OPEN BURNING
AP-42 Section 2.4
Reference Number
16

Emissions from Slash Burning and The Influence of Flame Retardant Chemicals

D. V. Sandberg and S. G. Pickford
Pacific Northwest Forest and Range Experiment Station

and

E. F. Darley
University of California

Pollutants sampled during the burning of 30 lb ponderosa pine fuel beds yielded emission factors for CO, hydrocarbon gases, and particulate matter of 146, 8.4, and 9.1 lb/ton of fuel, respectively. When similar beds were treated with diammonium phosphate flame retardant, these factors increased to 166, 11.7, and 19.3 lb/ton of fuel, respectively.

Gas chromatographic analysis of hydrocarbon gases showed that 15–40% of this material was composed of methane and ethylene. Ethane and acetylene were the next most abundant materials, with photochemically important materials constituting minor portions of this gaseous component. Fuel beds treated with flame retardant produced more olefins, and this production lasted throughout the smoldering phase of burning.

These tests showed that the smoldering phase of combustion is of major importance to air pollutant production during slash burning. The initial 80% of the fuel burned accounted for only 20–30% of HC and CO emissions. This suggests that a rapid mop-up of slash burns could substantially reduce air pollutant production.

Air pollutants from the open burning of logging slash have received attention since the early 1960's.[1–5] The Environmental Protection Agency (EPA)[6] published data based on reported factors indicating that emissions from wildfires and slash burning made up 9% of air pollutants in 1969.[7] Both slash burning and wildfires produce the same types of emissions and ordinarily occur at some distance from urban centers. Slash is often burned to reduce the hazard of accidental wildfire, but the need for regulating air quality must be weighed against the hazards from wildfire. Thus, evaluation of this pollution source depends on a detailed knowledge of the nature and amounts of emissions from slash burning.

The use of flame retardants in slash burning has been previously investigated.[8,9] Philpot *et al.*[10] reported the effects of two different retardant chemicals on the production rate and total amounts of particulate emissions from slash burning. Our paper describes the emission of hydrocarbon gases, CO, and total particulate matter from open burning of ponderosa pine logging slash, as well as the effects of a commercial diammonium phosphate (DAP) flame retardant at three [illegible].

Because slash burning is not a steady-state process, it is not well described by simple emission factors alone. This paper also describes the changes in emission rates with time and the effects of these changes on total emissions.

Methods

Nineteen fuel beds were constructed from ponderosa pine logging slash which was collected on the San Bernardino National Forest and transported to the U. S. Forest Service Fire Laboratory at Riverside, California. Twenty pounds of needles, twigs, and small branches were weighed onto a 3.6 ft square of hardware cloth, followed by 10 lb of larger branches and stems. These small fuel beds were the equivalent of a 50 ton/acre fuel loading, similar in size and distribution to actual logging slash.

Nine of the resulting beds were treated with a water solution of Phoschek 259,* a commercial DAP flame retardant. The retardant solution was sprayed onto the beds in three replicates of three DAP treatment levels: 1.8, 3.6, and 7.1% DAP on air-dry weight basis, corresponding to rates of 3, 6, and 12 gal/100 ft^2 of fuel bed surface, respectively. All three fuel beds in each treatment level were treated in the afternoon and burned the following morning to minimize variations in drying time. The remaining 10 beds were left untreated as controls.

The fuel beds were burned at the University of California, Riverside, campus. The burning table, tower, and instrumentation used in this study have been fully described elsewhere.[1] Continuous measurements were made of stack temperature, stack volume flow, fuel weight, CO, CO_2, and HC concentrations in the stack effluent during the burning of each fuel bed. Total particulate matter production for each fire was estimated from a sample collected on a glass fiber filter mat.

Combustion gases were drawn from the tower, filtered, and collected in 250 cc glass cylinders for later analysis by gas chromatography.[1]

These grab samples were collected from two untreated fuel beds and one treated fuel bed in each application rate. Samples were collected from these beds at the time of maximum stack temperature and again at the time of maximum hydrocarbon (HC) analyzer reading. An additional sample was collected during the final smoldering phase from one treated and one untreated fuel bed.

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* Use of brand names in this paper does not constitute an endorsement of the product by the U. S. Forest Service.

Ambient air temperature and relative humidity were measured before each pile was burned. Fuel moisture, just before burning, was measured by weight loss after oven drying for each fuel bed. Each fuel bed was ignited with a propane torch. Measurements were taken continuously from ignition until flaming had completely subsided (about 45 min). The burning table and tower were allowed to cool after each fire. Burning was restricted to the hours between 8:00 A.M. and 12:00 noon to minimize disturbance by wind. No burning was done if there was noticeable wind.

Results

All fuels had been cured in dry weather for at least 2 weeks. Moisture contents of the needles were 4 to 11%, of twigs 3 to 8%, and branches over 2 inches in diameter were 3 to 14%. Relative humidity varied from 41 to 80%, and temperatures varied from 70° to 90°F.

Fire intensity (energy release rate per unit area) is a function of rate of weight loss from the fuel bed. We, therefore, used the rate of weight loss as an expression of fire intensity. The peak fire intensities of the untreated fuel beds averaged 5.8 ± 0.6 lb/min. Peak intensities for the lightest to heaviest retardant application averaged 5.0 ± 0.2, 2.8 ± 0.4, and 1.9 ± 0.6 lb/min, respectively. No differences in fire intensity between untreated fuel beds were observed which we could positively associate with differences between fuel beds or weather conditions. Treated fuel beds had lower fire intensities, and one fuel bed with heavy retardant application (64°F ambient temperature and 84% humidity) failed to sustain flaming and was excluded from further analysis.

The particulate emissions from all untreated fuel beds averaged 9.1 ± 1.4 lb/ton of initial fuel (Table I). Total HC emissions and CO were 8.4 ± 2.0 and 146 ± 10 lb/ton of initial fuel, respectively. The average CO/CO_2 ratio was 0.051 ± 0.009.

8 Only about two-thirds of the fuel was consumed in each test, so emission factors for untreated fuel beds, based on the actual weight of fuel consumed, were also calculated. These emission factors were 12 ± 2, 11 ± 2, and 195 ± 18 lb/ton of fuel burned for particulate, HC and CO, respectively.

There was no significant difference between the emission factors based on initial fuel bed weight for the three levels of DAP treatments, so all treatments were considered together. For DAP treated fuel beds, the emissions per ton of initial fuel weight were 19.3 ± 3.3, 11.7 ± 3.1, and 166 ± 28 lb for particulate, HC, and CO respectively. The average CO/CO_2 ratio for retardant treated beds was 0.064 ± 0.014. Only the particulate emissions from treated fuel beds were significantly different from untreated fuel beds when initial fuel weight was the basis for comparison.

The effect of DAP was more pronounced when emissions were compared on the weight of fuel burned because the untreated fuel beds burned more completely. The emission factors determined in this way were all significantly increased by DAP application (Figure 1, Table I).

We were interested in the distribution of emission intensities during the course of burning. In a fuel bed such as logging slash, the fine fuels (twigs, needles) are rapidly consumed and the fire more slowly reduces the larger stems and branches. However, reduction of the hazard of wildfire in this slash is accomplished by removal of the twigs, needles, and smaller branches—a small proportion of the total fuel bed weight. We, therefore, plotted the cumulative weights of CO and HC emissions against cumulative weight loss from the fuel bed (Figure 2). We would have liked to make similar comparisons for particulate matter production versus cumulative weight loss. This would require a sampling system similar to Philpot's *et al.*,[10] which we did not have.

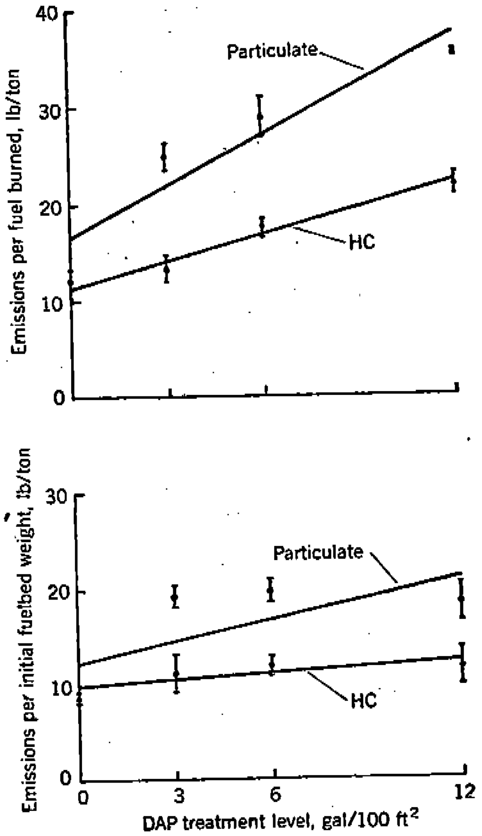

Figure 1. Particulate and hydrocarbon emission factors for untreated fuel beds and fuel beds treated with various levels of DAP. Mean and standard deviations of observations indicated by dot and vertical bar, respectively.

The results of the gas chromatographic (g.c.) analysis of the grab samples are given in Table II. The two major components of the stack gases in nearly all cases were methane and ethylene. Ethane and acetylene were the next most important components, and the remainder appeared to be quantitatively minor constituents. Of these minor gases, propylene and 1,3-butadiene were the most generally abundant.

We collected these samples at three different stages of burning: maximum plume temperature, usually about 5 min after ignition and corresponding to maximum smoke plume development; peak HC analyzer reading, which occurred as the fire was dying down some 10–15 min later; and a final sample when the fire was just smoldering. This latter phase usually lasted for 15–30 min during each test.

Table I. Emission factors for carbon monoxide, particulate matter, and hydrocarbon gases as determined in this study.

	Untreated	3 gal/ 100 ft²	6 gal/ 100 ft²	12 gal/ 100 ft²
	Lb/ton of initial fuel bed weight[a]			
Particulate	9 ± 1	19 ± 4	20 ± 3	19 ± 3
Hydrocarbon gases	8 ± 2	11 ± 4	12 ± 2	12 ± 4
Carbon monoxide	146 ± 10	174 ± 17	173 ± 12	143 ± 56
	Lb/ton of fuel burned[a]			
Particulate	12 ± 2	25 ± 3	30 ± 2	35 ± 1
Hydrocarbon gases	11 ± 2	15 ± 4	18 ± 2	22 ± 3
Carbon monoxide	195 ± 18	233 ± 27	272 ± 24	266 ± 39

[a] Mean and standard deviation of all observations.

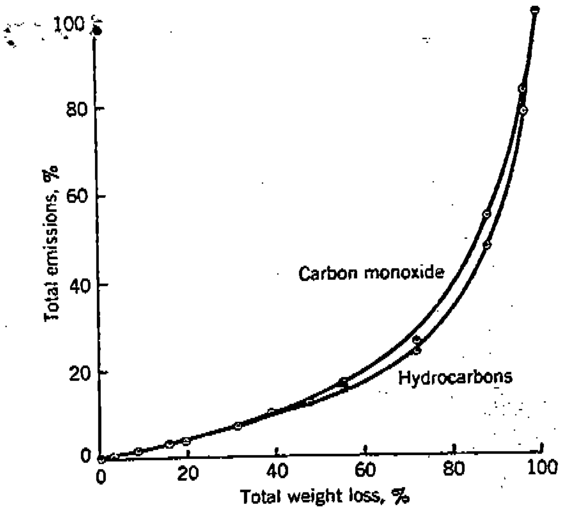

Figure 2. Relation of the proportion of total fuel consumed to the proportion of total pollutant emitted for nine untreated fuel beds.

When plume temperatures were the highest, the 3 and 6 gal/100 ft^2 treatments showed a general increase in both alkanes and alkenes. All DAP treatment levels showed an increase in alkenes, but not alkanes, at the time of maximum hydrocarbon evolution. The increase in isoprene with increasing DAP was the most pronounced trend we found. The overall differences in composition between treatment levels were rather slight in comparison with the differences between treated and untreated fuel beds. We, therefore, used the average of all three treatment levels for comparing treated with untreated fuel beds (Table III).

When stack temperatures peaked, the untreated fuel beds produced a greater proportion of the identified hydrocarbons. However, when the HC analyzer peaked, the treated beds produced greater proportions of olefins, and compounds other than ethylene constituted half of this increase. During final smoldering, the treated fuel beds produced greater proportions of the three classes of hydrocarbons; but only two samples were taken during this phase, and the differences may not be typical.

Our data indicate that the smoldering phase of fire activity is extremely important to the pollution potential of a fire. The contribution of hydrocarbons released from the last 3% (by weight) of fuel burned was as great as from the first 80% of fuel burned at high fire intensity (Figure 2). DAP appears to decrease the relative proportion of unidentified gases during this stage. Smoke from smoldering wildfires and prescribed burns often drifts near the ground and may reach populated areas. Compositional changes caused by DAP could be important in such instances.

Discussion

Previous measurements of emissions from burning logging slash have made no attempt to approach actual field conditions. The most similar tests are from the burning of landscape residue at the Riverside installation.[3] Our experiment used fuel beds similar in fuel loading and geometry to logging slash areas. Table IV shows that our emission factors for particulates and hydrocarbons from the experiment are somewhat lower than those used by EPA.[6] Our data also show distinct differences in pollutant emissions between DAP treated and untreated fuel beds.

Emission factors for wildfires and prescribed burning lump all carbon-containing gases into the single category of "hydrocarbons." Of greater importance, however, is the composition of this material. Our data show that the olefins with up to five carbon atoms (other than ethylene) constitute a minor fraction of the emission factor for HC. Ethylene, although present in amounts up to 20%, is less impor-

Table II. Gas-chromatographic analysis of hydrocarbon gases collected at various times during burning (%).

	Control 2			Control 5		3 gal/100 ft^2 retardant			6 gal/100 ft^2 retardant		12 gal/100 ft^2 retardant	
	Max. temp.	Max. HC[a]	Smolder phase	Max. temp.	Max. HC[a]	Max. temp.	Max. HC[a]	Smolder phase	Max. temp.	Max. HC[a]	Max. temp.	Max. HC[a]
					(all units are ppm)							
Total HC[a] by HFID analyzer	55	130	75	52	90	130	420	97	250	350	100	240
Methane	25.63	8.40	14.57	18.63	18.01	13.01	12.41	30.51	11.56	10.87	11.18	12.92
Ethane	1.41	1.01	1.64	13.19	10.24	8.40	1.79	3.38	0.64	6.72	7.35	5.80
Propane	0.02	0.36	0.45	0.15	0.23	0.14	0.34	0.84	0.26	0.38	0.26	0.61
n-Butane	0.12	0.05	0.09	0.13	0.12	0.08	0.10	0.21	0.08	0.10	0.18	0.50
iso-Butane	0.16	0.06	0.04	0.05	0.06	0.02	0.02	0.06	0.02	0.01	0.03	0.05
n-Pentane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
iso-Pentane	0.00	0.03	0.06	0.09	0.05	0.12	0.05	0.11	0.02	0.01	0.05	0.04
n-Hexane	0.00	0.00	0.00	0.00	0.00	0.13	0.08	0.00	0.00	0.00	0.00	0.00
Ethylene	15.28	9.89	1.05	11.44	19.98	11.60	14.81	6.38	11.93	13.42	9.52	13.22
Propylene	2.45	2.00	0.89	1.82	2.75	2.21	3.90	2.74	3.67	3.84	1.87	4.38
1-Butene	0.38	0.29	0.22	0.25	0.42	0.29	0.70	0.56	0.47	0.69	0.30	0.85
t-*2*-Butene	0.00	0.03	0.06	0.09	0.00	0.03	0.13	0.15	0.08	0.12	0.05	0.16
c-*2*-Butene	0.00	0.00	0.00	0.06	0.00	0.13	0.12	0.11	0.06	0.08	0.06	0.11
2-Methyl-butene-*1*	0.00	0.00	0.00	0.00	0.00	0.08	0.07	0.11	0.08	0.09	0.00	0.17
3-Methyl-butene-*1*	0.00	0.00	0.09	0.13	0.07	0.10	0.14	0.13	0.08	0.11	0.07	0.16
2-Methyl-butene	0.00	0.00	0.00	0.00	0.00	0.11	0.13	0.00	0.06	0.08	0.00	0.12
1,3-Butadiene	0.98	0.65	0.20	0.28	0.60	0.88	1.42	0.55	1.01	1.58	0.46	1.63
iso-Butene	0.47	0.36	0.12	0.32	0.48	0.40	0.73	0.40	0.57	0.80	0.35	0.92
1-Pentene	0.00	0.00	0.00	0.17	0.00	0.06	0.19	0.09	0.10	0.12	0.00	0.15
c-*2*-Pentene	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.08	0.00	0.05
t-*2*-Pentene	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.09	0.09	0.00	0.18
Acetylene	17.23	7.29	0.20	12.76	9.47	8.38	6.72	1.07	7.11	6.70	7.47	5.72
Methyl-acetylene	0.38	0.24	0.05	0.26	0.27	0.30	0.43	0.11	0.35	0.42	0.32	0.42
Isoprene	0.00	0.17	0.00	0.00	0.00	0.71	0.83	0.48	0.65	1.32	0.00	1.64

[a] HC—hydrocarbon reading.

Table [illegible]. Average % of total gaseous hydrocarbon emissions represented by various classes of compounds in grab samples taken at three stages of burning.

Compound or class	Peak stack temp.		Peak HC conc.[a]		End of fire	
	Untreated	Treated	Untreated	Treated	Untreated	Treated
Methane	22.23	11.87	12.33	12.00	14.57	30.51
Saturates other than methane	7.49	4.58	5.27	5.15	2.28	4.60
Total saturates	29.72	16.45	17.60	17.15	16.85	35.11
Ethylene	13.42	11.34	14.02	13.95	1.05	6.38
Olefins other than ethylene	3.71	5.62	3.84	9.16	1.58	5.32
Total olefins	17.13	16.95	17.85	23.11	2.63	11.70
Acetylene	15.07	7.33	8.18	6.48	0.20	1.07
Alkynes other than acetylene	0.31	0.53	0.26	0.42	0.05	0.11
Total alkynes	15.38	7.86	8.44	6.90	0.25	1.18
Total identified	62.24	41.26	43.89	47.16	19.73	47.99

Stage of Burning

[a]HC—total hydrocarbons.

Table IV. Comparison of emission factors derived in this study with those from Gerstle and Kemnitz[3] and the EPA.[6]

	This study	Gerstle and Kemnitz	EPA
(lb of emission/ton of initial fuel bed weight)			
Particulates	9 ± 1	17	17
Hydrocarbons	8 ± 2	30	20
Carbon monoxide	146 ± 10	65	60

tant as a component of photochemical reactions than 4-carbon olefins. However, ethylene will cause direct injury to vegetation and is an important air pollutant in that respect. Thus, while the application of DAP to woody fuel increases the proportion of non-ethylene olefins, this increase seems unimportant.

The composition of HC gases in the fraction not analyzed in our study is important to the air pollution potential from wildfire and prescribed burning. We would expect this uncharacterized fraction to contain organic acids, aldehydes, ketones, phenols, and heterocyclic compounds such as the furans. Knowledge of the effects of flame retardants on the production of these compounds is incomplete, but the size of this fraction suggested by our results should warrant further study.

The 24 gases identified by gas chromatography represent one-half or less of the total amount of carbon-containing gases detected by the HC analyzer. This flame ionization detector should respond linearly to increasing homologs of methane. However, the response is nonlinear with respect to unsaturation, branching, and oxygen-containing molecules. Thus, the amount of material unidentified during g.c. analysis is only an indication of the amounts of the unidentified gases in the stack effluent.

Conclusions

The use of DAP to reduce the pollution potential was largely disappointing. This retardant increased all pollutants, especially the particulate fraction, even though less fuel actually burned in treated fuel beds.

The main objective of slash burning is to eliminate the fine fuels that constitute a risk of wildfire. Our results show not only that this objective is met prior to the smoldering fire phase, but that most of the gaseous emissions occur during the latter phase. Fire management techniques that encourage maximum plume development ignore the contribution from the long smoldering phase. Large amounts of gaseous pollutants are released after the plume has disintegrated, and these emissions may find their way into urban areas via surface winds. Methods of burning which increase the proportion of high intensity burning or the rapid extinguishment of slash fires after burning the fine fuels should result in a pronounced decrease in amounts of gaseous pollutants.

The fuels in this experiment were free of living herbaceous vegetation, moist duff material, and soil that is always incorporated in real fuel beds. The fuels were cured in desert sun and approached the lower fuel moistures that would naturally occur in logging residue. For these reasons, the emission factors which we report are suggested as lower limits of what might reasonably be expected from broadcast slash burning.

Emission factors based on initial fuel weight do not fully describe the pollution potential from forest burning. Fire intensities vary widely during the burning period and are associated with corresponding changes in the composition and quantity of emissions. Varying proportions of the initial fuel weight are consumed, depending on wind, fuel moisture, fuel size and arrangement, etc. Hydrocarbons and carbon monoxide emissions are much more important during the die-down and smoldering burning periods than a simple emission factor may suggest. Therefore, further refinements to emission factors, per se, will add little to our knowledge of air pollution from slash burning. But better knowledge of the changes in emission rates during burning, as well as of various types and conditions of fuels, will result in a more rational basis for control regulations, if needed, and may also suggest practical ways to minimize air pollution from slash burning.

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Dr. Sandberg is professor of forestry, Colorado State University at Fort Collins, CO. Dr. Pickford is research forester, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Seattle, WA. Dr. Darley is plant pathologist, Statewide Air Pollution Research Center, University of California at Riverside, CA. This work was financed in part by Grants #800711 (formerly AP-00829) and #AP-01137-01 from EPA.