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Burning California Chaparral - An Exploratory Study of Some Common Shrubs and Their Combustion Characteristics

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Abstract. Prescribed fire is a tool used to manage vegetation in southern California. The nature and quantity of gaseous and particulate emissions have not been described for California chaparral. A study examining carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter emissions from fuel beds constructed from common chaparral shrubs was initiated. Chamise (*Adenostoma fasciculatum*), ceanothus (*Ceanothus crassifolius*),manzanita (*Arctostaphylos glandulosa*), and scrub oak (Q*uercus dumosa*) fuel beds were burned in December 1989, and March, May, and August, 1990. Gas and particulate matter samples were collected from 45 fires. Emission factors for CO_2 and particulate matter were affected by species and month individually; month and species interacted and affected CO emission factors. Pearson's correlation coefficient and Kendall's tau indicated that emission factors for CO and particulate matter were inversely related to combustion efficiency.

Keywords: Prescribed burning; Smoke; Chaparral; *Ceanothus crassifolius; Adenostoma fasciculatum; Arctostaphylos glandulosa; Quercus dumosa.*

Introduction

Periodic fire has been a part of the southern California landscape for centuries. The mountain slopes surrounding the Los Angeles basin are covered at lower elevations (below 1600 m) with chaparral vegetation characteristic of Mediterranean climates (Philpot 1977). Management of chaparral is practiced to create vegetational mosaics for wildlife and to minimize wildfire severity through fuel hazard reduction. It is essential that fire be maintained in the chaparral ecosystem for the ecological values it can provide. Prescribed fire is an important tool used for vegetation management under favorable weather conditions. Regulations governing release of emissions in the Los Angeles basin's airshed have become stricter. Knowledge of emissions from all sources including prescribed fire is required.

Information about the effects of species and month on chaparral smoke emissions is not available presently; however, larger scale field measurements have been made using airborne sampling systems (Einfield et al. 1989, Hegg et al. 1989) and ground-based tower systems (Ward and Hardy 1989). The airborne and tower systems are not well-suited for evaluating the effects of species and month on the release of smoke emissions. Such information is needed before smoke management guide-lines can be developed. The purpose of our study was to determine whether species and month affect emissions of carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter (pm). This paper describes results from an exploratory study designed to measure the emissions released from fuel beds constructed from common chaparral species burned during different seasons of the year.

Study Design and Methods

A randomized complete block design was used for this study. Three replications of experimental fires in four important chaparral shrub species were burned in December 1989, March, May, and August 1990 (total of 48 fires); however, only 45 fires were completed, resulting in an unbalanced block design. A block initially consisted of one fire per species in a given month (four fires). Chamise (*Adenostoma fasciculatum*), ceanothus (*Ceanothus crassifolius*), manzanita (*Actostaphylos glandulosa*), and scrub oak (*Quercus dumosa*) were selected for use in this study. These species represented a range in leaf character from needlelike in chamise to broad evergreen in manzanita.

Plant material was collected from the same field location for all four months. Each fuel bed was constructed by loosely piling approximately one kilogram (kg) of the selected species into a hemispherical shape. We did not attempt to keep packing ratio or any other fuel bed characteristic constant. Branches less

Table 1. Moisture content of samples of four common chaparral species by month.

	Month[2]			
Species[1]	12/89	3/90	5/90	8/'90
Cham	50.8 (2.0)	101.0 (0.0)	80.5 (1.5)	60.0 (0.5)
Cean	63.3 (0.3)	144.5 (1.5)	88.0 (1.0)	60.0 (0.5)
Manz	76.3 (4.3)	92.0 (l.0)	85.0 (2.0)	89.0 (0.0)
Quer	74.4 (0.2)	75.0 (2.0)	109.5 (1.5)	62.0 (0.5)

[1] Cham = *Adenostoma fasciculatum,* Cean = *Ceanothus crassifolius Manz = Arctostaphylos glandulosa,* Quer = *Quercus dumosa*
[2] Values are means expressed as a percentage of oven dry weight (standard error).

than 0.63 cm in diameter with foliage intact were used. Moisture content on an oven-dry weight basis was measured for each species for each month (Table 1). A variety of ignition techniques were used: ethyl alcohol, wood excelsior, and propane torch. Any effects due to ignition techniques were confounded with block and season effects.

Experimental fires were burned on a level table (1 m by 2 m) in a ventilated building at the U.S.D.A. Forest Service Fire Laboratory in Riverside, California. An aluminum hood and stack were constructed to channel smoke from each experimental fire. A high volume air sampler with a low velocity nozzle positioned parallel to the smoke column was placed in the stack approximately 1.8 m above the table. The sampler was used to collect particulate samples from the smoke column. A small pump collected a sample of the combustion gases behind the high volume sampler's glass-fiber filter. Air temperature at the nozzle was less than 250°F. This ensured solidification of aerosols. Particulate samples were collected by maintaining a constant pressure drop of 2.54 cm Hg across the filter. Sampling began after the ignition material was no longer visibly present. The gas and particle samples were gathered from primarily flaming combustion with a small component of smoldering combustion that was not quantified. Sampling ceased after the flaming phase had ended or the filter had become loaded with particulate matter. The fire was extinguished immediately in order to determine fuel consumption. Sampling times ranged from 0.25 to 2 minutes (Table 2). Gas and particulate samples were shipped to the U.S.D.A. Forest Service, Fire Sciences Laboratory in Missoula, Montana, for weighing and chemical analysis.

The 20.3 by 25.4 cm glass-fiber filters were weighed after being conditioned at 40 to 50 percent relative humidity and 72° F for 24 hours. A Mettler overhead beam balance with closed weighing chamber (accuracy of +/- 0.1 mg) was used. The gas sample bags were analyzed for CO and CO_2 by using both a nondispersive infrared technique (Horiba model PIR-2000) and a gas chromatographic technique that used a catalyzed methanizer to convert CO and CO_2 to equivalent molar quantities of methane before quantification with a hydrogen flame ionization detector (Carle System gas chromatograph (GC)). The total hydrocarbon content of the volatile gases was measured using the Carle GC.

Emission factors were determined using the carbon-mass balance method (Ward, et al. 1979, Radke et al. 1990). We assumed that carbon is released from the fuel in proms to the rate that the mass of the fuel is lost during consumption in the fire. This assumption was validated for laboratory fires by Nelson 1982). Emission factors were calculated for total particulate matter, CO, and CO_2 by dividing the emission concentration by the total carbon concentration and multiplying by two. Combustion efficiency was defined as the mass of carbon released in the form of CO_2 divided by the total mass of carbon released. It was expressed as a percentage of total carbon.

Analysis of variance (ANOVA) was used to test whether species and month interaction affected emission factors for CO, CO_2, and particulate matter. The hypotheses that species and month individually did not affect emission factors were also tested. The relationship between combustion efficiency and emission factors was examined also. Both Kendall's tau and Pearson's sample correlation coefficient were calculated to examine the relationships between combustion efficiency and emission factors for CO and PM (p.185-194, Hollander and Wolfe 1973; p. 277, Steel and Torrie 19180). Tau is a distribution-free statistic that is used to test the independence of two variables. The only assumptions necessary for hypothesis testing are 1) that each pair of observations is independent of the other pairs and 4) that the pairs come from the same underlying parent population. Tau measures the amount of association between the two variables -- i.e., does an increase in one variable cause an increase (or decrease) in the other variable? The sample correlation coefficient requires that assumption 1 be met and that the pairs of variables come from a bivariate normal distribution. The two statistics assume values ranging from –1 (perfect negative association) to 0 (no association) to 1 (perfect positive association). Both tests were performed because the distributional nature of emission factors is unknown.

Table 2. Summary of experimental fires used to determine effects of month of burning and plant species on CO, CO_2, and particulate matter (PM) emissions.

Fire	Date	Species[1]	Fuel Consumed (g)	Sample Time (min)	Volume Sampled (m^3)	Emission Factors (g/kg)		
						CO	CO2	PM
1	12/15/89	Cean	55.0	1.00[2]	3.72	95.0	1519.0	68.5
2		Quer	160.0	1.00	3.72	113.0	1597.0	23.6
3		Olam	100.0	1.00	3.72	87.0	1648.0	19.5
4		Manz	402.0	1.00	3.72	127.0	1495.0	58.1
5		Olam	713.0	1.00	3.72	61.0	1697.0	16.6
6		Cean	556.0	1.00	3.72	76.0	1659.0	22.6
7		Manz	447.0	1.00	3.72	159.0	1370.0	89.3
8		Quer	139.0	1.00	3.72	165.0	1497.0	31.6
9		Olam	200.0	1.00	3.72	67.0	1728.0	[3]
10	3/29/90	Olam	740.2	0.83	3.62	88.2	1660.1	20.3
11		Manz	427.2	2.25	10.03	104.8	1604.9	37.4
12		Cean	149.9	2.83	12.88	164.5	1513.5	39.2
13		Quer	855.1	2.00	8.73	67.7	1704.4	7.2
14		Cean	259.9	2.00	8.92	195.3	1440.2	103.8
15		Quer	171.9	1.00	4.37	187.2	1531.4	45.1
16		Olam	477.4	2.08	9.08	96.3	1634.5	15.9
17		Manz	346.2	1.25	5.81	142.0	1527.5	85.2
18		Cean	52.3	1.75	8.13	209.5	1451.2	65.4
19		Quer	445.5	1.58	7.05	82.8	1676.2	15.2
20		Quer	309.8	0.75	3.48	61.9	1717.7	7.8
21		Manz	468.9	1.92	8.38	178.2	1451.9	139.4
22	5/15/90	Olam	484.0	0.58	2.59	117.4	1512.1	15.3
23		Quer	197.5	1.00	4.46	149.3	1391.5	60.6
24		Manz	229.1	0.42	1.87	155.2	1174.0	134.0
25		Cean	587.2	1.33	5.95	169.3	1274.0	69.9
26		Manz	330.6	1.00	4.46	134.3	1427.6	49.3
27		Quer	677.2	0.75	3.27	113.1	1456.5	49.5
28		Cean	244.0	1.08	4.82	164.4	1250.3	107.0
29	5/16/90	Manz	303.9	1.25	5.57	140.3	1428.7	56.3
30		Olam	358.8	2.00	8.73	89.8	1605.9	13.2
31		Cean	176.8	1.08	4.82	176.3	1337.7	63.9
32		Quer	617.0	0.33	1.46	107.0	1377.2	109.0
33		Olam	440.9	0.50	2.18	106.5	1591.1	10.3
34	8/8/90	Quer	167.4	1.08	4.82	198.3	1478.8	29.0
35		Manz	80.5	1.25	5.57	211.9	1449.5	60.6
36		Olam	452.7	1.75	7.64	167.4	1516.6	14.0
37		Cean	194.1	1.33	5.95	257.4	1344.0	98.7
38		Olam	432.0	0.58	2.48	91.6	1670.9	10.1
39		Manz	90.7	0.75	3.34	208.1	1452.7	77.1
40		Cean	104.8	1.25	5.57	190.8	1484.7	52.6
41		Quer	455.0	0.83	3.62	278.7	1352.8	51.7
42		Cean	200.1	2.00	8.92	152.8	1511.2	52.5
43		Manz	135.5	1.33	5.95	163.3	1434.5	174.4
44		Quer	276.2	1.08	4.72	264.9	1247.7	160.5
45		Olam	76.5	2.00	8.92	181.1	1425.8	65.3

[1] See footnote 1. Table 1.
[2] Sampling times and volume flow rate not measured on 12/15/89. These values were assumed.
[3] Glass fiber filter missing.

Results

We experienced some difficulty in igniting the live fuels. Excelsior and the propane torch appeared to be the better ignition techniques. At other times, ignition and sustained combustion occurred very rapidly. Thus the combustion characteristics of the sample fires varied. considerably. Because of an oversight in the 12/89 fires, we had to assume a uniform volume flow rate and sampling time for all eleven fires (Table 2). This portion of the experiment will be repeated again in December 1990.

Moisture content of the branches and foliage changed over the year (Table 1). Ceanothus reached a maximum of 144 percent in March and chamise readied the minimum moisture content of 51 percent in December. Total volume of air sampled ranged from 1.46 to 12.88 m^3. Volume flow rates of the high volume sampler were typically between 4.18 and 4.46 m^3 per minute. Fuel consumption ranged from 52.3 to 855.1 g. The observed emission factors are also contained in Table 2. The range in emission factors was 62 to 279 g/kg for CO, 1248 to 1728 g/kg for CO_2, and 7 to 174 g/kg for particulate matter.

Table 3. Summary of ANOV As used to detect the effects of month and species on CO, CO_2, and particulate emissions (PM) produced by small-scale burning of chamise, scrub oak, ceanothus, and manzanita.

Combustion Product	Source	df[1]	SS[2]	p[3]
CO	Block (B)	2	195.13	0.9222
Month	(M)	3	48514.86	0.0001
Species	(S)	3	22240.43	0.0023
M*S	interaction	9	25496.89	0.0397
	Error	28	33614.34	
CO_2	B	2	1710.28	0.8829
	M	3	241785.66	0.0001
	S	3	204444.78	0.0001
	M*S	9	124392.57	0.0745
	Error	28	191343.96	
PM	B	2	4990.84	0.1508
	M	3	3703.96	0.4508
	S	3	24375.91	0.0017
	M*S	9	8662.92	0.6333
	Error	27	33173.33	

[1] Degrees of freedom.
[2] Partial sum of squares.
[3] Probability of a greater F value.

Month and species affected CO emission factors but these effects were not separated because of interaction (Table 3, p = 0.040). There was evidence that the interaction may not have had an effect on CO_2 emission factors (p = 0.075). CO_2 emission factors were affected by both month and species. Particulate matter emission factors were not affected by interaction between month and species (p = 0.633). Particulate matter emission factors were affected by species only. Because this was a preliminary study, no attempts were made to separate means for either month or species. Mean emission factors for particulate matter by month and species are contained in Table 4 and for CO_2 in Table 5.

There was good evidence of a negative relationship between combustion efficiency and CO emission factors (Table 6). Kendall's tau and Pearson's *r* indicated this. Similarly, the association between combustion efficiency and particulate matter emission factors was also negative. Both tau and *r* generally indicated this, i.e., the hypotheses that they equalled zero were rejected for all species except chamise. However, *r* indicated a negative relationship between combustion efficiency and particulate matter emissions for chamise.

Discussion

Species had an effect on emissions of particulate matter. Interaction between month and species affected CO and CO_2. Although not specifically noted, all species were observed to be in some stage of flowering or fruiting during the course of the study. The differences in moisture content were noted above. The month effect probably consisted of both an effect due to physiological condition and an effect due to moisture content.

The arrangement of the fuels on the burning table was not designed to simulate natural fuel bed characteristics. However, the fuels were arranged similarly for the various species during the entire study. In addition to the effect of arrangement on burning characteristics, the chemical content of the fuels may have changed over the range of months tested. It is believed, but has not been verified, that the extractive content is an additional variable that affects the emissions released during combustion of wildland fuels. The extractive content is one

Table 4. Mean particulate emission factors by month of burning and by species.

Month	n	EF[1]	Species	n	EF
12/89	9	39.28	Chamise	10	20.05
3/90	12	48.49	Scrub Oak	13	47.27
5/90	12	61.53	Ceanothus	11	67.65
8/90	12	70.54	Manzanita	11	87.37

[1] Emission factor in g/kg.

Table 5. Mean emission factors for $C0_2$ by month of burning and species.

Month	n	EF'	Species .	n	EF
12/89	10	1577.90	Chamise	11	1608.118
3/90	12	1576.12	Scrub Oak	13	1507.48
5/90	12	1402.22	Ceanothus	11	1434.98
8/90	12	1447.43	Manzanita	11	1437.85

[1] Emission factor in g/ka

variable that may have affected the burning characteristics of the species examined here. Thus the emission factors presented in this paper were for very artificial situations.

Although fuel bed variables were neither measured nor controlled in this experiment, the emission factors measured in this study were similar to those observed by Ward and Hardy (1989) for field measurements of smoke from prescribed burns in chaparral. Emission factors for particulate matter in our study exceed those reported by Ward and Hardy. They reported emission factors of 12 to 21 g/kg. The emission factors in the present study ranged from 20 to 87 g/kg (Table 4). Conversely, Ward and Hardy reported emission factors of 1600 to 1715 g/ kg for $C0_2$ and we measured emission factors of 1435 to 1608 g/kg (Table 5). Emission factors for CO ranged from 61 to 278 g/kg which is more than twice the range reported by Ward and Hardy (34 to 102 g/kg). More than likely, the differences are a result of the effect of fuel bed properties on combustion efficiency. The more porous, natural fuel array would be expected to burn with a higher combustion efficiency that the compact fuel beds created for this series of laboratory test fires. Using the data of Ward and Hardy (1989), combustion efficiencies for their field experiments ranged from 87 to 94 percent whereas our data suggested lower combustion efficiencies (mean of 81 percent). This result suggests that more carbon was converted to products of incomplete combustion in our laboratory experiments than in the near full-scale field experiments of Ward and Hardy (1989).
effect of species on emission factors (Table 4). Nevertheless, this pilot study has yielded new data regarding the effect of species on emission factors (Table 4).

Summary

Combustion characteristics of live chaparral fuels varied greatly. A propane torch and excelsior each provided good ignition of the fuels. Even though we did not keep characteristics of the fuel beds constant, our measured emission factors for CO, CO_2, and particulate matter generally agreed with other published studies. However, the ranges in emission factors were greater than the ranges reported in Ward and Hardy (1989).

Emission factors for particulate matter were affected by species only. Interaction between species and month had an effect on CO and CO_2 emission factors; individual factor effects were not separated. Emission factors for particulate matter and CO were negatively associated with combustion efficiency. This study provides baseline data for future laboratory and field studies of emissions arising from burning of chaparral and indicates that month and species are potentially important factors. Further research and measurement is needed before absolute emission factors and thus smoke Management guidelines for chaparral can be derived.

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Table 6. Summary of tests of association of CO and particulate matter emission factors with combustion efficiency. Association was measured using Kenda1l's tau and Pearson's sample correlation coefficient.

	Associations[1]							
	CO and CE				PM and CE			
Species[2]	Tau[3]	p[4]	r[5]	p[6]	Tau	p[4]	r[5]	p[6]
Cean	-0.86	0.003	-0.91	0.001	-0.64	0.026	-0.85	0.008
Cham	-0.71	0.013	-0.98	0.000	-0.14	0.652	-0.78	0.040
Manz	-0.36	0.216	-0.63	0.094	-0.50	0.083	-0.50	0.205
Quer	-0.91	0.000	-0.97	0.000	-0.82	0.001	-0.85	0.002

[1] CO = Carbon monoxide, CE = combustion efficiency, PM = particulate matter.
[2] Cean = *Ceanothus crassifolius*, Cham = *Adenostoma fasciculatum*, Manz = *Arctostaphylos glandulosa*, Quer = *Quercus dumosa* .
[3] Kendall's tau.
[4] Probability of achieving a greater tau.
[5] Pearson's sample correlation coefficient.
[6] Probability of achieving a greater r.

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