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An Evaluation of the Carbon Balance Technique for Estimating Emission Factors and Fuel Consumption in Forest Fires

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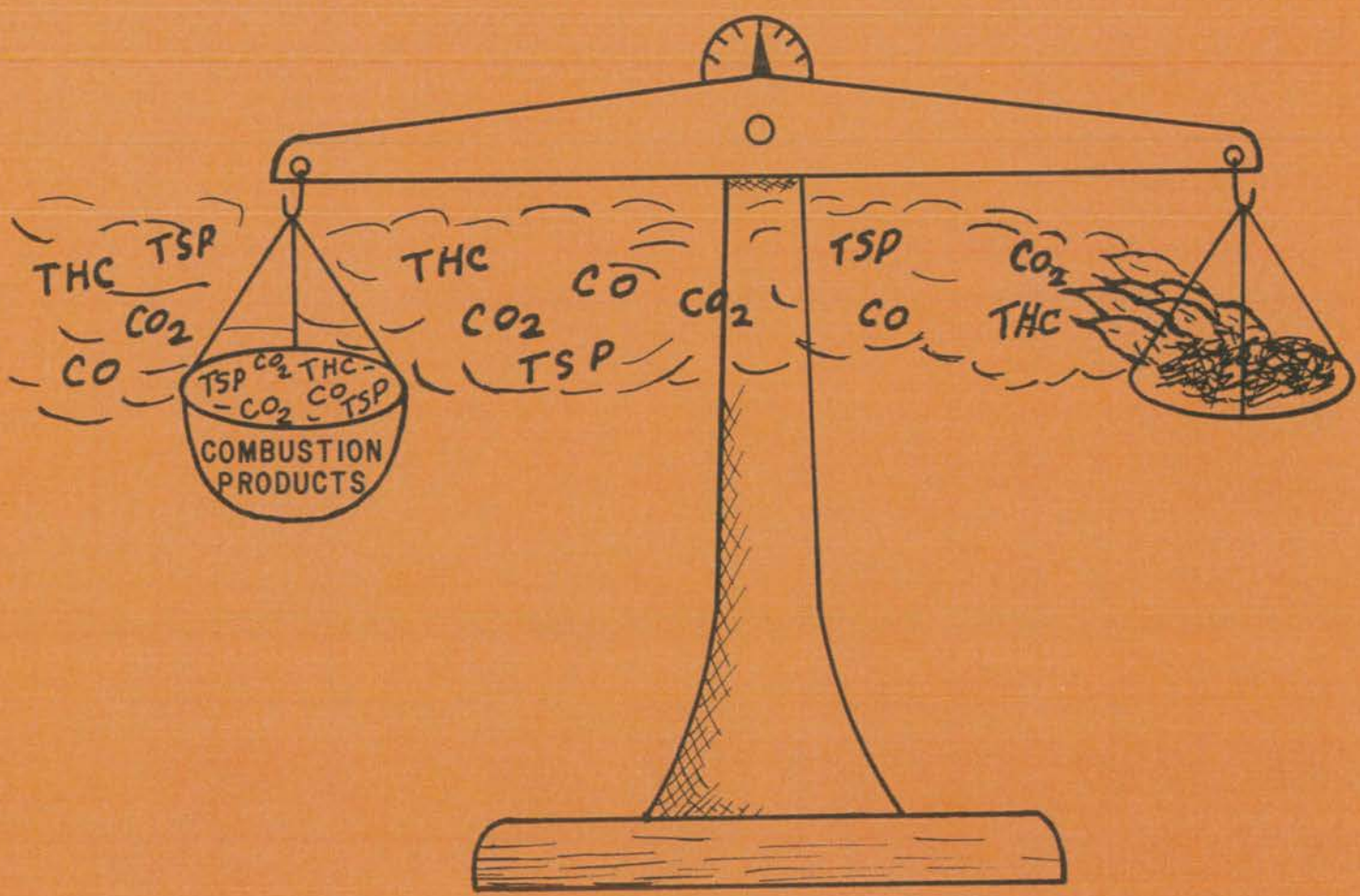

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An Evaluation of the Carbon Balance Technique for Estimating Emission Factors and Fuel Consumption in Forest Fires

by

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ABSTRACT.—Eighteen experimental fires were used to compare measured and calculated values for emission factors and fuel consumption to evaluate the carbon balance technique. The technique is based on a model for the emission factor of carbon dioxide, corrected for the production of other emissions, and which requires measurements of effluent concentrations and air volume in the plume. The maximum percent difference in values was about 15 percent. These differences followed the carbon balance percent differences closely, which indicates that field application of the technique should succeed to the extent that all carbon can be accounted for in sampling.
Keywords: Plume concentrations, laboratory fires, forest fire smoke, smoke management.

One of the problems addressed by research in forest fire behavior and smoke management is to minimize the production of undesirable emissions. Progress toward this goal depends, in part, upon development of practical methods for estimating forest fire emissions. In most of the previous research, emission factors[1] have been computed from measurements of mass concentration and fuel consumption. This approach is usually time consuming because fuels must be sampled before and after every burn. Also, because of the variability in natural fuels, some error is often introduced due to inadequate sampling.

An alternative method involves the principle of conservation of carbon atoms in the original fuel. This carbon balance technique is based on a combustion reaction involving production of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (THC), and particulate matter (TSP). The method seems well suited to forest fire applications in that both emission factor and fuel consumption estimates can be made without pre- and post-burn sampling of fuels.

Previous work utilizing the carbon balance technique is not extensive. Boubel and others (1969) were able to account for 99 ± 10 percent of the carbon in the original fuel while measuring emissions during laboratory burns of grasses from the Willamette Valley in Oregon. The technique was used by Goss and Miller (1973) to calculate particulate matter emission factors for burns of rice-field residue, and by Darley and others (1973) for agricultural and forest residues. Malte (1975) studied emissions data for burning Douglas-fir and larch slash fuels from laboratory and field studies. He combined carbon dioxide and particulate matter concentrations with a carbon balance approach to determine particulate matter, carbon dioxide, and carbon monoxide emission factors. Ward and others[2] used data collected on a single fire in southeastern Georgia to compare particulate emission factors measured by the following four independent methods: (a) aircraft sampling with a nephelometer, (b) aircraft sampling with particle counters, (c) surface sampling with filters, and (d) surface sampling with grab bags for use with a carbon balance technique. Emission factors obtained from all four methods were in substantial agreement. The carbon balance subsequently was used in field studies by Ward and others (1980). Vines and others (1971) and Evans and others (1976) assumed that amounts of CO, THC, and TSP produced by controlled burns in western Australia are negligible when compared with the CO_2 produced. They estimated the TSP emission factor by using measured concentrations of TSP and CO_2 in the plume and an emission factor for CO_2 of 1,830 g/kg (obtained from a chemical equation for complete combustion of the fuel). Whether carbonaceous products other than CO_2 can be ignored for purposes of estimating emission factors and fuel consumption in field burns is of practical interest and has provided much of the motivation for the work reported in this paper.

The present study is concerned with the feasibility of using concentration measurements of gaseous and particulate emissions for computing emission factors and fuel consumption in laboratory and field burns. It is assumed

[1] An emission factor for a given effluent is the mass of the effluent produced by a fire per mass of fuel consumed.

[2] Ward, D. E.; Nelson, R. M., Jr.; Adams, D. F. Forest fire smoke plume documentation. Pap. 79-6.3. Presented at the 72nd Annual Meeting of the Air Pollution Control Association; 1979 June 24-29; Cincinnati, OH. 24 p.

that the mass of all carbon-bearing effluents can be adequately accounted for by sampling the combustion products CO_2, CO, THC, and TSP. A model for the CO_2 emission factor is derived from a carbon balance and tested with experimental data from slash pine (*Pinus elliottii* Engelm.) needle beds burned in the Southern Forest Fire Laboratory combustion facility. These experiments are intended to extend the work of Evans and others (1976) by correcting the theoretical CO_2 emission factor for complete combustion to account for emission of other carbonaceous products. The CO_2 emission factor model is used with measured mass ratios to compute emission factors for other effluents and total fuel consumption. Comparisons are made between values based on the model and experimental measurements.

The observed mass ratios can be used to compute other mass ratios of interest such as THC:CO and TSP:CO. However, these ratios are not reported as such in this paper.

EMISSION MODELS

The combustion process includes preheating, flaming, and smoldering phases. Fire behavior and emissions data are not easily separated by combustion phase, and previous work on spreading fires has dealt mainly with overall emission factors, which represent weighted averages over all combustion phases. Only overall emission factors and emission models are discussed in this report. Quantities written with a circumflex (^) above them represent model values; quantities without a circumflex refer to measured values.

An Emission Factor Model for CO_2

The combustion products of forest fuels include CO_2, H_2O, CO, pure and oxygenated hydrocarbons, and particulate matter in forms and amounts dependent on fuel arrangement and composition, fuel moisture content, and burning characteristics. Because combustion is never complete, residue composed of carbonaceous and mineral material is left after the fire. Data from Knight and others (1975) and Hough and Albini (1978) suggest that for southern fuels about 2.5 percent of the original dry weight consists of mineral substances. The percentage of carbonaceous material remaining is dependent on the fuel and fire behavior, and is therefore more variable for any given fuel type. Although the percentage of carbon in the residue may be high in some cases, the amount of material remaining is usually sufficiently small (about 5 to 8 percent in slash pine needles) to make the amount of residual carbon insignificant when compared with the carbon leaving the fuel in the form of combustion products. For purposes of this paper, it is assumed that the carbon content of the residue is the same as that of the original dry fuel. With this simplification, an equation approximating the overall combustion of an ovendry fuel of composition $C_xH_yO_z$ can be written as

$$C_xH_yO_z + X_{O_2}O_2 \rightarrow X_{CO_2}CO_2 + X_{H_2O}H_2O + X_{CO}CO + X_{THC}C_qH_rO_sN_t + X_{TSP}C_uH_vO_w \quad (1)$$

where X refers to moles of the given component involved in burning 1 mol of fuel. In Equation (1), $C_qH_rO_sN_t$ denotes a mixture of hydrocarbons, including oxygenated and nitrogenated species. The mixture is referred to as total hydrocarbons. The solid- and liquid-phase hydrocarbons, designated as $C_uH_vO_w$, are referred to as particulate matter. The term $C_xH_yO_z$ represents consumed, rather than original, fuel because of the identical composition assumed for original and residual fuel. This assumption also means that a term to account for residue is not required in Equation (1). If a balance on carbon is written, then

$$x = X_{CO_2} + X_{CO} + qX_{THC} + uX_{TSP} \quad (2)$$

where, for example, qX_{THC} is the moles of carbon in X_{THC} moles of $C_qH_rO_sN_t$ produced in the consumption of 1 mol of fuel. An emission factor for CO_2 is, by definition,

$$\hat{EF}_{CO_2} = X_{CO_2}M_{CO_2}/M_F \quad (3)$$

where $\hat{EF}_{CO_2}$ (g/g) is based on Equation (1) and M_{CO_2} is the molecular weight of CO_2. The fuel molecular weight can be written as

$$M_F = (12x + y + 16z)\ \text{g/mol} \quad (4)$$

Substitution of Equations (2) and (4) into Equation (3) yields

$$\hat{EF}_{CO_2} = \frac{\left[\frac{xM_{CO_2}}{12x + y + 16z}\right]}{\left[1 + \frac{X_{CO}}{X_{CO_2}} + \frac{qX_{THC}}{X_{CO_2}} + \frac{uX_{TSP}}{X_{CO_2}}\right]} \quad (5)$$

A fuel composition corresponding closely to 50 percent C is given by x = 6, y = 9, z = 4 and is used here. This composition was used by Byram (1959) in combustion calculations and has since been verified in an approximate manner with analyses of southeastern fuels conducted by Knight and others (1975). Because M_{CO_2} = 44 g/mol, Equation (5) becomes

$$\hat{EF}_{CO_2} = \frac{1.82\ \text{g/g}}{\left[1 + \frac{X_{CO}}{X_{CO_2}} + \frac{qX_{THC}}{X_{CO_2}} + \frac{uX_{TSP}}{X_{CO_2}}\right]} \quad (6)$$

Effects of CO, THC, and TSP production on $\hat{EF}_{CO_2}$ can be evaluated through measurements of the ratios shown which,

it must be remembered, are molar (or mass) ratios of carbon.

For practical use, the C ratios of Equation (6) can be converted to ratios of mass concentrations (mg/m^3) through molecular weight ratios. The molecular weight of the hydrocarbon fraction is difficult to determine because both low- and high-molecular weight compounds are present in unknown quantities. For this study, propane (C_3H_8) with molecular weight of 44 g/mol is taken as a representative hydrocarbon. In addition, it is assumed that the particulate fraction is 95 percent C with a molecular weight of 12 g/mol. This figure may overestimate slightly the actual C percentage averaged over all combustion phases, but the error should not be large. Let R_i denote the ratio of effluent i mass concentration to CO_2 mass concentration, where i can represent CO, THC, or TSP. Then, through use of molecular weights, Equation (6) can be written as

$$\hat{EF}_{CO_2} = \frac{1{,}820 \text{ g/kg}}{[1 + 1.57R_{CO} + 3.0R_{THC} + 3.48R_{TSP}]} \quad (7)$$

If concentration data are in terms of parts per million (p/m),[3] the R_i represent ratios of molar concentrations and Equation (6) becomes

$$\hat{EF}_{CO_2} = \frac{1{,}820 \text{ g/kg}}{[1 + R_{CO} + 3.0\,R_{THC} + 0.95\,R_{TSP}]} \quad (8)$$

It is clear that when combustion is ideal, $R_{CO} = R_{THC} = R_{TSP} = 0$ in Equations (7) and (8) and $\hat{EF}_{CO_2} = 1{,}820$ g/kg. Dependent upon the units of experimental data, either Equation (7) or Equation (8) can be used for estimating emission factors and fuel consumption in forest fires. In the interest of simplicity, it is assumed for the remainder of this paper that concentrations are always expressed as mass concentrations. Thus Equation (7) is used in all subsequent calculations.

Model Applications

For field work, Equation (7) can be used in several ways, depending on how the effluent sampling is carried out. Most of the available information on surface-based particulate matter emissions for forest fires is based on sampling with filters in a method referred to as the flux method by Ward and others (see footnote 2). This method also can form the basis for sampling in the carbon balance technique. If the total flow of gaseous and particulate matter through a cross section of the entire plume is both measured and sampled for emissions during sample time, T, estimates can be made of the total fuel consumption and the fuel consumption rate during time T and of the corresponding emission factors. Several assumptions are inherent in the flux method. Probably the most critical one is that all effluents are present in a unit volume of sampled air in the proportion in which they were produced by the fire. Thus, the effects of plume processes such as fallout of particulate matter and conversion of sampled species to nonsampled species are regarded as negligible. Further, it is assumed that short-term variations in rate of effluent production and wind transporting the plume do not significantly affect the time-averaged concentrations and volumetric flow rate through a given plume cross section.

Consider a fire burning in a fuel type of interest with the combustion products transported downwind from the site. At some convenient downwind distance, let C_{CO_2}, A, and u represent the plume mass concentration of CO_2, cross-sectional area, and windspeed, respectively, averaged over sample time, T. If these quantities are representative of the entire plume, then the mass of fuel consumed during time T can be computed from

$$\hat{FC} = \frac{C_{CO_2} A u T}{\hat{EF}_{CO_2}} \quad (9)$$

where $\hat{EF}_{CO_2}$ is obtained from Equation (7). For most surface measurements it may not be possible to sample the entire plume because of limited manpower and instrumentation. Another complicating factor is variation in concentrations with height above the surface because effluents and ambient air are not uniformly mixed. Details on how the variables C_{CO_2}, A, and u can be used in the flux method under these complex sampling conditions are described by Ward and others (1974, 1980). If T is close to the total burning time, then $\hat{FC}$ should approximate the total consumption of fuel. An average fuel consumption rate for time T, $\hat{FCR}$, thus can be written as

$$\hat{FCR} = \frac{\hat{FC}}{T} = \frac{C_{CO_2} A u}{\hat{EF}_{CO_2}} \quad (10)$$

These same measurements may be used to estimate emission factors for CO, THC, and TSP. Because the R_i in Equation (7) are known, the emission factor for effluent i can be computed from

$$\hat{EF}_i = \hat{EF}_{CO_2} R_i \quad (11)$$

If information on emission factors only is desired, the flux method need not be used, although the measured R_i values should represent the entire plume cross section. The value of $\hat{EF}_i$ for effluent i can be estimated from combination of Equations (7) and (11).

A special case of the flux method and carbon balance technique uses Equation (7) in conjunction with sampling of effluents from smaller fires, such as those in laboratory experiments. This application of the flux method involves

[3] Although particulate matter concentrations are not measured in p/m, an equivalent concentration in p/m can be calculated from mass concentration data.

more controlled sampling than is possible with field burns, and was used in the experiments reported in this paper. In such studies, all effluents are usually funneled through an exhaust stack to the atmosphere and sampled continuously from ignition until the effluents are no longer produced at a significant rate anywhere in the fuel bed. Because of a highly variable burning rate with time, Equation (10) for rate of fuel consumption is best applied over short time intervals rather than over the total burning time.

METHODS

A series of experimental fires was conducted in the Southern Forest Fire Laboratory combustion facility to test the carbon balance technique as a means of estimating fuel consumption and emission factors for carbon dioxide, carbon monoxide, total hydrocarbons, and particulate matter. This section describes the experimental design, how the measurements were made, and possible sources of error.

Experimental Procedure

Experiments by a number of investigators have suggested that particulate matter emission factors are dependent on fire type and fire behavior variables (see Goss and Miller 1973, for example). Therefore, a requirement of this study was burning experimental fires throughout a range of fire intensities[4] to examine the emissions produced under different burning conditions. It was realized at the outset that even the highest intensity fires in these experiments would be located at the low end of the spectrum of real-world fire intensities. This limitation was due to the size of fire and rate of smoke production that could be accommodated within the 760-m^3 combustion room.

Eighteen fires consisting of nine headfires and nine backfires were burned in fuel beds made up of newly fallen slash pine needles. Use of only one fuel type reduced experimental variation in the data. The use of fuel moisture content, initial dry fuel loading, and fuel bed slope angle as independent variables provided a range of fire intensities. The study was conducted as two separate experiments. A block of nine headfires was burned first, followed by a block of nine backfires. Nominal levels of variation in the independent variables were as follows:

Moisture content	4, 11, 18 percent of dry fuel weight
Initial fuel loading	0.49, 1.46, 2.44 kg/m^2 (dry basis)
Fuel bed slope angle	0, 11.3, 22.5 degrees from horizontal

Basic designs for the two fire types are shown in figure 1. Within the block of headfires, fire CO2-1 was burned first and fire CO2-9 last. Backfires also were burned in ascending numerical order. It was assumed that experimental conditions did not vary with time. Such variation could cause errors in the results due to the order in which the fires were burned.

Prior to the experimental burns, several tests with pool fires were conducted to ensure that instrumentation was functioning properly. Carbon balances were run on two ethanol fires to check the carbon balance technique with a fuel of known composition. Mixing characteristics within the combustion room stack were also checked. Two xylene fires were then used to make similar tests with a soot-producing fuel.

Experimental Measurements

Fuel beds were constructed by uniformly distributing slash pine needles by hand into 1.22- by 0.92-m hardware cloth trays and then storing them in environmental cabinets for conditioning to the proper moisture content. Three beds were constructed for each of the three loading levels. These beds simulated in only a crude way the litter layers found in the field; gradients in moisture content and weathering found in real fuels were not present. In addition, the needles rested on a thin sheet of insulating material rather than on a moist layer of mineral soil.

An experiment began by placing the fuel bed on the burn table, which had been adjusted to the proper slope angle to simulate the effect of wind on the combustion process. Headfires were ignited at the bottom of the bed and were driven by the upslope component of buoyancy; backfires were ignited at the top of the bed and moved downslope against an upslope buoyancy force. All backfires reached a steady-state rate of spread, but this was not true for some headfires. Smoke from the fires was funneled through an exhaust stack directly above the bed. Samples of stack gas were withdrawn and prefiltered to remove particulate matter and moisture and then passed through stainless steel tubing to gas analyzers. Oxides of carbon were detected by MSA infrared analyzers; total hydrocarbons were detected with an MSA flame ionization detector. The total particulate matter samples were collected on 20- by 25-cm glass fiber filters in a high-volume sampler. Mass loss of the fuel bed was monitored with four load cells. An array of 0.16-cm diameter chromel-alumel thermocouples provided a vertical distribution of temperatures in the combustion zone and in the flame zone above the bed. Additional sensors were used to measure dynamic pressure and temperature of the stack gases for use in computing volumetric flow rates.

The fuel, fire, and emissions data were recorded in three ways. Some of the easily observed fuels and fire behavior data, as well as the particulate matter emissions and total fuel consumption, were recorded manually. Gas concentrations (in p/m) were recorded as functions of time on strip charts. These concentrations were later converted to total mass by the use of volume flow rates and sample times. In addition, gas concentrations, bed weight, stack

[4] Fire intensity is the rate of heat release per unit length of fire front in a spreading line fire.

Figure 1.–Experimental designs for headfires and backfires using fuel moisture, fuel loading, and fuel bed slope angle as independent variables.

HEADFIRES

	FUEL LOADING (kg/m^2)								
	0.49			1.46			2.44		
	SLOPE (degrees)			SLOPE (degrees)			SLOPE (degrees)		
MOISTURE (%)	0	25	50	0	25	50	0	25	50
4	CO2-7					CO2-5		CO2-1	
11		CO2-8		CO2-3					CO2-2
18			CO2-4		CO2-6		CO2-9		

BACKFIRES

	FUEL LOADING (kg/m^2)								
	0.49			1.46			2.44		
	SLOPE (degrees)			SLOPE (degrees)			SLOPE (degrees)		
MOISTURE (%)	0	25	50	0	25	50	0	25	50
4	CO2-16				CO2-17				CO2-12
11		CO2-15				CO2-11	CO2-13		
18			CO2-18	CO2-10				CO2-14	

temperatures, and pressures were sensed at 1-s intervals by a real-time data acquisition system. After each fire, the data were transferred to magnetic tape for storage and subsequent analysis.

Data Analysis

Data collected were categorized in terms of emissions production, fuel layer, and fire behavior variables. Unfortunately, magnetic tapes for two of the fires were accidentally destroyed. Therefore, gaseous emissions data were taken from the strip-chart records.

Balances between carbon in the consumed fuel and carbon measured as gases and particulate matter were made. Both the original and residual fuel (and hence fuel consumed) were assumed to contain 50 percent carbon. Carbon content of the particulate matter produced was assumed to be 95 percent; propane (C_3H_8) was assumed to represent an average chemical formulation of the many hydrocarbon gases produced.

Because only 2 of the 18 experimental fires were duplicates, additional tests were conducted to check the reproducibility of the results. Five headfires in slash pine needles were burned under nearly identical conditions. Dry fuel weights were 1,231 g, fuel moisture contents were 18 percent, and slope angles of the fuel layer from horizontal were 11.3 degrees. The mean total production of CO_2 per fire was 469 g with a standard error of 19 g. In addition, the mean particulate matter emission factor (based on gravimetric measurements) was 17.6 g/kg with a standard error of 1.1 g/kg. The maximum difference between carbon lost from the bed and carbon measured in the stack was 10.3 percent. These results indicate that repeated fires are reproducible and that much of the variation in the 18 experimental fires can be attributed to varying fuel and burning conditions.

RESULTS

Experimental Data Summary

Data for the 18 experimental fires are shown in table 1 with values of fuel consumption and total mass of CO_2, CO, THC, and TSP measured for the fires. In addition, R_i values (mass of effluent i divided by mass of CO_2) are given which can be used in equation (7) for computing a model emission factor for CO_2. The R_i data can also be used to compute other effluent mass ratios of interest. For

Table 1.–Effluent production, effluent mass ratios, fuel consumption, and carbon balance[a] for headfires and backfires in slash pine needles burned in the laboratory

Fire No.	Mass of effluent (g)				Fuel consumption (kg)	Percent difference carbon balance	$R_i = \frac{\text{Grams of i}}{\text{Grams of } CO_2}$, i = CO, THC,TSP		
	CO_2	CO	THC	TSP			R_{CO}	R_{THC}	R_{TSP}
					HEADFIRES				
CO2-1	3,828	355	40	73	2.526	2.7	0.0927	0.0104	0.0191
-2	4,470	320	20	60	2.597	9.5	.0716	.0045	.0134
-3	2,732	142	6	14	1.547	6.3	.0520	.0022	.0051
-4	752	28	2	3	.480	-8.2	.0372	.0027	.0040
-5	2,296	208	13	36	1.456	4.3	.0906	.0057	.0157
-6	2,244	152	7	32	1.382	3.1	.0677	.0031	.0143
-7	942	30	5	3	.514	7.2	.0318	.0053	.0032
-8	986	28	5	3	.525	9.1	.0284	.0051	.0030
-9	4,994	180	13	12	2.660	9.4	.0360	.0026	.0024
					BACKFIRES				
CO2-10	2,523	131	13	17	1.567	-0.6	.0519	.0052	.0067
-11	2,996	128	5	5	1.623	8.2	.0427	.0017	.0017
-12	4,558	229	17	6	2.655	2.5	.0502	.0037	.0013
-13	3,869	315	29	24	2.546	-2.9	.0814	.0075	.0062
-14	4.932	233	21	13	2.642	10.9	.0472	.0043	.0026
-15	895	58	7	3	.481	14.3	.0648	.0078	.0034
-16	931	33	2	2	.473	13.8	.0354	.0021	.0021
-17	2,813	131	10	5	1.578	5.6	.0466	.0036	.0018
-18	711	49	10	2	.459	-2.2	.0689	.0141	.0028

[a]The fuel is assumed to be 50 percent carbon for purposes of the carbon balance.

example, the ratio TSP:CO for the fire CO2-1 is 0.0191: 0.0927, or 0.206. Also shown in table 1 is the carbon balance percent difference which is based on the difference between carbon in the form of gases and particulate matter which is measured experimentally, and carbon which has disappeared from the fuel bed in the form of a weight loss.

Emission Factors and Fuel Consumption

Table 2 lists measured and computed values of emission factor for CO_2, CO, THC, and TSP. The model CO_2 emission factor comes from Equation (7) and all others come from Equation (11). Values of R_i for use in Equation (7) are listed in table 1. Also in table 2 are percent differences between measured and model values. These figures closely follow the carbon balance differences, as would be expected.

Table 3 compares total fuel consumption from Equation (9) with measured values. Total production of CO_2 in the numerator of Equation (9) is from table 1, whereas $E\hat{F}_{CO_2}$ in the denominator is from table 2. As for the emission factor data, percent differences between the calculated and measured values follow the accuracy of the carbon balance in table 1.

The carbon balance data show that measured carbon usually exceeds the assumed loss of carbon from the fuel bed, and that the maximum percent difference is about 15 percent. Tables 1, 2, and 3 also show that percent differences associated with quantities calculated from Equation (7) follow very closely those of the carbon balance. In table 2, almost the same differences are associated with each of the four effluents for a given fire. These results suggest that errors in measurement of CO_2 concentrations (and hence in $E\hat{F}_{CO_2}$) caused similar errors in quantities computed for other effluents by Equations (9) and (11). One source of error is lack of sensitivity in the CO_2 gas analyzer, which probably prevented accurate measurement of CO_2 background concentrations. This instrument was used, nevertheless, because others available could not measure the large concentrations of CO_2 produced occasionally during the fires. Another possible source of error is uncertainty in the carbon fraction of the original fuel. As will be shown later, only a small change from the assumed value of 50 percent would be necessary to bring measured values and those computed by Equations (7), (9), and (11) into excellent agreement.

Table 2.–Percent difference (P.D.) between measured emission factors (g/kg) and values computed from Equation (7) or Equation (11)

Fire No.	CO_2			CO			THC			TSP		
	Meas.	Eq. (7)	P.D.	Meas.	Eq. (11)	P.D.	Meas.	Eq. (11)	P.D.	Meas.	Eq. (11)	P.D.
						HEADFIRES						
CO2-1	1,515	1,464	3.4	141	136	3.6	15.8	15.2	3.9	28.9	28.0	3.2
-2	1,721	1,552	10.3	123	111	10.3	7.7	7.0	9.5	23.1	20.8	10.5
-3	1,766	1,646	7.0	92	86	6.7	3.9	3.6	8.0	9.0	8.4	6.9
-4	1,567	1,685	-7.3	58	63	-8.3	4.2	4.5	-6.9	6.3	6.7	-6.2
-5	1,577	1,499	5.1	143	136	5.0	8.9	8.5	4.6	24.7	23.5	5.0
-6	1,624	1,562	3.9	110	106	3.7	5.1	4.8	6.1	23.2	22.3	4.0
-7	1,833	1,690	8.1	58	54	7.1	9.7	9.0	7.5	5.8	5.4	7.1
-8	1,878	1,700	9.9	53	48	9.9	9.5	8.7	8.8	5.7	5.1	11.1
-9	1,877	1,697	10.1	68	61	10.9	4.9	4.4	10.8	4.5	4.1	9.3
						BACKFIRES						
CO2-10	1,610	1,624	-0.9	84	84	0.0	8.3	8.4	-1.2	10.8	10.9	-0.9
-11	1,846	1,688	8.9	79	72	9.3	3.1	2.9	6.7	3.1	2.9	6.7
-12	1,717	1,663	3.2	86	83	3.6	6.4	6.2	3.2	2.3	2.2	4.4
-13	1,520	1,553	-2.1	124	126	-1.6	11.4	11.6	-1.7	9.4	9.6	-2.1
-14	1,867	1,661	11.7	88	78	12.0	7.9	7.1	10.7	4.9	4.3	13.0
-15	1,861	1,601	15.0	121	104	15.1	14.6	12.5	15.5	6.2	5.4	13.8
-16	1,968	1,702	14.5	70	60	15.4	4.2	3.6	15.4	4.2	3.6	15.4
-17	1,783	1,669	6.6	83	78	6.2	6.3	6.0	4.9	3.2	3.0	6.5
-18	1,549	1,569	-1.3	107	108	-0.9	21.8	22.1	-1.4	4.4	4.4	0.0

Table 3.–Percent difference between measured fuel consumption and values computed from Equation (9)

Fire No.	Measured fuel consumption (kg)	Fuel consumption from Eq. (9) (kg)	Percent difference
	HEADFIRES		
CO2-1	2.526	2.615	3.5
-2	2.597	2.880	10.3
-3	1.547	1.660	7.0
-4	.480	.446	-7.3
-5	1.456	1.532	5.1
-6	1.382	1.437	3.9
-7	.514	.557	8.0
-8	.525	.581	10.1
-9	2.660	2.943	10.1
	BACKFIRES		
CO2-10	1.567	1.554	-0.8
-11	1.623	1.775	8.9
-12	2.655	2.741	3.2
-13	2.546	2.491	-2.2
-14	2.642	2.969	11.7
-15	.481	.559	15.0
-16	.473	.547	14.5
-17	1.578	1.685	6.6
-18	.459	.453	-1.3

Of interest is whether the TSP emission factor can be regarded as constant under different burning conditions. Although available data (Ward and others 1974, 1980) indicate that EF_{TSP} is a function of fireline intensity and fire type, the question is not yet fully resolved. The data of table 2 do not support the idea of a constant emission factor. Values of EF_{TSP} range from about 2 to 30 g/kg.

DISCUSSION

Feasibility of the Carbon Balance Technique

It is clear that the question of feasibility of the carbon balance technique for field applications cannot be answered in a final way with a single laboratory study. However, the results in tables 2 and 3 suggest that computational accuracy follows closely the accuracy of the carbon balance. Though the measured carbon exceeds carbon assumed lost from the fuel bed for all but four fires, this study tends to confirm the initial assumption that, for practical purposes, only CO_2, CO, THC, and TSP need be included as components in the carbon balance.

The present results indicate that if errors in effluent concentration and air volume measurement can be limited to 15 or 20 percent in field experiments, the carbon balance method should be acceptably accurate for most applications. However, a number of errors can be associated with the technique that should be pointed out. Among them are uncertainties in carbon percentages and molecular weights of original and residual fuel, and in hydrocarbons and particulate matter produced. Errors result from incomplete mixing and the nearly impossible task of sampling the entire plume. These errors are reduced considerably in laboratory experiments such as those reported in this study. Finally, errors caused by wall losses in instrument tubing, condensation, and desorption from filters must be contended with. Despite these and other possible errors, the results of the present study suggest that the carbon balance technique can be useful in both laboratory and field experiments.

Because of some of these uncertainties, definite statements about the accuracy of Equations (7), (9), and (11) cannot be made, though there is little doubt of their general validity. These equations produce smaller emission factor and larger fuel consumption values than those measured. The differences are consistent with two explanations: (a) error in the constant 1,820 g/kg of Equation (7) due to underestimation of the fuel carbon fraction, or (b) errors in CO_2 concentrations which affected subsequent computations. Other errors, such as those listed above, are believed to have produced only negligible effects in comparison with either (a) or (b). If (a) were true, a value of about 1,940 g/kg would bring the model values into agreement with the measurements. This implies a carbon fraction of about 53 percent in the original fuel. Though no data on needles of this experiment are available, elemental studies on six samples of slash pine needles by Knight and others (1975) produced a carbon percentage of 52.7 percent. On the other hand, zero readings on the CO_2 gas analyzer were undoubtedly in error due to lack of sensitivity at small concentrations. If the error was a systematic one (rather than random), CO_2 background concentrations may have been consistently underestimated, causing a slight overestimation of CO_2 for most of the fires. The extent to which errors (a) and (b) were present during the burns is unknown.

Practical Application

Successful application of the carbon balance technique as a measurement tool partially depends on the validity of the constant 1,820 g/kg in Equation (7). The remainder of the input to Equations (7), (9), and (11) comes from measurement of mass concentrations and air volume. The flux method discussed earlier seems well suited for either aerial or surface measurements made in field experiments. However, because the method has not been used extensively, little can be said of its possible limitations. In surface applications, the demands on personnel and equipment needed for adequate sampling may be a drawback. Studies of the extent of sampling required for meaningful results are needed. In aerial sampling with aircraft, a possible limitation (especially on small fires) is that effluent con-

centrations throughout most of the plume may not be much greater than background values. This problem was noted by Ward and others (see footnote 2).

A question of practical interest discussed earlier is whether carbonaceous products other than CO_2 can be ignored for purposes of estimating emission factors and fuel consumption in operational burns or smaller burns used for research purposes. The data in tables 1, 2, and 3 can be used to show that if all the R_i in Equation (7) are regarded as zero, computed emission factors for CO, THC, and TSP and corresponding fuel consumptions are within 20 percent of the measured values. If the measured R_{CO} is included in the calculations, the differences are within 15 percent. Therefore, these experiments indicate that accuracy is only slightly improved by accounting for emissions other than CO_2 in the analysis. The value of this result is that a TSP emission factor can be obtained from mass concentration measurements of CO_2 and TSP only, rather than requiring additional concentrations of CO and THC.

Experiments with the carbon balance technique under field conditions are needed. If proven feasible in these situations, the technique should be an aid to persons responsible for management of air quality as well as those engaged in fire and smoke management research. The method will provide estimates of emission factors for carbonaceous combustion products and of fuel consumed while requiring only measurements of effluent concentration and air volume.

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An evaluation of the carbon balance technique for estimating emission factors and fuel consumption in forest fires. Res. Pap. SE-231. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station; 1981. 9 p.

A technique based on a model for the emission factor of carbon dioxide, corrected for the production of other emissions, and which requires measurements of effluent concentrations and air volume in the plume, is evaluated by comparing measured values from experimental fires to calculated values.

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