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EMISSIONS FROM BURNING GRASS STUBBLE AND STRAW*

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Approximately a quarter of a million acres of grass land is burned in the Willamette Valley of Oregon during the period of late July to early September. The reasons for burning the fields are based on economic considerations which have been often stated(1). The air pollution burden from field burning is imposed upon all the residents of the valley, whether they be permanent, transient, or tourist.

It has been estimated that an average grass fire extending over one acre produces about 2×10^{22} fine particles (2). A recent study (3) showed that both suspended particulate and soiling index increased significantly during the field burning season in the Willamette Valley.

To obtain the data necessary to compile an accurate emission inventory for field burning it was first necessary to sample the source of pollution to determine the qualitative and quantitative emissions from different grass species under various burning conditions. This work was started during the summer of 1965 and the preliminary studies were reported to the Air Pollution Control Association(4).

The original field work pointed out some areas of weakness which needed to be strengthened before meaningful data could be obtained. For instance, in the original study, no carbon dioxide readings were made at the sampling heads used for particulate collection, so no value could be obtained of how much dilution air passed through the particulate sampling filter. Also, it was decided that gas samples were desirable in order to determine the amount of pollutant gases such as hydrocarbons, oxides of nitrogen, and carbon monoxide emitted during the burns.

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Emissions from Burning Grass Stubble and Straw

The emissions from burning the residue following grass-seed harvest were determined by means of a combined laboratory-field study. Samples of the straw and stubble residue were burned in the laboratory burning tower at the University of California at Riverside. Complete analyses were determined for gaseous and particulate emissions for the important grass species from the Willamette Valley of Oregon. Particulate emissions averaged 15.6 lb/ton of fuel burned. Carbon monoxide averaged 101 lb/ton of fuel burned. Hydrocarbon emission averages, in pounds per ton of fuel burned, were 1.74 for saturates plus acetylene, 2.80 for olefines, and 1.68 for ethylene. The NO_2 emission, at the temperature peak during the burn, averaged 29.3 ppm. Field studies, conducted by personnel from Oregon State University, measured only particulate emissions, carbon dioxide, and temperature over the burn. The carbon dioxide values were found to be similar to those obtained on the burning table at UCR and it was therefore concluded that the other gaseous emissions were similar and could be used as reasonably accurate for emission inventories. The temperature values obtained in the laboratory and field were also similar and further justifies extrapolating the burning table data to field situations. The particulate matter collected in the field studies averaged 15.55 lb of particulate per ton of fuel burned. This is the same average obtained for the burning table data which again serves to validate the emissions reported from Riverside. Much more variability was found in the particulate emissions obtained in the field which reflects the wider range of environmental conditions encountered in the field.

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University of California Burning Tower Studies

Because the sampling for gases in the field would be a very extensive and expensive procedure, an alternative method was utilized. Two lots of six species of grasses were harvested and sent to the University of California at Riverside where they were burned in a tower following procedures which have been described recently.[5] The gas samples included total hydrocarbon, CO_2, CO, and nitrogen oxides expressed as NO_2. Twenty-four individual hydrocarbons were analyzed from grab samples taken at specified intervals during each fire. In addition, particulate emissions for the visible smoke period were calculated from the weight of the material deposited on the filter in the gas sample line.

Two replicates of each lot of the six species were burned, making a total of 24 fires. The two lots of grasses differed in their moisture content. The first was relatively dry (less than 15%, dry weight basis) and the second was wetter (up to 71%) by virtue of a mixture of green regrowth and old dead stems and leaves which had been on the ground at time of collection. Since some of the grasses were difficult to burn because of the high moisture content, one or both replicates of the other (Blue, Annual Rye, Orchard) were allowed to dry somewhat before burning.

The results are given in Table I. The yield of particulates from burning the dry grasses varied from about 10 to 17 pounds per ton of material burned. There was a tendency for more particulate matter to be emitted with increase in moisture content of the grass. The average yield of all fires was 15.6 lb per ton of grass burned.

The yield of CO varied from 56 to 147 lb per ton of grass burned, the average for all fires being 101 lb. These values are only a little higher than those reported for rice and barley straw.[5] Annual rye was lower than other grasses in both the dry and dry-green series.

Table I. Yields of various pollutants from grasses collected in the Willamette Valley, Oregon, and burned in the tower at the University of California, Riverside.

Grass	% Moisture	Pounds/Ton of Grass Burned: Particulate	CO_2	CO	C	Sat.[a] + Acet.	Olefins	Ethylene	C Bal. %	NO_2 at Temp Peak, ppm
Dry Series										
Blue	5	16.5	2786	147	18	3.3	3.1	2.4	107	72
Per. Rye	6	12.0	2483	104	14	2.1	3.2	1.4	100	49
Bent	2	14.0	2557	124	14	2.1	2.0	0.9	98	21
Ann. Rye	9	10.5	2666	85	8	0.9	1.2	0.6	103	23
Fescue	9	13.0	2737	122	12	2.5	2.4	1.2	107	45
Orchard	15	11.5	2469	89	7	1.2	1.2	0.7	100	27
Dry-Green Series										
Blue	23	15.0	2407	95	8	1.0	2.0	1.2	111	44
Per. Rye	71	26.0	678	106	19	2.4	5.6	3.4	77	4
Bent	60	24.0	1277	109	19	2.1	5.0	3.1	94	13
Ann. Rye										
1	20	9.0	1855	56	4	0.4	1.0	0.6	103	37
2	55	11.0	969	60	6	0.8	2.4	1.8	102	..
Fescue	66	17.0	925	77	9	1.2	2.6	1.8	94	8
Orchard										
1	66	18.0	645	86	14	1.4	3.3	2.1	87	12
2	47	17.0	1558	113	16	1.7	4.0	2.3	90	5

[a] Without methane.

Hydrocarbons, expressed as total carbon, varied from 4 to 19 lb per ton, and here again annual rye tended to yield the lower amounts in both series. The average of all fires was 12.3 lb per ton of grass burned and is very comparable to earlier results from barley straw. Out of the 24 individual hydrocarbons the total olefins and ethylene alone averaged 2.80 and 1.68 lb per ton, respectively. These again are quite comparable to earlier results with grass straws.

Analyses for oxides of nitrogen expressed as NO_2 were made for all but one fire. Samples were taken at the temperature peak, since earlier work with woody fuels had demonstrated that the maximum NO_2 yield occurred at this point. Concentration varied from 21 to 72 ppm in the dry series and from 4 to 44 ppm in the dry-green series. The tendency was for wetter fuels to produce less NO_2.

In this set of fires, the carbon balance was calculated between the amount of carbon in the fuels and that accounted for in the various analyses. Microanalyses of each grass yielded a carbon content which ranged from 42 to 45%. Similar analyses were also made of the ashes. In the dry-green series, not all of the straw burned, and this residue was taken into account. Although not analyzed, it was assumed that all of the particulate matter deposited on the filter was carbon. Carbon recovery in the dry series ranged from 98 to 107% and that of the dry-green series from 77 to 111%. The lower percent recoveries were usually obtained from those fires wherein the CO_2 yields were less than 1000 pounds per ton of fuel burned. The over-all carbon balance mean and its standard deviation was 99 ± 10%.

Oregon State University Field Studies

The sampling apparatus used in previous field studies had proved to be satisfactory and only minor modifications were necessary. The particulate sampler was a Gelman Hurricane with an 8 in. by 10 in. filter holder. It was modified so that a 1 inch membrane filter of 0.8 micron pore size was operated in parallel with the larger filter. The membrane filter effectively collected a sample of all the smoke which was analyzed microscopically for the size determination. The 8 × 10 in. filter, of glass fiber, was used to obtain a sample of the smoke for gravimetric analysis.

A 3-kw gasoline powered light plant served as the power source for the particulate sampler. Power was carried from the generator to the sampler by overhead wires supported above the flames. The sample tower, supports, and generator are shown in Figure 1.

Temperature readings were taken at 1 in. below the ground surface, 6 in. above the ground surface at the top of the stubble, and at the particulate sampling head which was located approximately 15 ft above the ground. Chromel-alumel thermocouples were placed at the desired location and routed up the tower to a connector at the top.

In order to use the data from the burning tower, and properly correlate it with the data from actual field burns, it was necessary to analyze for a common pollutant from both burns. Continuous CO_2 measurements were made on both the tower and field burns so this became the common denominator for the correlation studies. By adjusting the field and laboratory data to common CO_2 values, the other emissions could be estimated for the field burns.

The CO_2 sampling system was constructed which consisted of a gas pickup at the top of the tower, connecting copper tubing to the sampling vehicle, and the nondispersive infrared instrument mounted in the vehicle. Calibration and zeroing gases for the IR instrument were mounted in the vehicle along with the necessary valves and gages.

The actual burning of the fields was done by personnel from the School of Agriculture so the test crew was only concerned with sampling the effluent. Fields burned were square, one acre in size. Before each burn, the sampling tower was placed toward the downwind edge of the field to be burned and the leads were connected. The particulate sampler was turned on long enough to obtain a flow reading through the filter. The CO_2 instrument was adjusted with the zero and full scale calibration gases. All temperature measuring instruments were set for ambient conditions. As the field was fired, all recording instruments were turned on. The flame front advanced toward the sampling tower and when the CO_2 recorder indicated 0.1%, the particulate sampler at the top of the tower was turned on. After the flame front had passed the tower, and the CO_2 reading decreased to 0.1%, the particulate sampler was turned off. When the field had cooled sufficiently for personnel to get to the tower, the particulate sampler was turned on long enough to obtain a final flow reading through the filter. Flow rates were taken as the average between initial and final flow readings. The filters and chart recordings were removed and sent to the laboratory for analysis and evaluation.

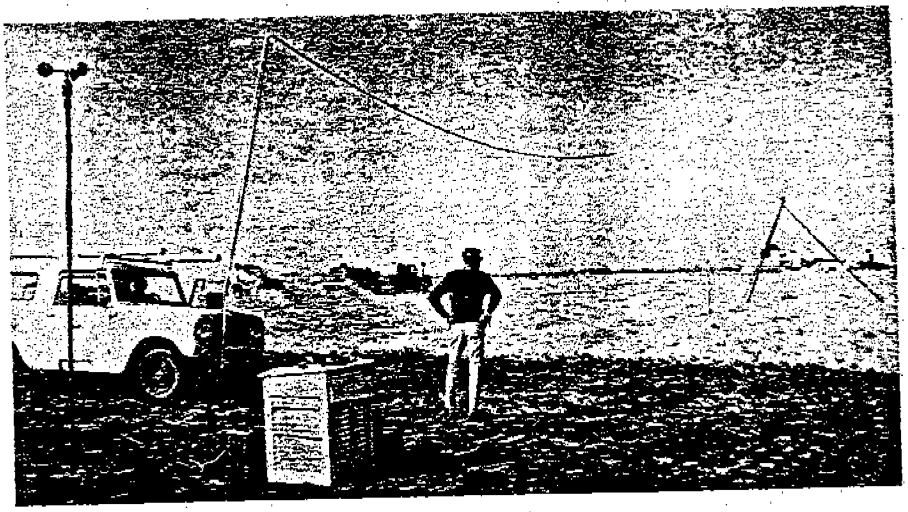

Figure 1. Sampling system for field studies.

Table II. Regression of CO_2, %, on temperature, °F, for Riverside Burning Tower data.

Grass	Correlation Coefficient, "r"	Mean Temp, °F	Mean CO_2, %	Constant, at Temp = zero	Slope of Regression	Standard Error of Slope
Blue	0.964	177.0	0.797	−0.369	0.00660	0.00034
Perenn. Rye	0.993	141.0	0.597	−0.404	0.00711	0.00016
Bent	0.943	146.0	0.490	−0.380	0.00595	0.00040
Annual Rye	0.993	122.0	0.447	−0.358	0.00660	0.00015
Fescue	0.964	146.0	0.620	−0.319	0.00646	0.00034
Orchard	0.989	115.0	0.311	−0.525	0.00724	0.00022
Combined	0.968	141.0	0.547	−0.386	0.00659	0.00013

Table III. Regression of CO, %, on temperature, °F, for Riverside Burning Tower data.

Grass	Correlation Coefficient, "r"	Constant, at Temp = zero	Slope of Regression
Blue	0.776	0.0124	0.000417
Perenn. Rye	0.750	−0.0003	0.000059
Bent	0.784	0.0046	0.000293
Annual Rye	0.786	0.0063	0.000233
Fescue	0.893	−0.0099	0.000432
Orchard	0.900	−0.0211	0.000386
Combined	0.802	−0.0054	0.000387

Table IV. Regression of unburned hydrocarbon, ppm, on temperature, °F, for Riverside Burning Tower data.

Grass	Correlation Coefficient, "r"	Constant, at Temp = zero	Slope of Regression
Blue	0.879	−2.821	0.186
Perenn. Rye	0.942	−3.032	0.144
Bent	0.764	0.196	0.081
Annual Rye	0.811	0.638	0.044
Fescue	0.955	−2.337	0.094
Orchard	0.948	−5.121	0.084
Combined	0.787	−3.962	0.125

Table V. Regression of CO_2, %, on temperature, °F, for field data.

Burn No.	Grass	Correlation Coefficient, "r"	Mean Temp, °F	Mean CO_2 %	Constant, at Temp = zero	Slope of Regression	Standard Error of Slope
9	Perennial Rye	0.817	252.0	0.580	−0.023	0.00240	0.00041
10	Perennial Rye	0.932	245.0	0.565	−0.244	0.00330	0.00026
9 & 10	Perennial Rye	0.878	248.0	0.572	−0.140	0.00287	0.00024
12	Annual Rye	0.783	217.0	0.443	−0.205	0.00299	0.00044
All	Combined	0.857	235.0	0.519	−0.164	0.00290	0.00020

Regression Analysis of Riverside Burning Tower Data

The data from the Riverside burning tower were analyzed to determine the extent of the correlation between the emissions. For the significant correlations, the regression equations were then determined to permit prediction of the unmeasured variables from the field studies. The results of the linear regression of CO_2 on temperature are shown in Table II. The carbon monoxide and the unburned hydrocarbon were also found to be correlated with the temperature of the effluent from the Riverside tower as indicated in Tables III and IV. For the burning tower at Riverside, therefore, reasonably valid predictions of CO_2, CO, and unburned hydrocarbon could be made if the temperature of the effluent were the only variable measured.

Regression Analysis of Field Data

On the runs where both the CO_2 and temperature were recorded, a linear regression of CO_2 on temperature was made to see if it would be valid to predict the CO_2 from the temperature data if a direct measurement were not available. Such was the case in the early field burns where the CO_2 was not measured because the instrumentation was delayed in shipment from the factory. Data were available for the runs 9, 10, and 12 where CO_2 and temperature were measured simultaneously. The results of the linear regression are shown in Table V.

Table VI. Results of summer 1967 field burns of various grasses.

Burn No.	Grass	# Particulate / Ton Fuel	# CO / Ton Fuel	# HC / Ton Fuel	Ambient Temp., °F	R.H. %	Wind Speed, mph
2	Blue	81.23	238	14.75	89.8	32	9
3	Orchard	15.54	130	10.78	71.5	50	6
4	Orchard	8.47	140	11.18	90.2	24	6
5	Perennial Rye	10.23	133	10.68	70.5	61	3
6	Red Fescue	1.31	102	9.14	79.8	64	11
7	Red Fescue	12.65	120	9.90	88.0	34	0
9	Perennial Rye	8.78	118	9.41	80.0	51	2
10	Perennial Rye	8.75	107	9.41	80.0	62	1
11	Red Fescue	5.24	126	10.02	84.0	64	12
12	Annual Rye	3.33	108	10.27	100.0	24	9

Combination of Field and Tower Data

Both the data from the Riverside burning tower and the fields show highly significant correlations between the CO_2 emission and the temperature indication. The regression lines are not the same, however. This was because the temperatures were not measured in a similar manner in each case. In the Riverside tower study, the hot gasses all passed the thermocouple as they escaped. The thermocouple was located about 24 ft above the burning fuel pile so conduction and radiation of heat from the hot gasses to the tower shell resulted in considerable cooling before the hot gasses reached the thermocouple. In the field study, the temperature was measured by a thermocouple about 15 ft above the fuel bed, the hot gasses were stratified because of dilution and turbulence in the plume, and the thermocouple was sensitive to radiant energy from the entire burning field.

The CO_2 data for both the tower and field burns was compatible, however, because the amount of CO_2 is a valid indicator of combustion. Complete burning of a given amount of fuel releases the same amount of CO_2 whether the fuel is burned in the tower or in the field. The CO_2 was therefore used as the common variable to relate the field data to the tower data. The following procedure was used: (1) The temperature indicated by the field thermocouple was used to estimate the % of CO_2 from the linear regression. If the field CO_2 was measured, as was done in the later field tests, this measured value was used and this first step was eliminated, (2) the CO_2 for the field was the same as it would have been for a similar fuel consumption on the tower so the same value was reported for the tower CO_2, (3) knowing the tower CO_2, the tower temperature could be estimated from the linear regression line, and (4) the CO and unburned hydrocarbon were estimated from the linear regressions of these terms versus temperature.

Although not as many field fires were analyzed as originally was planned, enough were sampled to validate the procedure and give reasonable estimating figures to be used for emission inventories. The measured and calculated variables from ten field fires adequately sampled during the summer of 1967 are reported in Table VI. Some fires are not reported due to loss of instrumentation or other circumstances resulting in incomplete information.

No statistically significant correlations were found between the environmental variables of ambient temperature, relative humidity, and wind speed and the measured variables or calculated emission variables. The highest value of emissions was found for the first fire, No. 2 in Blue grass. This was a smoldering fire during which the maximum temperature at the tower thermocouple only reached 200°F. During all the other fires, a maximum temperature of at least 450°F was recorded.

The average values for the emission variables from the field fires were:

	Pounds per ton of Fuel
Particulate matter	15.55
Carbon monoxide	132.2
Unburned hydrocarbon	10.55

The emission data followed a log-normal distribution about their respective mean values. These values are comparable to those obtained from the burning tower fires which had average values:

	Pounds per ton of Fuel
Particulate matter	15.6
Carbon monoxide	101.3
Unburned hydrocarbon	12.3

Conclusions

The emission values reported in this study will enable more accurate emission inventories and air pollution forecasts to be made in areas where grass burning is practiced. The fact that the emission values reported are somewhat lower than those used in previous studies does not lessen the magnitude of the problems associated with field burning. The visibility reduction, soiling, and nuisance problems are just as severe to those downwind from the burn whether the particulate emitted is 22 lb per ton of fuel or 16 lb per ton. The problems are the direct result of the burn itself, not some value reported in a paper.

The instrumentation developed and reported upon for this study will be used extensively in future burns. As larger numbers of burns are sampled, the variability due to error will be decreased and significant factors effecting the emission quantities will, hopefully, be determined. For the field burns in this projected set of experiments it will not be necessary to compare actual gas volumes generated by the flames but will be only necessary to compare the ratios of pollutant concentration, i.e., CO_2 to particulates, CO to HC, CO_2 to CO, etc., with the same ratios observed in the Riverside tower fires. If a reasonable agreement is indicated this would serve as proof that the Riverside tower data are truly representative of field burning and could be confidently used to predict the tons of effluent generated by the field burns.

Acknowledgments

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