D.W.T., and Ward, D.E. 1996. Open-path fourier transform infrared studies of large scale laboratory biomass fires. J. Geophys. Res. 101(D15), 20,167–21,080.