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Moisture effects on carbon and nitrogen emission from burning of wildland biomass

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Abstract

Carbon (C) and nitrogen (N) released from biomass burning have multiple effects on the Earth's biogeochemical cycle, climate change, and ecosystem. These effects depend on the relative abundances of C and N species emitted, which vary with fuel type and combustion conditions. This study systematically investigates the emission characteristics under different fuel moisture contents, through controlled burning experiments with biomass and soil collected from a typical alpine forest. Fuel moisture in general lowers combustion efficiency, shortens flaming phase, and introduces prolonged smoldering before ignition. It increases emission factors of incompletely oxidized C and N species, such as carbon monoxide (CO) and ammonia (NH_3). Substantial particulate carbon and nitrogen (up to 4 times C in CO and 75% of N in NH_3) were measured mainly from the pre-flame smoldering of fuels with high moisture contents; this process emits particles larger than soot agglomerates commonly observed in flaming smoke. Hydrogen (H)/C ratio and optical properties of particulate carbon from the high-moisture fuels show their resemblance to plant cellulous and brown carbon, respectively. These findings have implications for modeling biomass burning emission and impacts.

1 Introduction

On a global scale, biomass burning is an important process mobilizing carbon (C) and nitrogen (N) from the biosphere to the atmosphere, with 2–5×10^{15} g of C and 15–46×10^{12} g of N burned and released each year (Crutzen and Andreae, 1990). C emissions in the form of greenhouse gases including carbon dioxide (CO_2) and methane (CH_4) are known to contribute significantly to climate change (IPCC, 2007). N is an essential nutrient for all living organisms, and its emissions in the form of nitrous oxide (N_2O), nitrogen oxides (NO_x), ammonia (NH_3), particulate nitrogen, etc. can be utilized by the living organisms and therefore impact the ecosystem (Vitousek et al., 1997). In addition, many of the C- and/or N-containing volatile and particulate components from biomass burning play vital roles in radiative forcing, atmospheric chemistry, and air pollution (Keil and Haywood, 2003; Kondo et al., 2004; Crounse et al., 2009). The fate (i.e., atmospheric lifetime) and effect of biomass burning C and N depend on how they are distributed between gaseous and particulate phases and among various species. Dry deposition velocity of NH_3, for instance, is at least 10 times that of NO_x (Neirynck et al., 2007). N in NH_3 more likely remains where biomass burning occurs than being lost from the source region due to long-range transport.

The distribution of burning emissions is sensitive to fuel type and combustion conditions (e.g., fuel load, moisture content, and wind), which determines the relative importance of flaming and smoldering phases. Flaming combustion leads more to complete oxidation converting C and N to CO_2 and NO_x, respectively, than smoldering combustion (Koppmann et al., 2005; Chen et al., 2007). Particles are generated from both flaming and smoldering phases but differ in size, morphology, and optical properties (Reid et al., 2005a, b; Chen et al., 2006; Chakrabarty et al., 2006; McMeeking et al., 2009). Typically, light-absorbing black carbon with a structure consistent with soot agglomerates is found dominant in high temperature flames, while smoldering particles are whiter and more spherical in shape. Hygroscopicity of the particles increases with the inorganic fraction of particulate mass which depends more on fuel type than combustion conditions (Carrico et al., 2010).

Laboratory experiments are useful for controlling and investigating individual parameters effecting the biomass burning emission. The Fire LAb at Missoula Experiments (FLAME I and II) conducted in 2006 and 2007 investigated a wide range of biomass types and loads in a laboratory combustion setup (McMeeking et al., 2009). Fuels used during the FLAME study were dried sufficiently to readily ignite. A systematic investigation of the fuel moisture effect on biomass burning was not part of FLAME I and II and also rare in the literature. For natural wild fires and/or prescribed burns, however, moisture contents of wildland biomes could vary significantly corresponding to weather and climate conditions.

As part of the Tahoe Prescribed Fires and Nutrient Emission Experiment (TPFNEE), laboratory-controlled burning experiments were conducted with fuels prepared at different moisture levels. The experiments emphasized shrubs and downed materials that were subject to both prescribed burns and wild fires. This paper documents changes in emission factors of C and N species as a function of fuel moisture content. Based on continuous and time-integrated measurements, it also examines the emission mechanisms that are essential for developing process-based emission models. The Tahoe basin is a typical alpine forest in North America. Decades of fire suppression resulted in large biomass accumulation in this region. Prescribed burning is considered as an option for fuel reduction, and TPFNEE was tasked to provide a critical assessment on the environmental impact of such practices.

2 Methods

Biomass and soil samples were collected in the Lake Tahoe Basin in spring 2008 from two plots that were scheduled for prescribed burning by the United States Forest Service (USFS). Within each of the plots, ~50 bulk materials were acquired from the forest floor at randomly selected coordinates. These samples were then divided into: 1) litter (the surface layer which is not in an advanced stage of decomposition, typically consisting of freshly fallen and dried leaves, needles, twigs, stems, bark, and fruits; 2) duff (the layer dominated by partially to fully decaying leaves and branches); and 3) topsoil (mixture of mineral soil, humus, and/or degraded organic material). Murphy et al. (2006) showed that wild fires nearly deplete C and N in soils. Common aboveground shrubs were also collected and separated in the laboratory into leaves and stems of different diameters. Acquired materials were stored in sealed polyethylene bags under refrigeration (<4 °C).

The field moisture content of each sample was quantified by drying a small portion of it at 85 °C and measuring the weight loss after 24 h. Litter, duff, and soil showed moisture contents between 1–10% of dry mass, with median values of 3.5%, 5.0%, 3.8%, respectively. Moisture contents of plant samples (i.e., Bitterbrush, Green Leaf Manzanita, Huckleberry Oak, and Squaw Carpet) were higher, ranging from 6.5–50.0% for leaves and 9.3–49.0% for stems. Fractions of C and N in the dried mass were determined by CHNS-O analysis (Thermo EA1110-CHNS-O elemental analyzer, Thermo Nicolet Corporation, Waltham, USA).

To prepare fuels for desired/different moisture contents, individual litter, duff, and soil samples were first composited and air dried for a week under relative humidity of 30%. Calculated amounts of water were added into these samples to achieve fuels with moisture content of 10 or 20% of dry mass. Plant samples were also composited, and either air dried or soaked in water for 24 to 96 h. The fuel moisture content, determined from small fractions of samples, increased over time and gradually reached saturation (Fig. 1). Dry, 24-h soaked, and 96-h soaked biomass were used for the burning experiments. Table 1 shows the fuels and moisture levels examined in this study. The two wet moisture levels (II and III) simulated natural fuels of relatively high moisture contents. Two burns were conducted for each fuel-moisture combination.

Figure 2 shows the combustion facility and measurement suite. Fuels were loaded on a uniformly-heated hotplate (25 cm×25 cm) with adjustable temperatures up to 500 °C. Fuels were weighed before and after the experiment. Fuel loads were 23–69 g per burn. The hotplate kept fuels warm throughout the experiment to simulate large scale burns where environmental temperatures could be much higher than those in the laboratory without a heater. The hotplate was located in a 60-cm diameter fire pit. Horizontal air flow was kept calm, and most of the smoke was vented through the chimney with a fan. Fuels were ignited by a hot air gun (Looft Lighter) to reduce interferences from igniter emissions.

The smoke sampling probe consisted of 2-inch (5.08 cm) diameter conductive tubing stretching from the top of chimney, about 2 m above the fuels, to a mixing plenum (Fig. 2). Plumes generally reached the ambient temperature in the plenum. Through two size-cut cyclones, $PM_{2.5}$ (particles with aerodynamic diameter <2.5 µm) were sampled onto 1) Teflon filter (for $PM_{2.5}$ mass and elements) with calcium carbonate impregnated cellulous backup filter (for sulfur dioxide [SO_2]) and 2) quartz-fiber filter (for organic carbon [OC] and elemental carbon [EC] by the IMPROVE_A protocol (Chow et al., 2007a) and water-soluble ions) with citric acid impregnated cellulous backup filter (for NH_3). The analytical methods for filter samples are the same as described in Chow (1995) and Chow et al. (2004). Additionally, portions of quartz-fiber filters were submitted to the CHNS-O analyzer for quantifying total C (TC), N (TN), and hydrogen (TH) in $PM_{2.5}$. TC by CHNS-O analysis agrees with OC + EC within ±8%.

An Electric Low Pressure Impactor (ELPI) was used to measure particle size and number concentrations in real time. The ELPI has 12 stages covering an aerodynamic size range of 10 nm to 10 µm. Size retrieval followed the algorithm developed by Marjamäki et al. (2005). Through Teflon tubing from the plenum, gaseous species (CO_2, CO, NO_x, N_2O, NH_3, etc.) were continuously monitored by several analyzers including an extractive Fourier Transform Infrared (FTIR) Spectrometer (Midac, Costa Mesa, CA) and research-grade NO_x and NH_3 analyzers (TECO 42 and 17C, Thermo Scientific, Waltham, MA). The analyzers were calibrated against standards traceable to the National Institute of Standard and Technology before and after the experiments.

Since the experimental setup sampled only a fraction of smoke plumes, production efficiencies of gaseous and particulate species (per unit fuel consumption) were calculated using a carbon balance approach (Andreae and Merlet, 2001). The concentration ratio of a measured species over grand total carbon (GTC) released from a burn defines the emission factor (EF) of that species in, e.g., gram per kilogram of carbon burned, which can be scaled to gram per kilogram of fuel consumed with known carbon content of the fuel. GTC includes C in CO_2, CO, and $PM_{2.5}$. Volatile organic compounds (VOCs) including CH_4 were not measured, though under most circumstances VOCs are minor contributors, compared to CO_2 and CO, in the carbon budget of emissions (<5%).

3 Results and discussion

Dry and wet biomass fuels showed distinct fire behaviors. Dry fuels were ignited easily by hot air (600 °C) and flames quickly spread over the fuel. Residues after the burn were small except the duff composite, for which only half of the dry mass was combusted (Table 1). The duff sample likely contained substantial mineral material, as its carbon content (32%) was lower than the nominal value (i.e., 45–50%) for biomass (McMeeking et al., 2009). It took much longer for wet fuels to ignite when they were heated by the same hot air. Smoke was visible before ignition. Flaming periods were relatively short, followed by prolonged smoldering combustion. Wet fuels left more and variable amounts of unburnable residues than dry fuels. For soil, flames were absent throughout the experiments, and only 9–10% of the dry mass was consumed, regardless of moisture content.

3.1 Time-integrated carbon measurement

Particles from each individual burn were collected on a single set of Teflon and quartz-fiber filters that yielded burn-average chemical compositions. For comparison, all continuous measurements were baseline subtracted and integrated over the filter sampling period (Table 1). They were further normalized to the filter data, if available.

Combustion efficiency (CE), defined as the fraction of C emission in the form of CO_2, best indicates the relative importance of flaming (high CE) and smoldering (low CE) phases (Sinha et al., 2004; Janhäll et al., 2009). CE was >0.9 for all dry fuels (except soil) and was <0.9 for all wet fuels in this study (Table 1). In general, wet duff/leaves produce lower CEs than wet litter/stems, though there are no apparent differences between the two wet moisture levels (II and III). CO is usually found to carry most of the non-CO_2 carbon from biomass burning (Yokelson et al., 1996; Andreae and Merlet, 2001; McMeeking et al., 2009). For fuels with high moisture contents, however, particulate carbon can approach or exceed the carbon in CO emissions. The sum of OC and EC is shown (moisture level III, Table 1) to exceed 2–4 times carbon in CO for three stem burns and be 57–113% of carbon in CO for the rest of burns except soil.

The increased particulate carbon emissions from dry to wet fuels are likely of primary origins such as decomposition of plant material, since the experimental setup does not allow plumes to age extensively. Soil contains little biomass, and the influence of soil moisture on particulate carbon emission is limited (Table 1). Thermal/optical analysis indicates that most of the excess carbon is OC. Across all the burns, EC fraction in TC ranges from 0.01 to 0.68 with the highest values found from burning dry biomass. This is consistent with EC being generated from flaming combustion that intensifies with dry fuels. From such burns, Charkrabarty et al. (2006) identified soot-based particles similar to those from diesel engines.

The TH/TC ratio tends to increase with the OC fraction in TC (Fig. 3), which corroborates the dominance of hydrocarbon and elemental carbon in the (operationally-defined) OC and EC, respectively. For 17 biomass burns in which OC/TC >0.97, the average TH/TC ratio was 0.13±0.02. Considering H/C ratios of 0.167, 0.139, and 0.108 for carbohydrates $[(CH_2O)_n]$, cellulose $[(C_6H_{10}O_5)_n]$, and lignin $[(C_{10}H_{13}O_3)_n]$, respectively, the OC may result from decomposition of cellulose, which is the most abundant organic polymer in biomass (Gani and Naruse, 2007).

Particles from wet fuel combustion often appear yellowish to brownish on filters and in water extracts, in contrast to a black appearance from dry fuels (Andreae and Gelencser, 2006). A two-wavelength (370 and 880 nm) optical transmissometer (OT21, Magee Scientific Co, Berkeley, CA) was used to examine Teflon filters for wavelength-dependent absorption of particles. The absorption exponent (AE) was calculated by

$$\mathrm{AE} = \frac{\ln(\mathrm{ATN}_{370}) - \ln(\mathrm{ATN}_{880})}{\ln(370) - \ln(880)} \qquad (1)$$

where ATN is the filter attenuation used as a surrogate for light absorption (Moosmüller et al., 2009). The increasing AE towards higher OC/TC ratio (Fig. 3) shows that OC absorption is more skewed toward shorter wavelengths than EC absorption, a principle characteristic of brown carbon (BrC). Ultraviolet (UV) absorption by such BrC may be comparable to that by black carbon (Kirchstetter et al., 2004). Though levoglucosan ($C_6H_{10}O_5$) is regarded as the main product from cellulous decomposition during biomass burning and has been used as a marker for apportioning biomass burning contributions to ambient $PM_{2.5}$ (Simoneit et al., 1999; Rinehart et al., 2006; Chow et al., 2007b), it is colorless. Formation of BrC from biomass burning must involve not only thermal decomposition but also oxidation and/or other reactions in the plumes.

3.2 Time-integrated nitrogen measurement

Lobert et al. (1990) suggested that NO_x accounts for most of fuel N detected in biomass burning plumes, followed by NH_3, hydrogen cyanide (HCN), N_2O, and nitriles. This is the case for some dry biomass (i.e., litter and stems) burns in this study (Table 1). In other cases NH_3 carried the most nitrogen, while N_2O was below the detection limits and HCN was not measured. Particulate nitrogen, which was not previously addressed in Lobert et al. (1990), was found being very substantial from wet fuel combustion emissions. Only a small fraction of the particulate nitrogen was attributable to water soluble NO_3^- and NH_4^+. OPN (particulate nitrogen less NO_3^- and NH_4^+) EFs were particularly high (>3 g/kgC and up to 75% of N in NH_3) when burning wet duff and leaves (see moisture level II and III in Table 1). The fact that OPN and, to a less extent, NH_3 EFs are anti-correlated with CE for all fuel types, including soil, supports that they are favored products during smoldering combustion. This is not the case for NO_x.

It is possible that some N-containing gases, such as NH_3, mixed with $PM_{2.5}$ in plumes and/or on filters and was measured as OPN. NH_3 adsorbed on quartz-fiber filters should be detected as NH_4^+ under the current procedure (i.e., water extraction/automated colorimetry) while adsorption of other gases seems minor compared to the amounts of OPN observed. In addition, OPN is highly correlated with OC (r^2=0.87; slope=0.022) for all biomass burns. These evidences suggest that most OPN forms, along with OC, from the decomposition or pyrolysis of plant material and is in the form of organic nitrogen.

The nitrogen balance was evaluated by scaling N/GTC ratios in the combustion products to those in the fuels (Fig. 4). Better closures for wet fuels resulted, for the most part, from higher NH_3 and OPN emissions. Nearly 100% of N was recovered from the plumes of burning wet litter composite and bitterbrush leaves. In other burns, however, substantial N was missing. Besides HCN and nitriles, Lobert et al. (1990) suggested that up to 50% of biomass N could end up becoming molecular nitrogen (N_2), which cannot be detected in open fires due to the large N_2 fraction of the ambient air. Combustion experiments conducted in a closed chamber supplied with helium/oxygen air showed dominant N_2 emissions from biomass burning, particularly during flaming combustion (Kuhlbusch et al., 1991). The mechanism of N_2 formation is unclear, but such a process is clearly weakened or prohibited under the relatively low-temperature smoldering phase, leaving N available for other species.

3.3 Time-resolved measurement

Continuous data provide additional insights into the process of biomass burning emissions. Temporally-resolved dry- and wet-fuel combustion are compared in Fig. 5a–b using Manzanita leaves as an example. Flaming phase for wet Manzanita leaves, consistent with the period of highly elevated CO_2 concentrations, was rather brief (∼1 min) relative to that of dry Manzanita leaves (3–4 min), though it was in this period most of the CO_2 and NO_x were emitted. High thermal energy in the flames allows to break up plant organic matter into small fragments, producing CH_4, VOCs, CO, and NH_3, which are subsequently oxidized to CO_2 and NO_x. Dry fuels generate more intense flames, and therefore CO_2 and NO_x dominate the C and N species (except N_2) in the smoke. From the end of flaming phase through the smoldering phase, thermal energy weakens and higher fractions of CO, VOCs, and NH_3 are commonly observed (e.g., Fig. 5a and Chen et al., 2007). For wet fuels, NH_3 could be the dominant N species throughout the burn (e.g., Fig. 5b).

To investigate the emission of particle mass and the dominant size fraction, real-time ELPI particle size and number measurements were converted to particle volume concentration ($\mu m^3/cm^3$) and mean particle volume (V_p in μm^3) assuming spherical particles. From V_p the particle volume mean (aerodynamic) diameter (D_v) was calculated:

$$D_v = \left(\frac{6V_p}{\pi}\right)^{1/3} \qquad (2)$$

Soot particles that mostly consist of EC are expected to form in the flames, and indeed peaks of particle volume concentration track those of CO_2 well in Fig. 5a. D_v at the peaks was estimated to be 0.34–0.38 µm. Larger D_v up to 0.56 µm were observed right before the flames started, which could be related to the initial breakdown of plant organic matter. These large particles did not account for substantial $PM_{2.5}$ volume or mass from the dry fuel combustion. Reid et al. (2005) and Guyon et al. (2003) reported typical values of D_v ranging from 0.25–0.3 µm for fresh smoke, but with some values as high as 0.5 µm.

Figure 5b shows NH_3 emissions, in the absence of NO_x emission, during a prolonged heating/smoldering period before the wet Manzanita leaves were ignited. Unlike Fig. 5a, ELPI recorded intense particle emissions during this pre-flame period, and this explains the much higher OC and OPN EFs from the wet fuels. D_v that corresponded to each of the pre-flame peaks ranged from 0.56 µm to 0.81 µm, with the largest D_v occurring right before the flame started. These particles possibly consist of polyaccharides and/or its derivatives from the decomposition of cellulous. There is a smaller ELPI peak corresponding with the major CO_2 hump (flaming phase). Particle size at this peak appears to be smaller, i.e., D_v = 0.45 µm, but is more consistent with soot particles observed in Fig. 5a. Figure 5 illustrates common features of dry- and wet-fuel burns in this study.

4 Conclusions

To study the moisture effect on biomass burning emission, litter, duff, soil, and above-ground shrub vegetation had been collected from an alpine forest, prepared in the laboratory for three moisture levels (dry, partially wetted, and fully wetted), and submitted to laboratory-controlled combustion experiments. These experiments show that fuel moisture lowers the overall combustion efficiency, shortens the flaming phase, and prolongs smoldering before flames start. EFs of CO, OC, NH_3, and OPN increase with the fuel moisture content; the effect is generally larger for plant leaves and duff materials than for stems, litter, or soil. OC can be as much as 4 times C in CO. OPN is found to be up to 75% of N in NH_3 and highly correlated with OC (r^2=0.87).

CO_2 and CO emissions are mostly associated with flaming combustion and post-flame smoldering, respectively, and so are NO_x (flaming) and NH_3 (smoldering). N_2 emissions could be important especially during the flaming phase but cannot be quantified in open fires. The pre-flame smoldering of wet biomass mainly emits particles. These particles, with volume mean diameters of >0.55 µm, most likely consist of OC and OPN from decomposition of plant materials. It appears that higher thermal energy in flames is required to break the plant materials further into simpler C and N molecules facilitating a full oxidation. Particulate matter emissions associated with flaming combustion are relatively minor and smaller in size (e.g., 0.34–0.45 µm).

OC emitted from biomass burning, particularly with wet fuels, have H/C ratios similar to that of cellulous, the principle component of plant cells. However, the OC shows characteristics of BrC, absorbing UV much more strongly than cellulous. Though it is possible that polyaccharides and other derivatives of cellulous dominate the OC mass, how BrC is formed and its chemical nature warrant further investigations.

This study confirms that fuel moisture content is a critical factor controlling the C and N partitioning in biomass burning emissions. Since high-moisture fuels lead to substantial NH_3 and OPN emissions that have higher deposition rates, prescribed burning during wet seasons (e.g., spring in Lake Tahoe) would mitigate nutrient loss from long-range transport but increase the potential of nutrient deposition into the lake water. Distinct particle properties between low- and high-moisture fuel combustion imply different radiative effects of forest fires in dry and wet seasons. Moisture-dependent EFs and emission mechanisms represent an important step towards establishing accurate biomass burning emission inventories and source functions for global/regional climate models.

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Table 1. Time-integrated combustion efficiency (CE) and emission factors[a] for major C and N species from controlled burning experiments.

Plant Species		Downed Material			Aboveground Shrub					
		Composite			Bitterbrush		Manzanita		Squaw Carpet	
Parameter/Fuel Type		Litter	Duff	Soil	Leaves	Stems	Leaves	Stems	Leaves	Stems
Moisture Level I (Dry[f])	Carbon %[b]	50%	32%	3%	52%	48%	49%	48%	47%	50%
	Burned %[c]	92%	52%	9%	92%	81%	90%	98%	83%	93%
	CE	0.94	0.92	0.86	0.93	0.94	0.91	0.94	0.92	0.92
	CO	126.2	140.6	297.3	112.6	127.4	113.2	128.4	144.5	162.1
	OC[e]	2.5	(9.3)	14.9	9.1	6.4	(21.2)	5.5	11.3	4.7
	EC[e]	4.6	5.7	0.7	15.4	2.9	15.9	2.0	8.1	2.5
	NO_x	5.9	4.9	0.9	9.1	9.1	7.1	5.4	7.7	10.5
	NH_3	(1.3)	(3.7)	11.5	7.7	3.4	4.0	1.9	6.8	5.6
	NO_3^{-e}	0.04	0.03	0.09	0.05	0.12	0.16	0.12	0.07	0.09
	NH_4^{+e}	0.05	0.06	0.15	0.04	0.04	0.04	0.03	0.05	0.08
	OPN[e]	(0.24)	(0.44)	(0.31)	0.40	0.31	0.47	0.09	0.45	0.28
Moisture Level II	Moisture[d]	10%	10%	10%	73%	39%	40%	39%	48%	44%
	Burned %[c]	72%	47%	10%	88%	66%	73%	53%	69%	92%
	CE	0.79	0.70	0.80	0.88	0.82	0.72	0.89	0.67	0.86
	CO	253.2	444.9	431.4	113.2	261.3	(97.5)	107.1	(77.7)	(108.1)
	OC[e]	99.8	110.9	17.5	66.1	(66.6)	236.0	(62.8)	292.2	92.6
	EC[e]	5.2	1.0	1.5	(7.3)	3.7	5.6	2.3	8.5	2.6
	NO_x	6.4	6.7	2.8	9.9	13.0	(2.2)	(2.9)	(4.0)	(10.7)
	NH_3	4.3	(26.7)	24.7	10.2	10.7	10.0	3.8	11.9	11.0
	NO_3^{-e}	0.17	0.13	0.15	0.23	0.20	0.08	0.08	0.23	0.19
	NH_4^{+e}	0.24	0.15	0.21	0.10	(0.03)	0.31	(0.05)	0.28	0.08
	OPN[e]	1.62	3.57	0.99	2.03	1.39	4.4	(1.07)	(7.70)	2.73
Moisture Level III	Moisture[d]	20%	20%	20%	84%	57%	60%	52%	66%	57%
	Burned %[c]	80%	45%	9%	86%	78%	68%	92%	65%	90%
	CE	0.74	0.69	0.82	0.51	0.84	0.62	0.87	0.72	0.88
	CO	313.6	407.6	357.7	215.6	216.8	134.2	188.5	142.6	(133.1)
	OC[e]	116.6	131.1	22.1	393.6	67.8	315.3	43.1	210.4	(61.5)
	EC[e]	(7.6)	1.1	2.3	5.3	3.6	7.1	2.6	4.8	2.7
	NO_x	8.4	3.8	5.4	9.6	7.5	(2.7)	4.7	6.4	9.1
	NH_3	5.3	17.7	(24.5)	19.1	10.9	10.1	3.8	9.5	9.7
	NO_3^{-e}	0.20	0.09	0.10	0.28	0.18	0.12	0.11	0.14	0.13
	NH_4^{+e}	0.30	0.15	0.17	0.32	0.06	0.42	0.07	0.18	(0.05)
	OPN[e]	1.59	3.36	0.60	11.83	1.59	4.32	0.66	4.43	1.33

[a] In g/kgC (g per kilogram of carbon burned). Values are based on the average of two replicate burns and shown in bracket if the two replicates differ by more than a factor of 3. [b] Percentage of carbon in dry fuels. [c] Percentage of dry fuels burned. [d] Fuel moisture content in percentage. [e] Particulate species. [f] Moisture content <5%.

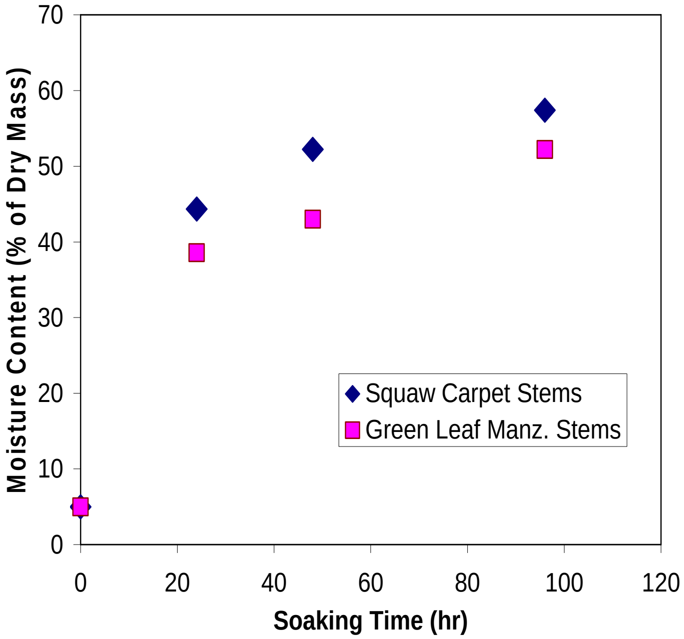

Fig. 1. Examples of fuel moisture content, starting air dried (0 h), as a function of time soaking in water. Excess water was drained before the measurement of moisture content.

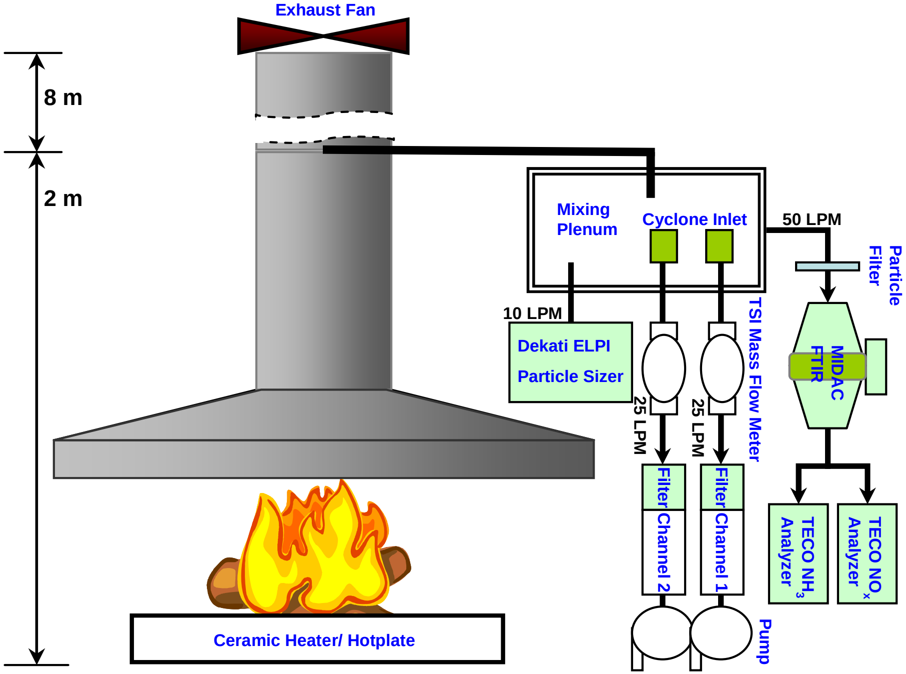

Fig. 2. Schematic of the controlled burning experiment configurations.

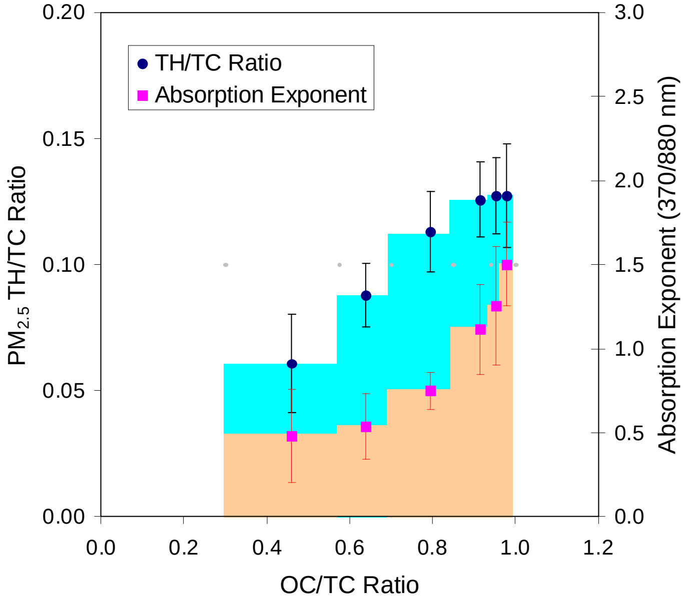

Fig. 3. Conditional means of TH/TC ratio and absorption exponent of biomass-burning $PM_{2.5}$ as a function of OC fraction in TC. The symbols correspond to 6 groups with OC/TC ratio of 1) 0.3–0.575, 2) 0.575–0.7, 3) 0.7–0.85, 4) 0.85–0.94, 5) 0.94–0.97, and 6) 0.97–1. Soil combustion samples were excluded from this analysis.

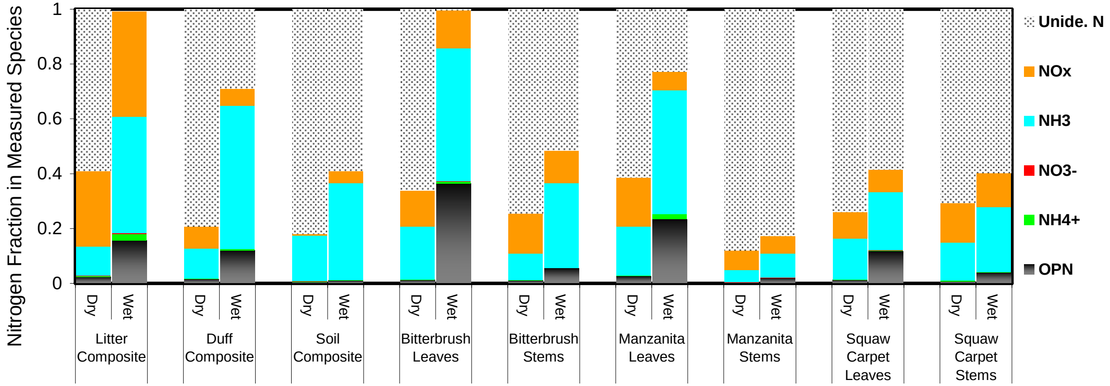

Fig. 4. Nitrogen balance with respect to fuel nitrogen content, determined from N/C ratios in smoke plumes and in fuels. Unidentified N (Unide. N) is the fuel N that is not accounted for by measured species. Dry and wet fuels correspond to the Moisture Level I and III in Table 1.

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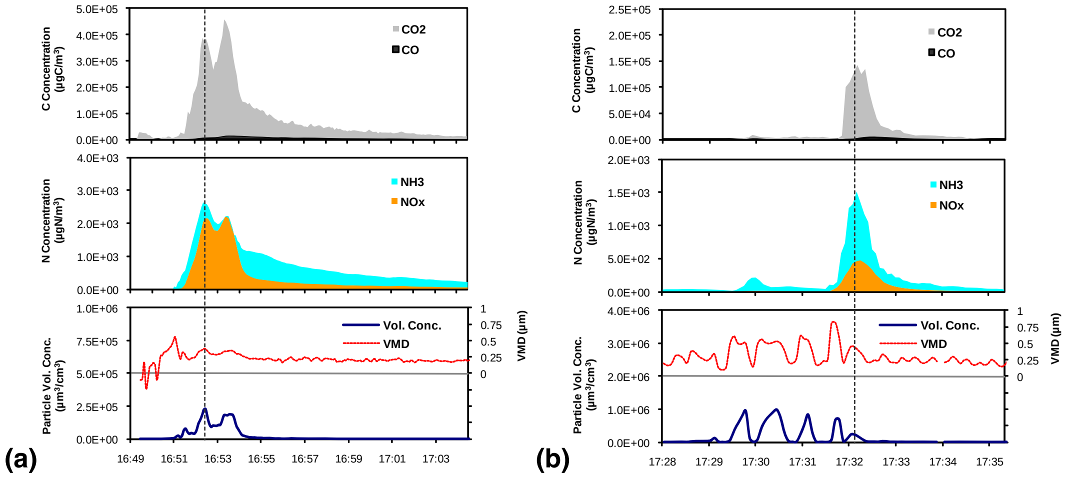

Fig. 5. Time series of gaseous (stacked area) and particulate concentrations during the burn of **(a)** dry and **(b)** wet Manzanita leaves. Particle size is represented by the volume mean (aerodynamic) diameter (VMD, D_v).