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Biomass burning emissions and potential air quality impacts of volatile organic compounds and other trace gases from temperate fuels common in the United States

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Abstract

A comprehensive suite of instruments was used to quantify the emissions of over 200 organic gases, including methane and volatile organic compounds (VOCs), and 9 inorganic gases from 56 laboratory burns of 18 different biomass fuel types common in the southeastern, southwestern, or northern United States. A gas chromatograph-mass spectrometer (GC-MS) provided extensive chemical detail of discrete air samples collected during a laboratory burn and was complemented by real-time measurements of organic and inorganic species via an open-path Fourier transform infrared spectrometer (OP-FTIR) and 3 different chemical ionization-mass spectrometers. These measurements were conducted in February 2009 at the U.S. Department of Agriculture's Fire Sciences Laboratory in Missoula, Montana. The relative magnitude and composition of the gases emitted varied by individual fuel type and, more broadly, by the 3 geographic fuel regions being simulated. Emission ratios relative to carbon monoxide (CO) were used to characterize the composition of gases emitted by mass; reactivity with the hydroxyl radical, OH; and potential secondary organic aerosol (SOA) precursors for the 3 different US fuel regions presented here. VOCs contributed less than 0.78 ± 0.12 % of emissions by mole and less than 0.95 ± 0.07 % of emissions by mass (on average) due to the predominance of CO_2, CO, CH_4, and NO_x emissions; however, VOCs contributed 70–90 (±16) % to OH reactivity and were the only measured gas-phase source of SOA precursors from combustion of biomass. Over 82 % of the VOC emissions by mole were unsaturated compounds including highly reactive alkenes and aromatics and photolabile oxygenated VOCs (OVOCs) such as formaldehyde. OVOCs contributed 57–68 % of the VOC mass emitted, 42–57 % of VOC-OH reactivity, and aromatic-OVOCs such as benzenediols, phenols, and benzaldehyde were the dominant potential SOA precursors. In addition, ambient air measurements of emissions from the Fourmile Canyon Fire that affected Boulder, Colorado in September 2010 allowed us to investigate biomass burning (BB) emissions in the presence of other VOC

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sources (i.e., urban and biogenic emissions) and identify several promising BB markers including benzofuran, 2-furaldehyde, 2-methylfuran, furan, and benzonitrile.

1 Introduction

Biomass burning (BB) emissions are composed of a complex mixture of gases and particles that may directly and/or indirectly affect both climate and air quality (Jaffe and Wigder, 2012; Sommers et al., 2014). Emissions include greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O); carcinogens such as formaldehyde and benzene; and other components harmful to human health including particulate matter, carbon monoxide (CO) and isocyanic acid (HNCO) (Crutzen and Andreae, 1990; Hegg et al., 1990; Andreae and Merlet, 2001; Demirbas and Demirbas, 2009; Estrellan and Iino, 2010; Roberts et al., 2010, 2011; Sommers et al., 2014). The co-emission of nitrogen oxides ($NO_x = NO + NO_2$) and reactive volatile organic compounds (VOCs, also known as non-methane organic compounds) from combustion of biomass may degrade local and regional air quality by the photochemical formation of tropospheric ozone (O_3), a hazardous air pollutant, and secondary organic aerosol (SOA) (Alvarado et al., 2015). This work is aimed at characterizing primary biomass burning emissions of organic and inorganic gases in order to identify key species that may contribute to O_3 and/or SOA formation.

Tropospheric O_3 may be formed in the atmosphere from the interactions of VOCs, NO_x, and a radical source such as the hydroxyl radical (OH), which is formed from the photolysis of O_3, aldehydes, hydroperoxides, or nitrous acid (HONO). OH is a key oxidant in the troposphere and it plays a pivotal role in determining the atmospheric lifetimes of reactive organic and inorganic gases. Oxidation of VOCs and other gases such as CO and CH_4 by OH leads to the formation of alkyl (R•), alkoxy (RO•), and alkylperoxy (RO_2•) radicals, where R represents a carbon-containing derivative. These radicals are important, but short-lived, intermediaries that aid in the conversion of NO to NO_2. Photolysis of NO_2 produced from the reaction of $RO_2• + NO$ is the principal

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source of tropospheric O_3; however, the amount of O_3 formed is dependent on the relative abundances of NO_x and VOCs (Carter, 1994). Biomass burning is a large, primary source of VOCs, NO_x, and HONO (i.e., O_3 precursors); however, these species are emitted at varying relative ratios depending on the fuel type and burn conditions making it difficult to predict O_3 formation from the combustion of biomass (Akagi et al., 2011; Jaffe and Wigder, 2012). An additional O_3 formation pathway involves the formation of peroxynitrates, such as peroxyacetic nitric anhydride (PAN), via $R(O)O_2\bullet + NO_2$ reaction. This pathway may diminish O_3 formation in fresh BB plumes due to the initial sequestration of NO_2, but enhance O_3 downwind formation via production of NO_2 from thermal dissociation of peroxynitrates (Jaffe and Wigder, 2012).

SOA is organic particulate mass that is formed in the atmosphere from the chemical evolution of primary emissions of organic species. Here, chemical evolution refers to a complex series of reactions of a large number of organic species that results in the formation of relatively low volatility and/or high solubility oxidation products that will readily partition to, or remain in, the particle phase (Kroll and Seinfeld, 2008). Oxidation may occur via addition of OH, O_3, or the nitrate radical (NO_3) to a double bond or result from the reactions of the $RO_2\bullet$ and/or RO• radicals formed from hydrogen abstraction of the parent compound. These pathways may result in oxidation products that contain polar functional groups such as ketones, aldehydes, alcohols, nitrates, and carboxylic acids that can have vapor pressures approximately 10 to 10 000 times lower than their parent compounds (Pankow, 1994) allowing for more efficient partitioning to the particulate phase. Thus, VOCs that are considered to be efficient SOA precursors are relatively reactive organic compounds whose oxidation products are of sufficiently low volatility and/or higher solubility than the parent VOC. SOA formation from BB emissions is highly variable and chemical modeling results suggest that there is a "missing large source of SOA" precursors that cannot be explained by known SOA precursors such as toluene (Alvarado et al., 2015).

Advances in instrumentation and complementary measurement approaches have enabled chemical analyses of a wide range of species emitted during laboratory-based

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biomass burning experiments (Yokelson et al., 1996, 2013; McDonald et al., 2000; Schauer et al., 2001; Christian et al., 2003; Veres et al., 2010; Hatch et al., 2015; Stockwell et al., 2015). This information supplements several decades of field measurements of BB emissions reported in the literature (Andreae and Merlet, 2001; Friedli et al., 2001; Akagi et al., 2011; Simpson et al., 2011). Chemically detailed, representative measurements of VOCs and other trace gases from biomass combustion are critical input to photochemical transport models aimed at reproducing observed downwind changes in the concentrations of reactive species including VOCs, O_3, peroxynitrates, and organic aerosol (Trentmann et al., 2003, 2005; Mason et al., 2006; Alvarado and Prinn, 2009; Heilman et al., 2014; Urbanski, 2014; Alvarado et al., 2015) and are essential to understanding impacts on chemistry, clouds, climate, and air quality.

For this study, a comprehensive suite of gas-phase measurement techniques was used to quantify the emissions of 200 organic gases, including methane and VOCs, and 9 inorganic gases from laboratory biomass burns of 18 fuel types from 3 geographic regions in the US (hereafter referred to as "fuel regions") in order to examine the potential atmospheric impacts of these gaseous emissions. We focus on the 56 fires sampled by a gas chromatograph-mass spectrometer (GC-MS), which is limited to sampling a relatively short, discrete segment of a laboratory burn. We begin by comparing mixing ratios measured by the GC-MS to those measured by infrared spectroscopy and proton-transfer-reaction mass spectrometry, both of which provide near-continuous sampling of laboratory fires. We then compare discrete ERs and fire-integrated ERs, representing the entirety of emissions from a laboratory burn, in order to quantify any potential bias that resulted from discrete vs. "continuous" sampling techniques.

In order to merge and compare datasets from multiple instruments, we report mean discrete emission ratios (ER) of the measured gases relative to CO for southwestern, southeastern, and northern fuel regions. Previous publications present fire-integrated ERs for the real-time measurement techniques (Veres et al., 2010; Warneke et al., 2011), fuel-based emissions factors (Burling et al., 2010; Yokelson et al., 2013), and comparisons between laboratory and field measurements of BB emissions (Burling

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et al., 2010, 2011; Yokelson et al., 2013). Yokelson et al. (2013) focused on retrieving an improved set of emission factors for prescribed fires by coupling lab and field work, but they performed only a cursory analysis of the atmospheric impacts. This paper provides a more detailed examination of the chemical composition of BB emissions from fires simulating each fuel region in order to identify key species that may impact air quality through formation of O_3 and/or SOA. We compare the chemical composition of the mass emitted, the reactivities of the measured gases with the hydroxyl radical in order to identify the key reactive species that may lead to O_3 formation, and utilize a model-derived metric to compare relative SOA potentials (Derwent et al., 2010) from each fuel region. Detailed chemical models are required to more accurately account for the various O_3 and SOA formation pathways, which is out of the scope of this study. In addition to the laboratory fire measurements, we present field-measurements of rarely-reported VOCs in ambient air during the Fourmile Canyon Fire that affected Boulder, Colorado in September 2010. The latter measurements revealed BB markers that were specific to the BB emissions, minimally influenced by urban or biogenic VOC emission sources, and were emitted in detectable quantities with long enough lifetimes to be useful even in aged, transported BB plumes.

2 Experimental

2.1 Fuel and biomass burn descriptions

The laboratory-based measurements of BB emissions were conducted in February 2009 at the U.S. Department of Agriculture's Fire Sciences Laboratory in Missoula, Montana. A detailed list of the biomass fuel types, species names, fuel source origin, and the carbon and nitrogen content of the fuels studied here are included in a previous paper by Burling et al. (2010). Up to 5 replicate burns were conducted for each of the 18 different fuels studied. These fuels are categorized into 3 geographic fuel regions based on where the fuels were collected. The data presented here include

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9 southwestern fuels from southern California and Arizona including chaparral shrub, mesquite, and oak savanna/woodland; 6 southeastern fuels represented the pine savanna/shrub complexes indigenous to coastal North Carolina and pine litter from Georgia; and 3 northern fuels including an Englemann spruce, a grand fir, and ponderosa pine needles from Montana. All fuels were harvested in January 2009 and sent to the Fire Sciences Laboratory where they were stored in a walk-in cooler prior to these experiments.

All biomass burns were conducted inside the large burn chamber (12.5 m × 12.5 m × 20 m height), which contains a fuel bed under an emissions-entraining hood, an exhaust stack, and an elevated sampling platform surrounding the exhaust stack approximately 17 m above the fuel bed (Christian et al., 2003, 2004; Burling et al., 2010). Each fuel sample was arranged on the fuel bed in a manner that mimicked their natural orientation and fuel loading when possible and was ignited using a small propane torch (Burling et al., 2010). During each fire, the burn chamber was slightly pressurized with outside air conditioned to a similar temperature and relative humidity as the ambient air inside the burn chamber. The subsequent emissions were entrained by the preconditioned ambient air and continuously vented through the top of the exhaust stack. The residence time of emissions in the exhaust stack ranged from ~ 5 to 17 s depending on the flow/vent rate. Each burn lasted approximately 20–40 min from ignition to natural extinction.

2.2 Instrumentation and sampling

A list of the gas-phase instruments used in this study, a brief description of their inherent sampling limitations, and references appears in Table 1. The gas chromatograph mass spectrometer (GC-MS) and the proton-transfer-reaction mass spectrometer (PTR-MS) were located in a laboratory adjacent to the burn chamber. The proton-transfer-reaction ion-trap mass spectrometer (PIT-MS), negative-ion proton-transfer chemical-ionization mass spectrometer (NI-PT-CIMS), and open-path Fourier trans-

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form infrared (OP-FTIR) optical spectrometer were located on the elevated platform inside the burn chamber.

Sampling inlets for the four mass spectrometers were located on a bulkhead plate on the side of the exhaust stack 17 m above the fuel bed. The GC-MS and PTR-MS shared a common inlet, which consisted of 20 m of unheated 3.97 mm i.d. perfluoroalkoxy Teflon tubing (Warneke et al., 2011). The portion of the inlet line inside the exhaust stack (40 cm) was sheathed by a stainless steel tube (40 cm, 6.4 mm i.d.) that extended 30 cm from the wall of the exhaust stack and was pointing upwards (away from the fuel bed below) in an effort to reduce the amount of particles pulled into the sample line. A sample pump continuously flushed the 25 m sample line with 7 L min^{-1} flow of stack air reducing the inlet residence time to less than 3 s. Separate inlets for both the PIT-MS and NI-PT-CIMS were of similar materials and design, but shorter lengths further reducing inlet residence times and allowing for sample dilution for the NI-PT-CIMS (Roberts et al., 2010; Veres et al., 2010).

The open optical path of the OP-FTIR spanned the full width of the exhaust stack so that the emissions could be measured instantaneously without the use of an inlet. All measurements were time aligned with the OP-FTIR in order to account for different inlet residence times and instrument response times. Previous comparisons of OP-FTIR to a PTR-MS with a moveable inlet confirmed the stack emissions are well-mixed at the height of the sampling platform (Christian et al., 2004). Other possible sampling artifacts, such as losses to the walls of the inlets, were investigated via laboratory tests and in-situ instrument comparisons (Burling et al., 2010; Roberts et al., 2010; Veres et al., 2010; Warneke et al., 2011).

2.3 Discrete sampling by in-situ GC-MS

A custom-built, dual-channel GC-MS was used to identify and quantify an extensive set of VOCs. For each biomass burn, the GC-MS simultaneously collected 2 samples, one for each channel, and analyzed them in series using either an Al_2O_3/KCl PLOT column (channel 1) or a semi-polar DB-624 capillary column (channel 2) plumbed to a heated

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4-port valve that sequentially directed the column effluent to a linear quadrupole mass spectrometer (Agilent 5973N). The sample traps for each channel were configured to maximize the cryogenic trapping efficiencies of high-volatility VOCs (channel 1) or VOCs of lesser volatility and/or higher polarity (channel 2) while minimizing the amount of O_3, CO_2 and water in each sample (Goldan et al., 2004; Gilman et al., 2010). For each channel, 70 mL min^{-1} was continuously sub-sampled from the high volume (7 L min^{-1}) sample stream for 20 to 300 s resulting in sample volumes from 23–350 mL each. Smaller sample volumes were often collected during periods of intense flaming combustion in order to avoid trapping excessive CO_2, which could lead to dry ice forming in the sample trap, thereby restricting sample flow. Larger sample volumes allowed for detection of trace species, but peak resolution would degrade if the column was overloaded. The mass spectrometer was operated in either total ion mode, scanning all mass-to-charge ratios (m/z) from 25 to 150 atomic mass units; or in selective ion mode, scanning a subset of m/z's. The majority of the samples were analyzed in selective ion mode for improved signal-to-noise; however, at least one sample of each fuel type was analyzed in total ion mode to aid identification and quantify species whose m/z may not have been scanned in selective ion mode. The entire GC-MS sampling and analysis cycle required 30 min; therefore, the GC-MS was limited to sampling each laboratory burn only once per fire for burns that lasted less than 30 min. GC-MS samples were collected at different stages of replicate burns in an effort to best characterize the emissions of each fuel type.

Each VOC was identified by its retention time and quantified by the integrated peak area of a distinctive m/z in order to reduce any potential interferences from co-eluting compounds. Identities of new compounds that had never before been measured by this GC-MS were confirmed by (1) matching the associated electron impact ionization mass spectrum when operated in total ion mode to the National Institute of Standards and Technology's mass spectral database, and (2) comparing their respective retention times and boiling points to a list of compounds previously measured by the GC-MS. Examples of these species include: 1,3-butadiyne (C_4H_2), butenyne (vinyl acetylene,

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C_4H_4), methylnitrite (CH_3ONO), nitromethane (CH_3NO_2), methyl pyrazole ($C_4H_6N_2$), ethyl pyrazine ($C_6H_8N_2$), and tricarbon dioxide (carbon suboxide, C_3O_2). For some species, we were able to identify the chemical family (defined by its molecular formula and common chemical moiety) but not the exact chemical structure or identity. For these cases, we present the emissions as a sum of the unidentified isomers for a particular chemical family (see Table 2). We report only the compounds that were above the limits of detection for the majority of the biomass burns and where the molecular formula could be identified.

Of the 187 gases quantified by the GC-MS in this study, 95 were individually calibrated with commercially available and/or custom-made gravimetrically-based compressed gas calibration standards. The limit of detection, precision, and accuracy are compound dependent, but are conservatively better than 0.010 ppbv, 15, and 25 %, respectively (Gilman et al., 2009, 2010). For compounds where a calibration standard was not available, the calibration factors were estimated using measured calibrations of compounds in a similar chemical family with a similar retention time, and when possible a similar mass fragmentation pattern. In order to estimate the uncertainty in the accuracy of un-calibrated species, we use measured calibrations of ethyl benzene, o-xylene, and the sum of m- and p-xylenes as a test case. These aromatic species have similar mass fragmentation patterns, are all quantified using m/z 91, and elute within 1 min of each other signifying similar physical properties. If a single calibration factor was used for all these isomers, then the reported mixing ratios could be miscalculated by up to 34 %. We therefore conservatively estimate the accuracy of all un-calibrated species as 50 %.

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2.4 Calculation of emission ratios

Emission ratios (ER) to carbon monoxide (CO) for each gas-phase compound, X, were calculated as follows:

$$\mathrm{ER} = \frac{\Delta X}{\Delta \mathrm{CO}} = \frac{\int_{t_{\mathrm{start}}}^{t_{\mathrm{end}}} (X_{\mathrm{fire}} - X_{\mathrm{bknd}}) \mathrm{d}t}{\int_{t_{\mathrm{start}}}^{t_{\mathrm{end}}} (\mathrm{CO}_{\mathrm{fire}} - \mathrm{CO}_{\mathrm{bknd}}) \mathrm{d}t} \quad (1)$$

where ΔX and ΔCO are the excess mixing ratios of compound X or CO, respectively, during a fire above the background. Background values, X_{bknd} and $\mathrm{CO}_{\mathrm{bknd}}$, are equal to the average mixing ratio of a species in the pre-conditioned ambient air inside the exhaust stack in the absence of a fire. For the OP-FTIR, PTR-MS, PIT-MS and NI-PT-CIMS, backgrounds were determined from the mean responses of the ambient air inside the exhaust stack for a minimum of 60 s prior to the ignition of each fire. At least one background sample was collected for the GC-MS each day. The composition and average mixing ratios of VOCs in the stack backgrounds were consistent over the course of the campaign and were generally much lower than the mixing ratios observed during biomass burns. For example, the average background ethyne measured by the GC-MS was 1.22 ± 0.33 ppbv (median = 1.21 ppbv) compared to a mean ethyne of 150 ± 460 ppbv (median = 42 ppbv) in the fires. The large standard deviation for ethyne in the biomass burns reflects the large variability in ethyne emissions rather than uncertainty in the measurement.

The type of emission ratio, discrete or fire-integrated, is determined by the sampling frequency of the instrument and sampling duration. The GC-MS is only capable of measuring discrete ERs, which represent the average ΔX relative to ΔCO for a relatively short portion of a fire corresponding to the GC-MS sample acquisition time. The OP-FTIR, PTR-MS, and NI-PT-CIMS are fast-response instruments that sampled every 1 to 10 s over the entire duration of each fire. These measurements were used to calculate both fire-integrated ERs that represent to $\Delta X/\Delta$CO over the entirety of a fire ($\mathrm{d}t \geq 1000$ s) (Burling et al., 2010; Veres et al., 2010; Warneke et al., 2011) as well

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as discrete ERs coincident with the GC-MS sample acquisition (dt = 20 to 300 s) as discussed in Sect. 2.3. We reference all ERs to CO because the majority of VOCs and CO are co-emitted by smoldering combustion during the fire whereas CO_2 emissions occur mostly from flaming (see Sect. 3.1). Additionally, ratios to CO are commonly reported in the literature for biomass burning and urban VOC emission sources. All data presented here are in units of ppbv VOC per ppmv CO, which is equivalent to a molar ratio (mmol VOC (mol CO)$^{-1}$).

2.5 Fourmile Canyon Fire in Boulder, Colorado

Ambient air measurements of biomass burning emissions from the Fourmile Canyon Fire that occurred in the foothills 10 km west of Boulder, Colorado were conducted from 7–9 September 2010. Over the course of the Fourmile Fire, approximately 25 km^2 of land including 168 structures burned. The burned vegetation consisted primarily of Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) mixed with juniper (*Juniperius scopulorum* and *communis*), mountain mahogany (*Cercocarpus*), and various shrubs and grasses common to the mountain zone of the Colorado Front Range (Graham et al., 2012). During the measurement period, down-sloping winds ranging from 1 to 12 m s^{-1} (mean = 3.5 m s^{-1}) periodically brought biomass burning emissions to NOAA's Earth Systems Research Laboratory located at the western edge of the city of Boulder. The previously described in-situ GC-MS was housed inside the laboratory and sampled outside air via a 15 m Teflon sample line (residence time < 2 s) attached to an exterior port on the western side of the building. CO was measured via a co-located vacuum-UV resonance fluorescence instrument (Gerbig et al., 1999).

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3 Results and discussion

3.1 Calculation of emission ratios

Temporal profiles of laboratory biomass burns provide valuable insight into the combustion chemistry and processes that lead to the emissions of various species (Yokelson et al., 1996). Figure 1 shows temporal profiles of an example burn in order to illustrate (i) flaming, mixed, and smoldering combustion phases/processes and (ii) the sampling frequencies and temporal overlap of the fast-response instruments compared to the GC-MS. Upon ignition, there is an immediate and substantial increase in CO_2 and NO_x ($NO + NO_2$) indicative of vigorous flaming combustion. This transitions to a mixed-phase characterized by diminishing CO_2 and NO_x emissions and a second increase in CO. The fire eventually evolves to a weakly-emitting, protracted period of mostly smoldering combustion (Yokelson et al., 1996; Burling et al., 2010). Figure 1 also includes the temporal profile of the modified combustion efficiency, $MCE = \Delta CO_2/[\Delta CO + \Delta CO_2]$, which is a proxy for the relative amounts of flaming and smoldering combustion (Yokelson et al., 1996). During the initial flaming phase of the fire, the MCE approaches unity due to the dominance of CO_2 emissions. The MCE gradually decreases during smoldering combustion when CO emissions are more prominent.

In order to compare measurements from multiple instruments, we calculated the average excess mixing ratios of a species, ΔX, measured by the fast-response instruments over the corresponding GC-MS sample acquisition times for all 56 biomass burns. We compare the measurements using correlation plots of ΔX for VOCs measured by the GC-MS vs. the same compound measured by the OP-FTIR or an analogous m/z measured by the PTR-MS. The slopes and correlation coefficients, r, were determined by linear orthogonal distance regression analysis and are compiled in Fig. 2a. The average slope and standard deviation of the instrument comparison is 1.0 ± 0.2 and $0.93 < r < 0.99$ signifying good overall agreement between the different

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measurement techniques for the species investigated here. A few comparisons are discussed in more detail below.

The largest difference between the GC-MS and the OP-FTIR observations was for propene (slope = 1.36) indicating that the GC-MS response is greater than the OP-FTIR; however, a correlation coefficient of 0.99 suggests that the offset is more likely from a calibration difference that remains unresolved. The possibility of a species with the same retention time and similar fragmentation pattern as propene that is also co-emitted at a consistent ratio relative to propene seems highly unlikely, but cannot be completely ruled out. For furan, the GC-MS had a lower response than OP-FTIR (slope = 0.77) indicating that the GC-MS may be biased low for furan or that the OP-FTIR may have spectral interferences that bias the measurement high. The temporal profiles of these measurements shown in Fig. 1 suggest that there was a spectral interference with the OP-FTIR measurement of furan as evidenced by the large emissions in the flaming phase that was not captured by the m/z 69 response of the PTR-MS. These early "spurious" OP-FTIR furan responses would (i) only affect the comparison for the GC-MS samples collected in the flaming phase of the fires and (ii) have not been observed in other biomass burning experiments utilizing this OP-FTIR (Christian et al., 2004; Stockwell et al., 2014).

Comparison of the GC-MS Σ (isoprene + furan) vs. PTR-MS m/z 69 has the lowest slope (GC-MS vs. PTR-MS = 0.64) indicating the contribution of other VOCs, e.g. cis- and trans-1,3-pentadienes, to the m/z 69 response of the PTR-MS in fresh smoke (Warneke et al., 2011). Carbon suboxide (C_3O_2) has also been shown to contribute to m/z 69 response for the PTR-MS technique (Stockwell et al., 2015). Direct comparisons of the real-time measurements for a variety of other species not measured by the GC-MS (e.g., formaldehyde, formic acid, and HONO) can be found elsewhere (Burling et al., 2010; Veres et al., 2010; Warneke et al., 2011).

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3.2 Comparison of discrete and fire-integrated ERs

Fire-integrated ERs represent emissions from all combustion processes of a biomass burn whereas discrete ERs capture a relatively brief snapshot of emissions from mixed combustion processes during a particular sampling period. Figure 1 includes time series of VOC to CO ERs measured by the real-time measurement techniques for select gases. Here we compare the 2 different measurement strategies, discrete vs. fire-integrated, in order to (i) determine if the discrete ERs measured by the GC-MS may be biased by the sample acquisition times which typically occurred within the first-half of a laboratory burn when emissions for most gases generally "peaked" and (ii) assess how well the discrete GC-MS samples are able to capture the fire-to-fire variability of emissions relative to CO. We do this by determining discrete ERs for the OP-FTIR or PTR-MS for each of the 56 biomass burns using Eq. (1) where t_{start} and t_{end} times correspond to the GC-MS sample acquisition. The discrete ERs are then compared to the fire-integrated ERs measured by the same fast-response instrument so that potential measurement artifacts will not affect the comparison.

The slopes and correlation coefficients, r, of discrete vs. fire-integrated ERs for select VOCs are summarized in Fig. 2b. These values were calculated using a linear orthogonal distance regression analysis of correlation plots of discrete vs. fire-integrated ERs as shown in Fig. 3. The average slope and standard deviation is 1.2 ± 0.2 indicating that the discrete ERs are generally higher than the fire-integrated ERs by 20 % on average. This positive bias is a consequence of the GC-MS sampling strategy which rarely included samples collected at the end of a burn (e.g., $t \geq 1000$ s in Fig. 1) when absolute emissions and ERs are lower for most species. Using the data in Fig. 1 as an example, 95 % of the emissions of benzene (in ppbv) occur between ignition and 1000 s, and the mean ER during this time is twice as large as the mean ER in the later portion of the fire (time = 1001 s to extinction). For VOCs emitted during the later stages of a fire (e.g., 1,3-benzenediol), the discrete ERs will likely underestimate the emissions relative to CO. For example, the discrete ERs for benzenediol for the southeastern and south-

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western fuels (Table 2) are 30 % lower than the mean fire-integrated ERs reported by Veres et al. (2010).

The ability of the GC-MS to capture the fire-to-fire variability in VOC emissions relative to CO is evaluated by the strength of the correlation, r, between the discrete and fire-integrated ERs (Fig. 2b). Species with the weakest correlations, such as ethyne and benzene, show a distinct bifurcation that is dependent upon the MCE of the discrete samples (Fig. 3). These compounds have significant portion of emissions in both the flaming and smoldering phases of a fire (see Fig. 1). For these types of compounds, discrete samples collected in the smoldering phase (low MCE) did not adequately represent the fire-integrated emissions that include the intense flaming emissions (high MCE) resulting in poor correlation between discrete and fire-integrated ERs for these species. In contrast, VOCs that had the strongest correlations between the discrete and fire-integrated ERs (e.g., methanol and toluene where $r > 0.88$) do not show a strong dependence on the MCE. Since CO is strongly associated with smoldering combustion (Yokelson et al., 1996; Burling et al., 2010), VOCs emitted primarily during this phase will be more tightly correlated with CO and the variability in the discrete vs. fire-integrated will be minimized.

In summary, the discrete GC-MS samples best characterize the fire-integrated emissions and fire-to fire variability of species produced primarily by smoldering combustion. We conservatively estimate these values to be within a factor of 1.5 of the fire-integrated ERs for the majority of the species measured. A similar conclusion was reached by comparing discrete ERs measured during the same fire to each other by Yokelson et al. (2013). While fire-integrated ERs are considered to best represent BB emissions, these analyses suggest that collecting and averaging multiple discrete ERs at various stages of the same or replicate burns, as presented here, are an adequate substitute when fire-integrated ERs cannot be determined. Fire-integrated ERs are commonly used to determine fuel-based emission factors for a fire, but care must be taken converting discrete ERs into emission factors, as also discussed for this data in Yokelson et al. (2013).

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3.3 Characterization of laboratory BB emissions

In order to merge datasets from multiple instruments, we report mean discrete ERs of over 200 organic gases, including methane and VOCs, and 9 inorganic gases relative to CO for the southwestern, southeastern, and northern fuel types in the United States (Table 2). Mean ERs for each of the 18 individual fuel types are available at http://www.esrl.noaa.gov/csd/groups/csd7/measurements/2009firelab/. This study utilizes discrete ERs to characterize the chemical composition of the molar mass emitted, the VOC-OH reactivity, and the SOA potential of the measured emissions from fires simulating each fuel region in order to compare potential atmospheric impacts of these emissions and identify key species that may impact air quality through formation of O_3 and/or SOA.

Figure 4 is a pictograph of all ERs presented in Table 2 as well as a histogram of the ERs for each of the 3 fuel regions in order to highlight commonalities and differences in the magnitudes and general chemical composition of each simulated fuel region. The distribution of ERs are shown as a function of three simple properties including the degree of unsaturation ($D = [2C + N - H + 2]/2$, where C, N, and H denote the number of carbon, nitrogen, and hydrogen atoms, respectively); the number of oxygen atoms; and molecular weight (MW) of individual VOCs. Atmospheric lifetimes and fates of VOCs will depend, in part, on these properties, which we use as simplified proxies for reactivity (D), solubility (O-atoms), and volatility (MW). Using this general framework, we highlight several key features that will be explored in further detail in the subsequent sections:

i. ERs are highly variable and span more than 4 orders of magnitude.

ii. The relative magnitude and composition of the gases emitted are different for each of the 3 geographic fuel regions, i.e., the distribution of ERs are unique to each fuel region.

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iii. Southwestern fuels generally have lower ERs and northern fuels have the largest ERs. Collectively, the molar emission ratios are a factor of 3 greater for the northern fuels than the southwestern.

iv. The largest ERs for all three fuel regions are associated with low molecular weight species (MW < 80 g mol^{-1}) and/or those that contain 1 or more oxygen atom(s). These species also have lower degrees of unsaturation ($D \leq 2$) and populate the upper left quadrants of Fig. 4. VOCs with the largest ERs common to all fuel types are formaldehyde, ethene, acetic acid, and methanol (Table 2).

v. Over 82 % of the molar emissions of VOCs from biomass burning are unsaturated compounds ($D \geq 1$) defined as having one or more pi-bonds (e.g., C-C or C-O double bonds, cyclic or aromatic rings, etc.). In general, these species are more likely to react with atmospheric oxidants and/or photo-dissociate depending on the chemical moiety, making unsaturated species potentially important O_3 and SOA precursors. VOCs that contain triple bonds (e.g., ethyne) are a notable exception as they tend to be less reactive.

vi. The number of VOCs in the upper right quadrants of Fig. 4 (increasing ERs and degree of unsaturation) is greatest for northern fuels and least for southwestern fuels. Many of the VOCs in this quadrant also have relatively high molecular weights (MW ≥ 100 g mol^{-1}) and most contain at least one oxygen atom (e.g., benzenediol and benzofuran). The combination of these physical properties indicate that these species are relatively reactive, soluble, and of low enough volatility to make them potentially important SOA precursors.

3.3.1 Molar mass emitted

Here we compare the magnitude and composition of biomass burning emissions as a function of molar mass, which is a readily calculated physical property used to quan-

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tify BB emissions. Molar mass ($\mu g\,m^{-3}$) emitted per ppmv CO is equal to:

$$\text{Molar Mass} = \sum \left(\frac{\text{ER} \cdot \text{MW}}{\text{MV}} \right) \quad (2)$$

where ER is the mean discrete emission ratio of a gas, MW is the molecular weight ($g\,mol^{-1}$), and MV is molar volume (24.5 L at 1 atm and 25 °C). For all 3 fuel regions, CO_2 was the overwhelmingly dominant gas-phase emission and singularly contributed over 95 % of the molar mass emitted. Collectively, CH_4 and the inorganic gases (e.g., CO_2, CO, NO_x, etc.) comprised over 99.05 % of all gaseous molar mass emitted and measured, while VOCs contributed only 0.27 ± 0.03, 0.34 ± 0.03, and 0.95 ± 0.07 % for the southeastern, southwestern, and northern fuels, respectively.

Figure 5a–c shows the fractional composition and total molar mass of measured VOCs emitted per ppmv CO for each fuel region. The molar mass emitted by northern fuels ($324 \pm 22\,\mu g\,m^{-3}$ ppmv CO^{-1}) is 3.5 times greater than the southwestern fuels ($92 \pm 9\,\mu g\,m^{-3}$ ppmv CO^{-1}). For all 3 fuel regions, the emissions are dominated by oxygen-containing VOCs (OVOCs), which collectively comprise 57–68 % of the total mass emissions. The largest contribution by a single chemical class is from OVOCs with low degrees of unsaturation ($D \leq 1$), which contribute 29–40 % of the total molar mass emitted. This chemical family is dominated by acetic acid, formaldehyde, and methanol emissions (Table 2). Compared to hydrocarbons and OVOCs, nitrogen-containing VOCs are emitted in substantially smaller fractions, less than 8 % of the total. Dominant nitrogen VOCs include hydrocyanic acid (HCN), isocyanic acid (HNCO), acetonitrile (CH_3CN), and methylnitrite (CH_3ONO). The addition of all nitrogen-containing organics presented here would add approximately 5 % to the nitrogen budget presented in Burling et al. (2010); however, this would still leave over half of the fuel nitrogen potentially ending up in the ash, or being emitted as N_2 or in other unmeasured gases based on the nitrogen content of the fuels which ranged from 0.48 to 1.3 %.

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One limitation of this analysis is the exclusion of "unknown" species, which are (i) gaseous compounds that were measured but remain unidentified and were therefore omitted from this analysis because the chemical formula and family could not be properly identified or (ii) were undetectable by the suite of instruments listed in Table 1. We estimate the mass contribution from the first scenario using the fuel-based emission factors compiled by Yokelson et al. (2013) for all measured species including "unknown" masses observed by the PIT-MS. These "unidentified" non-methane organic compounds (NMOC, equivalent to VOCs) accounted for 31–47 % of the mass emitted for the same fuels studied here (Yokelson et al., 2013). The second category of unobserved unknown species are likely to be of sufficiently high molecular weight, high polarity, and/or low volatility and thermal stability to escape detection by GC-MS, a variety of chemical ionization mass spectrometers, and the OP-FTIR. For example, BB emissions of species such as glyoxal, glycoaldehyde, acetol, guaiacols, syringols, and amines have been reported in the literature (McDonald et al., 2000; Schauer et al., 2001; McMeeking et al., 2009; Akagi et al., 2011, 2012; Hatch et al., 2015) but would not be detectable by any of the instruments used in this experiment. The contribution of these types of compounds is difficult to assess, so we roughly estimate an additional contribution of ~ 5 % to the total mass emitted could be from un-observed unknown VOCs. Collectively, we estimate that the species reported in Table 2 and compiled in Fig. 5a–c account for approximately 48–64 % of the expected mass of non-methane organic gases emitted from the fuels studied here. The total VOC molar mass emitted for each fuel type should be considered a lower limit and could increase by a factor of ~ 2. By extension, all of the totals presented in Fig. 5 should also be considered lower limits; however, the additional contribution of unidentified and/or un-measured species to the following discussions could not be determined.

3.3.2 OH reactivity of BB emissions

Oxidation of VOCs, often initiated by reaction with the hydroxyl radical (•OH), in the presence of NO_x ($NO + NO_2$) leads to the photochemical formation of O_3 and perox-

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ynitrates, including peroxyacetic nitric anhydride (PAN). Due to the complex relationship between O_3 production and VOC/NO_x ratios and peroxynitrates, we use OH reactivity as a simplified metric to (i) compare the magnitude of reactive gases emitted by combustion of fuels characteristic of each region and to (ii) identify key reactive species that may contribute to the photochemical formation of O_3 in a BB plume. Total OH reactivity represents the sum of all sinks of the hydroxyl radical (•OH) with all reactive gases and is equal to:

$$\text{OH reactivity} = \sum(\text{ER} \cdot k_{\text{OH}} \cdot A) \quad (3)$$

where ER is the discrete emission ratio for each measured gases (VOCs, CH_4, CO, NO_2, and SO_2; ppbv (ppm CO)$^{-1}$), k_{OH} is the first-order reaction rate coefficient of a gas with the hydroxyl radical (cm^3 molec^{-1} s^{-1}), and A is a molar concentration conversion factor (2.46×10^{10} molec cm^{-3} ppbv^{-1} at 1 atm and 25 °C). Reaction rate coefficients were compiled using the National Institute of Standards and Technology's Chemical Kinetics Database and the references therein (Manion et al., 2015). Based on the calculated OH reactivities of all measured species listed in Table 2, VOCs are the dominant sink of OH for all fuel regions contributing 70–90 (±16) % of the total calculated OH reactivity even though non-methane VOCs were only 0.27–0.95 % of the molar mass emitted.

Figure 5d–f shows the fractional contributions and total VOC-OH reactivities per ppmv CO for each of the 3 fuel regions. The fresh BB emissions from northern fuels have the highest OH reactivity (62 ± 10 s^{-1} ppmv CO^{-1}), which is 4.4 times greater than southwestern fuels (14 ± 3 s^{-1} ppmv CO^{-1}). Collectively, OVOCs provide the majority of the OH reactivity of the southeastern fuels (57 %), while hydrocarbons dominate the southwestern (52 %) and northern fuels (56 %). Northern fuels have the largest contribution from highly reactive terpenes (14 %) due to the ERs of these species being, on average, a factor of 5 greater than southeastern fuels and a factor of 40 greater than southwestern fuels.

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For all 3 fuel regions, alkenes have the largest contribution of any singular chemical class due to the large ERs of the reactive species ethene and propene, the latter of which is the single largest individual contributor to OH reactivity of any species measured. Oxidation of alkenes proceeds by OH addition to the double-bond or hydrogen abstraction and often results in the secondary formation of carbonyls (e.g., acetaldehyde and acetone), which are important peroxynitrate precursors (Roberts et al., 2007; Fischer et al., 2014). Primary emissions of formaldehyde is the second-largest contributor, after propene, to the OH reactivity of all VOCs emitted for all 3 fuel regions. Formaldehyde is reactive with OH and is a photolytic source of RO• radicals that also contribute to O_3 formation, in addition to being an air toxic.

Other important contributions to OH reactivity of BB emissions include highly unsaturated OVOCs (e.g., 2-propenal, methyl vinyl ketone, and methacrolein), polyunsaturated alkenes (e.g., 1,3-butadiene and 1,3-cyclopentadiene), and furans. The majority of these types of species are highly reactive with a variety of oxidants and many of their oxidation products are photochemically active. For example, oxidation of 1,3-butadiene results in highly reactive OVOC products including furans and 2-propenal, a precursor of peroxyacrylic nitric anhydride (APAN) (Tuazon et al., 1999). The OH reactivity of furans is dominated by 2-methylfuran, 2-furaldehyde (2-furfural), and furan. Alkyl furans have reaction rate coefficients on the order of $\sim 1 \times 10^{-10}$ cm^3 molec^{-1} s^{-1} at 298 K roughly equivalent to that of isoprene and the major oxidation products include dicarbonyls (Bierbach et al., 1992, 1995; Alvarez et al., 2009). Up to 27 furan isomers have been identified from the combustion of Ponderosa Pine (Hatch et al., 2015), indicating this is an important class of species that should be further explored in order to better determine their potential contributions to O_3 and SOA formation.

Nitrogen-containing VOCs contribute less than 4 % of the OH reactivity of all fuels due to the low reactivities of the most abundant emissions, which often contain –C≡N functional groups. Some nitriles, such as acetonitrile (CH_3CN), can have lifetimes on the order of months making these species good markers of long-range transport of

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BB plumes (Holzinger et al., 1999; de Gouw et al., 2003, 2006). Other more reactive nitrogen-containing organics including 2-propenenitrile, benzonitrile, and heterocyclic species such as pyrroles could serve as BB markers of fresh plumes (Friedli et al., 2001; Karl et al., 2007).

3.3.3 SOA potential of BB emissions

VOCs that are efficient SOA precursors are relatively reactive organic compounds whose oxidation products are of sufficiently low volatility or high solubility under some conditions. Aerosol yield is a measure of the mass of condensable compounds created from this oxidation per mass of VOC precursor; however, care must be taken to ensure that aerosol yields for various species were determined under comparable conditions (e.g., VOC : NO_x ratios, oxidant concentrations, etc.). In order to conduct comparisons of SOA potential on a consistent scale, we use a model-based unitless metric developed by Derwent et al. (2010) that "reflects the propensity of VOCs to form SOA on an equal mass basis relative to toluene". The photochemical transport model used to investigate SOA potentials (SOAPs) of 113 VOCs included explicit chemistry from the Master Chemical Mechanism (MCM v 3.1) using an idealized set of atmospheric conditions typical of a polluted urban boundary layer (Derwent et al., 2010). SOAPs were determined by the simulated mass of aerosol formed per mass of VOC reacted and is expressed relative to toluene (SOAP = 100). Species such as styrene and benzaldehyde have SOAP values of ~ 200 (i.e., twice as much potential SOA formed compared to toluene) and were used to estimate SOAPS for aromatics with unsaturated substituents, benzofurans, and benzenediols.

Figure 5g–i shows the composition and mean SOAPs of VOCs emitted for each of the 3 fuel regions. Southwestern fuels have the lowest SOA potential (480 per ppmv CO) compared to southeastern and northern fuels that have estimated SOAPs 2.7 and 5.1 times greater, respectively. Unsaturated OVOCs are the dominant fraction for all three fuel regions due to the relatively large ERs and SOAPs of benzenediols (sum of 1,2- and 1,3-), benzaldehyde, and phenols. Schauer et al. (2001) reports signifi-

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cant gaseous emissions of benzenediols from combustion of pine in a fireplace and shows that 1,2-benzenediol (o-benzenediol) is the dominant gas-phase isomer while 1,3-benzenediol (m-benzenediol) is primarily associated with the particle phase. The discrete ERs used in this comparison may underestimate the emissions and SOA contribution of several compounds emitted in the later portions of a laboratory burn when emissions of most VOCs and CO were lower as previously discussed (Sect. 3.2).

The largest contributions to SOAP from hydrocarbons include aromatics with saturated functional groups (if any) such as benzene and toluene and aromatics with unsaturated substituents such as styrene. Traditionally, these are the species that are thought to be the largest contributors to SOA formation from urban emissions (Odum et al., 1997; Bahreini et al., 2012), although predicted SOA is typically much lower than observed in ambient air suggesting that the aerosol yields may be too low or there are additional SOA precursors that remain unaccounted for (de Gouw et al., 2005).

Monoterpenes have a very small (< 2 %) contribution to total SOAP. The calculated SOAPs of monoterpenes are only 20 % that of toluene (Derwent et al., 2010). This is in contrast to measured aerosol yields which are approximately 1.7 times higher for monoterpenes compared to toluene (Pandis et al., 1992). As a sensitivity test, we increased the SOAPs of the monoterpenes by a factor of 10 bringing the SOAP ratio of monoterpenes to toluene in line with that of measured aerosol yields. This resulted in modest increases in total SOAP of only 2 % for SW and 5 % for SE fuels. N fuels had the largest increase in total SOAP at 16 %. With the adjusted monoterpene SOAPs, the fractional contribution of terpenes increased from 1.8 % (Fig. 5i) to 15 % of the total SOAP while the contribution of unsaturated OVOCs remained the dominant class but was reduced from 67 to 58 % of the total SOAP. This sensitivity test suggests that the contributions of monoterpenes are likely underestimated for northern fuels if the SOAP scale is used; however, the largest contributions to SOAP for the northern fuels continues to be from oxygenated aromatics (benzenediols, phenols, and benzaldehyde). For comparison, Hatch et al. (2015) estimated that the SOA mass formed from the combustion of Ponderosa Pine is dominated by aromatic hydrocarbons (45 %), terpenes

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(25 %), phenols (9 %), and furans (9 %); however, their analysis did not include contributions from benzenediols (not measured), benzaldehyde or benzofurans (measured but not included in estimate).

3.4 Field measurements of BB emissions

Here we present field-measurements of VOCs in ambient air during the Fourmile Canyon Fire that affected Boulder, Colorado in September 2010. The in-situ GC-MS measurements are shown in Fig. 6 and summarized in Table 3. We were able to identify and quantify a number of VOCs in ambient BB plumes that we had only previously observed in the fire emissions at the Fire Sciences Laboratory. Analysis of BB plumes from the Fourmile Canyon Fire afforded a unique opportunity to investigate BB emissions measured by this same GC-MS system in simulated and real fires and to explore issues associated with the presence of other VOC sources such as urban emissions and natural biogenic emissions during both the daytime and nighttime; with nighttime smoke measurements being very rarely reported (Adler et al., 2011).

First we identify the potential emission sources impacting the measurements. Acetonitrile is a common BB tracer that we use to help clarify periods of BB influence. As seen in Fig. 6, BB plumes are readily distinguished by concurrent increases in acetonitrile (CH_3CN), carbon monoxide (CO), and several VOCs. Species such as benzonitrile and furan are very tightly correlated with acetonitrile ($r > 0.94$, Table 3) and enhancements in ambient mixing ratios above detection limit only occur in the BB plumes indicating that BB was the only significant source of these compounds. VOCs such as isoprene and alpha-pinene were similarly enhanced in the BB plumes and well correlated with acetonitrile during BB episodes; however, the mixing ratios observed in the BB plume were generally lower than those observed at other times from the natural sunlight-dependent emissions of isoprene (e.g., 09:00–15:00 LT) and from the accumulation of monoterpenes in the nocturnal boundary layer (e.g., 9 August 2010 18:00 to 9 September 2010 06:00 LT). 3-Carene was the only monoterpene that had significantly higher mixing ratios in the BB plume than in biogenic emissions. Ethene, ethyne,

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benzene, styrene, and methanol were enhanced in the BB plumes but are also present in urban emissions. An urban plume at 06:00–09:00 LT 9 September 2010 (Fig. 6) is enhanced in all of these species and CO; however, acetonitrile is not enhanced.

Observed enhancement ratios of several VOCs relative to acetonitrile and CO are compiled in Table 3 along with the types of emission sources for each VOC. Figure 7 shows a comparison of the VOC to acetonitrile ratios of select species for the Fourmile Canyon Fire and the laboratory-based biomass burns of all fuel types. We have identified benzofuran, 2-furaldehyde, 2-methylfuran, furan, and benzonitrile as the "best" tracers for BB emissions from these observations. These species (i) were well correlated with both acetonitrile and CO in the BB plumes, (ii) had negligible emissions from the urban and biogenic sources impacting the measurement site, and (iii) had large enhancements in BB plumes. In theory, the relative ratios of these species to acetonitrile may also be used as a BB-specific photochemical clock since each of these species represent a range of reactivities that are much greater than that of acetonitrile (Table 3). We compared the enhancement ratios of each VOC marker vs. acetonitrile for the two BB plumes observed on 9 August 2010 in order to determine if the relative age of the two BB plumes could be distinguished. While the enhancement ratios for several VOCs in each plume were statistically different from one another, there was no clear relationship between the observed differences in the enhancement ratios and the relative reactivity of the VOCs. Thus, small differences in the observed enhancement ratios more likely relate to differences in the fuel composition, the relative ratio of flaming vs. smoldering emissions in each BB plume, or variable secondary sources. Given enough time for significant photochemistry to occur as a BB plume moves further from the source, these ratios could be more useful to estimate photochemical ages.

4 Conclusions

We report a chemically detailed analysis of the trace gases emitted from burning 18 different biomass fuel types important in the southwestern, southeastern, and northern

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US. A complementary suite of state-of-the-art instruments was used to identify and quantify over 200 organic and 9 inorganic gases emitted from laboratory burns. Most of the species were quantified via discrete sampling by the GC-MS, which also provided confirmation for the real-time PIT-MS and PTR-MS mass assignments (Warneke et al., 2011). The variability in emissions over the course of each biomass burn was measured in detail by the fast-response instruments providing valuable insight into the combustion chemistry and processes that govern the emissions of various species.

By comparing discrete and fire-integrated ERs for various VOCs relative to CO, we show that the discrete GC-MS samples adequately represented the fire-integrated ER within an average factor of 1.2 ± 0.2 and fire-to-fire variability for VOCs emitted mainly by smoldering, which are the majority of VOCs. Discrete ERs for VOCs emitted by both flaming and smoldering were highly variable and showed a clear bifurcation depending on the mix of combustion processes during sampling. This analysis highlights the importance of collecting multiple discrete samples at various stages of replicate burns if fire-integrated emissions cannot be measured to ensure adequate measurement of all VOCs.

The distribution of VOC emissions (magnitude and composition) was different for each fuel region. The largest total VOC emissions were from fuels representing the northern U.S. while southwestern U.S. fuels produced the lowest total VOC emissions. VOCs contributed less than 0.78 ± 0.12 % of total detected gas-phase emissions by mole and less than 0.95 ± 0.07 % by mass due to the predominance of CO_2, CO, CH_4, and NO_x emissions. However, VOCs contributed 70–90 ($\pm$16) % of the total calculated OH reactivity and 100 % of the potential SOA precursors emitted from combustion of biomass. Over 82 % of the VOC emissions by mole are unsaturated species including highly reactive alkenes, aromatics and terpenes as well as photolabile OVOCs such as aldehydes and ketones. VOCs with the largest ERs common to all fuel types are formaldehyde, ethene, acetic acid, and methanol.

OVOCs contributed the dominant fraction of both the total VOC mass emitted (> 57 %) and potential SOA precursors (> 52 %), and also contributed a significant

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fraction of the OH reactivity for all fuel regions making them an important class of VOCs to understand the air quality impacts of BB emissions. Reactive and photolabile OVOCs such as formaldehyde, 2-propenal (acrolein), and 3-butenal (crotonaldehyde) are toxic, a source of free radicals, and/or precursors of peroxynitrates that may contribute to O_3 formation downwind of the source. Furans are a class of OVOCs in BB emissions that contributed more than 14 % of the OH reactivity for all fuel regions; however, their potential as SOA precursors, particularly for species such as 2-furaldehyde and benzofuran, requires further study. The estimated SOA potential was dominated by oxygenated aromatics (benzenediols, phenols, and benzaldehyde). Potentially important species that were not measured but should be considered in future studies include glyxoal, glycoaldehyde, acetol, guaiacols, and syringols (Stockwell et al., 2015).

The Fourmile Canyon Fire in Boulder, CO, allowed us to identify and quantify a number of VOCs in ambient BB plumes that we had only previously observed in the emissions from laboratory fires at the Fire Sciences facility and investigate BB emissions in the presence of other VOC sources such as urban emissions and biogenic emissions during both the day and nighttime. We identified benzofuran, 2-furaldehyde, 2-methylfuran, furan, and benzonitrile as the "best" tracers for BB emissions from our observations. In theory, the relative ratios of these species to acetonitrile may also be used as a BB-specific photochemical clock since each of these species represent a range of reactivities assuming a negligible photochemical source.

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Table 1. Instrument description.

Name	Instrument	Meas. Description	Sampling Limitations	References
GC-MS	*Gas chromatograph-(Quadrupole) Mass Spectrometer*	Discrete sampling via cryogenic pre-concentration, chromatographic separation, and identification via retention time and electron impact ionization mass spectrum	Melting point > −185 °C boiling point < 220 °C sufficiently non-polar mass frag. (m/z): 26 to 150 a.m.u	Goldan et al. (2004) Gilman et al. (2010)
PTR-MS	*Proton Transfer Reaction-(Quadrupole) Mass Spectrometer*	Real-time sampling via proton transfer reactions with H_3O^+ and identification via protonated ion $(M+H)^+$ with quadrupole mass filter	Proton affinity greater than water; Protonated molecular mass or mass fragment (m/z): 20–240 a.m.u	Warneke et al. (2011)
PIT-MS	*Proton Transfer Reaction-(Ion Trap) Mass Spectrometer*	Real-time sampling via proton transfer reactions with H_3O^+ and identification via protonated ion $(M+H)^+$ with ion trap mass spectrometer	Proton affinity greater than water; Protonated molecular mass or mass fragment (m/z): 20–240 a.m.u	Warneke et al. (2011)
NI-PT-CIMS	*Negative Ion-Proton Transfer Reaction-(Quadrupole) Mass Spectrometer*	Real-time sampling via proton transfer reactions with $CH_3C(O)O^-$ and identification via deprotonated ion $(M-H)^-$ with quadrupole mass filter	Gas-phase acidity greater than that of acetic acid; Deprotonated molecular mass or mass fragment (m/z): 10–225 a.m.u	Veres et al. (2011) Roberts et al. (2011)
OP-FTIR	*Open Path-Fourier Transform Infrared Spectrometer*	Real-time spectral scanning via open path White cell, offline identification via compound specific infrared absorption features	Strong absoprtion features between 600–3400 cm^{-1} that are unique and have minimal interferences from other strong infrared-absorbers	Burling et al. (2011)

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Table 2. Mean VOC to CO discrete emission ratios (ERs) for the southwestern (SW), southeastern (SE), and northern (N) fuel regions.

Name	Formula	MW	*D*	*m/z*	SW Avg	(±SD)	npnts	SE Avg	(±SD)	npnts	N Avg	(±SD)	npnts
Alkanes (Saturated, *D* = 0)													
Ethane	C2H6	30	0	*27*	**1.8388**	(1.2846)	*25*	**4.5311**	(3.8024)	*23*	**6.8510**	(3.5152)	*4*
Propane	C3H8	44	0	*27*	**0.6317**	(0.9985)	*23*	**1.5957**	(1.2193)	*18*	**1.4633**	(0.9354)	*4*
Butane_iso	C4H10	58	0	*43*	0.0522	(0.0813)	*29*	0.2984	(0.4734)	*20*	0.0982	(0.0620)	*4*
Butane_n	C4H10	58	0	*43*	**0.1038**	(0.1829)	*29*	**0.3333**	(0.2902)	*20*	**0.4005**	(0.2804)	*4*
Propane_22dimethyl	C5H12	72	0	*57*	0.0003	(0.0008)	*29*	0.0004	(0.0008)	*23*	0.0006	(0.0007)	*4*
Pentane_iso	C5H12	72	0	*43*	0.0167	(0.0585)	*29*	0.0580	(0.0878)	*23*	0.0322	(0.0261)	*4*
Pentane_n	C5H12	72	0	*43*	0.0271	(0.0427)	*29*	0.0889	(0.0789)	*23*	0.1400	(0.1130)	*4*
Butane_22dimethyl	C6H14	86	0	*71*	0.0002	(0.0008)	*29*	0.0001	(0.0002)	*23*			*0*
Pentane_3methyl	C6H14	86	0	*57*	0.0009	(0.0010)	*9*	0.0089	(0.0117)	*16*	0.0045	(0.0031)	*4*
Hexane_n	C6H14	86	0	*57*	0.0159	(0.0225)	*29*	0.0572	(0.0516)	*23*	0.0814	(0.0634)	*4*
Heptane_n	C7H16	100	0	*43*	0.0218	(0.0176)	*9*	0.0640	(0.0387)	*14*	0.0836	(0.0674)	*4*
Octane_n	C8H18	114	0	*43*	0.0138	(0.0128)	*9*	0.0469	(0.0281)	*14*	0.0536	(0.0353)	*4*
Nonane_n	C9H20	128	0	*57*	0.0085	(0.0079)	*9*	0.0358	(0.0213)	*13*	0.0369	(0.0269)	*4*
Decane_n	C10H22	142	0	*57*	0.0083	(0.0060)	*9*	0.0310	(0.0222)	*14*	0.0330	(0.0212)	*4*
Undecane_n	C11H24	156	0	*57*	0.0111	(0.0054)	*8*	0.0412	(0.0304)	*12*	0.0425	(0.0208)	*4*
Alkenes (Saturated, *D* = 1)													
Ethene	C2H4	28	1	*27*	***5.8525***	(4.1077)	*25*	***8.1879***	(4.2382)	*21*	***18.3160***	(12.8430)	*4*
Propene	C3H6	42	1	*41*	**2.0801**	(2.0528)	*29*	**3.4917**	(2.1610)	*23*	**8.5115**	(3.4340)	*4*
Propene_2methyl	C4H8	56	1	*41*	0.1046	(0.1652)	*29*	0.2668	(0.2151)	*23*	0.3162	(0.3624)	*4*
Butene_1	C4H8	56	1	*41*	**0.2961**	(0.3761)	*29*	**0.4851**	(0.3320)	*23*	**1.5227**	(0.6632)	*4*
Butene_cis2	C4H8	56	1	*41*	0.0579	(0.0937)	*29*	0.1209	(0.0920)	*23*	0.2397	(0.1916)	*4*
Butene_trans2	C4H8	56	1	*41*	0.0615	(0.1036)	*29*	0.1427	(0.1174)	*23*	0.2732	(0.2648)	*4*
Butene_1_2methyl	C5H10	70	1	*55*	0.0202	(0.0256)	*29*	0.0391	(0.0284)	*23*	0.0881	(0.0462)	*4*
Butene_1_3methyl	C5H10	70	1	*55*	0.0091	(0.0202)	*8*	0.0152	(0.0168)	*15*	0.0183	(0.0164)	*4*
Butene_2_2methyl	C5H10	70	1	*55*	0.0224	(0.0317)	*8*	0.0996	(0.0634)	*14*	0.1881	(0.0965)	*4*
Cyclopentane	C5H10	70	1	*42*	0.0024	(0.0040)	*29*	0.0064	(0.0053)	*23*	0.0108	(0.0074)	*4*
Pentene_1	C5H10	70	1	*55*	0.0429	(0.0654)	*29*	0.0902	(0.0773)	*23*	0.2311	(0.1872)	*4*
Pentene_cis2	C5H10	70	1	*55*	0.0432	(0.0638)	*8*	0.1396	(0.0883)	*14*	0.2905	(0.1492)	*4*
Pentene_trans2	C5H10	70	1	*55*	0.0276	(0.0341)	*29*	0.0422	(0.0304)	*23*	0.1180	(0.0667)	*4*
Cyclopentane_1methyl	C6H12	84	1	*56*	0.0040	(0.0037)	*9*	0.0147	(0.0139)	*16*	0.0159	(0.0113)	*4*
Pentene_1_2methyl	C6H12	84	1	*56*	0.0890	(0.1102)	*9*	0.1782	(0.1162)	*14*	0.4980	(0.2945)	*4*
Cyclohexane	C6H12	84	1	*84*	0.0012	(0.0014)	*9*	0.0052	(0.0028)	*14*	0.0052	(0.0035)	*4*
Hexene_1	C6H12	84	1	*84*	0.1029	(0.1182)	*8*	0.2039	(0.0943)	*12*	0.4904	(0.2844)	*4*
Hexene_cis2	C6H12	84	1	*84*	0.0256	(0.0338)	*9*	0.0522	(0.0443)	*16*	0.1552	(0.0586)	*4*
Hexenes (sum of 3 isomers)	C6H12	84	1	*84*	0.0931	(0.1166)	*9*	0.1788	(0.1376)	*16*	0.5432	(0.2920)	*4*
Cyclohexane_methyl	C7H14	98	1	*83*	0.0023	(0.0023)	*8*	0.0097	(0.0063)	*14*	0.0111	(0.0071)	*4*
Heptene_1	C7H14	98	1	*56*	0.0547	(0.0595)	*9*	0.1168	(0.0721)	*14*	0.2868	(0.1559)	*4*
Octene_1	C8H16	112	1	*55*	0.0431	(0.0486)	*9*	0.1013	(0.0482)	*13*	0.1651	(0.0926)	*4*
Nonene_1	C9H18	126	1	*41*	0.0097	(0.0122)	*9*	0.0196	(0.0153)	*16*	0.0474	(0.0326)	*4*
Decene_1	C10H20	140	1	*56*	0.0133	(0.0159)	*9*	0.0260	(0.0228)	*16*	0.0812	(0.0415)	*4*
Undecene_1	C11H22	154	1	*55*	0.0103	(0.0100)	*9*	0.0279	(0.0292)	*16*	0.0647	(0.0251)	*4*

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Table 2. Continued.

Name	Formula	MW	*D*	*m/z*	SW Avg	(±SD)	npnts	SE Avg	(±SD)	npnts	N Avg	(±SD)	npnts
Alkynes and Alkenes (Polyunsaturated, $D > 0$)													
Ethyne	C2H2	26	2	*IR*	**2.3905**	(3.0119)	*27*	**1.7412**	(1.3580)	*23*	**5.0910**	(5.6894)	*4*
Propyne	C3H4	40	2	*39*	**0.2093**	(0.1503)	*29*	**0.1850**	(0.1626)	*23*	**0.7876**	(0.6405)	*4*
Butadiyne_13 (Diacetylene)	C4H2	50	4	*50*	0.0080	(0.0054)	*9*	0.0041	(0.0052)	*16*	0.0427	(0.0651)	*4*
Butenyne (Vinylacetylene)	C4H4	52	3	*52*	0.0285	(0.0452)	*9*	0.0154	(0.0190)	*16*	0.0824	(0.1062)	*4*
Butadiene_12	C4H6	54	2	*54*	0.0101	(0.0146)	*29*	0.0087	(0.0095)	*23*	0.0441	(0.0343)	*4*
Butadiene_13	C4H6	54	2	*54*	**0.4065**	(0.5315)	*29*	**0.4122**	(0.3530)	*23*	**1.8781**	(0.9509)	*4*
Butyne (1- or 2-)	C4H6	54	2	*54*	0.0221	(0.0287)	*9*	0.0158	(0.0146)	*16*	0.0693	(0.0300)	*4*
Cyclopentadiene_13	C5H6	66	3	*66*	0.1724	(0.3868)	*8*	0.1747	(0.0992)	*14*	0.5836	(0.3458)	*4*
Pentenyne isomer (e.g., propenylacetylene)	C5H6	66	3	*66*	0.0161	(0.0176)	*9*	0.0107	(0.0119)	*16*	0.0651	(0.0395)	*4*
Butyne_3methyl	C5H8	68	2	*67*	0.0090	(0.0166)	*9*	0.0103	(0.0108)	*16*	0.0426	(0.0303)	*4*
Cyclopentene	C5H8	68	2	*67*	0.0699	(0.1240)	*7*	0.1125	(0.0789)	*14*	0.2815	(0.1725)	*4*
Pentadiene_cis13	C5H8	68	2	*67*	0.0457	(0.0795)	*8*	0.0627	(0.0360)	*14*	0.1733	(0.0691)	*4*
Pentadiene_trans13	C5H8	68	2	*67*	0.0668	(0.1069)	*9*	0.1044	(0.0538)	*14*	0.2504	(0.0927)	*4*
Hexadienyne (e.g., divinylacetylene)	C6H6	78	4	*78*	0.0140	(0.0152)	*9*	0.0088	(0.0072)	*16*	0.0569	(0.0382)	*4*
Cyclopentadiene_methyl (sum of 2 isomers)	C6H8	80	3	*79*	0.0242	(0.0329)	*9*	0.0516	(0.0554)	*16*	0.1831	(0.1771)	*4*
Hexenyne (e.g., 2-methyl- 1-penten-3-yne)	C6H8	80	3	*80*	0.0110	(0.0127)	*9*	0.0102	(0.0117)	*16*	0.0674	(0.0545)	*4*
Cyclohexene	C6H10	82	2	*67*	0.0170	(0.0235)	*9*	0.0345	(0.0205)	*14*	0.0927	(0.0506)	*4*
Cyclopentene_1methyl	C6H10	82	2	*67*	0.0202	(0.0298)	*9*	0.0466	(0.0259)	*13*	0.1109	(0.0539)	*4*
Hexadiene_cis13	C6H10	82	2	*67*	0.0026	(0.0037)	*9*	0.0044	(0.0030)	*14*	0.0097	(0.0018)	*4*
Hexadiene_trans13	C6H10	82	2	*67*	0.0039	(0.0081)	*9*	0.0045	(0.0042)	*12*	0.0266	(0.0151)	*4*
Other C6H10 (sum of 5 isomers)	C6H10	82	2	*67*	0.0348	(0.0466)	*9*	0.0531	(0.0418)	*16*	0.1954	(0.0798)	*4*
Heptadiyne (sum of 2 isomers)	C7H8	92	4	*91*	0.0073	(0.0094)	*9*	0.0035	(0.0053)	*16*	0.0464	(0.0394)	*4*
Cyclohexene_1methyl	C7H12	96	2	*81*	0.0098	(0.0120)	*8*	0.0262	(0.0139)	*13*	0.0437	(0.0259)	*4*
Octadiene	C8H14	110	2	*55*	0.0347	(0.0531)	*9*	0.0673	(0.0416)	*16*	0.1387	(0.0536)	*4*
Nonadiene	C9H16	124	2	*54*	0.0020	(0.0027)	*9*	0.0048	(0.0048)	*16*	0.0171	(0.0077)	*4*
C10H14 non-aromatic (e.g., hexahydronaphthalene)	C10H14	134	4	*91*	0.0013	(0.0018)	*9*	0.0041	(0.0055)	*16*	0.0155	(0.0090)	*4*
Terpenes (Polyunsaturated $D > 1$)													
Isoprene	C5H8	68	2	*67*	**0.1289**	(0.1447)	*29*	**0.2428**	(0.1944)	*23*	**0.6942**	(0.4405)	*4*
Camphene	C10H16	136	3	*93*	0.0032	(0.0026)	*9*	0.0538	(0.0979)	*14*	0.1193	(0.1459)	*4*
Carene_3	C10H16	136	3	*93*	0.0050	(0.0052)	*8*	0.0289	(0.0303)	*12*	0.1578	(0.2107)	*4*
Limonene_D	C10H16	136	3	*68*	**0.0219**	(0.0249)	*29*	**0.1232**	(0.1302)	*23*	**0.8384**	(1.1869)	*4*
Limonene_iso	C10H16	136	3	*68*	0.0002	(0.0005)	*9*	0.0094	(0.0109)	*16*	0.0237	(0.0206)	*4*
Myrcene	C10H16	136	3	*93*	0.0075	(0.0106)	*8*	0.0068	(0.0055)	*10*	0.1313	(0.1849)	*4*
Pinene_alpha	C10H16	136	3	*93*	0.0058	(0.0051)	*9*	**0.1013**	(0.1454)	*15*	**0.8105**	(1.2079)	*4*
Pinene_beta	C10H16	136	3	*93*	0.0051	(0.0092)	*29*	0.0194	(0.0220)	*23*	0.1638	(0.1545)	*4*
Terpinene_gamma	C10H16	136	3	*93*	0.0044	(0.0026)	*5*	0.0118	(0.0066)	*4*	0.0310	(0.0336)	*2*
Terpinolene	C10H16	136	3	*93*	0.0053	(0.0020)	*4*	0.0131	(0.0163)	*8*	0.0339	(0.0435)	*4*
Sesquiterpenes (sum of all isomers)	C15H24	204	4	*205+*	**0.0092**	(0.0088)	*29*	0.0669	(0.0786)	*23*	0.0915	(0.0659)	*4*

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Table 2. Continued.

Name	Formula	MW	*D*	*m/z*	SW Avg	(±SD)	npnts	SE Avg	(±SD)	npnts	N Avg	(±SD)	npnts
Aromatics with saturated subsituents (*D* = 4)													
Benzene	C6H6	78	4	*78*	**0.8385**	(0.7301)	*29*	**0.7008**	(0.3680)	*23*	**2.1381**	(1.3236)	*4*
Toluene	C7H8	92	4	*91*	**0.3549**	(0.3417)	*29*	**0.6196**	(0.4414)	*23*	**1.3375**	(0.5725)	*4*
Benzene_ethyl	C8H10	106	4	*91*	0.0495	(0.0498)	*29*	0.0829	(0.0583)	*23*	0.1766	(0.0919)	*4*
Xylene_o	C8H10	106	4	*91*	0.0391	(0.0418)	*29*	0.0730	(0.0527)	*23*	0.1429	(0.0579)	*4*
Xylenes_m&p (sum of 2 isomers)	C8H10	106	4	*91*	0.0981	(0.1136)	*29*	**0.2107**	(0.1546)	*23*	**0.5088**	(0.2484)	*4*
Benzene_123trimethyl	C9H12	120	4	*105*	0.0150	(0.0137)	*9*	0.0617	(0.0425)	*15*	0.0906	(0.0562)	*4*
Benzene_124trimethyl	C9H12	120	4	*105*	0.0172	(0.0217)	*29*	0.0416	(0.0291)	*23*	0.0828	(0.0339)	*4*
Benzene_135trimethyl	C9H12	120	4	*105*	0.0090	(0.0083)	*9*	0.0234	(0.0154)	*15*	0.0401	(0.0158)	*4*
Benzene_1ethyl_2methyl	C9H12	120	4	*105*	0.0094	(0.0114)	*9*	0.0164	(0.0122)	*15*	0.0374	(0.0193)	*4*
Benzene_1ethyl_3&4_methyl (sum of 2 isomers)	C9H12	120	4	*105*	0.0186	(0.0228)	*29*	0.0395	(0.0312)	*23*	0.1265	(0.0737)	*4*
Benzene_isoPropyl	C9H12	120	4	*105*	0.0041	(0.0042)	*9*	0.0073	(0.0065)	*14*	0.0290	(0.0211)	*4*
Benzene_nPropyl	C9H12	120	4	*91*	0.0081	(0.0096)	*9*	0.0173	(0.0102)	*14*	0.0331	(0.0204)	*4*
Benzene_isoButyl	C10H14	134	4	*91*	0.0056	(0.0065)	*9*	0.0119	(0.0104)	*16*	0.0248	(0.0145)	*4*
Benzene_nButyl	C10H14	134	4	*91*	0.0065	(0.0078)	*9*	0.0151	(0.0129)	*16*	0.0329	(0.0193)	*4*
Benzene_1methyl_4isopropyl (p-Cymene)	C10H14	134	4	*119*	**0.1081**	(0.2713)	*29*	0.1030	(0.0974)	*23*	0.1726	(0.1400)	*4*
Benzene_nPropyl_methyl (sum of 2 isomers)	C10H14	134	4	*105*	0.0074	(0.0084)	*9*	0.0200	(0.0187)	*16*	0.0420	(0.0213)	*4*
Benzene_14diethyl	C10H14	134	4	*119*	0.0007	(0.0011)	*9*	0.0018	(0.0039)	*16*	0.0165	(0.0074)	*4*
Xylene_ethyl (sum of 2 isomers)	C10H14	134	4	*119*	0.0093	(0.0102)	*9*	0.0149	(0.0144)	*16*	0.0379	(0.0158)	*4*
Aromatics with unsaturated substituents (*D* > 4)													
Benzene_ethynyl (Phenylethyne)	C8H6	102	6	*102*	**0.0323**	(0.0238)	*9*	0.0153	(0.0163)	*16*	0.0686	(0.0700)	*4*
Styrene (Phenylethene)	C8H8	104	5	*104*	**0.0883**	(0.0840)	*29*	**0.1067**	(0.1054)	*23*	**0.3361**	(0.2437)	*4*
Indene	C9H8	116	6	*115*	**0.0358**	(0.0446)	*9*	**0.0408**	(0.0325)	*16*	**0.1311**	(0.1116)	*4*
Benzene_1propenyl	C9H10	118	5	*117*	0.0046	(0.0054)	*9*	0.0039	(0.0045)	*16*	0.0135	(0.0074)	*4*
Benzene_2propenyl	C9H10	118	5	*117*	0.0067	(0.0066)	*9*	0.0097	(0.0080)	*16*	0.0236	(0.0103)	*4*
Benzene_isoPropenyl	C9H10	118	5	*118*	0.0052	(0.0059)	*9*	0.0049	(0.0050)	*16*	0.0232	(0.0129)	*4*
Styrene_2methyl	C9H10	118	5	*117*	0.0142	(0.0125)	*9*	0.0153	(0.0140)	*16*	0.0414	(0.0176)	*4*
Styrene_3methyl	C9H10	118	5	*117*	0.0229	(0.0255)	*9*	**0.0297**	(0.0234)	*16*	**0.0865**	(0.0420)	*4*
Styrene_4methyl	C9H10	118	5	*117*	0.0080	(0.0097)	*9*	0.0143	(0.0116)	*16*	0.0314	(0.0122)	*4*
Indane	C9H10	118	5	*117*	0.0084	(0.0066)	*8*	0.0155	(0.0069)	*13*	0.0261	(0.0108)	*4*
Naphthalene	C10H8	128	7	*128*	0.0070	(0.0048)	*9*	0.0040	(0.0050)	*16*	0.0215	(0.0122)	*4*
Indene_1or3methyl	C10H10	130	6	*130*	0.0010	(0.0009)	*9*	0.0004	(0.0011)	*16*	0.0079	(0.0059)	*4*
Naphthalene_12dihydro	C10H10	130	6	*130*	0.0062	(0.0054)	*9*	0.0099	(0.0103)	*16*	0.0277	(0.0106)	*4*
Naphthalene_13dihydro	C10H10	130	6	*130*	0.0062	(0.0066)	*9*	0.0099	(0.0113)	*16*	0.0339	(0.0120)	*4*
Benzene_1butenyl	C10H12	132	5	*117*	0.0021	(0.0028)	*9*	0.0027	(0.0038)	*16*	0.0140	(0.0048)	*4*
Benzene_methylpropenyl (2-phenyl-2-butene)	C10H12	132	5	*117*	0.0274	(0.0443)	*9*	0.0179	(0.0179)	*16*	0.0436	(0.0270)	*4*
Styrene_ethyl	C10H12	132	5	*117*	0.0048	(0.0052)	*9*	0.0063	(0.0105)	*16*	0.0196	(0.0085)	*4*

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Table 2. Continued.

Name	Formula	MW	D	m/z	SW Avg	(±SD)	npnts	SE Avg	(±SD)	npnts	N Avg	(±SD)	npnts
Nitrogen-containing organics													
Acid_Hydrocyanic (Hydrogen cyanide)	HCN	27	2	*IR*	**1.2331**	(1.2922)	29	**2.7807**	(1.6904)	23	**3.0223**	(2.2719)	4
Acid_Isocyanic	HNCO	43	2	*42–*	**0.8433**	(0.6858)	16	**0.8046**	(0.5742)	17	**1.3360**	(0.2301)	2
Methylnitrite (Nitrous acid, methyl ester)	CH3NO2	61	1	*61*	**0.8994**	(1.1114)	*7*	0.5241	(0.5064)	*12*	0.7641	(0.8964)	*3*
Nitromethane	CH3NO2	61	1	*61*	0.0272	(0.0237)	*9*	0.0323	(0.0326)	*16*	0.0713	(0.0868)	*4*
Acetonitrile	C2H3N	41	2	*41*	0.7731	(0.9389)	*29*	**0.9841**	(0.5366)	*23*	**1.6524**	(0.8811)	*4*
Hydrazine_11dimethyl	C2H8N2	60	0	*60*	0.0636	(0.1324)	*9*	0.1360	(0.2705)	*16*	0.1976	(0.2297)	*4*
Propenenitrile_2 (Acrylonitrile)	C3H3N	53	3	*53*	0.0869	(0.0731)	*29*	0.1199	(0.0754)	*23*	0.3217	(0.2551)	*4*
Propanenitrile (Cyanoethane)	C3H5N	55	2	*54*	0.0314	(0.0380)	*9*	0.0432	(0.0366)	*16*	0.0981	(0.0803)	*4*
Pyrrole	C4H5N	67	3	*67*	0.0393	(0.0591)	*9*	0.0367	(0.0392)	*16*	0.1066	(0.1088)	*4*
Pyrazole_1methyl	C4H6N2	82	3	*82*	0.0074	(0.0073)	*9*	0.0198	(0.0176)	*16*	0.0359	(0.0161)	*4*
Diazine_methyl (sum of 3 isomers)	C5H6N2	94	4	*94*	0.0292	(0.0312)	*9*	0.0535	(0.0456)	*16*	0.1125	(0.0303)	*4*
Pyrrole_1methyl	C5H7N	81	3	*80*	0.0202	(0.0299)	*9*	0.0083	(0.0105)	*16*	0.0217	(0.0304)	*4*
Pyrazine_2ethyl	C6H8N2	108	4	*108*	0.0062	(0.0092)	*9*	0.0152	(0.0113)	*16*	0.0296	(0.0168)	*4*
Benzonitrile (Cyanobenzene)	C7H5N	103	6	*103*	0.0622	(0.0334)	*9*	0.1395	(0.0757)	*16*	0.1380	(0.0746)	*4*
OVOCs with low degrees of unsaturation (D = 1)													
Formaldehyde	CH2O	30	1	*IR*	***5.3939***	(3.1497)	29	***12.2348***	(7.2935)	23	***17.9180***	(10.5410)	4
Acid_Formic	CH2O2	46	1	*IR*	0.6359	(0.5705)	29	1.6007	(1.1054)	23	1.7538	(1.9738)	4
Methanol	CH4O	32	0	*31*	**3.6175**	(2.9726)	*29*	**7.7807**	(5.5412)	*23*	***13.6981***	(8.7348)	*4*
Acetaldehyde	C2H4O	44	1	*44*	1.5503	(1.1511)	*29*	2.8332	(1.8131)	*23*	5.4742	(3.5540)	*4*
Acid_Acetic	C2H4O2	60	1	*IR*	***5.3926***	(3.2343)	*29*	***13.0293***	(8.8369)	*23*	**9.6068**	(6.2350)	*4*
Formate_methyl (Formic Acid, methyl ester)	C2H4O2	60	1	*60*	0.0675	(0.0390)	*8*	0.1031	(0.0626)	*15*	0.2096	(0.0831)	*4*
Acid_Glycolic	C2H4O3	76	1	*75–*	0.0068	(0.0061)	15	0.1183	(0.1251)	17	0.0114	(0.0115)	2
Ethanol	C2H6O	46	0	*31*	0.0498	(0.0617)	*29*	0.4817	(0.8472)	*23*	0.2673	(0.1892)	*4*
Acetone	C3H6O	58	1	*43*	0.6501	(0.7408)	*29*	1.6035	(1.1498)	*23*	2.6208	(1.0656)	*4*
Propanal	C3H6O	58	1	*58*	0.2135	(0.2333)	*29*	0.4497	(0.3177)	*23*	0.9246	(0.3186)	*4*
Acetate_methyl (Acetic Acid, methyl ester)	C3H6O2	74	1	*74*	0.4593	(0.4854)	*9*	0.6741	(0.4345)	*16*	0.6537	(0.3598)	*4*
Formate_ethyl (Formic Acid, ethyl ester)	C3H6O2	74	1	*30*	0.0214	(0.0157)	*5*	0.0349	(0.0160)	*10*	0.0472	(0.0228)	*4*
Butanal_n	C4H8O	72	1	*72*	0.0496	(0.0610)	*29*	0.0850	(0.0641)	*23*	0.1971	(0.0829)	*4*
Butanone_2 (MEK)	C4H8O	72	1	*43*	0.1788	(0.2216)	*29*	0.4143	(0.3061)	*23*	0.8027	(0.3109)	*4*
Propanal_2methyl	C4H8O	72	1	*72*	0.0535	(0.0599)	*9*	0.1426	(0.0933)	*15*	0.1657	(0.0976)	*4*
Propanoate_methyl (Prop- anoic Acid, methyl ester)	C4H8O2	88	1	*88*	0.0064	(0.0085)	*9*	0.0081	(0.0082)	*16*	0.0186	(0.0110)	*4*
Butanol_1	C4H10O	74	0	*56*	0.8294	(1.6678)	*8*	0.2327	(0.2540)	*16*	0.1434	(0.0695)	*4*
Butanal_2methyl	C5H10O	86	1	*57*	0.0442	(0.0476)	*9*	0.1398	(0.0760)	*13*	0.1323	(0.0939)	*4*
Butanone_2_3methyl	C5H10O	86	1	*43*	0.0243	(0.0315)	*9*	0.0780	(0.0394)	*14*	0.1092	(0.0551)	*4*
Pentanone_2	C5H10O	86	1	*43*	0.0576	(0.0457)	*8*	0.1095	(0.0537)	*14*	0.1791	(0.0935)	*4*
Pentanone_3	C5H10O	86	1	*57*	0.0381	(0.0366)	*8*	0.0869	(0.0483)	*15*	0.1330	(0.0562)	*4*
Butanoate_methyl (Butryic Acid, methyl ester)	C5H10O2	102	1	*74*	0.0024	(0.0041)	*9*	0.0558	(0.1431)	*16*	0.0097	(0.0063)	*4*
Hexanal_n	C6H12O	100	1	*56*	0.0192	(0.0223)	*29*	0.0342	(0.0224)	*23*	0.0635	(0.0431)	*4*
Hexanone_2	C6H12O	100	1	*43*	0.0101	(0.0063)	*8*	0.0269	(0.0092)	*12*	0.0462	(0.0268)	*4*
Hexanone_3	C6H12O	100	1	*43*	0.0314	(0.0315)	*9*	0.0834	(0.0317)	*13*	0.1646	(0.0868)	*4*

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Table 2. Continued.

Name	Formula	MW	*D*	*m/z*	SW Avg	(±SD)	npnts	SE Avg	(±SD)	npnts	N Avg	(±SD)	npnts
OVOCs with high degrees of unsaturation (*D* > 1)													
Propenal_2 (Acrolein)	C3H4O	56	2	*56*	**0.8189**	(0.6824)	*29*	**1.3107**	(0.8806)	*23*	**3.5441**	(1.6919)	*4*
Acid_Acrylic	C3H4O2	72	2	*71–*	0.0409	(0.0438)	16	0.2159	(0.1637)	17	0.3672	(0.3881)	2
Acid_Pyruvic	C3H4O3	88	2	*87–*	0.0140	(0.0140)	15	0.1073	(0.1266)	17	0.0562	(0.0537)	2
Butenal_2 (Crotonaldehyde)	C4H6O	70	2	*70*	0.1218	(0.1286)	*29*	0.3234	(0.2207)	*23*	0.5275	(0.1642)	*4*
Methacrolein (MACR)	C4H6O	70	2	*41*	0.0895	(0.1077)	*29*	0.1807	(0.1257)	*23*	0.5501	(0.3146)	*4*
Methylvinylketone (MVK)	C4H6O	70	2	*55*	0.4003	(0.5191)	*29*	0.8953	(0.6389)	*23*	2.1216	(0.8712)	*4*
Butadione_23	C4H6O2	86	2	*86*	0.2147	(0.2059)	*29*	0.6435	(0.4616)	*23*	1.2062	(0.5357)	*4*
Acrylate_methyl (2-Propenoic Acid, methyl ester)	C4H6O2	86	2	*85*	0.0159	(0.0178)	*9*	0.0223	(0.0149)	*16*	0.0470	(0.0227)	*4*
Acetate_vinyl (Acetic Acid, vinyl ester)	C4H6O2	86	2	*86*	0.0004	(0.0012)	*9*	0.0000	0.0000	*16*	0.0048	(0.0095)	*4*
Dioxin_14_23dihydro	C4H6O2	86	2	*58*	0.0023	(0.0044)	*9*	0.0043	(0.0059)	*16*	0.0179	(0.0162)	*4*
Cyclopentenedione	C5H4O2	96	4	*96*	0.0056	(0.0080)	*9*	0.0265	(0.0337)	*16*	0.0401	(0.0326)	*4*
Cyclopentenone	C5H6O	82	3	*82*	0.0825	(0.1208)	*9*	**0.9873**	(1.1659)	*16*	0.9221	(0.6570)	*4*
Pentenone (e.g., Ethyl vinyl ketone)	C5H8O	84	2	*84*	0.2682	(0.4437)	*9*	0.8946	(0.5222)	*16*	1.4135	(0.6686)	*4*
Pentanone_cyclo	C5H8O	84	2	*84*	0.1145	(0.1015)	*9*	0.3433	(0.2471)	*16*	0.7012	(0.2870)	*4*
Butenal_2_2methyl	C5H8O	84	2	*84*	0.0072	(0.0064)	*9*	0.0250	(0.0210)	*16*	0.0384	(0.0136)	*4*
Methacrylate_methyl (Methacrylic Acid, methyl ester)	C5H8O2	100	2	*100*	0.0306	(0.0333)	*9*	0.1055	(0.0335)	*13*	0.1287	(0.0537)	*4*
Phenol	C6H6O	94	4	*95+*	**0.4262**	(0.4242)	*25*	0.7740	(0.6275)	*21*	**2.4947**	(1.6182)	*4*
Benzene_12&13diol (sum of 2 isomers)	C6H6O2	110	4	*109–*	0.2438	(0.1859)	*13*	**3.1107**	(3.3461)	*17*	**3.9631**	(1.9126)	*2*
Benzaldehyde	C7H6O	106	5	*77*	0.2212	(0.1661)	*29*	0.4717	(0.3259)	*23*	0.6995	(0.2661)	*4*
Phenol_methyl (sum of cresol isomers')	C7H8O	108	4	*109+*	**0.4807**	(0.4799)	*25*	0.7770	(0.6290)	21	2.0703	(1.4093)	*4*
Furans (heterocyclic OVOCs, *D* = 1)													
Furan	C4H4O	68	3	*68*	**0.2680**	(0.2474)	*29*	**0.7302**	(0.4732)	*23*	**1.1090**	(0.4337)	*4*
Furan_25dihydro	C4H6O	70	2	*70*	0.0083	(0.0126)	*9*	0.0154	(0.0438)	*16*	0.0071	(0.0141)	*4*
Furan_tetrahydro	C4H8O	72	1	*72*	0.0022	(0.0027)	*9*	0.0014	(0.0027)	*16*	0.0101	(0.0067)	*4*
Furaldehyde_2 (Furfural)	C5H4O2	96	4	*95*	**0.3567**	(0.2119)	*9*	**1.5298**	(1.0837)	*16*	**1.2999**	(0.6550)	*4*
Furaldehyde_3	C5H4O2	96	4	*95*	0.0152	(0.0135)	*9*	0.0585	(0.0403)	*16*	0.0687	(0.0330)	*4*
Furan_2methyl	C5H6O	82	3	*82*	**0.2847**	(0.3634)	*9*	**0.6908**	(0.4118)	*16*	**1.2105**	(0.4806)	*4*
Furan_3methyl	C5H6O	82	3	*82*	0.0272	(0.0311)	*29*	0.0776	(0.0582)	*23*	0.1758	(0.0661)	*4*
Furan_25dimethyl	C6H8O	96	3	*96*	0.0328	(0.0472)	*9*	0.0857	(0.0587)	*16*	0.1808	(0.1005)	*4*
Furan_2ethyl	C6H8O	96	3	*81*	0.0167	(0.0218)	*29*	0.0387	(0.0285)	*23*	0.0821	(0.0288)	*4*
Benzofuran	C8H6O	118	6	*118*	0.0902	(0.0666)	*9*	0.1366	(0.0734)	*16*	0.2504	(0.0957)	*4*
Benzofuran_methyl (sum of 4 isomers)	C9H8O	132	6	*131*	0.0599	(0.0444)	*9*	0.1078	(0.0938)	*16*	0.1980	(0.0363)	*4*

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Table 2. Continued.

Name	Formula	MW	*D*	*m/z*	SW Avg	(±SD)	npnts	SE Avg	(±SD)	npnts	N Avg	(±SD)	npnts
Methane and Inorganic Gases													
Methane	CH4	16	-	*IR*	**40.911**	(24.945)	*29*	**62.302**	(32.218)	*23*	**96.707**	(28.737)	*4*
Carbon Monoxide	CO	28	-	*IR*	**1000**	(0)	*29*	**1000**	(0)	*23*	**1000**	(0)	*4*
Carbon Dioxide	CO2	44	-	*IR*	**18202**	(20970)	29	**31170**	(71256)	23	**17999**	(14000)	4
Tricarbon Dioxide (Carbon suboxide)	C3O2	68	-	*68*	0.0024	(0.0030)	*9*	0.0040	(0.0055)	*16*	0.0044	(0.0042)	*4*
Ammonia	NH3	17	-	*IR*	12.530	(8.838)	*29*	14.797	(6.131)	*23*	20.761	(16.928)	*4*
Nitrogen Oxide	NO	30	-	*IR*	**38.788**	(51.194)	*29*	**39.695**	(91.842)	*23*	**26.530**	(24.243)	*4*
Nitrogen Dioxide	NO2	46	-	*IR*	7.051	(8.565)	*29*	12.254	(21.246)	*23*	10.583	(10.218)	*4*
Nitrous Acid	HONO	47	-	*46–*	2.504	(2.827)	*16*	4.563	(6.049)	*17*	4.946	(5.254)	*2*
Sulfur Dioxide	SO2	64	-	*IR*	5.600	(9.993)	*29*	7.901	(14.488)	*23*	8.408	(5.347)	*4*
Hydrochloric Acid	HCl	36	-	*IR*	0.992	(2.574)	*29*	1.398	(4.825)	*23*	0.472	(0.719)	*4*
Total ERs (mmol (mol CO)$^{-1}$)					**19356**			**32403**			**19317**		
$\sum$ ERs for all nitrogen-containing species (mmol (mol CO)$^{-1}$)					**65**	***0.34 %***	***N***	**77**	***0.24 %***	***N***	**71**	***0.37 %***	***N***
$\sum$ ERs for all VOCs and *% of total emissions*					**46**	***0.24 %***	***VOC***	**90**	***0.28 %***	***VOC***	**150**	***0.78 %***	***VOC***
$\sum$ ERs for unsaturated VOCs and *% of total VOC*					**39**	***84 %***	*Unsat*	**74**	***82 %***	*Unsat*	**126**	***84 %***	*Unsat*
$\sum$ ERs for oxygenated VOCs and *% of total VOC*					**24**	***53 %***	*Oxy*	**57**	***63 %***	*Oxy*	**81**	***54 %***	*Oxy*

MW = molecular weight (g mol^{-1}); *D* = Degrees of unsaturation; *m/z* = mass fragment used to quantify a species where (+) denotes measurements by the PTR-MS or PIT-MS, (–) denotes measurements by the NI-PT-CIMS, and (IR) denotes measurements by the OP-FTIR. All other measurements are by GC-MS; avg = mean; SD = standard deviation; and npts = number of points used to calculate average and standard deviation.
Bold ER = largest 3 ERs for each compound class.
Bold and italic ER = largest 3 ERs for all VOCs.
Description of naming scheme: propane_22dimethyl is equivalent to 2,2-dimethylpropane. If the exact compound identity could not be determined, then the species are identified using general names that reflect the chemical family and formula are used. For example, hexenes (sum of 3 isomers) may include species such as cis- and trans-3-hexene. Alternative names, such as p-Cymene for 1-methyl-4-isopropylbenzene, or common abbreviations such as MEK for Butanone_2 are also included.

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Table 3. Slopes and correlation coefficients (r) for VOC to carbon monoxide (CO) and VOC to acetonitrile (CH_3CN) ratios observed in biomass burning (BB) plumes from the Fourmile Canyon Fire as identified in Fig. 6.

VOC Name	VOC vs. CO		VOC vs. CH_3CN		Emission Sources			Rxn Rate Coefficient	
	Slope	r	Slope	r	BB	Urban	Biogenic	kOH[a]	vs. CH_3CN[b]
Furan_2methyl	0.0003	0.88	0.0470	0.95	yes			111	5550
Carene_3	0.0004	0.96	0.0654	0.98	yes		yes	85	4250
Furan	0.0004	0.70	0.1153	0.95	yes			67	3355
Butadiene_13	0.0002	0.98	0.0296	0.94	yes	yes		67	3330
Styrene	0.0001	0.97	0.0209	0.94	yes	yes	yes	58	2900
Propene_2methyl	0.0004	0.98	0.0648	0.98	yes	yes		51	2570
Furaldehyde_2	0.0003	0.93	0.0491	0.98	yes			48	2400
Benzofuran	0.0001	0.97	0.0210	0.99	yes			37	1860
Butene_1	0.0004	0.98	0.0571	0.99	yes	yes		31	1570
Propene	0.0040	0.97	0.6385	0.99	yes	yes		26	1315
Propanal	0.0010	0.95	0.1481	0.90	yes	yes		20	1000
Propenal_2	0.0009	0.98	0.1366	0.98	yes	yes		19	955
p-Cymene[c]	0.0003	0.97	0.0415	0.97	yes		yes	15	750
Benzaldehyde	0.0010	0.98	0.1444	0.95	yes		yes	14	700
Ethene	0.0082	0.97	1.3526	0.92	yes	yes		8.5	425
Benzene	0.0019	0.99	0.2835	0.96	yes	yes		1.2	60
Butanone_2 (MEK)	0.0010	0.93	0.1640	0.94	yes	yes	yes	1.2	60
Benzonitrile	0.0003	0.88	0.0499	0.94	yes			1.0	50
Butadione_23	0.0002	0.77	0.0384	0.89	yes		yes	0.25	12.5
Acetonitrile	0.0062	0.96	1.0000	1.00	yes			0.020	1

Bold face denotes VOCs that are the best available BB markers.
[a] Rxn Rate Coefficient $\times 10^{12}$ = first order reaction rate coefficient of VOC + OH reaction at STP.
[b] Ratio of rxn rate coefficients for VOC vs. acetonitrile (CH_3CN) $\times 10^{12}$ at STP.
[c] Benzene_1methyl_4isopropyl.

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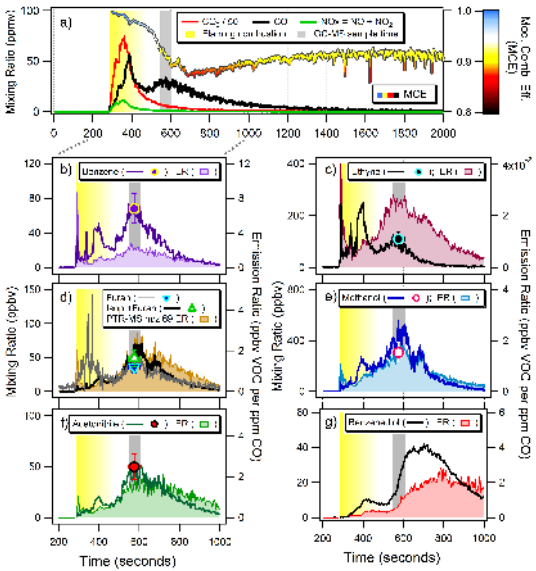

Figure 1. Temporal profiles of mixing ratios and emission ratios (ER) of select gases and the modified combustion efficiency (MCE) for an example laboratory burn of Emory Oak Woodland fuel from Fort Huachuca, Arizona. **(a)** Mixing ratios of CO_2, CO, and NOx measured by OP-FTIR. The MCE trace is colored by the key and scale on the right. The vertical bars represent the flaming combustion phase of the laboratory burn (yellow) and the GC-MS sample acquisition time (grey). **(b–f)** Discrete GC-MS measured mixing ratios are shown as markers. **(b–g)** Mixing ratios measured by PTR-MS (benzene, m/z 69 = isoprene + furan + other, and acetonitrile), OP-FTIR (furan, ethyne, and methanol), and NI-PT-CIMS (benzenediol) are shown as lines and the corresponding VOC to CO ERs are shown as filled traces.

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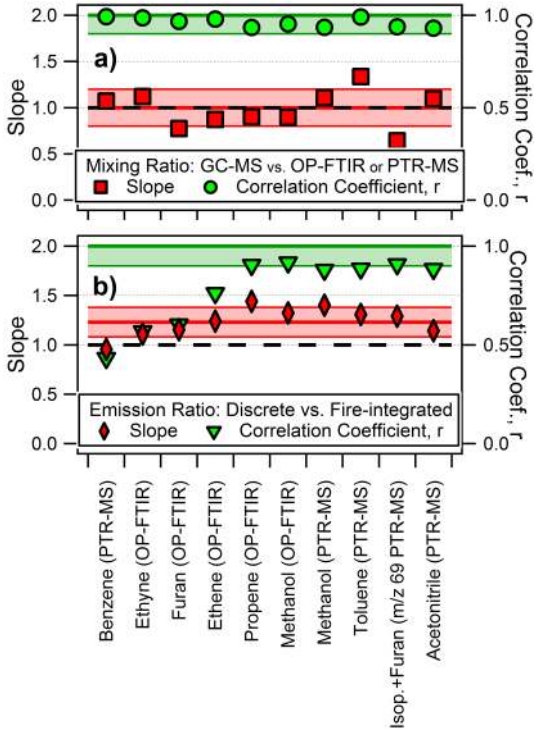

Figure 2. Slopes and correlation coefficients, *r*, determined from correlation plots of **(a)** mixing ratios measured by the GC-MS vs. the average mixing ratio measured by the OP-FTIR or PTR-MS during the GC-MS sample acquisition time and **(b)** discrete vs. fire-integrated emission ratios of select VOCs relative to CO as measured by the OP-FTIR or PTR-MS. The black dashed line represents slopes equal to 1. The average of the slopes and the standard deviation is shown by the red shaded bands. The green bands represent $r > 0.90$.

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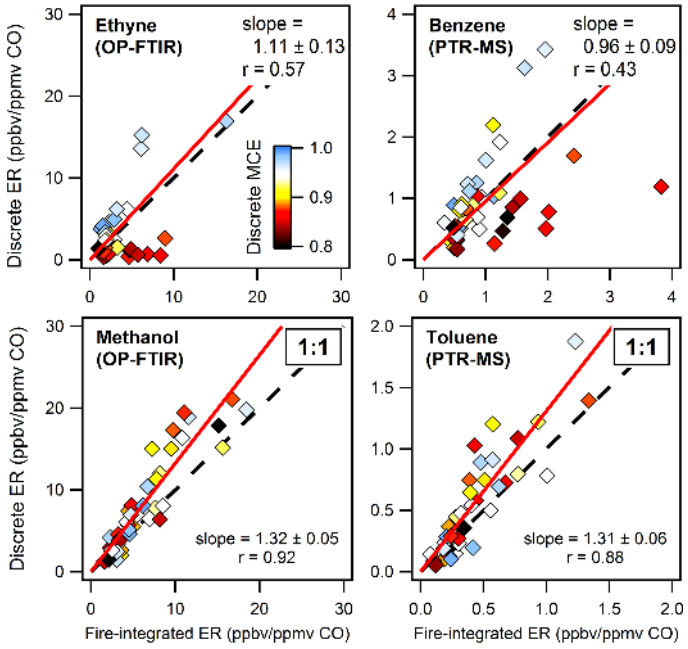

Figure 3. Correlation plots of the discrete vs. fire-integrated emission ratios (ER) for ethyne and methanol measured by the OP-FTIR and benzene and toluene measured by the PTR-MS. Each data point represents one biomass burn and are colored by the modified combustion efficiency (MCE) corresponding to the discrete sampling times of the GC-MS. MCE values near unity are associated with flaming combustion and lower MCE values are associated with smoldering combustion. The linear 2-sided regression lines forced through the origin are shown as red lines and the 1 : 1 ratio is shown by the dashed lines.

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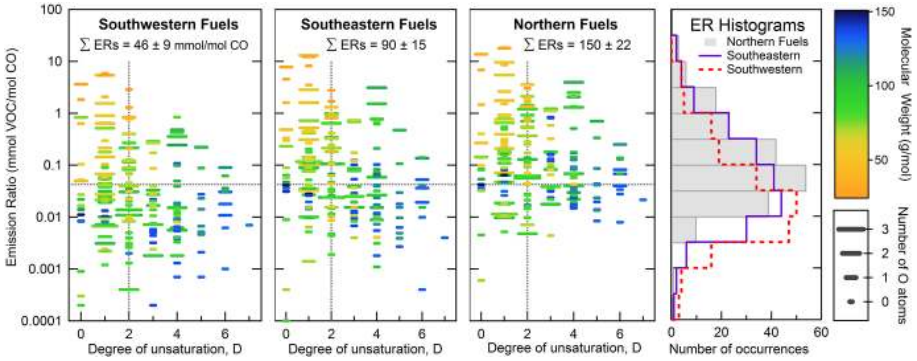

Figure 4. Discrete molar emission ratios for all VOCs reported in Table 2 as a function of the degree of unsaturation, D, for each fuel region. Emission ratios are colored by the corresponding molecular weight and the marker width represents the corresponding number of oxygen (O) atoms. The dashed lines represent the median values for all VOCs from all fuel regions (ER = 0.0427 mmol mol^{-1} CO and D = 2). The histogram on the right summarizes the distribution of molar emission ratios for each fuel region.

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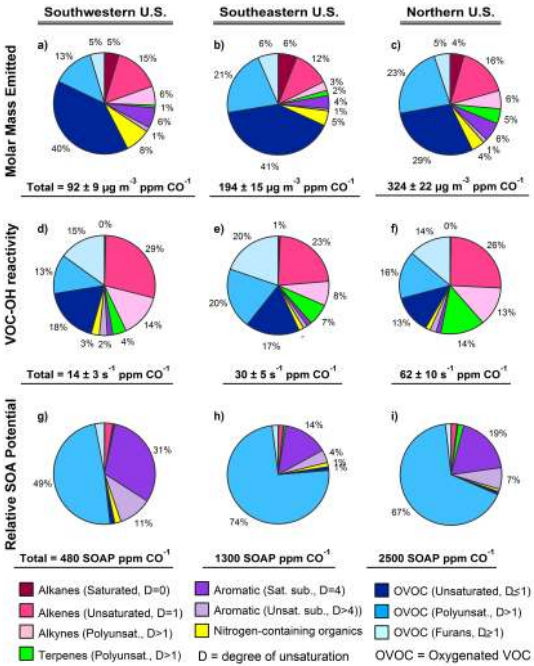

Figure 5. Contributions of (non-methane) VOCs reported in Table 2 to **(a–c)** the molar mass emitted, **(d–f)** OH reactivity, and **(g–i)** relative SOA potential for the southwestern, southeastern, and northern fuel regions. Totals for each fuel region are shown below each pie chart.

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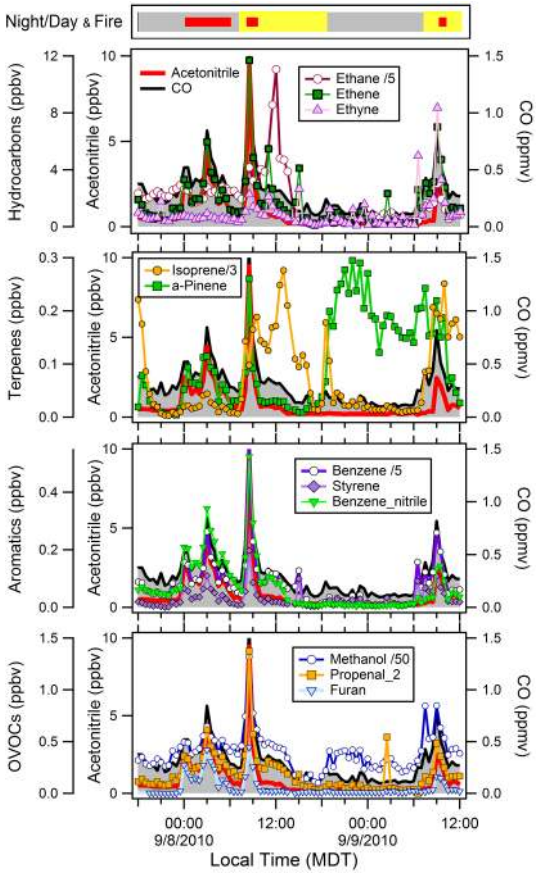

Figure 6. Time series of ambient air measurements in Boulder, Colorado, during the Fourmile Canyon Fire. The top bar indicates nighttime (grey), daytime (yellow), and biomass burning plumes (red markers). CO and acetonitrile are included in all 4 panels.

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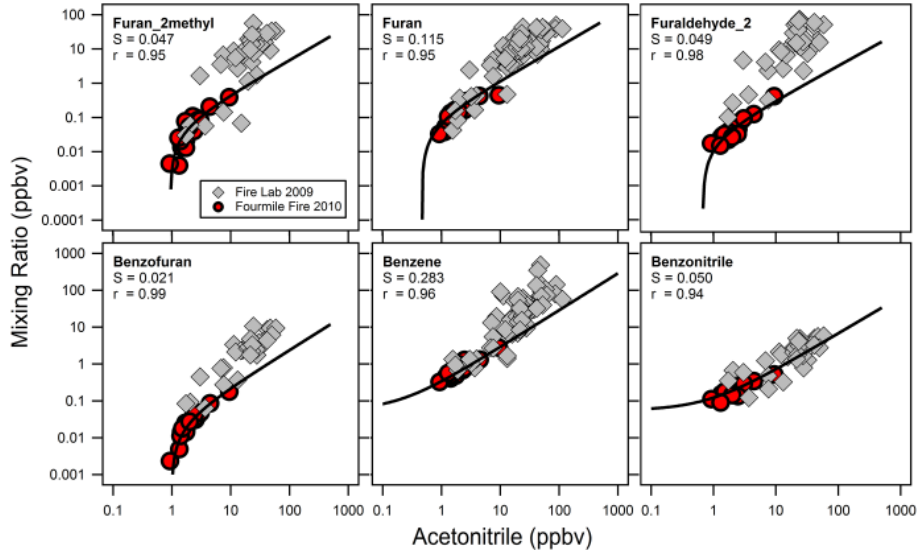

Figure 7. Correlation plots of VOCs vs. acetonitrile for all 56 laboratory biomass burns (grey markers) and Fourmile Canyon Fire (red markers correspond to the BB plume identified in Fig. 6).

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