

COMPOSITION OF CARBONACEOUS SMOKE PARTICLES FROM  
PRESCRIBED BURNING OF A CANADIAN BOREAL FOREST:  
1. ORGANIC AEROSOL CHARACTERIZATION BY GAS CHROMATOGRAPHY

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## ABSTRACT

In this study we examine the molecular organic constituents (C8 to C40 lipid compounds) collected as smoke particles from a Canadian boreal forest prescribed burn. Of special interest are (1) the molecular identity of polar organic aerosols, and (2) the amount of polar organic matter relative to the total mass of aerosol particulate carbon.

Organic extracts of smoke aerosol particles show complex distributions of the lipid compounds when analyzed by capillary gas chromatography/mass spectrometry. The molecular constituents present as smoke aerosol are grouped into non-polar (hydrocarbons) and polar (-2 oxygen atoms) subfractions. The dominant chemical species found in the boreal forest smoke aerosol are unaltered resin compounds (C20 terpenes) which are abundant in unburned conifer wood, plus thermally altered wood lignins and other polar aromatic hydrocarbons.

Our results show that smoke aerosols contain molecular tracers which are related to the biofuel consumed. These smoke tracers can be related structurally back to the consumed softwood and hardwood vegetation. In addition, combustion of boreal forest materials produces smoke aerosol particles that are both oxygen-rich and chemically complex, yielding a carbonaceous aerosol matrix that is enriched in polar substances. As a consequence, emissions of carbonaceous smoke particles from large-scale combustion of boreal forest land may have a disproportionate effect on regional atmospheric chemistry and on cloud microphysical processes.

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## Introduction

Biomass combustion is a significant source of aerosol particles to the global troposphere. Smoke aerosol produced from global biomass burning contributes 7% of total particle emissions, 39% of particulate organic matter, and >86% elemental carbon particle emissions to the global troposphere each year (Crutzen and Andrea, 1990; Andrea, 1991; Levine *et al.*, 1995). Because global biomass burning accounts for a considerable portion of the total emissions of particulate carbon to the troposphere, this emission source is believed to have a potentially significant role in climate forcing (IPCC, 1995; Penner *et al.*, 1994).

Smoke aerosol contains both organic (OC) and elemental (EC) carbon components. These two chemical forms of carbonaceous particulate matter are thought to be key anthropogenic aerosol types which are associated with climate forcing mechanisms (Penner *et al.*, 1994). Organic carbon aerosols interact directly by clear-sky backscatter of solar radiation, and indirectly by influencing cloud condensation nuclei (CCN) properties which affect cloud albedo and cloud droplet lifetime. Forcing by elemental carbon particles is due primarily to absorption of solar radiation. Penner *et al.*, 1992 calculated a global average direct forcing by aerosol particles emitted by global biomass burning of  $-0.8 \text{ W m}^{-2}$ , and with an associated range of uncertainty of  $-0.3$  to  $-2.2 \text{ W m}^{-2}$ . More recently, the Intergovernmental Panel on Climate Change (IPCC) reported a revised global and annual mean direct forcing for biomass burning of  $-0.05$  to  $-0.6 \text{ W m}^{-2}$  based on additional model calculations (IPCC, 1995). The indirect forcing of climate due to anthropogenic aerosols produced from biomass cannot yet be estimated. This deficiency is due to the lack of empirical and theoretical knowledge which relates the number populations of CCN and cloud drops to measured or calculated aerosol mass concentrations, size distributions, and chemical compositions (Penner *et al.*, 1994). Consequently, a strategy for quantifying the climate forcing by anthropogenic aerosols produced from biomass burning would include small-scale experiments where both microphysical and chemical properties are linked to measured smoke plume optical properties and to local meteorological phenomena.

A prescribed burn of boreal forest in Ontario, Canada, occurred in August, 1989. The Hill Homestead fire provided an experimental opportunity for the scientific community studying biomass burning to examine many features of the fire, which included measurement of

smoke plume aerosol chemical, optical, and microphysical properties. An important consequence of the fire and its emissions was that a precipitating thunderstorm developed. Table 1 summarizes key characteristics measured and observed for the August, 1989 Hill Homestead prescribed burn.

The focus of this paper is to describe the microchemical characteristics of the smoke plume carbonaceous particles. Our approach in the present paper adopts an analytical scheme which focuses on the mass and distribution of solvent-soluble aerosol organics that are measured by high resolution gas chromatograph with flame ionization detection (GC-FID). Here, we inventory the proportions of elemental (EC) and organic (OC) carbon to the total mass of particulate carbon, and in addition, generate key information relating to the mass contributions of polar organic compounds present as aerosol particulate matter. Overall, our analytical approach provides a systematic accounting method for airborne concentrations of radiatively important bulk carbon smoke constituents, and provides insight into the molecular composition of polar and nonpolar organics present as smoke aerosol. The chemical information generated by this project can be linked to other empirical data relating to integrated smoke plume optical properties, particle emission factors, and hydrological phenomena that were reported earlier for the Hill Homestead prescribed burn.

### Sample Collection

Smoke plume aerosol was collected under full-fire and smoldering conditions using a helicopter platform (Cofer *et al.*, 1991). Aerosol particulate matter was collected on pre-fired quartz microfiber filters (102-mm diameter) and represented total particle size range samples. Collection times were 1.0 minute (full-fire conditions) or 4.0 minutes (smoldering conditions) per sample at flow rates of 360 liters per minute. The disparity between the two sampling times was based on the need to provide sufficient sample mass loadings for organics characterization while at the same time preventing overloading of the quartz microfiber filter. Several samples of the full-fire (n=2) and the smoldering (n=2) smoke plume aerosol were collected as integrated samples of smoke plume particulate matter which represented variable ambient mass concentrations present for the two fire regimes. Additional samples were collected to monitor background aerosol concentrations and to provide a check for sampling-

derived artifacts, if present. A travel blank was deployed to monitor the storage and handling conditions that existed for the collected samples filters and was used later to assess the total analytical background for possible carbonaceous artifacts (Mazurek *et al.*, 1991). All filters were stored and shipped in annealed borosilicate glass jars that were fitted with Teflon-lined caps. After collection, the samples were transported to the laboratory and then stored at  $-27^{\circ}\text{C}$  until analyzed. This was done to prevent possible sample volatilization and chemical degradation.

### **Analytical Methods**

#### **Bulk Carbon Composition:**

A  $\frac{1}{4}$ -section of filter ( $15.9\text{ cm}^2$ ) was removed from the exposed area of each sample filter and from the blank filters which were designated for bulk carbon analysis. The remaining  $\frac{3}{4}$ -portion of the filter ( $47.7\text{ cm}^2$ ) was reserved for organics evaluation using GC-FID and gas chromatography/mass spectroscopy (GC-MS). Measurement of organic carbon and elemental carbon was determined by a thermal evolution and combustion technique (Johnson *et al.*, 1981; Cary, 1987). Detection limits for organic carbon, carbonate carbon, and elemental carbon were  $0.2\text{ }\mu\text{g C-atoms cm}^{-2}$ , with an analytical accuracy of  $\pm 5.7\%$ .

#### **Organic Aerosol Characterization by Gas Chromatography**

##### **Sample Preparation:**

The smoke aerosol samples collected on quartz fiber filters for organics analysis were grouped to form a full-fire composite (1.50 filters) and a smoldering composite (1.50 filters). A laboratory procedural blank sample was prepared by placing together 2 unused prefired quartz fiber filters. Each filter set was placed into a separate annealed heavy-walled borosilicate extraction bottle fitted with a Teflon-lined cap. A known quantity of perdeuterated tetracosane ( $n\text{-C}_{24}\text{D}_{50}$ ) was added to each filter composite to serve as an extraction recovery standard. A ratio of  $1\text{ }\mu\text{g } n\text{-C}_{24}\text{D}_{50} : 150\text{ }\mu\text{g C}$  was followed as a guide to the approximate mass of surrogate standard to be added to each organic sample composite (Mazurek *et al.*, 1993). The mass of total carbon contained in each filter composite was

calculated from the results of the bulk carbon analyses obtained by the thermo-optical/combustion method.

#### Sample Extraction and Derivatization:

Aerosol organics were isolated from the insoluble particles and the quartz fiber sampling media using a previously described and validated extraction protocol (Mazurek *et al.*, 1987; 1993). Samples were extracted successively in two 50 ml portions of hexane followed by three 50 ml portions of a 2:1 benzene/isopropanol mixture. Extraction conditions involved low intensity ultrasonic agitation at room temperature. After each extraction step, the extract was filtered and transferred into a single boiling flask that contained ultimately all five solvent extractions for a given filter composite. The extracts were concentrated by rotary vacuum distillation followed by further vaporization of residual solvent into a slow stream of ultrapure nitrogen gas. Each extract was divided into two aliquots. One aliquot of each extract was derivatized by addition of diazomethane to convert organic acids to their methyl esters and acidic hydroxy compounds to their methoxy analogues. The underivatized aliquot was designated as the *neutral* fraction and the derivatized aliquot was designated as the *acid+neutral* fraction. The *acid* fraction was calculated by difference by subtracting the mass of neutral organics from the mass of *acid+neutral* organics as measured by GC-FID analysis.

#### High-Resolution Gas Chromatography:

Characterization of the quantity of (1) non-polar (*neutral* fraction) organics and (2) polar plus neutral organics (*acid+neutral* fraction) present in the Hill Homestead smoke aerosol extracts was performed using a Varian 4600 high-resolution gas chromatograph (HRGC) fitted with a flame ionization detector (sensitivity  $10^{-12}$  v) and a conventional Grob injector (injector temperature 300 C). 1-Phenyldodecane was used as a coinjection standard at a concentration of 30.0 ng/ $\mu$ l. The analytical column was a 30-m fused-silica DB-1701 column (bonded 86% dimethyl 14% cyanopropylphenyl polysiloxane, 0.25  $\mu$ m film thickness, 0.32 mm i.d., J&W Scientific, Rancho Cordova, CA). Temperature programming consisted of injection at 65 C, isothermal hold at 65 C for 10 min, temperature increase of 10 C for 21 min, followed by an isothermal hold at 275 C for another 49 minutes. An external standard mixture

containing 17 normal alkanes ( $C_{10}H_{22}$  to  $C_{36}H_{74}$ , with concentrations of 9.7 ng/ $\mu$ l to 15.7 ng/ $\mu$ l per compound) was injected onto the GC either the same day or within 24 hours of injection of the Hill Homestead smoke aerosol samples. The careful timing and sequencing of standard and sample injections was intended to verify consistent instrumental performance and chromatographic conditions needed for organics quantitation.

## Results

### Smoke Aerosol Carbon Inventory:

Carbon species inventories were constructed for full-fire (Figure 1a) and smoldering conditions (Figure 1b). These inventories are based on mass relationships obtained for quantifiable constituents of particulate carbon present as smoke aerosols. The carbon inventories are based on the following mass determinations:

*total particulate carbon mass : organics mass : elutable organics mass :*

*neutral elutable organics mass : acid elutable organics mass.*

The total particulate carbon mass was determined by the EC/OC bulk carbon combustion procedure described above. The organics mass was calculated using the mass of organic carbon (OC) obtained for each filter composite (obtained from combustion analysis) followed by multiplication of the OC masses by a conversion factors of 1.4 (Mazurek *et al.*, 1993). The 1.4 conversion factor was applied to account for molecular compositions identified by GC/MS, which in addition to carbon atoms, included hydrogen, oxygen, and trace amounts of nitrogen, chlorine and phosphorus (Mazurek *et al.*, 1995).

Although it is difficult to account for the conversion of biomass carbon to smoke aerosol particulate matter throughout the entire duration of the Hill Homestead prescribed burn with the limited number of samples obtained (*e.g.*, two smoke integrated smoke plume filter samples per composite), nevertheless, it is possible to observe the relative importance of OC and EC as smoke plume constituents for the two fire regimes. Full-fire conditions produced ambient mass concentrations which were roughly twice the levels found during smoldering conditions. Also, during smoldering conditions EC was generated at a slightly lower proportion (3% total particulate carbon mass) relative to full-fire conditions (7% of total



particulate carbon mass). For both full-fire and smoldering conditions, OC accounts for greater than 92% of the total particulate carbon ambient mass.

The preponderance of OC mass relative to EC mass that is seen for both fire regimes has important implications concerning the distribution of OC and EC fractions as smoke particulate matter. We view the smoke particles as internally mixed particles having cores which consist of low volatile chemical substances (*e.g.*, soot, macromolecular OC, inorganic particles, soil dust), and with the organic carbon fraction forming the outer layer of the particle. Simoneit *et al.*, 1993, 1995 and Standley and Simoneit, 1987, 1990, 1994, have shown that carbonaceous smoke aerosols obtained from combustion of softwood and hardwood fuels, and also as emissions from residential wood burning and from slash burning of alder and pine forest, involves stripping of organic compounds from wood by a steam distillation process. As the smoke plume is cooled and diluted with ambient air, the volatilized organics condense onto pre-existing particles of low volatility, thus forming organic-coated smoke aerosol particles. Consequently, the surface properties of smoke plume carbonaceous aerosols are more likely to be influenced by the chemical composition of this condensable organic carbon aerosol fraction.

The optical characteristics of the internally mixed EC and OC carbonaceous smoke plume particles are much more complex, depending also on particle size and shape. Radke *et al.*, 1991 measured integrated plume optical properties (Table 1) for the Hill Homestead prescribed burn. A mean single scattering albedo of 0.84 (N=3) and a mean specific absorption of  $0.59 \text{ m}^2 \text{ g}^{-1}$  were reported. At this time, it is not clear how the smoke OC fraction influences plume integrated optical properties, whether this fraction may also enhance scattering and absorption of light at visible wavelengths. However, we note that smoke OC may enhance the absorption of solar radiation at visible wavelengths based on our observations of the brown colored filters which were seen especially for the full-fire smoke samples. In addition, the fraction of OC smoke aerosol that was soluble in the organic extraction solvents yielded dark to moderately yellow-colored, clear solutions for the full-fire and the smoldering samples. The yellow extracts indicate that the solvent soluble portion of smoke OC, also absorbs light at visible wavelengths. Thus, our observations of the Hill Homestead smoke aerosols suggest that microphysical descriptions of biomass burning aerosols must account for

the absorption of visible light by OC smoke aerosols in addition to that which is normally attributed only to the EC fraction of smoke carbonaceous aerosol particles. Moreover, the absorption of visible light by organic smoke aerosols will vary as the composition of this carbon fraction changes as a function of combined fire efficiency, fuel characteristics, and burn site environmental factors.

#### Organics Characterization by High Resolution Gas Chromatography:

Smoke aerosol organics isolated from the Hill Homestead prescribed burn are complex mixtures of individual organic compounds, some of which are detected quantitatively by GC-FID. The fraction of solvent soluble aerosol organics that are identified by GC-FID are referred to as *elutable organics* (Figure 1a and 1b). Smoke aerosol organics contain roughly 25% elutable organics and 75% nonelutable organics for both full-fire and smoldering conditions. The composition of elutable organics can be evaluated in greater detail since this fraction is amenable to analysis by GC-FID and GC-MS. However, the vast proportion of smoke carbonaceous aerosol is present as nonelutable organics. The nonelutable organics fraction consists of (1) macromolecular compounds which are not soluble in the organic solvent mixture; or (2) are compounds which are soluble in the extraction solvents but are either of too high molecular weight (> 500 atomic mass units) and/or too great polarity to elute through the GC analytical column.

An important bulk chemical characteristic of the elutable organics is the acidity or relative polarity of the organic components (Figures 1a and 1b). Recall, that in this GC-FID application, the acid elutable organics fraction are those organic compounds which are detected by FID only after undergoing a chemical conversion step that selectively targets acidic hydrogen atoms attached to either aliphatic or aromatic carboxyl groups or to aromatic hydroxyl groups. The acid elutable organics comprised 17% (full-fire) and 19% (smoldering) of the elutable organics mass isolated from the Hill Homestead prescribed burn smoke particles. Overall, acid elutable organics contributed 5% (full-fire) and 6% (smoldering) of the total mass of the smoke plume carbonaceous particulate matter.

Our GC-FID analysis of acidic smoke aerosol organics provides a mechanism for evaluating the ambient mass concentrations and chemical composition of polar smoke aerosol

organic matter. The polar organics fraction is composed, in part, by the acid elutable organics fraction that can be measured via GC-FID (approximately 5% of the total mass of carbonaceous particulate matter for both fire regimes). Additional polar smoke aerosol organic matter may be contributed by the nonelutable organics fraction, which in our analytical approach accounts for up to 77% (full-fire) and 75% (smoldering) of the smoke particulate organic matter (Figure 1a and 1b). Although at the present time we can measure a small fraction of the aerosol polar organic species by conventional solvent extraction and GC analytical methods, nevertheless, we can account for the remainder of smoke particulate organic matter with our carbon inventory approach. Thus for the smoke aerosols studied, up to 80% of the smoke organic carbon fraction may be composed of polar compounds, and roughly 5% of this organic carbon fraction consists of elutable organic species which contain at least one reactive, acidic hydrogen atom per molecule.

It is important to bring focus to the polar organic carbon fraction of smoke particles since this fraction may act as CCN. The polarized nature of the chemical bonds which comprise organic substances contained in this fraction (*e.g.*, carboxylic acids, phenolic substances, aromatic ketones, aromatic aldehydes, aromatic ethers) provides a physical mechanism by which these organics may interact with atmospheric water vapor. As noted by Radke *et al.*, 1991 (Table 1), accumulation mode smoke aerosol particles (0.1  $\mu\text{m}$  to 2.0  $\mu\text{m}$  particle diameters) had measured scavenging efficiencies of 40% to 50%, indicating that the smoke plume aerosols in this size range were relatively efficient CCN. A consequence of the effective scavenging behavior exhibited by the smoke aerosol particles (estimated to be approximately 60% carbon by mass) was manifest with the occurrence of a persistent thunderstorm which produced heavy precipitation. In addition, the precipitating cumulus clouds with depths > 2 km that developed in the vicinity of the Hill Homestead prescribed burn were shown to remove effectively accumulation mode particle and supermicron smoke particles with 30% to 90 % efficiency (Radke *et al.*, 1991).

Besides measurement of the mass of *neutral* and *acid+neutral* fractions of aerosol organics, GC-FID analysis provides distributions of the elutable compounds as a function of retention volume or, alternatively, of retention time if chromatographic and instrumental conditions remain constant from one injection to the next. We have employed GC-FID

analysis in earlier studies of Los Angeles organic aerosol (Mazurek *et al.*, 1987; 1989; 1993; Hildemann *et al.*, 1991; 1994; Rogge *et al.*, 1993a;) and in studies of urban sources of fine organic aerosols which included among other fine particle emission sources, vehicle exhaust (Rogge *et al.*, 1993b), wood smoke (Simoneit *et al.*, 1993; Hildemann *et al.*, 1990), road dust (Rogge *et al.*, 1993c), and surface abrasion products from urban vegetation (Rogge *et al.*, 1993d). Details of the mass quantitation procedure were reported by Hildemann *et al.*, 1994. The technique employs GC-FID response factors that correspond to 17 individual *n*-alkanes ranging from C<sub>10</sub>H<sub>22</sub> to C<sub>36</sub>H<sub>74</sub>. The mass response factors that are generated by the *n*-alkane standard series are applied to 17 mass intervals, each containing a single *n*-alkane standard homologue. By dividing up the mass of complex elutable organics into successive mass intervals (*i.e.*, retention volumes) having separate mass response factors, more accurate measurement of the mass of total elutable organics is achieved (Hildemann *et al.*, 1994; Lee *et al.*, 1984). Conversion of GC-FID area counts to organic mass concentrations is calculated as follows:

Mass between C<sub>*n*</sub> and C<sub>*n*+1</sub>=

$$\frac{\text{Mass } nC_{24}D_{50} \text{ added to sample}}{\text{Counts } nC_{24}D_{50}} \times \frac{\text{Counts between } C_n \text{ and } C_{n+1}}{RRF_{nC_{24}D_{50}}} \times RRF_{C_n}$$

where

$RRF_{nC_{24}D_{50}}$  = Relative Response Factor for  $nC_{24}D_{50}$

and

$RRF_{C_n}$  = Relative Response Factor of alkane C<sub>*n*</sub>.

The RRF values for individual compounds were calculated as:

$$RRF_{\text{compound } A} = \frac{\text{Counts 1-phenyldodecane}}{\text{Mass 1-phenyldodecane}} \times \frac{\text{Mass compound } A}{\text{Counts compound } A}$$

The calculations are applied to each GC-FID analysis of *neutral* and *acid+neutral* extraction aliquots. The mass of *acid* elutable organics for each mass interval is obtained by subtracting the mass of *neutral* elutable organics from the mass of *acid+neutral* elutable organics.

Figure 2 shows the ambient mass distributions of *acid* and *neutral* elutable organics that were isolated from smoke plume particulate matter collected during the August, 1989, Hill Homestead prescribed burn. The distribution of elutable species gives a compositional breakdown of these aerosol components with respect to the *n*-alkane standard series mass range. The fill-fire (Figure 2a) and smoldering (Figure 2b) elutable organics have generally similar organic species distributions, although the ambient mass concentrations for the full-fire sample are twice the levels measured for the smoldering elutable organics. Carbon number maxima for both the full-fire and the smoldering fire regimes peak roughly at C<sub>25</sub>, with generally unimodal distributions. We find the carbon number maxima of special interest since boreal forest vegetation, and in particular, gymnosperm species such as those present at the prescribed burn site, contain substantial quantities of diterpenoid (C<sub>20</sub> compounds) molecular species (Poucher, 1991; Simonsen, 1947; 1949; 1952; Pinder, 1960). As part of the overall analysis scheme for the composition of smoke aerosol organics derived from combustion of boreal forest vegetation, we prepared quantitative standard mixtures of diterpene compounds. Retention volumes for the diterpenes coincided with those of the C<sub>20</sub> to C<sub>26</sub> *n*-alkanes. The mass interval coinciding with C<sub>25</sub> *n*-alkane contains the molecular tracer, dehydroabietic acid (derivatized as its methyl ester analog). Dehydroabietic acid is a dominant molecular tracer of wood smoke combustion from gymnosperm woods (*e.g.*, Simoneit et al., 1993; Standley and Simoneit, 1987, 1990, 1994; Radzi bin Abas *et al.*, 1995) and is the organic compound found in greatest abundance in the Hill Homestead smoke plume aerosol. Thus, the mass interval plots give quantitative distributions of elutable organics that evolve from combustion of boreal forest vegetation during combustion conditions of variable intensity. In addition, the GC-FID mass distribution plots provide a further breakdown of the acidic versus neutral chemical properties of the elutable smoke organics in relation to the distribution of C<sub>10</sub>H<sub>22</sub> to C<sub>36</sub>H<sub>74</sub> normal alkane standards.

## Conclusions

The Hill Homestead prescribed burn provided an experimental opportunity for atmospheric scientists to conduct an intensive investigation of microphysical, chemical, and optical properties of smoke plume aerosols emitted as a result of biomass combustion. In this paper we account for the mass of the total carbon present as smoke particulate matter and can measure its distribution as radiatively important EC and OC aerosol subfractions by invoking a carbon species inventory method. Use of GC-FID permits an additional measurement of acidic elutable organics collected as smoke particulate matter.

Our carbon inventory shows that OC is the dominant form of particulate carbon for both full-fire and smoldering burn phases. EC is emitted in a slightly higher proportion to OC during full-fire conditions compared to smoldering conditions. Since OC accounts for > 92% of the total mass of carbonaceous smoke particulate matter collected for both fire regimes, and the OC fraction is a complex mixture of organics having a wide range of volatility (*i.e.*, from semivolatile compounds at ambient temperature having volatilities approximately equivalent to  $n\text{-C}_{11}\text{H}_{24}$ , to relatively nonvolatile species with ambient volatilities greater than that of  $n\text{-C}_{36}\text{H}_{74}$ ), we infer an internally mixed distribution of the EC and OC smoke particles. The cores of the smoke particles consist of low volatility EC and OC species, with the outer layers containing OC species of relatively higher volatility. As a consequence, the surface properties of smoke plume carbonaceous aerosols are more likely to be influenced by the chemical composition of the condensable organic carbon species.

A portion of the polar smoke organics were analyzed by GC-FID. This acid elutable organics fraction was 5% of the total mass of particulate carbon for full-fire and smoldering burn conditions. However, an additional 75% to 77% of the total smoke organics mass is not amenable to analysis by GC-FID (*i.e.*, nonelutable organics, Figure 1a and 1b) and this fraction of smoke aerosol organic matter is thought to contain highly polar organic species.

Organic extracts of smoke aerosol particles show complex distributions of  $\text{C}_{10}$  to  $\text{C}_{36}$  lipid compounds when analyzed by GC-FID. The molecular constituents present as smoke aerosol are grouped into neutral and acid subfractions which are subdivided into mass intervals using an *n*-alkane standard series. The dominant chemical species found in the boreal forest

smoke aerosol are unaltered resin compounds ( $C_{20}$  terpenes) which are abundant in unburned conifer wood, plus thermally altered wood lignins and other polar aromatic hydrocarbons.

Our observations of smoke carbonaceous particulate matter suggest that in addition to EC containing particles, the OC portion also contains light-absorbing matter. The absorption of visible light by OC containing smoke particles varies as the composition of this carbon fraction changes as a function of fire efficiency, fuel characteristics, and burn site environmental factors. Thus, models which estimate the direct radiative effects of biomass burn aerosol particulate matter must also consider the presence of partially pyrolyzed organic matter as a contributor to light absorption within the smoke plume.

Finally, a direct consequence of the emissions from the Hill Homestead fire was manifest in the occurrence of a localized, mature thunderstorm with heavy precipitation. Although we lack at present the theoretical understanding which relates CCN number populations and cloud droplets to measured or calculated aerosol mass concentrations, size distributions, and chemical compositions, the microphysical and microchemical measurements obtained for the Hill Homestead fire furnish an empirical data set which will help to develop a theoretical basis which links microscale aerosol characteristics to observable meteorological and climatological effects.

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**Table 1. Characteristics of the Hill Homestead Prescribed Burn, August 1989**

	<i>Property</i>	<i>Reference</i>
<b><u>Fuel Source</u></b>		
Boreal forest composition	13% spruce 25% balsam fir 46% white birch/poplar 12% decayed wood 4% misc. wood	<i>Cofer et al., 1991</i>
Mass of woody material	9 to 10 kg m <sup>-2</sup>	
Total area burned	486 hectares	
Mass of fuel consumed	606 kg m <sup>-2</sup>	
<b><u>Particle emission factors</u></b>		
	<i>g smoke/kg fuel burned</i> <i>particle diameter</i>	<i>Radke et al., 1991</i>
	5.5 ± 3.5      < 2 µm	
	10.5 ± 6.5      < 3.5 µm	
	6.9 ± 4.3      < 48 µm	
<b><u>Integrated plume optical properties</u></b>		
	Mean single scattering albedo of 0.84 (N=3)	<i>Radke et al., 1991</i>
	Mean specific absorption of 0.59 m <sup>2</sup> g <sup>-1</sup> (N=4)	
<b><u>Hydrological properties</u></b>		
	Scavenging efficiency of 40% to 50% for accumulation mode particles (0.1 to 2.0 µm particle diameters)	<i>Radke et al., 1991</i>
	Cumulonimbus clouds developed	
	Persistent, mature thunderstorm developed with heavy precipitation	

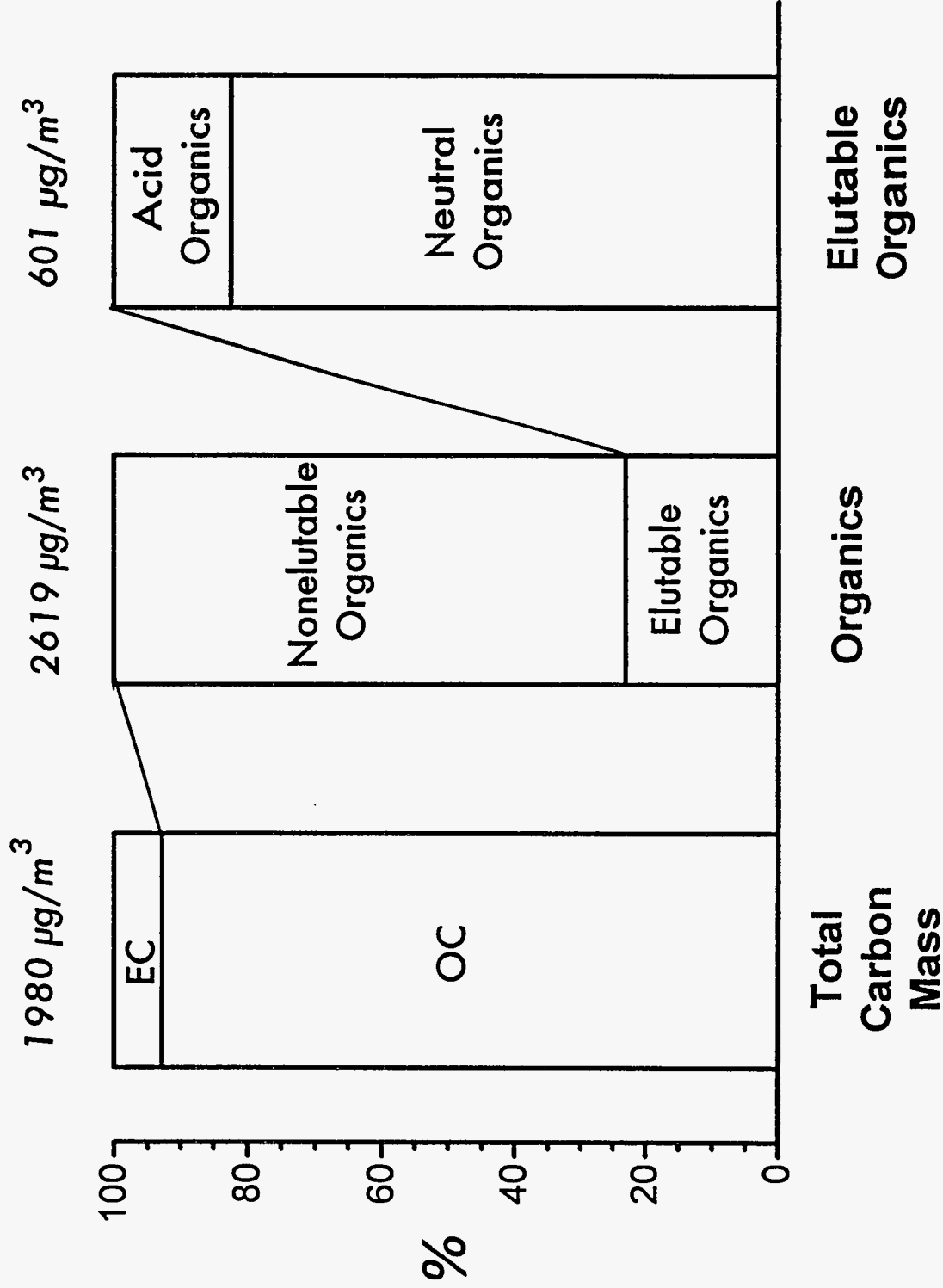
## List of Figure Captions

Figure 1. Carbon species inventories determined for (a) full-fire and, (b) smoldering samples collected as total particle samples from the August, 1989, Hill Homestead prescribed burn.

Figure 2. Distributions and ambient mass concentrations of *acid* and *neutral* elutable organics obtained from GC-FID analyses of (a) full-fire total particle, (b) smoldering total particle composites collected during the Hill Homestead prescribed burn. Histogram intervals contain the *n*-alkane homolog listed below each bin. The starting point for a mass interval corresponds to the elution time of the interval *n*-alkane.

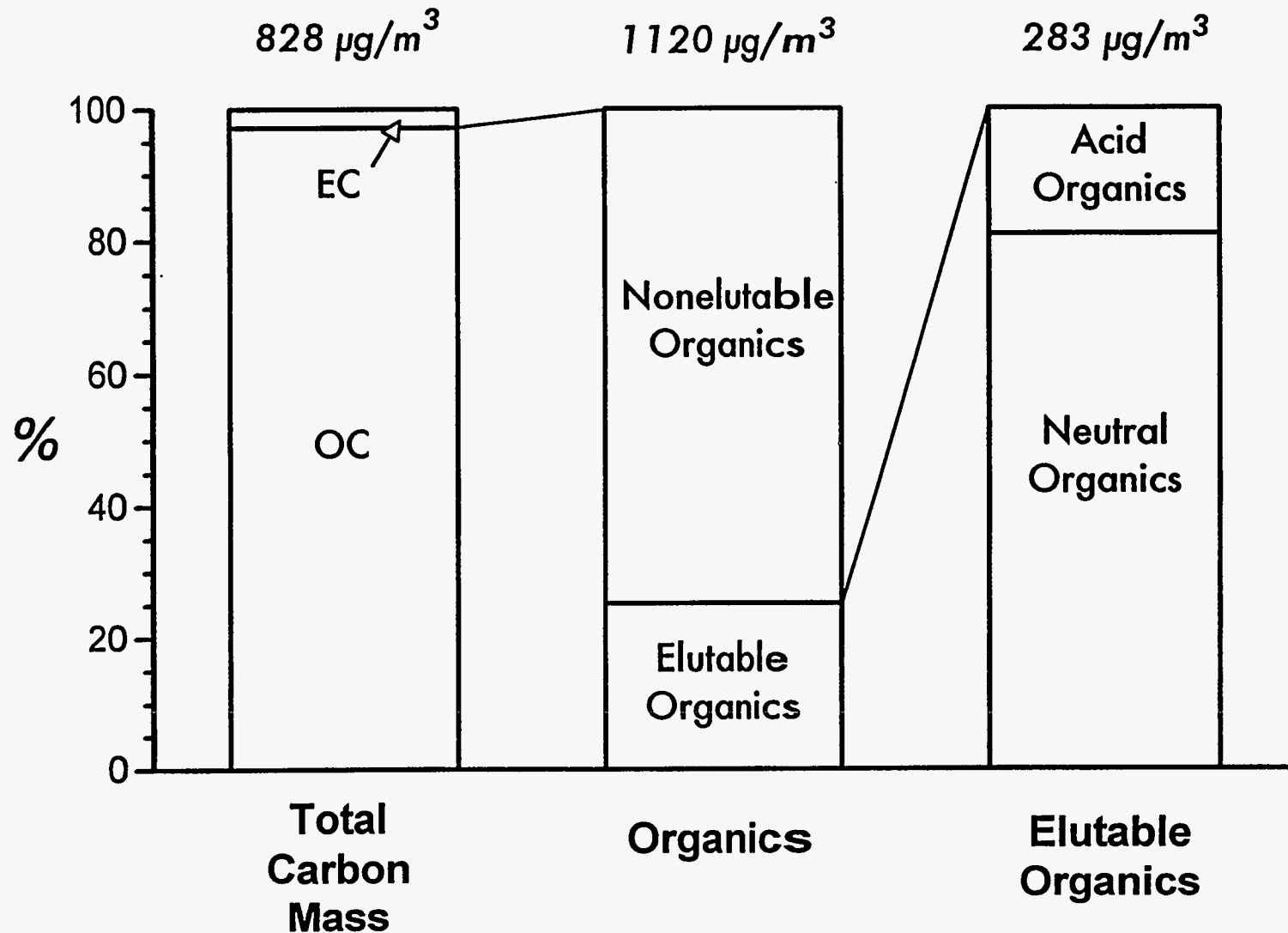
# a) Full-Fire Conditions

Hill Homestead Prescribed Burn, Ontario, Canada

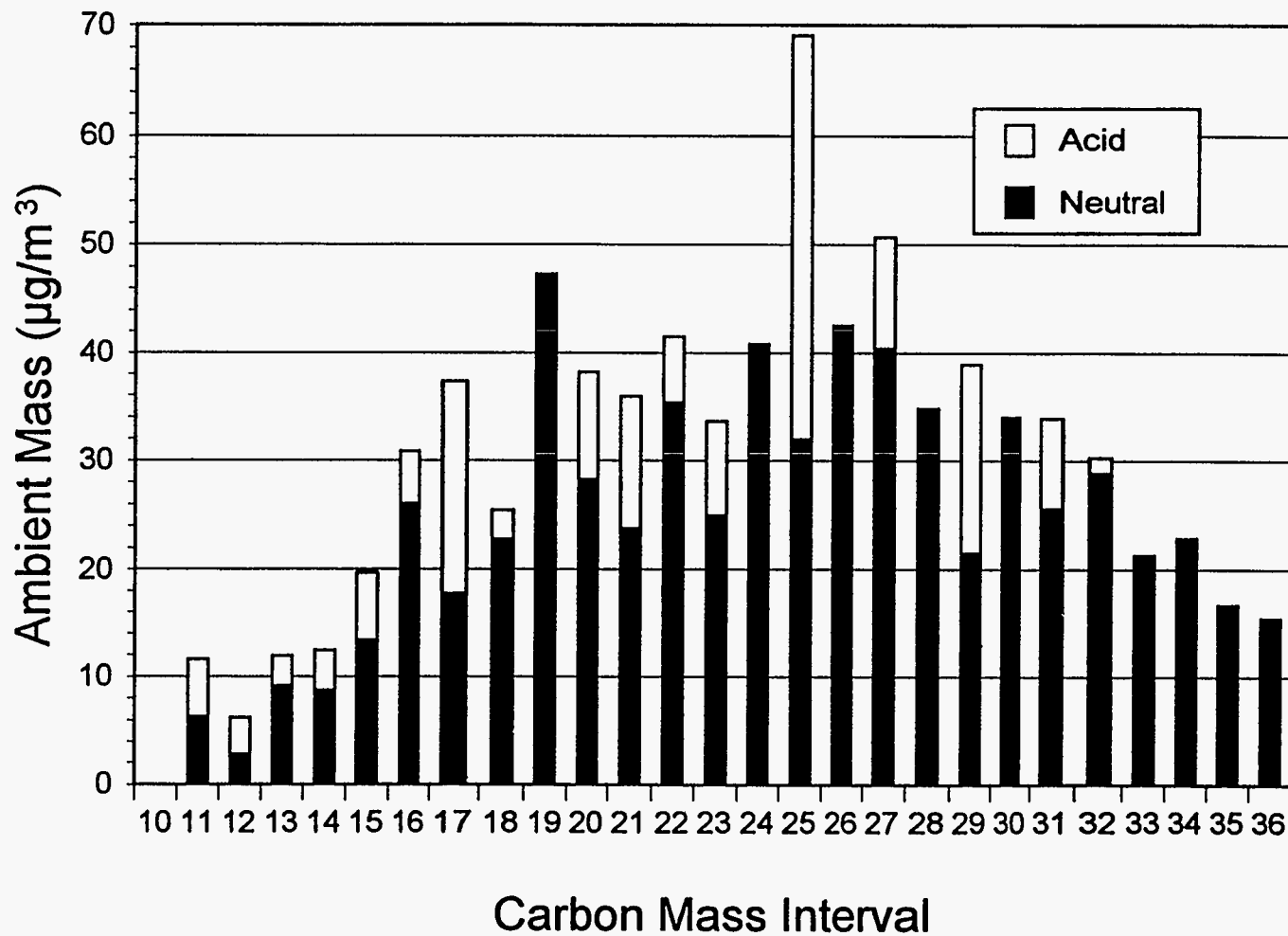


## b) Smoldering Conditions

Hill Homestead Prescribed Burn, Ontario, Canada



a) Full-Fire Smoke Plume -- Boreal Forest Hill Homestead, Ontario, Canada



**b)** Smoldering Smoke Plume -- Boreal Forest Hill Homestead, Ontario, Canada

