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ORGANIC AND ELEMENTAL PROFILES FOR SMOKE FROM PRESCRIBED FIRES

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Emissions from prescribed fires in several different fuel types in the Pacific Northwest have been characterized. The characteristics of the particles less than 2.5 micrometers in diameter are reported as functions of fire behavior and fuel types. Profiles of trace elements and carbon for each fuel type and combustion phase are used to ratio composite profiles dependent on the level of burning activity, on a seasonal basis, by fuel type. Examples of stylized profiles are presented that may improve source apportionment of smoke from prescribed fires at receptor sites.

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The protection of air quality in class I areas (primarily Wilderness Areas and national parks) was mandated by Congress to be the responsibility of Federal land managers. Smoke from prescribed fires has been indicated as the major contributor to degradation of visibility in the Pacific Northwest. All sources that impact regional air quality need to be assessed, and the USDA Forest Service has principal responsibility to protect air resources in Wilderness Areas as well as other lands administered by the Agency. In the Pacific Northwest, State agencies have provided assistance through the use of receptor modeling--chemical mass balance (CMB) techniques--to determine those sources impacting air quality. One of the problems in using CMB is the need to have representative profiles for the sources. Because of the potential error associated with a large source-profile variance, concern exists over the accuracy of the results of the source apportionment.

The USDA Forest Service is assisting State agencies in developing representative source profiles for materials in smoke from prescribed fires. Chemical mass balance methods are being used that primarily examine the trace elements, organic carbon, and elemental carbon content of the fine particle mass. Planned improvements in regional source apportionment will increase the number of materials used in source profiles by including profiles of polynuclear organic material (POM) fraction.[1]

This paper discusses the variances associated with source profiles for the trace elements and other trace materials found in the POM fraction of the particulate matter. Sufficient differences may exist between organic compound profiles for slash burning, diesel engine emissions, and residential wood combustion to allow their distinction using CMB.

Background

Some of the variability in emissions production from prescribed fires can be explained by fire and fuel parameters. Emissions from open fires are an especially complex mixture of compounds. Many of the compounds are in both a gaseous and liquid phase because the vapor pressures of these materials are near ambient temperatures. The variability in the kinds of compounds produced from prescribed fires

results from several factors:

1. Forest managers use fire under many fuel and weather conditions.

2. The fuel burned is a complex mixture of sizes of material, stages of decay, and parts of the plant (e.g., needles, wood, bark).

3. The ash content of the wood and other materials ranges over at least one order of magnitude.

4. The cycle of the fire from ignition to extinction is a high-intensity, flaming combustion period followed by a residual, low-intensity combustion period typified by smoldering (glowing) combustion. Emissions are poorly mixed from these separate processes and often enter different altitude strata of the atmosphere because of the extremely different rates of heat release.

These factors affect the rate of heat release and combustion efficiency of the fire--which further affects the mix of combustion products.

Receptor Models

Receptor models in the Pacific Northwest use chemical and physical properties of airborne pollutants to apportion the natural and anthropogenic sources contributing to particulate matter concentrations at air-quality monitoring sites. Receptor models have proven to be a valuable tool for source apportionment locally where few complex sources exist and the major sources have well-defined emissions profiles. Examples include the isolation of residential wood combustion as a major contributor to air-quality degradation in Medford and Beaverton, Oregon, and most recently around Olympia, Washington.[2] Recent attempts have been made to use receptor modeling techniques on a larger scale to model the contribution of major sources to regional air quality degradation.[3]

The apportionment process requires identifying several characteristics of the particulate matter-- at least as many characteristics as sources of pollutants. Apportionment is simpler if a characteristic is unique to a given source. Generally, although the

characteristics are common to a number of sources, they are produced in different proportions by each source. These unique profiles are used to apportion the mass of each of the components between the sources containing those components through a least-square multiple-fitting procedure. Source types of similar chemistry cannot be distinguished. If air-parcel trajectories and the activity of the sources in question are known, though, reasonably accurate estimates of source contributions are claimed.[3]

To accurately apportion a source, the profile used must accurately represent the particulate matter which impacted the receptor site--this is a difficult profile to obtain when the source has highly variable emissions.[2] This paper focuses on the variances associated with the production of key emissions used in the apportionment of smoke from slash burning at receptor sites. POM profiles are examined for their variances of production with the idea that they will be used in the CMB models to improve their accuracy. New insight is emerging on the variances of trace-emissions production associated with fuel-type differences and differences in fire behavior. This paper is a review of progress on defining the variation of a single source type, vegetative burning.

Combustion Principles

Processes affecting combustion efficiency are largely responsible for the diversity of combustion products from open fires. Various fuel- and weather-related variables dominate in controlling combustion efficiency; for example, the moisture content of forest fuel limits the heat available for pyrolyzing the solid fuel. The fuel moisture may limit the rate of fuel consumption. A result of burning high-moisture-content fuels is an increase in carbon monoxide and associated higher molecular-weight hydrocarbon species.

Fire intensity, or the rate of energy release per unit area, is related to the degree of turbulence in the combustion zone and is closely coupled to the maximum temperature in the flame envelope. This turbulence increases the entrainment of ash and likely contributes to the breakup of the ash material into particulate matter. By percentage, the greatest abundance of large particles results from the most intense fires. Mounting evidence suggests that emission factors for fine particles are lower for high-intensity prescribed fires.[4] For high-intensity fires, the organic carbon fraction of the particles is more

completely consumed thereby leaving a higher percentage of elemental carbon.

Scope and Objectives

Data discussed in this paper are for broadcast burns of logging slash from coniferous species which include tests of broadcast burns of the logging slash of Douglas fir/western hemlock (short-needled conifer) and of ponderosa pine (long-needled conifer). Broadcast burns of logging slash of hardwood species was also examined. Additional tests were conducted where the logging residues were piled by tractors and also where the piles were constructed by crane (with no fine fuel component). For one set of tests, samples were taken from a line of fires burning in chaparral fuels in southern California.

The objectives for the research included a need to identify emission factors for criteria emissions and emission factors for trace materials.[4] The trace materials included trace elements of atomic numbers greater than 13, anions, selected trace gases, organic and elemental carbon, and POM compounds.

Procedures

The samples were collected from 1984 to 1987 by a special sampling system that supports sample packages in the convection column above slash fires of near full-scale size (Figure 1). The packages were designed to take simultaneous samples of particulate matter and gases from the same space and to measure the temperature and vertical velocity of the gases at that location. The sampling procedures were designed to obtain separate samples of emissions for the flaming and smoldering combustion phases. Concurrent with particulate matter sampling, grab samples of the gases were collected at a constant-volume-flow rate in aluminized mylar bags and later transferred to stainless steel cylinders for trace gas analyses. The gases and particulate matter were sampled for discrete time periods ranging from 10 minutes for the flaming phase (20 meters above the fuel) to 180 minutes for the smoldering phase (10 meters above the fuel). Measurements were made of both the rate of production of the emissions and the rate of fuel consumption over the life cycle of the fire--ignition, flaming, smoldering, and extinction. The carbon-mass balance procedure

was used to assess the mass of fuel consumed in producing the emissions measured. Also, because gaseous and particulate matter samples were collected simultaneously, an assessment of the content of selected trace elements could be made of both the gaseous and particulate matter samples. The procedures for computing emission factors and source strength have been described previously.[5,6]

The particulate matter samples were stratified into total particulate matter (PM) and particulate matter with particle diameters of less than 2.5 μm mean mass diameter (PM2.5). The PM samples were collected with open-faced filters, and the PM2.5 filter holders used a cyclone presampler to provide the size separation. The filter mediums were arranged systematically in the same matrix for collecting samples of particulate matter for each of the two combustion phases (See Table I). The type of filter, size of filter, rate of flow of sample gas, and type of analysis making up the matrix are listed in Table I.

Because about 0.5 gram of PM is required to profile the compounds of the POM fraction, lightly loaded filters (8 by 10 inch, glass fiber) from matching fuel types and fire phases were combined. This reduced the number of tests from 5 to 3. The POM was removed from the PM through extraction by using dichloromethane. Classes of compounds were further separated by dividing the POM into polarity classes. The specific compounds were determined through gas chromatography. These procedures are outlined in more detail by White et al.[7]

The rate of fuel consumption was measured by the carbon-flux method. This method also allowed measurement of the flux of emissions; thus, the production of trace materials was weighted by the mass of particulate matter produced by each phase of combustion.

Statistical methods applied to the data included calculating the coefficient of variation--the standard deviation of the sample population divided by the mean for the sample. The coefficient of variation is an important statistic incorporating not only the sampling and analytical error but also the range of the variable resulting from the response of the variable to other influences.

Results

The results of this research are divided into a discussion of the

variances associated with the trace element content of the PM2.5 and a discussion of how this variability is handled in developing source profiles for open burning of wildland fuels that can be used for source apportionment through receptor modeling techniques.

Variances of Trace Element and Carbon Content of PM2.5.

Trace Element Content of PM2.5. The trace elements for samples of PM2.5 for the six different fuel types are shown by combustion phase in Table II. The coefficients of variation are presented in Table III. The data are for broadcast burns of different species of logging slash (Douglas fir-western hemlock, hardwoods, and ponderosa pine) and for piles of slash (dozer piles including fine fuel and crane piles of large woody fuel). One set of data is for chaparral fuels burned with line fires.

Differences in composition of the PM2.5 are noted between the samples for the flaming and smoldering phases as illustrated for K, Cl, and S in Figure 2. Ward and Hardy found for the conifer fuel type that the sum of the composition of the three elements (K, Cl, and S) was correlated with rate of heat release ($r = 0.92$).[5] Observations made for the larger set of data reported in Table II substantially agree with this earlier finding. For example, measurements of the K content of PM2.5 for the chaparral fuel type of the Angeles National Forest in the Los Angeles basin consisted of nearly 10 percent K, 4.3 percent Cl, and 2.3 percent S for the flaming phase samples. The rate of energy release was in excess of 5 megaWatts per meter of fire front. These levels of K are nearly twice those for the hardwood broadcast burns of western Oregon and western Washington.

The coefficient of variation for the trace materials contained with the PM2.5 (Table III) was generally lowest for K, Cl, and S and ranged higher for Ca, Fe, and Pb (Figure 3). The coefficient of variation was highest for the broadcast burns of hardwood units; it ranged from 100 to 220 percent for the flaming-phase emissions and from 50 to 185 percent for the smoldering-phase emissions. Even though the overall concentration of trace elements was higher for the chaparral fires, the coefficient of variation was consistently lower than for the other fuel types for the series of elements illustrated in Figure 3.

The Pb content for the PM2.5 was highest in the Los Angeles basin

and lowest for the broadcast burns east of the Cascade Range in Washington and Oregon (Figure 4). The effect of rate of heat release observed for other trace elements (K, Cl, and S) may have played a role in the increased concentration of Pb. It is generally conceded, however, that the deposition of materials from the atmosphere in the Los Angeles basin is greater than for most other places on the West Coast.

Carbon Content of PM2.5. The combined organic and elemental carbon content of the PM2.5 makes up about 45 to 70 percent of the PM2.5 (Figure 5). The elemental carbon content varies inversely with the rate of heat release of the fire and is produced in different quantities with different fuel and fire conditions. The resulting coefficients of variation for the individual fuel types and combustion phase conditions are higher for the elemental carbon than for either the organic or total carbon (Figure 6). For the fire conditions associated with the tests for the conifer fuel type, the coefficient of variation for the total carbon is 7 percent and 31 percent for the organic carbon--a reduction in the overall variance. This result is not true for all fuel types tested; e.g., for the chaparral fuel tests the coefficient of variation for total carbon is 13 percent and for organic carbon, 7 percent. The coefficient of variation for total carbon is less than 10 percent for the 5 major fuel types in the Pacific Northwest and less than 14 percent for chaparral. Even for the smoldering combustion conditions, the coefficient of variation is extremely low for all fuel types except for the conifer fuel types.

The low coefficient of variation for the organic and total carbon content of the PM2.5 suggests that low variances may be associated with the production of at least some of the POM compounds.[8] The variances associated with POM compounds were investigated and some of the heavier molecular weight polycyclic aromatic hydrocarbons were found to have coefficients of variation of less than 20 percent.

Development of Profiles for Receptor Modeling

Table II contains the average trace element profiles by fuel type. These data represent a cross section of burning conditions for each fuel type. The coefficient of variation associated with each trace element for each fuel type expresses the relative standard deviation for each condition (Table III). Recognizing the wide range of prescriptions where fire is used to meet forest management objectives, it is not surprising

that the variances associated with the production of emissions is fairly large--the coefficient of variation in Table III is greater than 40 percent for all but the piled-materials tests.

Fuel Type and Season of Burning Considerations. Several different fuel types are sometimes burned simultaneously in the same fire and more often in the same air-shed. The mix of these emissions therefore provides the composite of detail for the profile of trace elements, ions, and carbon needed to effectively apportion the contribution of these sources at a receptor site. Generally, different combinations of materials are burned seasonally and are associated with the meteorology of a given area over time. This results in the required fuel conditions coming into prescription (The combination of moisture content of the fuel, windspeed and direction, relative humidity, and temperature needed to create the right burning conditions to meet the objectives for managing the site.) and in other fuel situations no longer being in prescription. These phenomena result in different average mixes of forest materials being burned on a given day and during a given season of the year.

The effect of fuel types on emissions production and on the characteristics of the emissions profiles is complex. In addition, the fire behavior and quantity of fuel consumed on each unit burned depends on the weather and the season. During spring and early summer, the large-diameter fuels (> 15.24 cm diameter) hold the moisture absorbed during the winter months well into the summer even though the fine fuels (materials < 2.54 cm diameter) respond quickly to the ambient weather conditions. The duff, or partially decayed organic material of the forest floor, also has a large lag in the drying rate. The result is that fuel is unavailable to be consumed by fires early in the summer. These phenomena are being used effectively by forest managers to reduce the total smoke from prescribed burning in the Pacific Northwest.[9] A second consequence of the high moisture content of the duff and heavy fuels is a reduced residence time of the flaming combustion phase and a greatly reduced quantity of fuel consumption during the smoldering combustion phase. The result is large differences in the proportion of fuel consumed during the flaming combustion phase as compared to the smoldering combustion phase and reduced rates of heat release during spring and early summer.

We have factored into the profiles used for receptor modeling these differences in fuel type and consumption through stylizing models of the

typical mix of fuels consumed seasonally along with the fuel consumption ratio by combustion phase (Table IV).

Emission Factor Considerations. Emission factors for the production of PM2.5 by fuel type by phase of combustion are important to estimating the abundance of the trace elements in the atmosphere. Fuel consumption parameters shown in Table V were multiplied by the emission factors used to update the U.S. Environmental Protection Agency Emission Factor Summary (AP-42) (Table VI). An example of the weighting process is illustrated in Table VII for the winter profile, which is 100 percent pile burning of landing piles and tractor-piled slash. Factored into the winter profile is a reduced percentage consumption of the fuels during the flaming combustion phase. This results in a greater percentage of the PM2.5 production occurring during the smoldering phase which also affects the profile.

Regional Profiles. By using the technique outlined in Table VII, regional profiles were developed for the trace elements and carbon for 5 different combinations of fuel consumption by fuel-type conditions. These differences are related closely to seasonal effects although other factors influence the fuel consumption by fuel type variables: i.e., regulations affecting burning, unusual weather patterns, and localized fuel types. The rationale for selecting the specific conditions for the profiles has been discussed previously in this paper. In general, the cases listed in Table V are regional extremes. Other air-shed conditions and local influences could be factored to develop more specific profiles to meet the needs of targeted communities or subregions.

Variation among profiles is illustrated by the bar chart in Figure 7, where the composite profiles are compared with the profile for slash fire smoke used in the regional visibility study known by the acronym PANORAMAS. Major differences exist between the fitting elements S, Cl, and K with minor differences for the soil components Al and Si. The differences result from the mix of fuel types contributing to the emissions profiles.

Figure 8 illustrates the constancy of the organic and elemental carbon between composited profiles listed in Table VIII. Although the variation in the production of elemental carbon, for example, is large; the overall effect averages out across the range of test-fire conditions for each of the individual profiles.

Further differences in the profiles exist and are dependent on the

change in the mix of emissions from flaming and smoldering combustion processes. Some of these differences are seasonally dependent because of normal weather patterns and the effect weather has on drying forest fuels. The PANORAMAS profile was developed from a limited data set that did not include many of the fuel types factored into the regional composite profiles presented in Table VIII and Figure 7. In fact, the PANORAMAS profile represents a composite of the lower intensity fires and partially explains the deviations for K, Cl, and S from the other composite profiles in Figure 7.

Conclusions

A sensitivity analysis is now being performed by using the profiles listed in this paper to determine the relative effects on the apportionment of the prescribed burning sources affecting regional levels of ambient air quality. Other profiles may be needed to reflect changes in burning practices and to reflect local impacts resulting from general gradient wind influences.

Future profiles and receptor modeling techniques are planned that will use a number of organic compound species. There seems to be a good basis for including the organic compound species in the profiles based on the low variance associated with the carbon profiles for the different regional and seasonal profiles.

An approach to developing profiles that integrate seasonal and localized effects has been presented. Whether the differences in the accuracy of the apportionment process will significantly change with improved specificity of the profiles is being tested with the data base developed during the PANORAMAS regional visibility study.

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Table I. The matrix of filters used in collecting the particulate matter by combustion phase for fire tests.

Type of filter	Particle size	Filter size	Sample volume	Analytical procedure(s)
Glass fiber	<2.5 μm	37 mm	2 lpm	Carbon analysis
Glass fiber (PUF-backed)	Total	47 mm	5 lpm	B(a)P analysis using HPLC and UV fluorescence
Glass fiber	Total	47 mm	7 lpm	B(a)P analysis using HPLC and UV fluorescence
Glass fiber	Total	8- X 10-inches	40 cfm	POM profiling using HPLC and GC mass-spec technique
Teflon	<2.5 μm	37 mm	2 lpm	Trace element analysis using X-ray fluorescence

Table II. The average profiles for the Pacific Northwest fuel types by phase of combustion.

Profile	Conifer		Hardwood		P.pine		Tractor-piled		Crane-piled		Chaparral	
	F	S	F	S	F	S	F	S	F	S	F	S
Na	2.734	0.732										
Al	0.120	0.101	0.280	0.181	0.081	0.105	0.181	0.056	0.025	0.013	0.261	0.077
Si	0.091	0.187	0.427	0.336	0.152	0.148	0.348	0.052	0.016	0.013	0.699	0.238
P			0.237	0.093	0.088	0.048	0.128	0.039	0.011	0.007	0.209	0.096
S	0.341	0.114	1.118	0.503	0.558	0.162	0.950	0.228	0.229	0.125	2.297	0.838
Cl	0.556	0.118	2.703	0.468	0.554	0.226	0.921	0.227	0.196	0.107	4.323	1.549
K	1.419	0.126	5.014	0.577	2.103	0.501	3.895	0.606	1.195	0.818	9.896	3.988
Ca	0.182	0.127	0.181	0.183	0.112	0.073	0.619	0.071	0.074	0.077	0.581	0.268
Ti	0.218	0.124	0.019	0.013	0.010	0.005	0.018	0.002	0.001	0.002	0.015	0.010
V	0.069	0.031	0.006	0.004	0.003	0.002	0.007	0.001	0.001	0.000	0.004	0.002
Cr	0.113	0.024	0.018	0.003	0.003	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Mn	0.038	0.020	0.023	0.011	0.018	0.008	0.045	0.005	0.019	0.018	0.010	0.014
Fe	0.057	0.061	0.107	0.062	0.010	0.057	0.030	0.003	0.006	0.007	0.121	0.020
Ni	0.009	0.010	0.024	0.003	0.005	0.002	0.011	0.027	0.000	0.000	0.002	0.001
Cu	0.009	0.010	0.021	0.001	0.000	0.000	0.007	0.000	0.001	0.001	0.003	0.000
Zn	0.118	0.016	0.154	0.014	0.115	0.025	0.389	0.012	0.054	0.012	0.181	0.040
Br	0.048	0.025	0.124	0.019	0.033	0.008	0.146	0.012	0.004	0.002	0.110	0.035
Ag			0.077	0.030	0.028	0.018	0.172	0.008	0.005	0.004	0.097	0.026
Cd			0.169	0.066	0.045	0.014	0.066	0.015	0.001	0.004	0.055	0.015
Sn			0.088	0.043	0.013	0.018	0.196	0.000	0.005	0.000	0.031	0.000
Pb	0.154	0.078	0.211	0.031	0.068	0.019	0.234	0.010	0.007	0.003	0.425	0.082
Carbon												
Organic	36.4	51.9	60.3	61.7	55.1	61.0	49.0	53.1	59.8	60.4	48.0	63.9
Elemental	18.8	3.4	8.3	2.7	10.9	4.1	8.2	2.9	2.3	1.1	9.2	7.8
Total	55.0	55.3	68.6	64.4	66.0	65.1	57.2	56.0	62.1	61.4	57.2	71.7

Table III. The coefficient of variation (CV) for the Pacific Northwest average profiles, by fuel type by phase of combustion (values are expressed in percent).

Profile	Conifer		Hardwood		P.pine		Tractor-piled		Crane-piled		Chaparral	
	F	S	F	S	F	S	F	S	F	S	F	S
Na	134	66										
Al	69	96	155	89	47	66	46	12	35	59	87	
Si	70	118	122	121	54	115	33	47	200	89	54	
P			107	85	39	48	31	19	36	53	27	
S	43	58	109	98	53	68	53	19	15	41	37	
Cl	57	53	117	48	60	74	37	8	13	43	39	
K	57	50	124	98	55	79	59	31	18	41	36	
Ca	127	81	220	188	46	129	23	16	25	24	53	
Ti	101	72	154	103	96	156	95	100	117	55	86	
V	177	80	152	140	95	120	61	65	128	151	124	
Cr	172	66	239	129	178	173			200	88		
Mn	88	87	129	121	46	103	66	53	24	34	64	
Fe	179	123	212	140	75	165	68	173	72	33	59	
Ni	87	55	226	147	106	62	116	167	200	200	42	
Cu	87	55	176	142		173	133		55	68	24	
Zn	80	61	121	130	60	76	57	39	37	36	31	
Br	44	50	84	53	76	57	72	22	67	78	52	
Ag			202	115	63	70	74	128	85	116	85	
Cd			235	174	106	70	158	148	200	87	78	
Sn			196	153	118	80	93		200	155	77	
Pb	63	70	176	133	100	68	86	43	116	74	37	
Carbon												
Organic	31	16	3	4	7	5	11	4	7	4	7	
Elemental	87	23	57	37	51	27	45	49	15	33	52	
Total	7	16	6	5	7	3	9	1	7	5	14	

Table IV. Seasonal profiles for the Pacific Northwest region for flaming (F) and smoldering (S) combustion phases.

Profile Elements	Regional		Spring		Summer		Autumn		Winter	
	F	S	F	S	F	S	F	S	F	S
Na	0.848	0.470	1.177	0.321	0.844	0.399	1.601	0.600	0.000	0.000
Al	0.108	0.104	0.100	0.101	0.205	0.137	0.126	0.105	0.103	0.034
Si	0.154	0.166	0.129	0.152	0.289	0.243	0.147	0.172	0.182	0.032
P	0.056	0.019	0.048	0.026	0.141	0.042	0.047	0.011	0.070	0.023
S	0.519	0.150	0.466	0.141	0.804	0.289	0.488	0.138	0.590	0.176
Cl	0.610	0.167	0.555	0.176	1.741	0.276	0.757	0.149	0.559	0.167
K	2.171	0.273	1.847	0.344	3.559	0.332	2.050	0.198	2.545	0.712
Ca	0.246	0.114	0.162	0.097	0.204	0.152	0.199	0.122	0.346	0.074
Ti	0.074	0.082	0.099	0.057	0.079	0.073	0.132	0.103	0.010	0.002
V	0.024	0.021	0.032	0.014	0.025	0.019	0.042	0.026	0.004	0.001
Cr	0.036	0.016	0.050	0.011	0.045	0.015	0.068	0.020	0.000	0.000
Mn	0.031	0.016	0.027	0.013	0.029	0.016	0.032	0.018	0.032	0.011
Fe	0.031	0.058	0.031	0.057	0.079	0.061	0.048	0.061	0.018	0.005
Ni	0.007	0.007	0.007	0.006	0.017	0.007	0.009	0.008	0.005	0.013
Cu	0.005	0.006	0.004	0.004	0.015	0.006	0.008	0.008	0.004	0.001
Zn	0.167	0.018	0.125	0.020	0.152	0.015	0.138	0.017	0.222	0.012
Br	0.060	0.019	0.043	0.015	0.093	0.022	0.057	0.022	0.075	0.007
Ag	0.049	0.007	0.021	0.010	0.055	0.014	0.026	0.004	0.088	0.006
Cd	0.029	0.008	0.025	0.008	0.098	0.030	0.028	0.005	0.034	0.010
Sn	0.052	0.007	0.015	0.009	0.061	0.020	0.027	0.004	0.100	0.000
Pb	0.123	0.057	0.109	0.044	0.181	0.056	0.141	0.068	0.121	0.006
Carbon										
Organic	49.1	55.0	47.0	56.9	52.1	56.3	44.5	53.6	54.4	56.7
Element	10.6	3.5	13.7	3.7	11.0	3.1	14.2	3.4	5.2	2.0
Total	59.7	58.5	60.7	60.6	63.1	59.4	58.7	57.0	59.7	58.7

Table V. Fuel consumption parameters used to calculate seasonal profiles for each fuel type (Fuel represents percentage of total fuel for the region and flaming (F) represents the percent consumption during the flaming combustion phase for the specific fuel type.)

Fuel type	Regional composite		Spring/early summer		Summer		Autumn		Winter	
	Fuel	F	Fuel	F	Fuel	F	Fuel	F	Fuel	F
	---(%)---		---(%)---		---(%)---		---(%)---		---(%)---	
Piled slash	42	90	15	75	10	95	10	95	100	85
DF/WH	24	33	45	60	40	30	55	25	0	30
Mixed con	19	33	8	60	0	30	20	25	0	30
P.pine	6	33	16	60	0	35	5	33	0	35
Hardwood	4	33	0	70	50	50	7	50	0	50
Underburn	5	50	16	60	0	40	3	40	0	40

Table VI. Emission factors for PM2.5 by phase of combustion for Pacific Northwest fuel types.

Fuel type	Emission Factor, PM2.5	
	Flaming	Smoldering
	----- (g/kg) -----	
Piled slash	4	4
Mixed Conifer	7	14
P. pine	6	16
Hardwood	6	13
Underburns	20	40

Table VII. Equation used for calculating composite profiles and an example for the winter profile.

The following equation was used in computing the combined relative contribution of each species to PM2.5 in developing the profiles for the various seasons and for the annual regional profile:

$$C\{P,SPEC\} = \frac{\text{Sum over fuel types } (PM2.5\{T,SEAS,P\} * SCC\{SPEC,P,T\})}{\text{Sum over fuel types } (PM2.5\{T,SEAS,P\})}$$

where,

- P = Combustion phase, flaming (F), smoldering (S), or a fire weighted composite (F&S).
- SPEC = Species, i.e., carbon, ions or trace elements.
- T = Fuel type.
- SEAS = Season.
- SCC = The source contribution coefficient, i.e., the percent of PM2.5 which is SPEC, for combustion phase P and fuel type T (Table II).
- C = The combined source contribution coefficient for a species SPEC, and combustion phase P, summed over all fuel types.
- TYPE = Percent of fuel type T consumed during season SEAS (Table V).
- CONSUM = Percent of fuel type T consumed during phase P and season SEAS (Table V).
- EFPM2.5 = Emission factor (g/kg) for PM2.5 for combustion phase P and fuel type T (Table VI).

$$PM2.5\{T,SEAS,P\} = TYPE\{T,SEAS\} * CONSUM\{T,SEAS\} * EFPM2.5\{P,T\}$$

For fire weighted average source contribution coefficients:

$$C\{P,SPEC\} = \frac{\text{Sum over fuel types } (C\{P\} * PM2.5\{T,SEAS,P\})}{\text{Sum over fuel types } (PM2.5\{T,SEAS,P\})}$$

The following example is for the species aluminum for the winter profile. The assumption is made that 50 percent of the fuel is consumed in tractor piled slash and 50 percent in crane piled slash. It is further assumed that the emission factor for crane piled slash is the same as that for tractor piled slash.

$$C\{F,Al\} = \frac{(.5*.85*4*.181) + (.5*.85*4*.025)}{(.5*.85*4) + (.5*.85*4)} = 0.103 \text{ units}$$

$$C\{S,Al\} = \frac{(.5*.15*6*.056) + (.5*.15*6*.013)}{(.5*.15*6) + (.5*.15*6)} = 0.034 \text{ units}$$

$$C\{F\&S,Al\} = \frac{(.5*.85*4*.103) + (.5*.15*6*.034)}{(.5*.85*4) + (.5*.15*6)} = 0.088 \text{ units}$$

Table VIII. Fire-averaged profiles for the Pacific Northwest region, by season. Averages are from profiles for both phases of combustion, as shown in Table IV.

Profile	Regional Composite	Spring/ Early Summer	Summer	Autumn	Winter
	----------(fire average)----------				
Na	0.598	0.691	0.521	0.789	0.000
Al	0.105	0.100	0.156	0.109	0.088
Si	0.162	0.142	0.255	0.168	0.150
P	0.031	0.036	0.069	0.018	0.060
S	0.275	0.282	0.431	0.205	0.503
Cl	0.317	0.340	0.678	0.264	0.477
K	0.914	0.994	1.217	0.548	2.162
Ca	0.158	0.125	0.166	0.137	0.289
Ti	0.079	0.075	0.075	0.109	0.008
V	0.022	0.022	0.021	0.029	0.003
Cr	0.023	0.028	0.023	0.029	0.000
Mn	0.021	0.019	0.020	0.021	0.028
Fe	0.049	0.046	0.066	0.058	0.015
Ni	0.007	0.006	0.009	0.009	0.007
Cu	0.006	0.004	0.008	0.008	0.003
Zn	0.068	0.066	0.053	0.040	0.178
Br	0.033	0.027	0.042	0.029	0.061
Ag	0.021	0.015	0.025	0.008	0.071
Cd	0.015	0.015	0.049	0.009	0.029
Sn	0.022	0.012	0.031	0.009	0.079
Pb	0.079	0.072	0.090	0.081	0.097
Carbon					
Organic	53.0	52.6	55.2	51.9	54.9
Elemental	5.9	8.0	5.3	5.5	4.6
Total	58.9	60.6	60.4	57.3	59.4

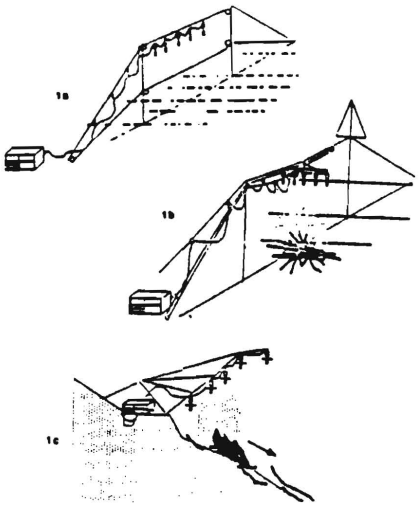

Figure 1. Several configurations of the steel tower and cable support system allow measurements of emissions over broadcast burns (1a), in higher intensity plumes from piled slash (1b), and in the emissions plume from chaparral tests.

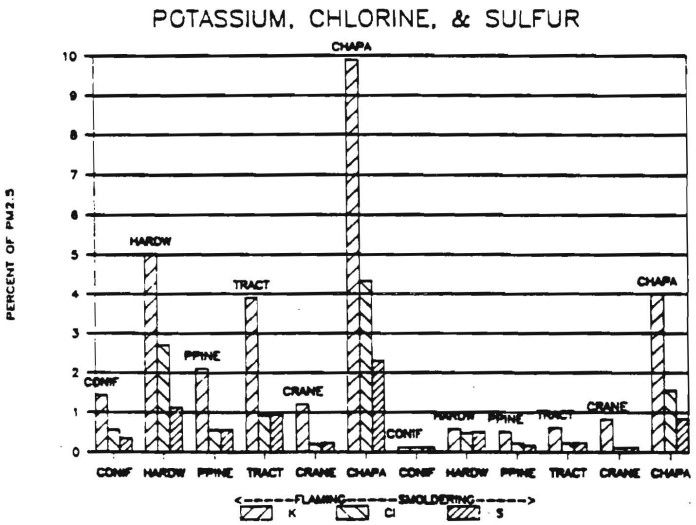

Figure 2. The differences in composition of the PM2.5 for the flaming and smoldering phases are illustrated for K, Cl, and S.

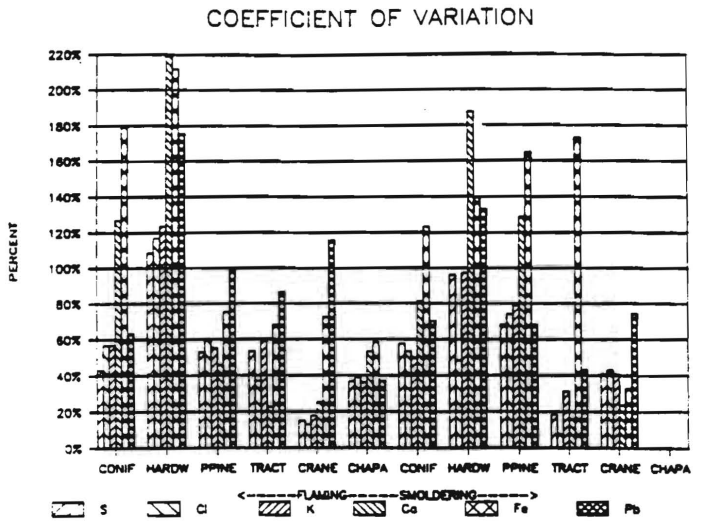

Figure 3. The coefficient of variation for the trace materials contained with the PM2.5 was generally lowest for K, Cl, and S and ranged higher for Ca, Fe, and Pb.

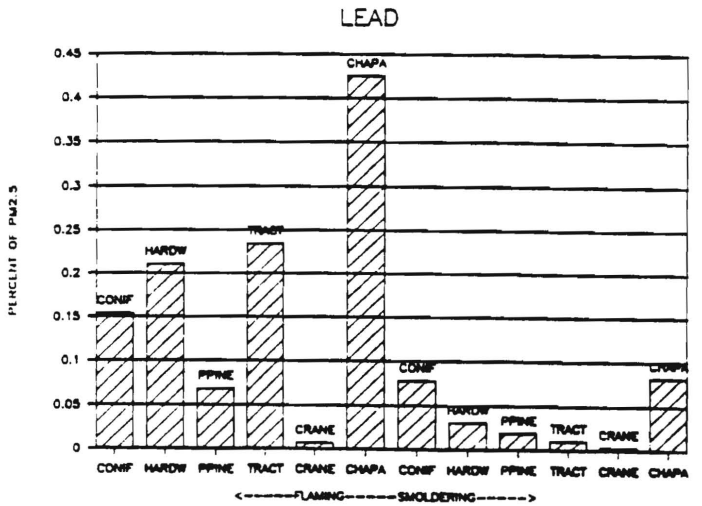

Figure 4. The Pb content of PM2.5 was highest in the chaparral of the Los Angeles Basin area and was lowest for broadcast burns On the east side of the Cascade Range in Oregon and Washington.

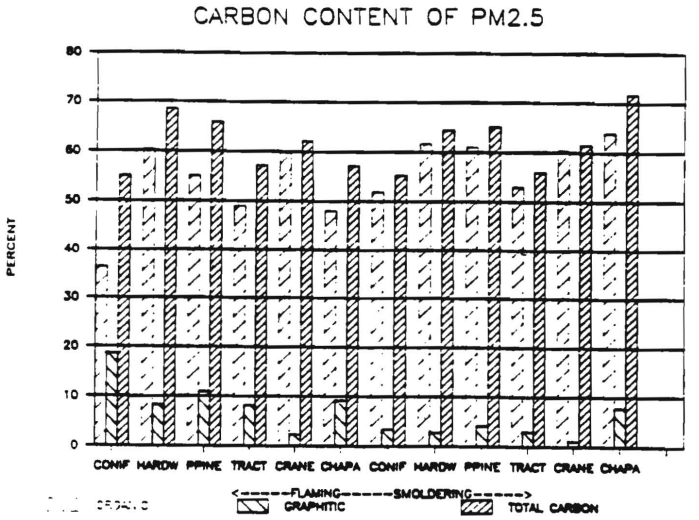

Figure 5. The combined organic and elemental carbon content of the PM2.5 makes up about 45 to 70 percent of the PM2.5.

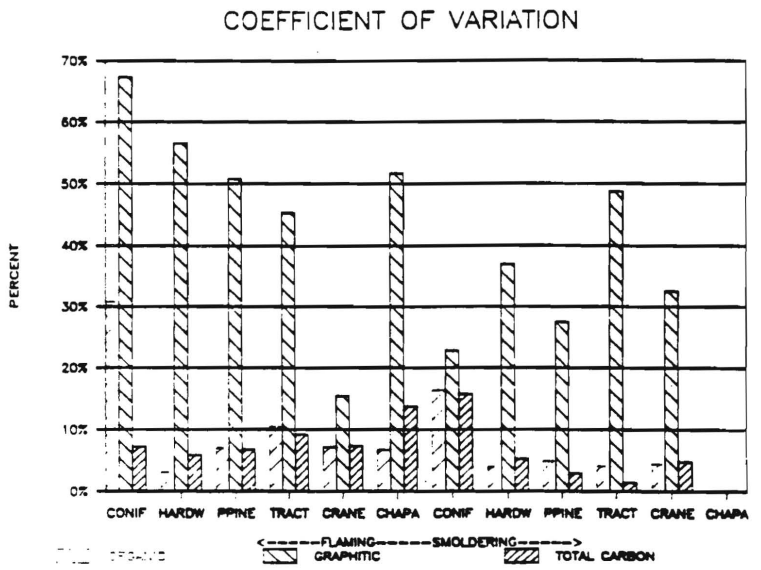

Figure 6. The coefficients of variation (CV) for organic and elemental carbon for individual fueltypes. The CV is higher for the elemental carbon than for either the organic or total carbon.

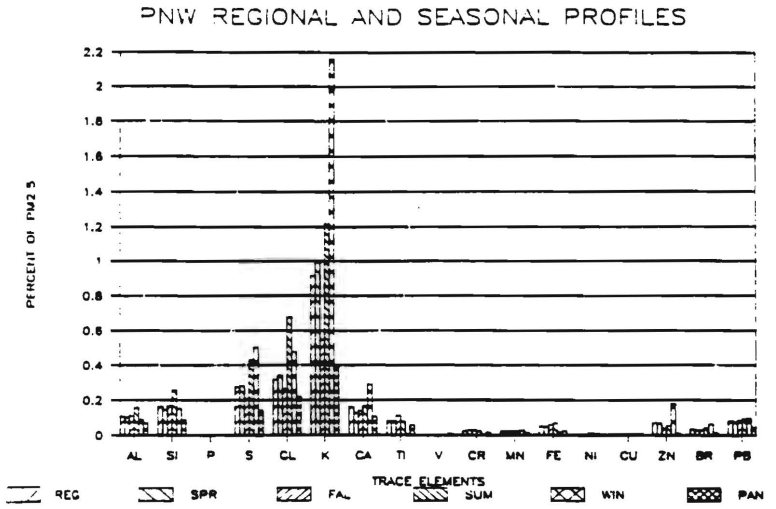

Figure 7. Pacific Northwest regional profiles for the regional composite, for each season, and for the PANORAMAS.

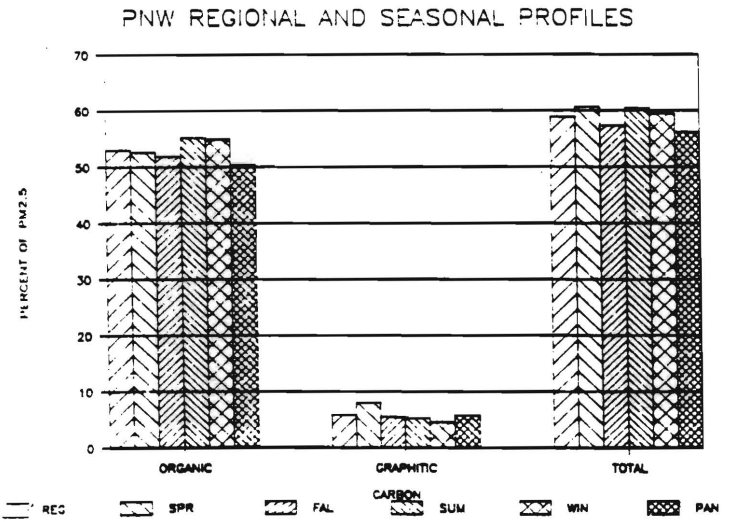

Figure 8. The composited regional and seasonal profiles for organic and elemental carbon are relatively constant.