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A SAMPLING SYSTEM FOR MEASURING EMISSIONS FROM WEST COAST PRESCRIBED FIRES

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Introduction

Open burning of woody material and other vegetation can produce significant quantities of incompletely oxidized combustion products. These materials degrade air quality by contributing to background levels of gaseous and particulate matter pollutants. It has been estimated that prescribed fires in the Pacific Northwest produce about 100 thousand metric tons of particulate matter per year.[1] Without current systems for managing smoke, local pollution problems would likely be severe. A major objective of the Forest Residues and Energy Program at the USDA Forest Service's Pacific Northwest Forest and Range Experiment Station is the development of techniques for reducing emissions of pollutants at the source.

The production of emissions from prescribed fires is affected by the various fuel, fire, and atmospheric variables. Performing preburn operations such as fuel modification or fire prescription planning can reduce the quantity of pollutants produced. In order to creditably recommend to fire managers techniques for reducing emissions, knowledge is needed regarding the magnitude of the potential for reducing emissions. This paper discusses a sampling system we developed for measuring emissions production and a set of emissions data for a series of test fires. The sampling system makes it possible to measure emission factors for criteria pollutants, emission rates, heat release rate, and fuel consumption all as functions of time. The analytical procedures rely heavily on a carbon-mass balance between fuel carbon and emissions carbon.

Background

Emissions

Ward et al.[2] used the carbon-mass balance technique for assessing emission factors for particulate matter, carbon monoxide, methane, and nonmethane hydrocarbons. (An emission factor is defined as the mass of an emission produced per unit of forest fuel consumed, usually expressed in units of g kg^{-1} or lbs ton^{-1}.) A cable and tower system was used to suspend gas and particulate matter samplers over the broadcast burn units (Figure 1). Results of three separate tests demonstrated the following emission factors for particulate matter for broadcast-burned logging slash:

Flaming combustion phase	12 g kg^{-1}
Smoldering phase	27 g kg^{-1}

This system was not equipped for assessing emission rates nor for monitoring the rate of fuel consumption as a function of time.

Researchers have utilized a variety of techniques to measure emissions from the burning of biomass. Their work shows emission factors for particulate matter to range from 2 to more than 100 g kg^{-1} of fuel consumed.[3]

Laboratory combustion-hood experiments generally incorporate a weighing system to monitor the rate of fuel consumption along with analyzers to measure the rate of emissions production. The comparability of laboratory-derived emissions data from modeled fuel beds and field-derived emissions data has been checked only under a limited range of conditions for line source fires.[4] A system capable of sampling full-scale fires in undisturbed fuels is needed.

Fuels and Combustion

Forest fuels have characteristics that affect the rate of consumption and the rate and mix of emissions produced. Forest fuels differ in amounts of extractives, nitrogen, proportion of lignin to cellulose, etc. but, in general, have a fairly constant ratio of carbon to other elements present. Carbon represents about 50% of the fuel mass.[5,6]

When forest fuels are burned, a preheating phase precedes ignition and flame attachment to the fuel particles and is followed by a smoldering or glowing combustion period. The flaming phase generally predominates in the initial phases of a broadcast burn. As ignition progresses, the flaming and smoldering combustion processes produce a mix of combustion products. Near the end of ignition, smoldering emissions predominate.

Combustion efficiency declines as the temperature and rate of oxidation decrease. Combustion efficiency is defined as the percentage of fuel carbon that forms carbon dioxide. As combustion efficiency increases, carbon available for the formation of other combustion products decreases. Combustion efficiencies for prescribed fires vary between 54% and 95%, although they may be lower for the smoldering phase.[7] Change in combustion efficiency is concurrent with change in the rate of fuel consumption.

Objectives

The carbon-mass balance method for quantifying emissions requires that the concentration of carbonaceous gases and particulate matter be sampled and accurately differentiated from gases in the background air. To calculate fuel consumption, it is necessary to measure the flux of carbon through a plane of known orientation. This necessitates sampling both the concentration of emissions and velocity of the vertical plume (buoyancy-induced plume updraft) during the sampling period.

Use of the sampling system described in this paper can provide:

1. Verification of emissions data derived from current laboratory combustion-hood methods with data collected under field conditions.
2. Assessment of emissions from fuel complexes with live fuels as a major component.
3. Measurement, in situ, of consumption rates from undisturbed fuel complexes as a function of time.
4. Measurement of emissions source strengths from undisturbed fuel complexes as a function of time.

The Sampling System

A number of parameters must be sampled simultaneously. We developed 5 sample packages, 4 of which contained instruments for sampling gas, particulate matter, vertical plume velocity, and air-temperature (Figure 2). The fifth sampler collected only gas and samples of particulate matter.

The sample packages consist of:

1. A Gilian high-volume, (3-4 lpm), battery-powered pump for sampling particulate matter (Model II HFS 113UT).[8]
2. A Calibrated Instruments, Inc., pulse pump for sampling gases 0.01 to 1.0 lpm.
3. A Kurz Model 455 velocity probe for high-temperature environments.
4. A Chromel Alumel thermocouple probe.

Velocity Probes

The velocity probes were fitted with cylindrical shrouds to protect them from horizontal wind and assure that only the vertical component of the plume velocity would be measured. The shape and dimensions of the cylinder must make it possible for the probe to approximate a cosine response to windspeed as the probe rotates about its axis. During wind tunnel tests of several cylinders of different dimensions, a cylindrical shroud 4 inches in diameter by 4 inches long (10 x 10 cm) gave the closest approximation to a cosine response (Figure 3).

Support Towers and Cable System

Two 50-foot (16-m) towers were equipped with sheaves and a continuous cable. Hangers were attached to the cable to support the sample packages. The design enabled the sample packages to remain vertical so the velocity probes would always sample the vertical component of the plume velocity (Figure 1).

Sampling System Operation

The sample packages were equipped with preweighed (tared) 47-mm glass fiber filters (1 each for the gas sample port and the particulate matter port) and an evacuated 5-liter aluminized-mylar gas sample collection bag. The sample packages were attached to the hangers at 10-m intervals along the cable over the area to be burned. As each package was attached to a hanger, it was connected to a wiring harness. The samplers were first extended at the 50-foot (16-m) height for sampling emissions of the flaming combustion phase. The packages were then returned to the ground, fitted with new filter holders and bags, and reattached for sampling of emissions during the smoldering combustion phase.

After the sample packages were positioned, the main wiring harness connector was attached to the control panel (Figure 4). For each of the four velocity and temperature probes, incremental measurements of accumulated vertical plume run and temperature were recorded. A special form was used to record data at 2-minute intervals during sampling periods or less often, depending on the fire dynamics.

Example of Data--Results and Discussion

Three units where old-growth timber had been clearcut (Tenas 10, Tenas 7, and Ankle Biter) in western Washington were selected for sampling. Each unit had been logged 2 years prior to burning and contained concentrations of live fuels. The units were burned during late August of 1982. Samples of gases and particulate matter were collected over periods of 20, 30, and 60 minutes. The first sample was collected during the flaming combustion period. The other two samples show the combustion-decay rate during the smoldering period. The bag samples were analyzed for CO, CO_2, NMHC, and CH_4, using gas chromatographic techniques. A Cahn 4100 electrobalance was used to determine the mass of total suspended particulate matter (TSP) sampled on the glass fiber filter mats. Data are presented in Table I. Concentrations of CO_2 were highest during the flaming phase, with the concentration dropping to less than 100 ppm above background during the smoldering phase.

Table I. Example of concentrations of carbon-containing gases and particulate matter for three time periods for Tenas 10.

TIME PERIOD	SAMPLE #	CO_2	CO	NMHC	CH_4	TSP
		(ppm carbon)				($\mu g\ m^{-3}$)
	51	3456	265	7.8	20.2	56167
2038 to	52	3545	191	6.0	14.5	31333
2058	53	2139	79	3.0	5.8	29333
	54	1430	62	2.1	5.6	23167
	55	952	34	1.6	4.4	17667
	61	777	103	3.9	9.6	10111
2121 to	62	981	139	5.2	12.9	12111
2151	63	1259	199	3.9	19.2	24000
	64	1712	289	5.7	27.7	55333
	65	1248	179	3.4	27.3	23111
	71	491	27	1.8	4.0	2111
2225 to	73	478	35	2.2	4.2	2944
2325	74	491	37	1.8	4.4	2778
	75	466	34	2.2	4.0	3000

Calculation of Emission Factors

Emission factors for all compounds quantified are presented in Table II. An emission factor is the mass produced per unit of forest fuel consumed. The amount of fuel consumed (f) that contributes to the emissions formed and contained in a unit volume is calculated by summing the carbon content of each of the emissions in the unit volume according to equation (1) and dividing by the fuel carbon ratio:

$$f = (\Sigma C_n)/R \qquad (1)$$

Where:

f = Fuel consumed, mg m^{-3}
C_n = The carbon fraction of the emission n, mg m^{-3}
n = CO_2, CO, NMHC, CH_4, TSP
R = The carbon fraction of the fuel elemental analysis, 0.5 g of carbon per gram of fuel.

Emission factors (EF_n) are calculated by dividing the mass of emission produced by the amount of fuel consumed in producing the emissions according to the following:

$$EF_n = \frac{E_n}{f}\,\frac{1000g}{kg} \qquad (2)$$

Where,

E_n = Mass of emissions n, mg m^{-3}
n = CO_2, CO, NMHC, CH_4, TSP
f = Fuel consumed, mg m^{-3}.

Table II. Example of emission factors for CO_2, CO, NMHC, CH_4, and particulate matter (TSP) for 3 time periods for a test fire (Tenas 10). Also listed are the concentration of carbon and the fuel consumed in producing the carbon for flaming (F) and smoldering (S) combustion phases.

SAMPLE #	CARBON (mg m^{-3})	FUEL (mg m^{-3})	EMISSION FACTORS CO_2	CO	NMHC (g kg^{-1})	CH_4	TSP
51F	1722	3443	1629	87	3.8	3.5	16.3
52F	1702	3403	1695	64	2.9	2.5	9.2
53F	950	1900	1703	47	2.4	1.4	15.4
54F	588	1176	1667	59	2.4	2.2	19.7
55F	334	668	1646	56	3.0	2.7	26.4
Weighted mean		2727	1669	67	3.1	2.6	14.9
61S	279	557	1409	208	11.0	9.4	18.2
62S	400	801	1439	196	10.5	9.2	15.1
63S	580	1159	1425	195	5.3	9.9	20.7
64S	881	1761	1401	187	5.3	9.7	31.4
65S	562	1123	1451	180	4.6	9.1	20.5
Weighted mean		1233	1423	191	6.5	9.5	23.1
71S	89	180	1503	162	13.0	8.7	11.8
73S	88	177	1394	216	17.3	9.6	16.6
74S	96	191	1413	212	12.2	9.6	14.5
75S	82	164	1371	226	18.6	9.6	18.3
Weighted mean		179	1421	204	15.1	9.4	15.2

The weighted mean emission factor for each sample period is computed by weighting the emissions by the quantity of carbon sampled, according to the following equation:

$$\overline{EF}_n = \left(\sum_{i=1}^{j} EF_{ni} C_i \right) \Big/ \sum_{i=1}^{j} C_i \qquad (3)$$

Where,

$\overline{EF}_n$ = The weighted emission factor for emission n, g kg^{-1}
EF_{ni} = The emission factor for emission n at point i, g kg^{-1}
n = CO_2, CO, NMHC, CH_4, TSP
C_i = The mass of carbon sampled at point i, mg
j = Number of sample points.

Table III summarizes the emission factors for 3 separate tests conducted in Washington during August 1982. The sensitivity of the technique is illustrated by the consistency of the emission factors. For example, the combustion efficiency decreases from about 0.8 to 0.9 for the flaming combustion phase to 0.7 to 0.8 for the smoldering phase. In general, emission factors for the incompletely oxidized combustion products increase as EF_{CO2} decreases.

Table III. Summary of emission factors for the three units sampled.

UNIT	COMBUSTION PHASE[a]	CO_2	CO	NMHC	CH_4	TSP	COMBUSTION EFFICIENCY[b]
		EMISSION FACTORS ($g\ kg^{-1}$)					
ANKLE BITER	F	1644	85	4.0	3.4	13.0	.90
	S	1534	136	6.0	6.7	18.1	.84
	S	1360	226	9.9	10.6	23.4	.74
TENAS 10	F	1669	67	3.1	2.6	14.9	.91
	S	1423	191	6.5	9.5	23.1	.78
	S	1421	204	15.1	9.4	15.2	.78
TENAS 7	F	1538	127	6.9	5.0	22.5	.84
	S	1353	241	9.6	8.9	20.2	.74
	S	1297	266	10.2	13.4	21.6	.71

[a]Combustion phase: flaming (F) and smoldering (S).

[b]Combustion efficiency is defined as the actual EF_{CO2} divided by the theoretical EF_{CO2}. The theoretical EF_{CO2} would occur if all of the fuel carbon is converted to CO_2 and has a value of 1833 $g\ kg^{-1}$.

Fuel Consumption

Our method for measuring fuel consumption as a function of time for broadcast burning as a function of time is unique. To our knowledge, it is also the only technique that allows for measurement of emissions produced and fuel consumed concurrently from undisturbed fuel beds as a function of time.

The measured vertical plume run for the three sample periods is listed in Table IV. The flux of carbon per unit area can be computed by multiplying the plume run by the carbon concentration from Table II. Then, dividing by time and fuel ratio, we use the following equation to compute the rate of fuel consumption:

$$\dot{w} = W\ C\ t^{-1}\ R^{-1} \qquad (4)$$

where:

$\dot{w}$ = The rate of fuel consumption per unit area, $g\ m^{-2}\ s^{-1}$ or $lb\ ft^{-2}\ min^{-1}$.
W = The vertical plume run during the sample period t, m.
C = The carbon concentration, $g\ m^{-3}$.
t = The length of time during sample collection, s.
R = Dimensionless ratio of the carbon elemental content of the consumed fuel, 0.5 g carbon per gram of fuel.

Fuel consumption at each of the sample stations is listed in Table IV.

Table IV. Example of vertical wind run and fuel consumption data by flaming (F) and smoldering (S) combustion sampling periods.

SAMPLE NUMBER	VELOCITY MEAN ($m\ s^{-1}$)	VERTICAL PLUME (m)	FUEL CONSUMPTION ($g\ m^{-2}$)	FUEL CONSUMPTION ($lb\ ft^{-2}$)	RATE OF FUEL CONSUMPTION ($g\ m^{-2}\ s^{-1}$)
52F	0.485	582.2	1981.3	0.406	1.651
53F	0.297	356.0	676.4	0.138	0.564
54F	0.596	714.8	840.6	0.172	0.700
55F	0.559	671.4	448.5	0.092	0.374
62S	0.567	1020.2	817.2	0.167	0.454
63S	0.504	906.8	1051.0	0.215	0.584
64S	0.838	1508.1	2655.7	0.544	1.475
65S	0.716	1289.4	1450.6	0.297	0.806
72S	0.208	749.6	133.8	0.027	0.037
73S	0.185	664.6	117.6	0.024	0.033
74S	0.242	869.4	166.1	0.034	0.046
75S	0.263	947.1	155.3	0.032	0.043

Interpretation of Combined Data

Fuel consumption shows the effect of fuel, weather, and ignition on the duration and the degree of offset of the consumption peak. For example, the Tenas 7 unit had a fairly rapid, but short fuel consumption period with very rapid diedown. On the other hand, the Tenas 10 and Ankle Biter units exhibited a broad, but more uniform, consumption rate (Figure 5b). Total consumption on a unit-area basis is calculated by integrating under the rate curves. Thus, Ankle Biter, Tenas 10, and Tenas 7 had 7.7, 4.2, and 2.5 kg m^{-2} fuel consumption, respectively. The fuel consumption values agree with total fuel consumption based on reduced diameter of woody fuels and observations of involvement of woody fuels in the combustion process.

The offset in peak emissions for Ankle Biter and Tenas 10, in Figure 5c, is partly due to the increase in emission factors over time (Figure 5a). For the flaming phase, the EF_{TSP} values measured for green fuels average 40% higher than previous measurements of broadcast burned units without live fuels. The smoldering phase EF_{TSP} values are lower than those previously reported. The unit area source strength is calculated by combining the emission factor and fuel consumption data, as shown in figure 5c.

Conclusions

Using the system of sampling gas, particulate matter, air velocity, and air temperature, we have been able to measure fuel consumption, emission factors, and emissions source strength from operational prescribed fires as a function of time. For the first time, a technique exists for measuring emissions produced from undisturbed fuel beds. Data on emission factors, fuel consumption, and source strength, such as those exhibited in Figures 5a to 5c, can be used to prepare guidelines for prescription burning that will reduce emissions and accomplish the land manager's objectives.

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8. The use of trade, firm or corporati [redacted] the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U. S. Department of Agriculture of any product or service to the exclusion of others which may be suitable.

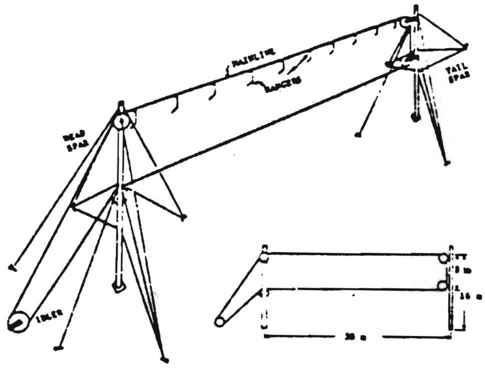


Figure 1. Cable and tower system used for suspending samplers over burned units.

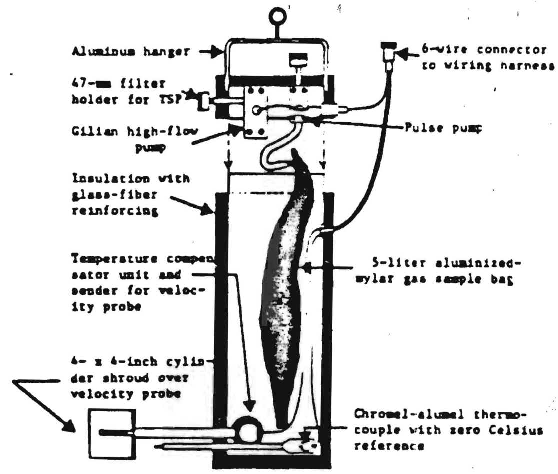


Figure 2. Cutaway view of sample package for sampling gases, TSP, velocity, and air temperature.

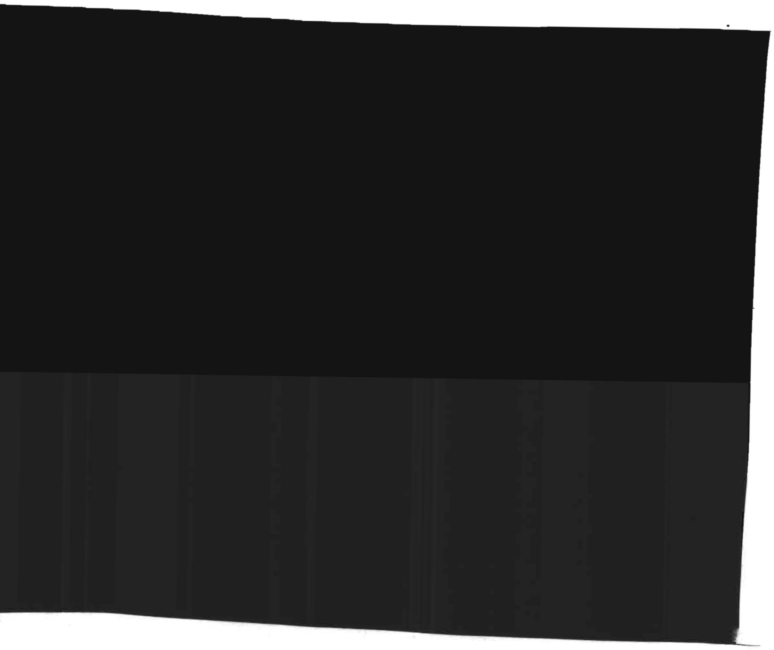


Figure 5a. TSP and CO emission factors (g kg^{-1})

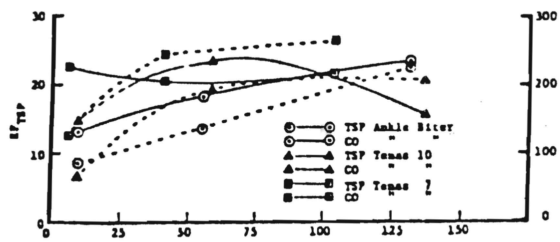


Figure 5b. Fuel consumption (g m^{-2}s^{-1})

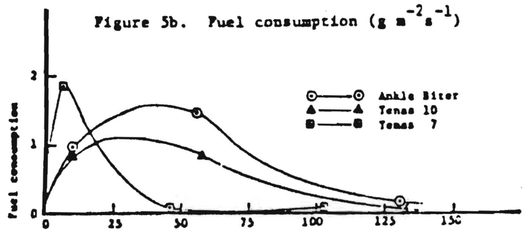
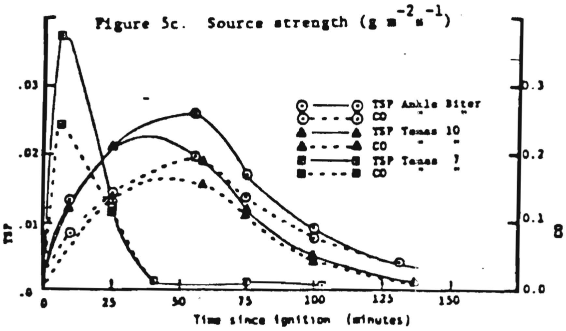


Figure 5c. Source strength (g m^{-2}s^{-1})



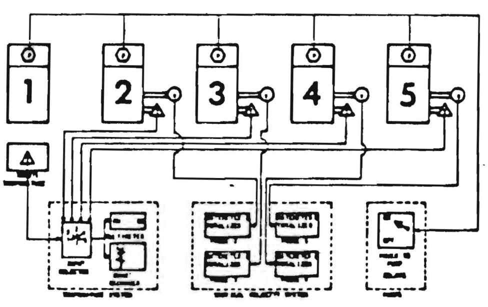


Figure 4. Abbreviated schematic of wiring harness showing pumps ○, velocity probes ○, and temperature probes △.