

LABORATORY-BASED EXPERIMENTAL MEASUREMENT OF PARTICULATE EMISSION FACTORS FOR WILDLAND FUELS

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1. INTRODUCTION

The practice of prescribed burning in wildland areas is a useful tool for managing wildlife ecosystems and reducing the potential of severe wildfire. However, the impact of prescribed fire emissions on surrounding communities is often problematic, as the release of biomass combustion products can have severe effects on local and regional air quality. Of particular concern is the dispersion of particulate matter of less than 2.5 μm in size ($\text{PM}_{2.5}$), as it has been identified as a significant risk to public health (Shusterman et al, 1993). A practical metric for determining the amount of pollutant released during a prescribed burn is the emission factor (EF), which is a measure of pollutant production in relation to the amount and type of fuel burned. Emission factors are key components of pollution dispersion models. Little recent emissions data exist for fuels common to the southwestern United States, specifically those contained in chaparral. The objective of the research presented is to obtain EFs for specific chaparral species mixes found along the central coast of California using modern instrumentation. Laboratory-scale experiments using simulated brush loadings were used to obtain emissions data for each fuel type. Controlled laboratory conditions provide the best possible means to examine the effect of various factors on EF and control many of the environmental variables which influence combustion in cellulosic fuels.

2. EXPERIMENTAL METHODS

2.1 Experimental Setup

Experiments were conducted in the Missoula Fire Sciences Laboratory, at the USFS Rocky

Mountain Research Station in Missoula, MT. The combustion laboratory featured a fuel bed at the base of a 1.6 m diameter, 22 m high central exhaust stack. At the bottom of the stack, a 3.6 m diameter flue hood was attached directly above the fuel bed. A platform encircled the stack at an elevation of 17 m to allow for installation of sampling equipment. An environmental conditioning system introduced pressurized outdoor air to promote emissions entrainment through the stack. Mean flow velocity through the stack in the predominant flow direction was 1.5 m/s, as measured at platform height in the center of the duct, using a handheld anemometer. This facility has been used extensively for biomass emissions characterization (Christian et al, 2003; Chen et al, 2006).

2.2 Sampling Equipment

Measurements of $\text{PM}_{2.5}$ concentrations were obtained using DustTrak laser photometers (Model 8520, TSI, Inc.)². Sampling equipment was placed on the upper platform, and Teflon tubing was used to connect the photometers to a measurement probe placed within the exhaust stack. Additionally, a separate photometer was

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placed within the combustion laboratory, away from the fire, to determine if a significant background particulate concentration could be detected. The flow was assumed to be well-mixed at measurement height, which has been verified by previous experiments (Christian et al, 2003). A suite of chemical and particle characterization equipment accompanied the photometers. The additional instrumentation was used to obtain emission factors for a variety of gaseous and particulate species using additional methods which are beyond the scope of this paper.

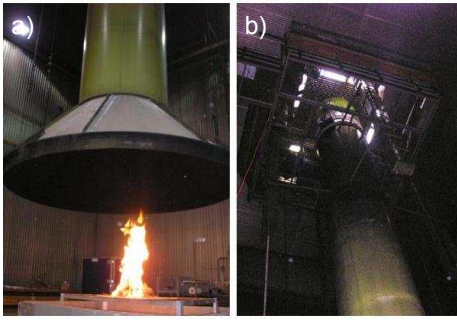


Fig. 1. a) Fire under laboratory flue, b) Looking up at instrumentation platform

2.3. Fuels and Fuel Bed

Nine types of chaparral fuels were tested. The fuel bed consisted of a 2 m x 1 m metal table covered with thermal insulation. Electronic load cells supported the fuel bed to provide real-time fuel mass loss data. Fuels were arranged in an attempt to simulate their natural arrangement in the field in terms of orientation, bulk density, and fuel loading. Fuels were ignited using a butane torch and were allowed to burn to completion.

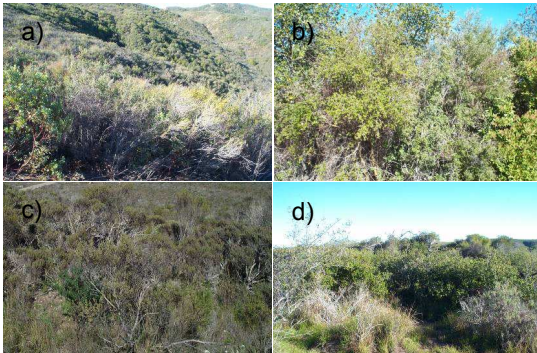


Fig. 2. Selected chaparral fuels a) Chamise/Scrub oak, b) Ceanothus, c) Coastal Sage Scrub, d) Maritime chaparral

3.0 CALCULATION OF EMISSIONS FACTORS

The classical definition of the emissions factor, as described in Christian et al (2003), is

$$EF_X \text{ (g kg}^{-1}\text{)} = \frac{m_X}{m_{\text{burned}}} \quad (1)$$

where EF_X is the emission factor of compound X, m_{burned} is the mass of dry fuel consumed (kg), and m_X is the total mass of pollutant X emitted (g). In a well-mixed duct within which the products of combustion are collected, a method of obtaining m_X is proposed by Dhammapala et al (2006) as

$$m_X = \int_{t_0}^t \Delta C_X Q_{\text{duct}} dt \quad (2)$$

where ΔC_X is the concentration of pollutant measured within the stack at platform height (mg m^{-3}), Q_{duct} is the volumetric flow rate through the exhaust duct ($\text{m}^3 \text{s}^{-1}$), t_0 is time of ignition (s), and t is the time at conclusion of smoldering (s). For this experiment, Eq. (2) was computed numerically using simple trapezoidal integration based on a 3 second measurement interval.

Upon burn conclusion, a significant amount of matter remained on the fuel bed. This remaining mass is a mix of unconsumed dry fuel, partially burned fuel, char, and ash. The mass of residual matter varied by fuel type, but reached as much as 90% of dry fuel mass in some cases. For this reason, two types of emissions factors are presented

$$EF_1 \text{ (g kg}^{-1}\text{)} = \frac{m_X}{m_{\text{dry}}} \quad (3)$$

$$EF_2 \text{ (g kg}^{-1}\text{)} = \frac{m_X}{m_{\text{dry}} - m_{\text{remaining}}} \quad (4)$$

where m_{dry} is the total dry fuel mass at ignition (kg), and $m_{\text{remaining}}$ is the mass of residual matter remaining on the fuel bed at the end of the smoldering period (kg). By definition, emissions factors are to be obtained using the actual mass of fuel burned over the entire combustion period. However, fuel consumption is rarely absolute, even in laboratory scale experiments. Previous

experiments (Delmas et al, 1995; Ward et al, 1999) used an alternate method of obtaining emissions factors; carbon mass balance. This method does not require weighing of the biomass, but instead assumes that all carbon content of the biomass consumed during the fire is released into the atmosphere as measurable carbon compounds. The emissions factors are then calculated using a total carbon balance.

An alternate method of obtaining emission factors was employed during the experiment, as described in Hosseini et al (2009). This method uses Teflon membrane filters to collect particulate matter, size-segregated to collect only PM_{2.5}. The filters were connected to the exhaust stack via a steel sampling line. The mass of PM_{2.5} emitted is then calculated using Eq. (5)

$$m_x = m_{\text{filter}} \times \frac{Q_{\text{duct}}}{Q_{\text{line}}} \quad (5)$$

where m_{filter} is the amount of mass on the filter as measured post-burn (kg), and Q_{line} is the volumetric flow rate through the filter sampling line ($\text{m}^3 \text{s}^{-1}$). The emissions factor is then obtained using Eq. (1). A similar method of particle collection was also used to measure particulate matter emission from burning of California chaparral in a laboratory setting, as highlighted in Weise et al (1991).

In addition to the total fire emissions factors, EF's for the flaming and smoldering periods are presented in this study, based on the definition in Eq. (3). For this experiment, the flaming period is defined as the time elapsed from ignition until the last visible flame is extinguished. The smoldering period begins at the end of the flaming period, and continues until all fuel has been consumed or instrument readings are below minimum detection thresholds. Moisture within the fuel was assumed to have evaporated during the flaming period, and thus the smoldering EFs were calculated using fuel mass uncorrected for moisture. Previous biomass research (Hardy et al, 1996) suggests that particulate emissions

factors during smoldering are, in general, greater than those obtained during the flaming period.

3.1 Fuel Moisture

Moisture content for all fuels was determined using an oven-drying method (USDA Forest Products Laboratory Wood Handbook, 1999). Fuel samples were weighed, then placed in an oven at approximately 105°C to promote evaporation. Samples were re-weighed at four hour intervals, and drying continued until mass loss became negligible. Dry fuel mass in Eq. (3) was then obtained using the expression

$$m_{\text{dry}} = \frac{m_{\text{total}}}{1 + M} \quad (6)$$

where m_{total} is the total mass of moist fuel (g), and M is the moisture content expressed as a fraction of total fuel mass. Moisture content for selected fuels is reported in Table 3.

3.2 Modified Combustion Efficiency

Previous research (Christian et al, 2003) has suggested that the emissions factors of biomass fuels are related to the efficiency of combustion. Combustion efficiency is defined as the ratio of carbon emitted as carbon dioxide (CO_2) to the total amount of carbon released during the burn. Because of the difficulty of measuring *all* carbon species released, a *modified combustion efficiency* (MCE) is proposed by Christian et al (2003)

$$\text{MCE} = \frac{\Delta C_{\text{CO}_2}}{\Delta C_{\text{CO}_2} + \Delta C_{\text{CO}}} \quad (7)$$

where ΔCO_2 is the mixing ratio of CO_2 and ΔCO is the mixing ratio of carbon monoxide (CO), in excess of background. Prior research indicates that CO_2 and CO account for 95% of carbon released during biomass combustion (Ward and Hardy, 1991). Because combustion efficiency tends to be lowest during smoldering, the MCE serves as a measure of the relative amount of flaming and smoldering combustion. Throughout this experiment, MCE was determined using a five-gas analyzer that simultaneously measures

the concentration of CO₂, CO, sulfur dioxide (SO₂), nitrogen oxides (NO_x) and oxygen (O₂). The instrument uses a non-dispersive infrared (NDIR) sensor to detect the absorption of infrared light through a range of wavelengths. Because individual gases absorb at specific wavelengths, the real-time concentration of each species in the exhaust flue can be determined. MCE was then calculated using Eq. (7).

4. RESULTS AND DISCUSSION

A typical PM_{2.5} concentration profile is shown in Fig. 3a (Maritime Chaparral). In general, peak particulate concentration occurred within the first 200 seconds of burning, then exhibited a steep decline. Within fuel types, concentration profiles exhibited similar behavior, except in cases of poorly sustained combustion. The concentration profiles were compared with those obtained in by Pan et al (2008) (Fig 3b). Although the study used a different fuel (bamboo skewers), the authors also used the direct method of obtaining EFs in a laboratory setting. While the PM_{2.5} concentration profiles from both experiments showed an initial rise in particulate concentration during the first 200 seconds of burning, the bamboo skewer fuel maintained a consistent particulate concentration through the flaming period. However, this experiment took place inside a wind tunnel, inside which the fire had fresh, unburned fuel at the flame front throughout the burn.

The mean emissions factors and MCE obtained for each fuel type are presented in Table 1. The EF for each fuel species cannot be compared directly to EPA AP-42, as data exists only for generalized chaparral and sagebrush for the Pacific southwest region. Moreover, the published values for chaparral were obtained using a field-based carbon mass balance method, as described in Delmas et al (1995) and Ward et al (1999). The calculated emissions factors were compared to emissions factors obtained during the same experiment, The apparatus in Weise et al (1991) was of smaller scale (sampler height only 1.8 m above fuel bed), measurements only occurred only during flaming

combustion, and fuel moisture content was higher (greater than 50% of dry fuel mass for all fuels). Further analysis is required to address the discrepancy between the two experiments. In general, the emissions factors obtained during smoldering were greater than those for the flaming and total fire. However, high variability was observed in the smoldering EF's. For five of eight fuels, the EF was shown to decrease with increasing MCE (flaming). However, additional investigation is required to determine the significance of this relationship. The composition of particles must be known in order to determine their contribution to the overall carbon balance.

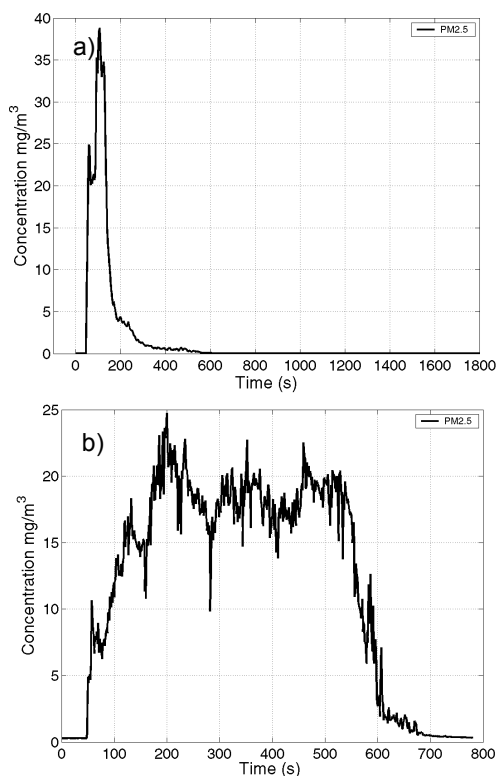


Fig. 3. Comparison of PM_{2.5} concentration profiles

a) Maritime Chaparral, b) Bamboo skewers (Pan et al, 2008)

5. SUMMARY AND CONCLUSIONS

Experiments to determine PM_{2.5} emissions factors for southwestern chaparral biomass fuels were carried out. Particle concentration was measured using laser photometers, and emissions factors were calculated using the direct method. Modified combustion efficiency was determined using a non-dispersive infrared technique. Two separate emissions factors were obtained, using total dry fuel mass and net dry fuel mass consumed, respectively. Additionally,

individual emissions factors were obtained for the flaming and smoldering periods. The calculated emissions factors were compared to published values, as well as data obtained for identical fuels using filter methods. The amount of unconsumed

fuel vs. ash and particle composition needs to be quantified to provide a better understanding of emissions in relation to fuel consumption.

Table 1. PM_{2.5} Emissions Factors for selected southwestern chaparral fuels

Fuel type	PM _{2.5} EF ₁ (g kg ⁻¹) ^a	P _{2.5} EF ₂ (g kg ⁻¹) ^a	PM _{2.5} EF (flaming) (g kg ⁻¹) ^a	PM _{2.5} EF (smoldering) (g kg ⁻¹) ^a	PM _{2.5} EF (g kg ⁻¹) [14] ^b	PM _{2.5} EF (g kg ⁻¹)	MCE (Flaming)
Chamise/Scrub Oak	3.27±1.50	3.69±1.81	3.26±2.04	6.90±4.62	1.25	20.05 ^c	0.89±0.01
Chaparral ^d	N/A	N/A	6.75±0.6 ^e	10.8±1.05 ^e	N/A	8.65±0.60 ^{e, 8^f}	N/A
Ceanothus	1.31±0.48	2.12±1.60	1.20±0.20	16.1±26.1	5.29	67.65 ^c	0.92±0.02
Maritime Chaparral	2.55±0.69	2.71±0.75	3.21±1.78	21.2±20.1	0.58	N/A	0.91±0.04
Coastal Sage Scrub	2.71±0.57	2.87±0.62	5.30±1.18	5.93±2.13	3.11	47.27 ^c	0.89±0.06
California Sagebrush	3.54±0.32	3.83±0.38	5.03±1.64	4.63±2.19	4.49	N/A	0.90±0.01
Manzanita	1.04±0.22	1.12±0.26	1.13±0.28	2.07±1.50	2.29	87.37 ^c	0.89±0.01
Oak Savanna	0.68±0.20	0.75±0.21	0.78±0.21	1.14±1.13	1.63	N/A	0.92±0.03
Oak Woodland	1.37±0.58	1.43±0.57	0.74±0.49	5.09±3.87	3.62	N/A	0.96±0.05
Masticated Mesquite	1.14±0.15	1.22±0.14	0.98±0.57	5.48±7.22	1.54	N/A	0.90±0.02

a. Data represented as mean ± one standard deviation of the mean

b. Data obtained from Hosseini et al (2009) using Teflon filters

c. Data obtained from Weise et al (1991) using glass fiber filters

d. Southwestern chaparral fuel (multiple species)

e. Data obtained from Hardy et al (1996) during field measurements using carbon mass balance method

f. Data obtained from US EPA AP-42

ACKNOWLEDGEMENTS

The authors acknowledge support for this research through contract SI-1648 from the Strategic Environmental Research and Development Program (SERDP). We are also grateful to the technical staff at the USDA Forest Service Fire Sciences Laboratory in Missoula, MT and the Forest Fire Laboratory in Riverside, CA.

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