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Wildland fire emissions, carbon, and climate: Emission factors

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ABSTRACT

While the vast majority of carbon emitted by wildland fires is released as CO_2, CO, and CH_4, wildland fire smoke is nonetheless a rich and complex mixture of gases and aerosols. Primary emissions include significant amounts of CH_4 and aerosol (organic aerosol and black carbon), which are short-lived climate forcers. In addition to CO_2 and short-lived climate forcers, wildland fires release CO, non-methane organic compounds (NMOC), nitrogen oxides ($NO_x = NO + NO_2$), NH_3, and SO_2. These species play a role in radiative forcing through their photochemical processing, which impacts atmospheric levels of CO_2, CH_4, tropospheric O_3, and aerosol. This paper reviews the current state of knowledge regarding the chemical composition of emissions and emission factors for fires in United States vegetation types as pertinent to radiative forcing and climate. Emission factors are critical input for the models used to estimate wildland fire greenhouse gas and aerosol emission inventories.

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1. Introduction

Emissions from wildland fires are a significant source of carbonaceous aerosol, CO, greenhouse gases (CO_2, CH_4), and a vast array of other gases, including non-methane organic compounds (NMOC) (van der Werf et al., 2010; Akagi et al., 2011; Wiedinmyer et al., 2011) (wildland fire is defined as non-agricultural open biomass burning). Inventories of wildland fire emissions are an essential input for atmospheric chemical transport models that are used to understand the role of wildland fires in the atmosphere and climate. An emission factor specifies the amount of a product generated per unit amount of an activity that generates the product. A wildland fire emission factor is usually expressed as the mass of a gas or aerosol species produced per unit mass of vegetation burned (on a dry mass basis). Emission factors are critical inputs for the models used to estimate wildland fire greenhouse gas and aerosol (organic aerosol (OA) and black carbon (BC)) emission inventories (Section 1.1). This chapter reviews the current state of knowledge regarding the chemical composition of fire emissions and emission factors as pertinent to radiative forcing and climate.

1.1. Background

Wildland fire emissions of a species X is typically estimated as the product of area burned (A), fuel loading (FL), combustion completeness (CC), and a specific emission factor (EFX) (Seiler and Crutzen, 1980; Urbanski et al., 2011):

$$E_X = A \times FL \times CC \times EFX \qquad (1)$$

Fuels are defined as biomass (dead and live) that is available for combustion (Sandberg et al., 2001). While most emission models are based on Eq. (1), the source of inputs is highly variable and depends on the purpose of the emission model. Details on how emission models are employed to provide input for air quality and atmospheric chemical modeling may be found elsewhere (Larkin et al., 2009; van der Werf et al., 2010; Urbanski et al., 2011; Wiedinmyer et al., 2011; Larkin et al., 2013, 2014).

Wildland fuels typically have an oven-dry-mass carbon content of 35–55% (Susott, 1996; McMeeking et al., 2009; Burling et al., 2010) and it is the carbon containing emissions (along with a few nitrogen containing species) that have the most significant impact on the chemistry and composition of the atmosphere. The distribution of carbon mass in emissions from fires in temperate conifer forests is shown in Fig. 1. About 95% of the carbon is released as CO_2, CO, and CH_4. CO_2 is a long-lived greenhouse gas and CH_4 is a short-lived climate forcer (Sommers et al., 2012, 2014). The global warming potential of CH_4 relative to CO_2 is 21 on a 100 years time horizon (Solomon et al., 2007). While the vast majority of carbon is emitted as CO_2, wildland fire smoke is nonetheless a rich and complex mixture of gases and aerosols. CO_2 is relatively inert and it is the more reactive, if less abundant, species that are responsible for much of the important atmospheric chemistry. Initial emissions from biomass burning include significant amounts of aerosols that are short-lived climate forcers. The primary aerosols produced by wildland fires are diverse in size, composition, and morphology, and in the consequent chemical and physical properties (McMeeking et al., 2009; Chakrabarty et al., 2010; Levin et al., 2010; Pratt et al., 2011) that impact direct and indirect aerosol radiative forcing (Sommers et al., 2012, 2014). In addition to CO_2 (emissions also include small amounts of the

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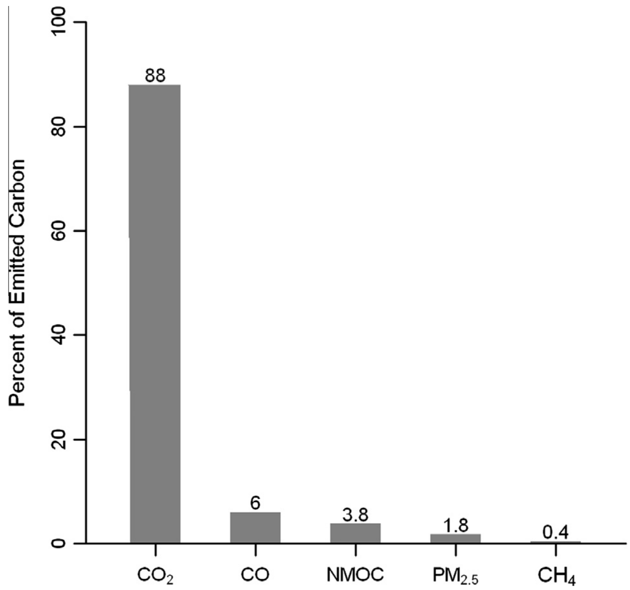

Fig. 1. Partitioning of carbon emissions for pine forest understory prescribed fires. This figure is based on data from Table 2 of Yokelson et al. (2013) and does not consider unidentified NMOC.

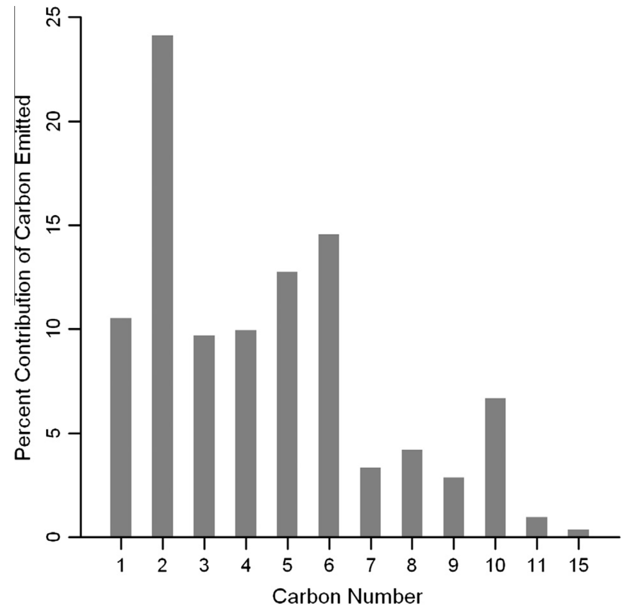

Fig. 2. Partitioning of NMOC emissions by carbon number for pine forest understory prescribed fires. This figure is based on data from Table 2 of Yokelson et al. (2013) and does not consider unidentified NMOC.

long-lived greenhouse gas N_2O) and short-lived climate forcers, wildland fires release CO, non-methane organic compounds (NMOC), nitrogen oxides ($NO_x = NO + NO_2$), NH_3, and SO_2. These gases affect radiative forcing through their photochemical processing, which impacts levels of CO_2, CH_4, tropospheric O_3, stratospheric water vapor, and aerosol (Shindell et al., 2009; Heilman et al., 2013). The impact of fire emissions on atmospheric composition and the realized radiative forcing depends on the composition of the emissions, location, and ambient environment (chemical and meteorological). The impact of wildland fire emissions on radiative forcing is complex and highly variable and is beyond the scope of this paper. The reader is referred to Shindell et al. (2009) and Heilman et al. (2013) and references therein for details.

Over 200 gases have been identified in fresh smoke (Yokelson et al., 2013), the vast majority of which are NMOC. The NMOC in wildland fire smoke is distributed across a wide range of compounds with about half the emitted carbon residing in species containing $\geqslant$5 carbon atoms (Fig. 2). Wildland fires are a significant source of NMOC in the global atmosphere (see Akagi et al., 2011 and references therein), despite the fact that these compounds comprise only a small fraction of the total carbon emitted by fires. NMOC play an important role in tropospheric chemistry by contributing to the formation of O_3 and secondary organic aerosol (Alvarado and Prinn, 2009; Yokelson et al., 2009). The production of NMOC by wildland fires is an area of active research. Recent laboratory studies of emissions employing advanced mass spectrometry instrumentation have observed many NMOC which could not be identified, despite state of the art identification methods. In these studies, 31–72% of the NMOC mass detected could not be identified, with high mass compounds (>100 amu) accounting for the largest fraction of unidentified mass (Warneke et al., 2011; Yokelson et al., 2013). These unidentified, high mass compounds are believed to be primarily oxygenated organic compounds or aromatics and are anticipated to play an important role in the formation of aerosol (Warneke et al., 2011).

Fresh smoke aerosol number and mass are principally in fine particulates, $PM_{2.5}$ (particles with an aerodynamic diameter $\leqslant$2.5 μm) (Reid et al., 2005). The majority of particle mass is organic aerosol (OA), but black carbon (BC) and inorganic aerosol (e.g., nitrate, sulfate, ammonium, and chloride) generally comprise 5–20% of $PM_{2.5}$ mass (Reid et al., 2005). While the particulate mass emitted by wildland fires is dominated by organic compounds, the individual particles may often be internal mixtures containing organic carbon, elemental carbon, and inorganics (Pratt et al., 2011). These trace inorganic components may have a significant impact on the chemical and physical properties, and hence an important influence on their radiative forcing.

1.2. Terminology

Emission factors (EFs) are critical input for the models used to estimate wildland fire emission inventories (Larkin et al., 2009; van der Werf et al., 2010; Urbanski et al., 2011; Wiedinmyer et al., 2011; Larkin et al., 2012, 2014). EF are determined by measuring the concentration of pollutants in fresh smoke and in the ambient air outside the smoke plume. This section defines the terms associated with the measurement of EF.

1.2.1. Excess mixing ratio

The basic metric used to quantify fire emissions is the excess mixing ratio, which for a species X is defined as $\Delta X = X_{\text{plume}} - X_{\text{background}}$, where X_{plume} and $X_{\text{background}}$ are the mixing ratio of X in the fresh smoke plume and the background air, respectively (Ward and Radke, 1993). Mixing ratio is the ratio of the moles or mass of an atmospheric constituent to the moles or mass of dry air.

1.2.2. Emission ratio

The emission ratio of species X (ER_X) is defined as $ER_X = \Delta X/\Delta Y$ where ΔY is the excess mixing ratio of a smoke tracer, which is a co-emitted species with a reasonably long atmospheric lifetime, typically CO or CO_2. Emission ratios can be used to calculate EF using the carbon mass balance method (Yokelson et al., 1999).

1.2.3. Emission factor

The EF for species X, defined as the mass of X emitted per mass of dry biomass consumed, in units of g kg^{-1}, may be estimated using (Yokelson et al., 1999):

$$EFX = F_C \times 1000(\mathrm{g\ kg}^{-1}) \times \frac{MM_X}{12} \times \frac{ER_X}{C_T} \quad (2)$$

In Eq. (2), F_c is the mass fraction of carbon in the dry biomass, MM_X is the molar mass of X (g mole^{-1}), 12 the molar mass of carbon (g mole^{-1}), ER_X is the emission ratio of X to CO_2 and C_T is given by:

$$C_T = \sum_{j=1}^{n} N_j \times \frac{\Delta C_j}{\Delta CO_2} \quad (3)$$

where n is the number of carbon containing species measured, N_j is the number of carbon atoms in species j, and ΔC_j is the excess mixing ratio of species j. The carbon mass balance method assumes that all of the biomass carbon consumed in the fire is volatized as gases and aerosol, which are measured as excess mixing ratios and is included in the sum of Eq. (3). However, as discussed above, the vast majority of carbon emitted is in CO_2, CO, and CH_4, and inclusion of only these compounds in C_T results in only a minor overestimate of emission factors (Yokelson et al., 2007).

1.2.4. Combustion efficiency

Combustion efficiency (CE), the fraction of burned fuel carbon converted to CO_2, and modified combustion efficiency (MCE), MCE = $\Delta CO_2/(\Delta CO_2 + \Delta CO)$, both depend on the relative amount of flaming and smoldering combustion (Ward and Radke, 1993). Because determining CE requires measuring all of the carbon released, which is impractical under most conditions, MCE is typically used to characterize the relative fractions of flaming and smoldering combustion.

1.3. Combustion process, fuels, and emissions

The composition of initial wildland fire emissions is affected by several factors including: (1) the structure and arrangement of fuels, (2) the fuel chemistry, (3) fuel condition (growth stage, moisture, and soundness of woody material), and (4) meteorology. The combustion of vegetation in a wildland fire includes the complex thermal degradation processes of distillation and pyrolysis, char oxidation (also known as gasification or "glowing combustion"), and the oxidation of the released gases in flaming combustion. They occur simultaneously and often in proximity (Yokelson et al., 1996; Ottmar, 2001; Benkoussas et al., 2007). Certain fuel types, arrangements, and conditions tend to favor flaming or smoldering combustion (Ottmar, 2001). Burning of fine woody fuels, grass, litter, and foliage tends to occur predominantly by flaming combustion. In contrast, smoldering combustion dominates the burning of large diameter woody fuels (downed branches, logs, and stumps) and ground fuels (duff, peat, and organic soils).

The chemical composition of smoke is related to the combustion characteristics of a fire, especially the relative amounts of flaming and smoldering combustion. Some species are emitted almost exclusively by flaming or smoldering, while the emissions of others are substantial from both processes. Flaming combustion produces the gases CO_2, NO, NO_2, HCl, SO_2, HONO, and N_2O (Lobert, 1991; Burling et al., 2010), as well as BC (Chen et al., 2007; McMeeking et al., 2009). The species CO, CH_4, NH_3, many NMOC, and OA are associated with smoldering combustion (McMeeking et al., 2009; Burling et al., 2010). Some NMOC have been linked with both flaming and smoldering combustion (Lobert, 1991; Yokelson et al., 1996; Burling et al., 2010). The N, S, and Cl content of biomass can vary greatly between different fuels and often leads to substantial but variable emissions of gases, such as SO_2, HCl, and various nitrogen containing species (Burling et al., 2010). Finally, some elements are common in biomass but rarely found in the gas or aerosol phase such as P, which follows N in order of abundance, but evidently ends up mostly in the ash (Raison et al., 1985).

MCE may be used to estimate the relative amounts of flaming and smoldering combustion in a fire. Laboratory studies have shown that MCE is ~0.99 for pure flaming combustion (e.g., fine fuels completely engulfed in flame (Yokelson et al., 1996; Chen et al., 2007)), while the MCE for smoldering combustion varies over ~0.65 to 0.85, with 0.80 being a typical value (Akagi et al., 2011). Since many species are predominantly emitted during either flaming or smoldering combustion, the emission factors of many compounds correlate with MCE. Laboratory studies of the combustion of fine fuels show a strong correlation between MCE and EF for many compounds (Yokelson et al., 1997; Christian et al., 2003; McMeeking et al., 2009; Burling et al., 2010); see Fig. 3. In contrast, laboratory measurements of pure smoldering combustion of duff, organic soils, and large diameter woody fuels show poor correlation between MCE and EF (Yokelson et al., 1997; Bertschi et al., 2003). The weak relationship for these fuels holds even for compounds that show a strong MCE–EF correlation for fine fuels.

In the natural environment, flaming and smoldering combustion often occur simultaneously, and the fuel components involved are frequently diverse. Consequently, field measurements show variable correlation between EF and MCE. Recent airborne field measurements of prescribed fires found a strong correlation between MCE and EF for many compounds from conifer forest understory burns in North Carolina and California (Burling et al., 2011). But the same study found that EFs for only a handful of the same species were well correlated with MCE for prescribed fires in southwestern shrub ecosystems. Tower-based field measurements for a limited number of species also indicate EF–MCE can have variable slope and degree of correlation depending on vegetation type, region, and other factors (Urbanski et al., 2009).

Combustion that is not influenced by fire related convection sufficient to loft the emissions above the surface layer has been defined as residual smoldering combustion (RSC; Wade and Lunsford, 1989). RSC is often thought of as a post flame front phenomenon, but it can also occur when a fire is producing a convective column that is unable to entrain all of the fire emissions or when the fire is not producing enough heat to sustain strong convection (Bertschi

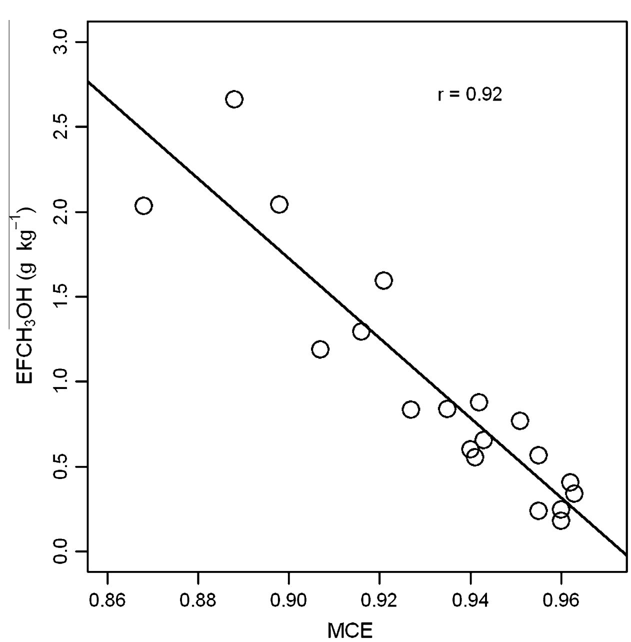

Fig. 3. Emission factor for CH_3OH (g kg^{-1}) plotted as a function of modified combustion efficiency (MCE) for laboratory combustion of pine understory fine fuels. Data from Yokelson et al. (2013) (Supplementary Material, Table S1, Geographic Region = SE). The correlation coefficient is $r = 0.92$.

et al., 2003). While smoldering usually accounts for the majority of the biomass burned during RSC, under certain conditions, such as high winds, the amount of biomass burned during RSC by flaming combustion could be significant. Consumption of coarse woody debris (dead wood with a diameter >7.6 cm), duff and organic soils (F and H layers of the forest floor (Ferderer, 1982)) typically dominates RSC; however, litter (identifiable, non-woody material on the surface such as needles, leaves, and bark), fine dead wood (diameter <7.6 cm), grasses and shrubs not consumed in the initial flaming front may also contribute. RSC may persist for hours to days following the passage of the flame front (Ward and Hardy, 1991; Ward et al., 1992; Ottmar, 2014). Limited ground-based field measurements of post fire front RSC have shown poor correlation of EF with MCE (Burling et al., 2011) supporting laboratory findings from studies of RSC prone fuels (Yokelson et al., 1997; Bertschi et al., 2003).

2. Emission factor synthesis

We have synthesized best estimate EF for 7 fire types and 3 classes of RSC prone fuels. The primary data sources for the fire type EF were airborne and tower based field measurements. These platforms measure convectively lofted emissions and by definition exclude RSC. We refer to the fire type EF as lofted EF (EF_{lofted}) and to the EF for RSC prone fuels as RSC EF (EF_{RSC}). Our EF_{lofted} were categorized by fire types common in the United States: prescribed fires in temperate conifer forests (subdivided into regions Southeast, Southwest, and Northwest), Western shrublands, and grasslands and wildfires in mixed-conifer forests of the Northwest and in boreal forests. The fire type categories were crafted to represent broad, fire-prone vegetation classes in the United States, as permitted by available EF data. We compiled EF_{RSC} from measurements of smoldering phase EF for fuel classes typically involved in RSC: coarse dead wood (logs and stumps) and ground fuels (duff, organic soil, and peat). EF_{RSC} for ground fuels are estimated for temperate forest organic soil/duff and boreal forest organic soil/duff.

Wildland fire emissions may undergo rapid chemical transformation through gas-phase reactions with free-radicals, photolysis by solar radiation, and heterogeneous processes (e.g., the uptake of gases by aerosol) (Heilman et al., 2014). The atmospheric fate of emissions and their subsequent role in climate is simulated with atmosphere composition – climate models which require initial emissions as input (Heilman et al., 2014). Our synthesis therefore presents initial EF. We use criteria similar to those employed by Akagi et al. (2011) and define initial EF as those based on measurements in fresh smoke – smoke that has not experienced significant photochemical processing, about 5–20 min old.

The preferred source of data for our synthesis is in situ measurements of emissions from fires in the natural environment. While field studies are our preferred source for EF, laboratory studies have some distinct advantages. In the laboratory, a much broader range of compounds can be measured than is possible in field experiments[1] and emissions can be measured for "pure" flaming or smoldering combustion processes. The recent study of Yokelson et al. (2013) coupled field and laboratory measurements to provide best estimate emission factors for >200 trace gases for semiarid shrublands and pine-forest understory prescribed fires and smoldering organic soil. We have used the laboratory based emission measurements from Yokelson et al. (2013) to derive EF_{lofted} estimates for forest fires when field measurements are not available. Our EF_{RSC} is based on limited ground-based measurements and a sizeable body of laboratory work.

2.1. Data criteria and methodology

Our synthesis presents estimated EF for CO_2, CO, CH_4, NMOC, $PM_{2.5}$, NO_x, N_2O, NH_3, and SO_2 for each fire type and RSC fuel category. We have compiled EF for 194 individual NMOC species identified in the laboratory fires of Yokelson et al. (2013). In addition to the 194 NMOC, Yokelson et al. (2013) reported EF for 147 species which were measured using advanced mass spectrometry techniques, but could not be identified. We have used their EF for unidentified species to estimate EF for the sum of unidentified NMOC ($EF\sum$Unidentifed NMOC). $PM_{2.5}$ includes OA and BC as well as non-carbon inorganic aerosol, which comprise a small fraction of aerosol mass emitted by wildland fires (Reid et al., 2005; Akagi et al., 2011; Pratt et al., 2011). Due to a lack of data, we do not provide estimates of EF for OA and BC aerosol separately.

When field measured EF were available from multiple studies for a particular fire type or RSC fuel category, they were averaged to provide the best estimate EF and their standard deviation was taken as the uncertainty. If field measured EF were available from only one study then its average and standard deviation were taken as the best estimate EF and uncertainty, respectively. In the absence of field data, we derived best estimate EF from laboratory studies (as described below) or used the best estimate values reported in the synthesis of Yokelson et al. (2013).

Emission factors for individual NMOC for different types of forest fires were estimated using the pine-forest understory data from 19 laboratory burns of Yokelson et al. (2013) (Supplemental Material, Table S1). We used this data to derive a linear relationship for predicting the EF for the sum of 194 NMOC ($EF\sum$NMOC) as a function of MCE. The plot of $EF\sum$NMOC vs. MCE and statistics for the linear regression are provided in Fig. 4. For each forest fire type we considered, when field measured EF were not available for a NMOC species identified in Yokelson et al. (2013) its EF was estimated using the our best estimate MCE (Table 1) and the linear fit shown in Fig. 4 under the assumption that the relative contribution of each individual species to the sum of NMOC is constant:

$$EFX(MCE) = (a + b \times MCE) \times \lambda_X \tag{4}$$

In Eq. (4), a and b are the regression coefficients from Fig. 4 and λ_X is the relative contribution of species X to the sum of NMOC:

$$\lambda_X = \frac{\overline{EFX}}{\overline{EF\Sigma NMOC}} \tag{5}$$

where $\overline{EFX}$ and $\overline{EF\Sigma NMOC}$ are the mean EF for X and the sum of NMOC, respectively, from the 19 laboratory burns of Yokelson et al. (2013) that were used in this analysis. This approach provides only a very rough estimate of EFX since the actual dependence of individual EF on MCE varies among species and the EF for some species are not well correlated with MCE. Additionally, the 19 lab fires we used did not include ground fuels or coarse woody debris, which could be a significant portion of the fuel consumed in wildfires and some prescribed fires. Since the smoldering combustion of large diameter woody fuels and ground fuels are generally not well correlated with MCE (Bertschi et al., 2003), this adds additional uncertainty to our EF estimates. The uncertainty in the EFX derived using this method were estimated as $\sqrt{\sigma_{FIELD} + \sigma_{LAB}}$ where σ_X estimates the uncertainty of the EF extrapolation of the lab data and σ_{FIELD} represents uncertainty in the MCE for a particular fire type. The term σ_{FIELD} was calculated as $b \times \lambda_X \times \sigma_{MCE}$, where the first two terms are from Eq. (4) and the last is the standard deviation of MCE for a particular fire type (Table 1). σ_X was calculated as:

[1] In the laboratory, smoke generated by fires can be sampled prior to significant dilution providing higher concentrations and greater signal-to-noise and thus allowing for a greater range of species to be measured. Additionally, logistical and technical restraints limit the instrumentation that may be deployed in the field compared to the lab.

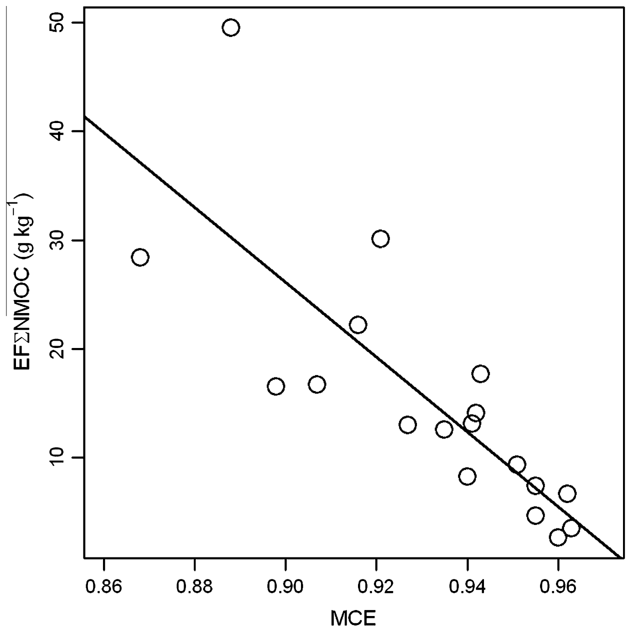

Fig. 4. Emission factor for the sum of total NMOC, EF∑NMOC, as a function of MCE. The figure shows data from Yokelson et al. (2013) (Supplementary Material, Table S1, Geographic Region = SE, excluding fire numbers 48 and 77 due to missing data). Regression statistics are: intercept = 335.65 (56.65), slope = −343.90 (60.67), R^2 = 0.654, number of observations = 19. Numbers in parentheses are the standard error.

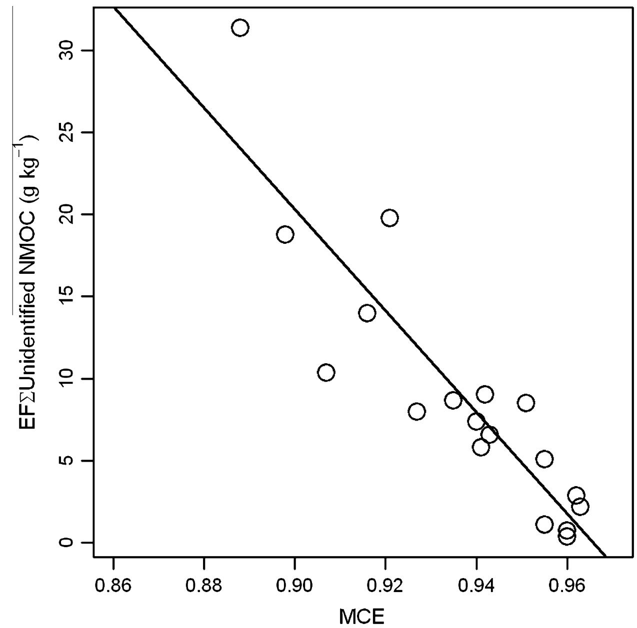

Fig. 5. Emission factor for the sum of total Unidentified NMOC, EF∑ Unidentified NMOC, as a function of MCE. The figure shows data from Yokelson et al. (2013) (Supplementary Material, Table S1, Geographic Region = SE, excluding fire numbers 48, 60, and 77 due to missing data). Regression statistics are: intercept = 298.73 (36.08), slope = −309.34 (38.50), R^2 = 0.801, number of observations = 18. Numbers in parentheses are the standard error.

$$\sigma_X = \frac{\sigma_{LAB}}{\overline{EFX}} \times EFX(MCE) \tag{6}$$

where σ_{LAB} and $\overline{EFX}$ are the standard deviation and mean of EFX, respectively, from the lab burns of Yokelson et al. (2013). This method was used to estimate EF_{lofted} for individual NMOC for the 5 forest fire types and EF_{RSC} for woody fuels when field data was not available.

In the case of Western shrubland fuels (e.g., chaparral), both field measurements and laboratory studies show a poor correlation between EF for individual NMOC and MCE (Burling et al., 2010, 2011; Yokelson et al., 2013). In contrast to the pine-forest understory fuels, EF∑NMOC was poorly correlated with MCE for the semiarid shrubland lab data of Yokelson et al. (2013). Because the EF reported by Yokelson et al. (2013) synthesize both laboratory and field measurements, we believe this approach provides the best estimate for both Western shrubland and grassland prescribed fires. We are not aware of any additional studies that could be used to update or improve their compilation. We therefore do not report EF of individual NMOC for Western shrubland and grassland fires but direct readers to consult Yokelson et al. (2013).

In addition to EF for 194 identified NMOC, Yokelson et al. (2013) also measured EF for 147 NMOC that could not be identified. The emissions of these unidentified NMOC was substantial, the sum of EF for these unidentified NMOC (EF∑Unidentified NMOC) equaled 45% of the EF sum for the identified NMOC (EF∑NMOC) for the pine understory fuels. We used their EF∑Unidentified NMOC data from the 19 pine understory lab burns to derive a linear relationship to extrapolate the lab data to MCE of different forest fire types. The plot of EF∑Unidentified NMOC vs. MCE and statistics for the linear regression are provided in Fig. 5. The linear fit was used to estimate EF∑Unidentified NMOC for different forest fire types and EF_{RSC} for woody fuels.

The RSC EF are based on limited ground based field studies and are heavily supplemented with measurements from laboratory studies. We have averaged laboratory measured EF from multiple studies, including the organic soil EF from Yokelson et al. (2013), to derive best estimate EF in the absence of field data. Many of the ground fuel EF for NMOC have been measured only in the Yokelson et al. (2013) study and for these species the best estimate EF we recommend is simply that published in their study. In the case of coarse dead wood, rough estimates of EF for NMOC were derived using the same approach we employed for forest fires.

2.2. Emission factors

Best estimate EF_{lofted} and EF_{RSC} for CO_2, CO, CH_4, ∑NMOC, ∑Unidentified NMOC, $PM_{2.5}$, NO_x, NH_3, N_2O, and SO_2 are given in Tables 1 and 2, respectively. Estimated EF for individual NMOC are provided in Tables A.1 and A.2. Our compilation delineates EF by the vertical disposition of the smoke when it attains buoyant equilibrium with the local atmosphere. This distinction allows for overlap between the fire characteristics these EF classes represent. The airborne and tower measurements on which EF_{lofted} are based may include a significant component of emissions from the smoldering combustion of fuel elements for which we report EF_{RSC}. For example, a strong convective column may entrain emissions from the post flame front combustion of coarse woody debris, stumps, and duff. Urbanski (2013) reported that smoke from wide spread smoldering within fire perimeters was lofted and entrained into the main plume when sampling emissions from wildfires in mixed-conifer forest of the northern Rockies. The total fire EF for any species will be a combination of EF_{lofted} and EF_{RSC} (Burling et al., 2011):

$$EF_{TOTAL} = EF_{lofted} \times (1 - F_{RSC}) + EF_{RSC} \times F_{RSC} \tag{7}$$

where F_{RSC} is the fraction of total fuel consumption that occurs during RSC (i.e., fuel consumption that produces emissions which are not lofted). Applying Eq. (7) to model emissions requires estimating F_{RSC}, which is difficult. In the simplest case, one could assume the consumption of smoldering prone fuels (coarse woody debris and duff) occurs exclusively as a post fire front phenomenon that

Table 1
Estimated MCE and EF (g kg^{-1}) for different fire types. Numbers in parentheses are estimated uncertainty (see Section 2.1).

Species	Prescribed fire southeast conifer forest		Prescribed fire southwest conifer forest		Prescribed fire northwest conifer forest		Prescribed fire western shrubland		Prescribed fire grassland		Wildfire northwest conifer forest		Wildfire boreal forest	
	EF	Note	EF	Note	EF	Note	EF	Note	EF	Note	EF	Note	EF	Note
MCE	0.933 (0.013)	1	0.924 (0.015)	8	0.906 (0.013)	10	0.935 (0.017)	19	0.947 (0.018)	22	0.883 (0.010)	12	0.917 (0.014)	15
Carbon dioxide (CO_2)	1703 (171)	1	1653 (34)	8	1598 (39)	10	1674 (38)	19	1705 (44)	22	1600 (19)	12	1641 (107)	15
Carbon monoxide (CO)	76 (15)	1	87 (18)	8	105 (13)	10	74 (18)	19	61 (21)	22	135 (11)	12	95 (36)	15
Methane (CH_4)	2.32 (1.09)	1	3.15 (0.91)	8	4.86 (1.37)	10	3.69 (1.36)	19	1.95 (1.05)	22	7.32 (0.59)	12	3.38 (1.46)	15
$\sum$NMOC	16.04 (10.88)	2	18.67 (17.36)	2	26.98 (15.57)	2	17.50 (13.44)	20	16.77 (11.59)	23	33.87 (17.36)	2	23.15 (13.13)	2
$\sum$Unidentified NMOC	10.02 (9.23)	3	12.95 (10.89)	3	18.36 (10.78)	3	7.14 (9.87)	21	7.14 (9.87)	21	25.68 (12.12)	3	15.17 (10.62)	3
$PM_{2.5}$	12.58 (3.99)	4	14.40 (5.02)	8	17.57 (5.13)	10	7.06 (0.78)	19	8.51 (5.12)	22	23.20 (10.40)	13	21.50 (4.80)	16
Nitrogen oxides as NO (NO_x)	1.70 (0.93)	5	1.88 (1.03)	9	2.06 (0.04)	11	2.18 (0.78)	19	2.18 (0.78)	19	2.00 (1.00)	14	1.00 (0.12)	17
Ammonia (NH_3)	0.14(0.14)	6	0.50(0.69)	7	1.53(0.42)	11	1.50 (1.43)	19	1.50 (1.43)	19	1.50(0.75)	14	0.79(0.40)	18
Nitrous oxide (N_2O)	0.16(0.21)	24	0.16(0.21)	24	0.16(0.21)	24	0.25 (0.18)	25	– (–)	26	0.16(0.21)	24	0.41(–)	24
Sulfur dioxide (SO_2)	1.06(0.41)	7	1.06(0.41)	7	1.06(0.41)	7	0.68 (0.15)	19	0.68 (0.15)	19	1.06(0.41)	7	1.06(0.41)	7

Notes:
1. Average of fire average values from the airborne measurements of Burling et al. (2011) (North Carolina fires), Akagi et al. (2013) and Yokelson et al. (1999) and the tower based measurements of Urbanski et al. (2009) (southeast US conifer forest fires).
2. Sum of individual EFNMOC from Table A.1.
3. Estimated based on MCE using regression equation derived from the laboratory data of Yokelson et al. (2013) (see Section 2.1).
4. Average of fire average values from the airborne measurements of Burling et al. (2011) (North Carolina fires) and the tower based measurements of Urbanski et al. (2009) (southeast US conifer forest fires).
5. Average of fire average values from the airborne measurements of Burling et al. (2011) (North Carolina fires) and Akagi et al. (2013).
6. Average of fire average values from the airborne measurements of Burling et al. (2011) (North Carolina fires), Akagi et al. (2013) and Yokelson et al. (1999).
7. Value is from Table 2 (Pine-forest Understory fire type) of Yokelson et al. (2013).
8. Average of Arizona fires from tower based study of Urbanski et al. (2009).
9. Estimated as the average of Southeast and Northwest prescribed fire values based on intermediate MCE value.
10. Average of fire average values from the airborne measurements of Burling et al. (2011) (California fires) and the tower based measurements of Urbanski et al. (2009) (Montana, Oregon, and British Columbia conifer forest fires).
11. Average of fire average values from the airborne measurements of Burling et al. (2011) (California fires).
12. Wildfire season averages reported in airborne study of Urbanski (2013).
13. Estimate reported in Urbanski (2013).
14. Rough estimate based on average of fire average values from the airborne measurements of Burling et al. (2011) (California fires).
15. Average of values from the airborne studies of Simpson et al. (2011), Goode et al. (2000) and Nance et al. (1993).
16. Value from Nance et al. (1993) who reported $PM_{3.5}$. However, since coarse mode particles (2.5–10 μm diameter) typically account for only ~10% of the mass fraction of fresh smoke particles (Reid et al., 2005), $EFPM_{3.5}$ will not be significantly different from $EFPM_{2.5}$.
17. Average of values from the airborne studies of Simpson et al. (2011) and Nance et al. (1993).
18. Average of values from the airborne studies of Goode et al. (2000) and Nance et al. (1993).
19. Value is from Table 2 (Semiarid Shrublands fire type) of Yokelson et al. (2013).
20. Sum of EF for identified NMOC from Table 2 of (Semiarid Shrublands fire type) of Yokelson et al. (2013). Uncertainty is the sum of the reported standard deviations.
21. Sum of EF for unidentified NMOC from Table 2 of (Semiarid Shrublands fire type) of Yokelson et al. (2013). Uncertainty is the sum of the reported standard deviations.
22. Average of grassland fires from tower based study of Urbanski et al. (2009).
23. This value reflects the sum of NMOC from Table 2 (Semiarid Shrublands) of Yokelson et al. (2013) and the following species from Urbanski et al. (2009): EFC_2H_2 = 0.42 (0.16), EFC_2H_4 = 1.21 (0.54), C_2H_6 = 0.25 (0.18), EFC_3H_4 = 0.05 (0.04), EFC_3H_6 = 0.48 (0.34), C_3H_8 = 0.09 (0.07), values in parenthesis are 1 standard deviation.
24. Taken from Table 1 of Akagi et al. (2011).
25. Taken from Table 2 (Chaparral) of Akagi et al. (2011).
26. A best estimate EF could not be provided due to lack of data.

Table 2
Estimated MCE and EF (g kg^{-1}) for RSC prone fuels. Numbers in parentheses are estimated uncertainty (see Section 2.1).

Species	Stumps and Logs		Temperate forest duff/organic soil		Boreal forest duff/organic soil	
	EF	Note	EF	Note	EF	Note
MCE	0.796 (0.037)	1	0.752 (0.047)	6	0.790 (0.028)	11
Carbon dioxide (CO_2)	1408 (48)	1	1305 (157)	6	1436 (33)	11
Carbon monoxide (CO)	229 (46)	1	271 (51)	6	244 (43)	11
Methane (CH_4)	13.94 (3.89)	1	7.47 (5.79)	7	8.42 (3.36)	11
$\sum$NMOC	45.25 (36.78)	2	68.67 (67.79)	2	54.33 (42.84)	2
$\sum$Unidentified NMOC	39.65 (30.78)	3	179.00 (179.00)	8	129.29 (129.29)	10
$PM_{2.5}$	33 (20)	4	50 (16)	9	20.6 (20.6)	10
Nitrogen oxides as NO (NO_x)	0 (0)	5	0.67 (0.67)	10	0.67 (0.67)	10
Ammonia (NH_3)	0.48 (0.38)	5	2.67 (2.67)	10	2.67 (2.67)	10
Nitrous oxide (N_2O)	– (–)	12	– (–)	12	– (–)	12
Sulfur dioxide (SO_2)	– (–)	12	1.76 (1.76)	10	1.76 (1.76)	10

Notes:
1. Average of ground-based measurements of Akagi et al. (2013) and Burling et al. (2011) (CL – unit ME samples 1–4), and Hao et al. (2007) (logs and stumps from Southeast and West).
2. Sum of NMOC from Table A.2.
3. Sum of unidentified NMOC estimated based on MCE using regression equation derived from the laboratory data of Yokelson et al. (2013) (see text).
4. Estimate based on linear regression of $EFPM_{2.5}$ vs. MCE using data from Burling et al. (2011) and Urbanski et al. (2009) (Southeast and West conifer forests), Hobbs et al. (1996) and Radke (1991) (Myrtle/Fall Creek, Silver, and Mable Lake fires). Regression statistics: slope = −212.25 (21.93), intercept = 210.77 (20.18), residual standard error = 4.10, R^2 = 0.64, n = 54.
5. Average of ground-based measurements of Akagi et al. (2013) and Burling et al. (2011) (CL – unit ME samples 1–4).
6. Average of ground-based measurements of Geron and Hays (2013) and Hao et al. (2007) (duff from Southeast and West).
7. Average and standard deviation of ground-based measurements of Hao et al. (2007) (duff from Southeast and West).
8. Sum of Unidentified NMOC from Table A.1 (Organic Soil) of Yokelson et al. (2013) adjusted by the ratio (68.67/49.61). In the ratio 68.67 is our estimate of identified EFNMOC and 49.61 is the sum of identified EFNMOC from Table A.1 (Organic Soil) of Yokelson et al. (2013). Uncertainty is estimated as 100%.
9. Average of ground-based values reported by Geron and Hays (2013) (Table 1, ground fire). Uncertainty estimated as half their range of reported values.
10. Value is from Table 2 (Organic Soil fire type) of Yokelson et al. (2013) with uncertainty estimated as 100%.
11. Average and standard deviation of ground-based measurements of Hao et al. (2007) (Alaska duff).
12. A best estimate EF could not be provided due to lack of data.

contributes only to RSC. However, the actual partitioning of emissions from the consumption of these fuels types is likely to be highly dependent on fire characteristics and atmospheric conditions and therefore highly variable and difficult to accurately predict. We do not provide recommendations regarding the weighting of the EF_{lofted} and EF_{RSC} for particular fire types. Guidance on the relative importance of flaming and smoldering combustion and biomass consumption by fuel class according to fire characteristics and vegetation type may be found in Ottmar (2014), Weise and Wright (2014), Hyde et al. (2011), de Groot et al. (2009) and Brown et al. (1991).

2.2.1. Forest fires

We have compiled best estimate forest fire EF for three types of prescribed fires – temperate conifer forests in the Southeast, Southwest, and Northwest, and two types of wildfires – mixed-conifer forests of the Northwest and boreal forests. Fire average MCE for these datasets are shown in Fig. 6. The availability of field data was greatest for the Southeast prescribed fires with the recent study of Akagi et al. (2013) providing EF for >70 NMOC, while that for Northwest wildfires was the most limited, with EF available for only CO_2, CO, and CH_4. When field measurements were not available for NMOC, we estimated the EF based on the fire type MCE (Fig. 6 and Table 1) using the approach described in Section 2.1. The accuracy of this method was evaluated by comparing estimated EF (EF_{est}) with field measured EF (EF_{field}) for 69 NMOC from 4 Southeast prescribed fires from Akagi et al. (2013) (Block 6, Block 9b, Block 22b, Pine Plantation of their Table A.1). Compared with their 4 fire average EF our EF$\sum$NMOC was low by 0.64 g kg^{-1} (5%) and the mean absolute error of the 69 EFX was 0.08 g kg^{-1}.

Best estimate EF for forest fires are given in Tables 1 and A.1. Our Southeast prescribed fire EF differ from the conifer understory recommendations of Yokelson et al. (2013) in that we include airborne measurements from Akagi et al. (2013) and tower based measurements from Urbanski et al. (2009) and we have not included the

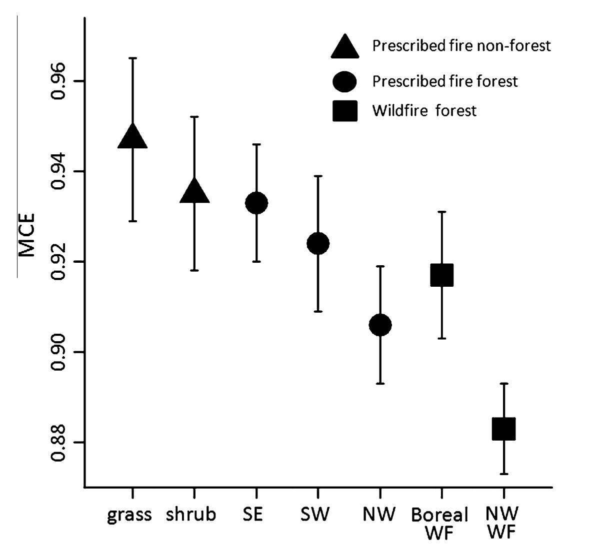

Fig. 6. MCE for different fire types from Table 1. SE = southeast, SW = southwest, NW = northwest, and WF = wildfire. Error bars are 1 standard deviation.

Sierra Nevada Mountain fires of Burling et al. (2011). Tables 1 and A.1 provide reference lists describing the origin of each EF.

2.2.2. Western shrublands and grasslands

Field data for fires in shrublands and grasslands is extremely limited. Yokelson et al. (2013) synthesized laboratory and field measurements to provide best estimate EF for semiarid shrublands (chaparral and oak savanna). We are not aware of any additional studies that could be used to update or improve their compilation and we believe their synthesis provides the best estimate for Western shrubland prescribed fires. Urbanski et al. (2009) report EF for a limited number of species for prescribed fires in grasslands and these measurements were combined with the semiarid shrubland

EF from Yokelson et al. (2013) to provide the EF listed in Table 1. With the exception of the C_2 and C_3 hydrocarbons listed notes of Table 1, we have not included EF for individual NMOC for Western shrubland and grassland fires. We recommend readers consult the semiarid shrubland data of Yokelson et al. (2013) for EF not included in Table 1.

2.2.3. Residual smoldering combustion

Best estimate EF_{RSC} are provided in Tables 2 and A.2. The EF were derived from a combination of ground-based field measurements and laboratory measurements of "pure" smoldering combustion. The primary data sources for the coarse woody debris category are the field measurements of Hao et al., 2007, Burling et al. (2011) and Akagi et al. (2013). Emission factors for NMOC not measured in these studies were estimated from the category MCE using the method described in Section 2.1. However, laboratory studies have found EF for the smoldering combustion of large diameter woody fuels and ground fuels are often not well correlated with MCE (Bertschi et al., 2003) indicating our MCE based extrapolation of lab measured EF is subject to significant uncertainty. The EF we estimate in this manner should be considered rough estimates and we have assigned them generous uncertainties. We evaluated the uncertainty of our MCE based EF estimation method by comparing estimated EF (EF_{est}) with field measured EF (EF_{field}) for 65 NMOC from the ground-based measurements of 3 Southeast prescribed fires reported by Akagi et al., 2013. Compared with their 3 fire average EF, the error (observed–predicted) in $EF\sum NMOC$ was + 3.23 g kg^{-1} (+11%) and the mean absolute error of the 65 EFX was 0.28 g kg^{-1}. The field data available for RSC of ground fuels is limited to CO_2, CO, CH_4, and $PM_{2.5}$ reported by Hao et al., 2007 and Geron and Hays (2013). The vast majority of EF we report for RSC of ground fuels is derived from laboratory studies. The reference lists for Tables 2 and A.2 clearly describe the origin of each EF.

3. Conclusions

We have developed best estimate EF for United States wildland fires based on a review of the literature. Over the past decade, substantial progress has been made in quantifying biomass burning EF. However, significant gaps in the current knowledge of EF exist in four areas: wildfires in temperate forests, residual smoldering combustion, aerosol speciation, and nitrogen containing compounds. The first area is specific to the United States, while the latter three are pertinent to open biomass burning in many regions of the world.

3.1. Wildfires in temperate forests

Reliable published EF for wildfires in temperate forests are extremely limited. The study of Urbanski (2013) reported emissions of CO_2, CO, and CH_4 from wildfires in the northern Rocky Mountains, United States. They found that the MCE of these fires was substantially lower than that measured for prescribed fires in temperate conifer forests (Urbanski et al., 2009; Burling et al., 2011; Akagi et al., 2013) indicating prescribed fires may not be a suitable proxy for estimating emission from wildfires. They speculated that the lower MCE of the wildfires they measured may have resulted from greater consumption of smoldering prone fuels in wildfires compared with typical prescribed fires. Using their MCE, we estimated EF for 196 NMOC using EF – MCE relationship derived from previously published laboratory data (Section 2.1). However, this approach provides only a rough estimate for EF and we assign large uncertainties to these estimates (Table 2). Field measurements of wildfire EF for NMOC, NO_x, and $PM_{2.5}$ are needed to address this knowledge gap and reduce the uncertainty in our estimated EF.

3.2. Residual smoldering combustion

The recent field studies of Burling et al. (2011) and Akagi et al. (2013) have greatly improved our knowledge of gas phase emissions from RSC of coarse woody fuels. However, these studies did not include PM emissions and quantification of $EFPM_{2.5}$ remains an important need for understanding emissions from RSC of woody fuels. Our compilation relied on laboratory measurements to estimate EF for NMOC from RSC of duff and organic soils. Field measurements of NMOC emissions from RSC of ground fuels in both the Southeast and Western United States are needed.

3.3. Nitrogen containing gases

The dominant nitrogen containing species emitted by the burning of wildland fuels are NH_3 (from smoldering combustion), NO_x (from flaming combustion), and HCN, which is produced by both. The emission of these species depends on both fuel nitrogen content and MCE (Burling et al., 2011). The partitioning of fuel nitrogen among nitrogen containing emissions also appears to be dependent on the fuel components burned (Burling et al., 2011). Because the nitrogen content of fuel consumed by wildland fires may be highly variable, the true EF for a specific region, vegetation type, or fire event could differ substantially from the best estimate EF compiled here. One factor that can increase the nitrogen content of fuels is the deposition of anthropogenic nitrogen (Fenn, 1991). Yokelson et al. (2011) reported high $EFNO_x$ and $EFNH_3$ for Mexican forests impacted by urban pollution. In general, an improved understanding of the dependence of EF for nitrogen containing compounds on MCE and fuel component specific nitrogen content is needed.

3.4. Speciation of aerosol emissions

Field measurements of EF for BC and OA, and of aerosol speciation in general, are needed. Much recent laboratory work has been done to characterize particle emissions (e.g., Chen et al., 2006, 2007; McMeeking et al., 2009; Levin et al., 2010). However, as discussed by Akagi et al. (2011), the applicability of these measurements to natural fires is uncertain due to the different dilution and cooling regimes often employed in laboratory studies of biomass burning particle studies and the rapid initial evolution of particle emissions.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2013.05.045.

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Table A.1. Estimated EF (g kg^{-1}) for non-methane organic compounds for different forest fire types. Numbers in parentheses are estimated uncertainty (see Sect. 2.1).

	Prescribed Fire Southeast Conifer Forest		Prescribed Fire Southwest Conifer Forest		Prescribed Fire Northwest Conifer Forest		Wildfire Northwest Conifer Forest		Wildfire Boreal Forest	
Species	EF	note	EF	note	EF	note	EF	note	EF	note
Hydrogen Cyanide (HCN)	0.613 (0.220)	1	0.302 (0.270)	3	0.765 (0.078)	9	0.540 (0.460)	3	0.890 (0.290)	12
Formaldehyde (HCHO)	1.681 (0.429)	2	1.256 (0.995)	3	2.235 (0.573)	9	2.248 (1.670)	3	1.975 (0.900)	12
Methanol (CH_3OH)	0.986 (0.553)	2	1.152 (0.914)	3	2.515 (0.940)	9	2.061 (1.534)	3	1.305 (0.260)	12
Isocyanic Acid (HNCO)	0.090 (0.059)	3	0.110 (0.071)	3	0.147 (0.089)	3	0.198 (0.115)	3	0.126 (0.078)	3
FormicAcid (HCOOH)	0.116 (0.158)	2	0.282 (0.243)	3	0.184 (0.094)	9	0.505 (0.412)	3	0.470 (0.120)	12
Ethyne (C_2H_2)	0.362 (0.135)	4	0.296 (0.032)	8	0.312 (0.104)	10	0.376 (0.479)	3	0.237 (0.100)	12
Ethene (C_2H_4)	1.090 (0.205)	5	1.036 (0.131)	8	1.381 (0.322)	10	1.825 (1.671)	3	1.310 (0.330)	12
Ethane (C_2H_6)	0.288 (0.173)	6	0.416 (0.111)	8	0.665 (0.230)	11	1.077 (1.427)	3	0.610 (0.280)	12
Acetonitrile (CH_3CN)	0.032 (0.016)	7	0.161 (0.121)	3	0.215 (0.153)	3	0.289 (0.201)	3	0.300 (0.060)	12
Acetaldehyde (CH_3CHO)	0.641 (0.124)	7	0.838 (0.674)	3	1.119 (0.861)	3	1.500 (1.133)	3	0.953 (0.747)	3
Ethanol (CH_3CH_2OH)	0.012 (0.009)	7	0.179 (0.261)	3	0.239 (0.344)	3	0.320 (0.459)	3	0.027 (0.029)	12
Acetic Acid (CH_3COOH)	1.489 (0.867)	2	2.493 (1.874)	3	3.020 (0.990)	9	4.461 (3.119)	3	2.420 (0.900)	12
Glycolaldehyde ($C_2H_4O_2$)	0.305 (0.394)	1	0.419 (0.329)	13	0.725 (0.629)	9	0.916 (0.605)	13	0.506 (0.368)	13
Methyl Formate ($C_2H_4O_2$)	0.014 (0.011)	3	0.017 (0.013)	3	0.022 (0.017)	3	0.030 (0.022)	3	0.019 (0.014)	3
1,1-Dimethylhydrazine ($C_2H_8N_2$)	0.020 (0.040)	3	0.024 (0.049)	3	0.032 (0.064)	3	0.043 (0.086)	3	0.027 (0.055)	3
Glycolic Acid ($C_2H_4O_3$)	0.028 (0.030)	3	0.034 (0.036)	3	0.046 (0.047)	3	0.061 (0.063)	3	0.039 (0.041)	3

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
Propyne (C_3H_4)	0.056 (0.006)	7	0.025 (0.022)	3	0.033 (0.029)	3	0.044 (0.038)	3	0.029 (0.010)	12
Propylene (C_3H_6)	0.426 (0.139)	4	0.527 (0.100)	8	0.723 (0.258)	10	0.698 (0.516)	3	0.445 (0.160)	12
Propane (C_3H_8)	0.094 (0.060)	6	0.153 (0.065)	8	0.242 (0.126)	11	0.509 (0.451)	3	0.230 (0.050)	12
Acrylonitrile (C_3H_3N)	0.054 (0.027)	7	0.025 (0.026)	3	0.034 (0.034)	3	0.045 (0.046)	3	0.029 (0.030)	3
Propanenitrile (C_3H_5N)	0.007 (0.008)	3	0.009 (0.010)	3	0.012 (0.014)	3	0.016 (0.018)	3	0.010 (0.012)	3
Acrolein (C_3H_4O)	0.323 (0.108)	7	0.256 (0.199)	3	0.342 (0.253)	3	0.458 (0.332)	3	0.291 (0.220)	3
Acetone (C_3H_6O)	0.651 (0.269)	7	0.431 (0.362)	3	0.575 (0.465)	3	0.770 (0.613)	3	0.370 (0.100)	12
Propanal (C_3H_6O)	0.088 (0.080)	3	0.108 (0.098)	3	0.144 (0.126)	3	0.193 (0.166)	3	0.123 (0.109)	3
Carbonsuboxide (C_3O_2)	0.001 (0.001)	3	0.001 (0.001)	3	0.001 (0.001)	3	0.002 (0.002)	3	0.001 (0.001)	3
Acrylic Acid ($C_3H_4O_2$)	0.029 (0.022)	3	0.035 (0.027)	3	0.047 (0.034)	3	0.062 (0.045)	3	0.040 (0.030)	3
Ethyl Formate ($C_3H_6O_2$)	0.005 (0.006)	3	0.006 (0.007)	3	0.009 (0.009)	3	0.011 (0.013)	3	0.007 (0.008)	3
Methyl Acetate ($C_3H_6O_2$)	0.007 (0.013)	7	0.131 (0.116)	3	0.174 (0.149)	3	0.234 (0.197)	3	0.148 (0.129)	3
Pyruvic Acid ($C_3H_4O_3$)	0.014 (0.017)	3	0.017 (0.020)	3	0.023 (0.026)	3	0.030 (0.035)	3	0.019 (0.023)	3
1,3-Butadiyne (C_4H_2)	0.001 (0.000)	3	0.001 (0.001)	3	0.001 (0.001)	3	0.001 (0.001)	3	0.001 (0.001)	3
Butenyne (C_4H_4)	0.002 (0.002)	3	0.003 (0.003)	3	0.003 (0.003)	3	0.004 (0.004)	3	0.003 (0.003)	3
1,3-Butadiene (C_4H_6)	0.258 (0.043)	7	0.136 (0.112)	3	0.181 (0.144)	3	0.243 (0.190)	3	0.070 (0.008)	12

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
1,2-Butadiene (C_4H_6)	0.001 (0.002)	3	0.002 (0.002)	3	0.002 (0.002)	3	0.003 (0.003)	3	0.002 (0.002)	3
1-,2-Butyne (C_4H_6)	0.010 (0.002)	7	0.003 (0.002)	3	0.004 (0.003)	3	0.005 (0.004)	3	0.003 (0.003)	3
trans-2-Butene (C_4H_8)	0.035 (0.018)	7	0.034 (0.038)	3	0.046 (0.050)	3	0.061 (0.066)	3	0.020 (0.003)	12
1-Butene (C_4H_8)	0.131 (0.034)	7	0.108 (0.107)	3	0.145 (0.139)	3	0.194 (0.184)	3	0.077 (0.009)	12
2-Methylpropene (C_4H_8)	0.053 (0.062)	3	0.064 (0.075)	3	0.086 (0.099)	3	0.115 (0.131)	3	0.073 (0.085)	3
cis-2-Butene (C_4H_8)	0.028 (0.016)	7	0.028 (0.031)	3	0.038 (0.040)	3	0.050 (0.054)	3	0.015 (0.002)	12
i-Butane (C_4H_{10})	0.010 (0.004)	7	0.068 (0.123)	3	0.090 (0.163)	3	0.121 (0.218)	3	0.021 (0.004)	12
n-Butane (C_4H_{10})	0.036 (0.016)	7	0.094 (0.108)	3	0.126 (0.142)	3	0.168 (0.188)	3	0.076 (0.015)	12
Pyrrole (C_4H_5N)	0.006 (0.008)	3	0.008 (0.010)	3	0.010 (0.013)	3	0.014 (0.018)	3	0.009 (0.012)	3
Furan (C_4H_4O)	0.178 (0.155)	1	0.270 (0.257)	3	0.490 (0.113)	9	0.483 (0.440)	3	0.280 (0.030)	12
Methacrolein (C_4H_6O)	0.039 (0.004)	7	0.048 (0.045)	3	0.064 (0.058)	3	0.086 (0.076)	3	0.043 (0.005)	12
Methyl Vinyl Ketone (MVK,C_4H_6O)	0.058 (0.036)	7	0.231 (0.201)	3	0.309 (0.259)	3	0.414 (0.341)	3	0.097 (0.012)	12
Crotonaldehyde (C_4H_6O)	0.181 (0.162)	3	0.221 (0.197)	3	0.296 (0.254)	3	0.396 (0.335)	3	0.252 (0.220)	3
2,5-Dihydrofuran (C_4H_6O)	0.001 (0.002)	3	0.001 (0.003)	3	0.001 (0.003)	3	0.002 (0.005)	3	0.001 (0.003)	3
n-Butanal (C_4H_8O)	0.032 (0.013)	7	0.026 (0.026)	3	0.035 (0.033)	3	0.047 (0.044)	3	0.030 (0.029)	3
Methyl Ethyl Ketone (MEK,C_4H_8O)	0.098 (0.028)	7	0.131 (0.132)	3	0.175 (0.171)	3	0.234 (0.226)	3	0.110 (0.030)	12

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
2-Methylpropanal (C_4H_8O)	0.021 (0.013)	7	0.030 (0.037)	3	0.040 (0.048)	3	0.054 (0.064)	3	0.034 (0.041)	3
Tetrahydrofuran (C_4H_8O)	0.000 (0.000)	3	0.000 (0.001)	3	0.000 (0.001)	3	0.001 (0.001)	3	0.000 (0.001)	3
1-Butanol ($C_4H_{10}O$)	0.063 (0.080)	3	0.077 (0.098)	3	0.103 (0.129)	3	0.138 (0.171)	3	0.088 (0.110)	3
Cyclopentenone (C_5H_6O)	0.004 (0.004)	3	0.005 (0.005)	3	0.006 (0.007)	3	0.009 (0.009)	3	0.005 (0.006)	3
2,3-Butadione ($C_4H_6O_2$)	0.167 (0.161)	3	0.204 (0.195)	3	0.272 (0.253)	3	0.364 (0.334)	3	0.232 (0.218)	3
Vinyl Acetate ($C_4H_6O_2$)	0.000 (–)	3	0.000 (–)	3	0.000 (–)	3	0.000 (–)	3	0.000 (–)	3
Methyl Acrylate ($C_4H_6O_2$)	0.005 (0.004)	3	0.006 (0.005)	3	0.008 (0.006)	3	0.010 (0.008)	3	0.007 (0.005)	3
2,3-Dihydro-1,4-Dioxin ($C_4H_6O_2$)	0.002 (0.002)	3	0.002 (0.002)	3	0.003 (0.003)	3	0.004 (0.004)	3	0.002 (0.002)	3
Methyl Propanoate ($C_4H_8O_2$)	0.003 (0.003)	3	0.004 (0.004)	3	0.005 (0.005)	3	0.007 (0.007)	3	0.004 (0.004)	3
1,3-CyclopentadienePIT (C_5H_6)	0.028 (0.032)	3	0.034 (0.039)	3	0.045 (0.052)	3	0.061 (0.068)	3	0.039 (0.044)	3
Pentenyneisomers (C_5H_6)	0.002 (0.002)	3	0.002 (0.002)	3	0.003 (0.003)	3	0.004 (0.004)	3	0.002 (0.002)	3
Isoprene (C_5H_8)	0.140 (0.029)	7	0.072 (0.073)	3	0.096 (0.094)	3	0.129 (0.125)	3	0.074 (0.017)	12
trans-1,3-Pentadiene (C_5H_8)	0.023 (0.006)	7	0.020 (0.018)	3	0.026 (0.023)	3	0.035 (0.031)	3	0.022 (0.020)	3
cis-1,3-Pentadiene (C_5H_8)	0.010 (0.009)	3	0.012 (0.011)	3	0.016 (0.014)	3	0.022 (0.019)	3	0.014 (0.012)	3
Cyclopentene (C_5H_8)	0.045 (0.004)	7	0.024 (0.023)	3	0.032 (0.030)	3	0.043 (0.040)	3	0.027 (0.026)	3
Pentadieneisomer (C_5H_8)	0.002 (0.002)	3	0.003 (0.003)	3	0.003 (0.003)	3	0.005 (0.005)	3	0.003 (0.003)	3

Table A.1 continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
Cyclopentane (C_5H_{10})	0.002 (0.002)	3	0.003 (0.003)	3	0.004 (0.004)	3	0.005 (0.005)	3	0.003 (0.003)	3
1-Pentene (C_5H_{10})	0.030 (0.005)	7	0.030 (0.032)	3	0.040 (0.041)	3	0.054 (0.055)	3	0.034 (0.036)	3
2-Methyl-1-Butene (C_5H_{10})	0.019 (0.005)	7	0.013 (0.014)	3	0.017 (0.018)	3	0.023 (0.024)	3	0.015 (0.015)	3
trans-2-Pentene (C_5H_{10})	0.016 (0.007)	7	0.013 (0.014)	3	0.018 (0.019)	3	0.024 (0.025)	3	0.015 (0.016)	3
3-Methyl-1-Butene (C_5H_{10})	0.014 (0.002)	7	0.004 (0.004)	3	0.005 (0.006)	3	0.007 (0.007)	3	0.004 (0.005)	3
cis-2-Pentene (C_5H_{10})	0.009 (0.005)	7	0.033 (0.032)	3	0.043 (0.041)	3	0.058 (0.055)	3	0.037 (0.036)	3
2-Methyl-2-Butene (C_5H_{10})	0.024 (0.002)	7	0.022 (0.022)	3	0.030 (0.029)	3	0.040 (0.039)	3	0.025 (0.025)	3
2,2-Dimethylpropane (C_5H_{12})	0.000 (0.001)	3	0.001 (0.001)	3	0.001 (0.001)	3	0.001 (0.002)	3	0.001 (0.001)	3
i-Pentane (C_5H_{12})	0.028 (0.002)	7	0.031 (0.041)	3	0.041 (0.054)	3	0.056 (0.072)	3	0.019 (0.005)	12
n-Pentane (C_5H_{12})	0.007 (0.004)	7	0.042 (0.047)	3	0.055 (0.062)	3	0.074 (0.082)	3	0.027 (0.008)	12
1-Methylpyrrole (C_5H_7N)	0.002 (0.003)	3	0.003 (0.004)	3	0.004 (0.005)	3	0.005 (0.006)	3	0.003 (0.004)	3
3-Methylfuran (C_5H_6O)	0.018 (0.017)	3	0.022 (0.020)	3	0.030 (0.026)	3	0.040 (0.035)	3	0.025 (0.023)	3
Other C_6H_{10} (isomer 4)	0.153 (0.153)	7	0.164 (0.176)	3	0.219 (0.230)	3	0.294 (0.305)	3	0.187 (0.198)	3
1-Methylcyclopentane (C_6H_{12})	0.058 (0.054)	3	0.071 (0.065)	3	0.095 (0.084)	3	0.127 (0.112)	3	0.081 (0.073)	3
Pentenone (C_5H_8O)	0.317 (0.292)	3	0.387 (0.355)	3	0.517 (0.458)	3	0.693 (0.605)	3	0.440 (0.396)	3
Cyclopentanone (C_5H_8O)	0.087 (0.101)	3	0.106 (0.123)	3	0.141 (0.160)	3	0.189 (0.213)	3	0.120 (0.138)	3

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
2-Methyl-2-Butenal (C_5H_8O)	0.005 (0.005)	3	0.006 (0.007)	3	0.008 (0.009)	3	0.011 (0.011)	3	0.007 (0.007)	3
2-Methylbutanal ($C_5H_{10}O$)	0.026 (0.034)	3	0.031 (0.042)	3	0.042 (0.055)	3	0.056 (0.073)	3	0.036 (0.047)	3
3-Methyl-2-Butanone ($C_5H_{10}O$)	0.011 (0.005)	7	0.020 (0.021)	3	0.027 (0.027)	3	0.036 (0.036)	3	0.023 (0.023)	3
2-Pentanone ($C_5H_{10}O$)	0.022 (0.022)	3	0.027 (0.026)	3	0.036 (0.034)	3	0.049 (0.045)	3	0.031 (0.029)	3
3-Pentanone ($C_5H_{10}O$)	0.018 (0.019)	3	0.023 (0.023)	3	0.030 (0.030)	3	0.040 (0.040)	3	0.026 (0.026)	3
Methyl Diazine (isomer1,$C_5H_6N_2$)	0.009 (0.009)	3	0.011 (0.011)	3	0.014 (0.014)	3	0.019 (0.019)	3	0.012 (0.012)	3
Methyl Diazine (isomer2,$C_5H_6N_2$)	0.004 (0.003)	3	0.004 (0.004)	3	0.006 (0.005)	3	0.008 (0.007)	3	0.005 (0.005)	3
Methyl Diazine (isomer3,C_5H_6N2)	0.002 (0.004)	3	0.002 (0.005)	3	0.003 (0.006)	3	0.004 (0.008)	3	0.003 (0.005)	3
3-Furaldehyde ($C_5H_4O_2$)	0.013 (0.015)	3	0.016 (0.018)	3	0.022 (0.024)	3	0.029 (0.031)	3	0.019 (0.020)	3
2-Furaldehyde ($C_5H_4O_2$)	0.067 (0.048)	7	0.395 (0.467)	3	0.528 (0.611)	3	0.707 (0.812)	3	0.450 (0.525)	3
Cyclopentenedione ($C_5H_4O_2$)	0.007 (0.011)	3	0.009 (0.013)	3	0.012 (0.017)	3	0.016 (0.023)	3	0.010 (0.015)	3
Methyl Methacrylate ($C_5H_8O_2$)	0.022 (0.021)	3	0.026 (0.026)	3	0.035 (0.033)	3	0.047 (0.044)	3	0.030 (0.029)	3
Methyl Butanoate ($C_5H_{10}O_2$)	0.011 (0.024)	3	0.013 (0.029)	3	0.017 (0.039)	3	0.023 (0.052)	3	0.015 (0.033)	3
Benzene (C_6H_6)	0.283 (0.044)	7	0.225 (0.218)	3	0.300 (0.282)	3	0.402 (0.374)	3	0.550 (0.110)	12
Divinylacetylene (C_6H_6)	0.002 (0.001)	3	0.002 (0.002)	3	0.003 (0.002)	3	0.003 (0.003)	3	0.002 (0.002)	3
Methyl Cyclopentadiene (isomer 1,C_6H_8)	0.006 (0.008)	3	0.007 (0.010)	3	0.010 (0.013)	3	0.013 (0.017)	3	0.008 (0.011)	3

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
Methyl Cyclopentadiene (isomer 2,C_6H_8)	0.006 (0.008)	3	0.007 (0.010)	3	0.010 (0.013)	3	0.013 (0.017)	3	0.008 (0.011)	3
Hexenyne (C_6H_8)	0.002 (0.003)	3	0.003 (0.004)	3	0.004 (0.005)	3	0.005 (0.007)	3	0.003 (0.005)	3
cis-1,3-Hexadiene (C_6H_{10})	0.001 (0.001)	3	0.001 (0.002)	3	0.002 (0.002)	3	0.003 (0.003)	3	0.002 (0.002)	3
trans-1,3-Hexadiene (C_6H_{10})	0.004 (0.005)	3	0.005 (0.006)	3	0.006 (0.007)	3	0.008 (0.010)	3	0.005 (0.006)	3
1-Methylcyclopentene (C_6H_{10})	0.003 (0.002)	3	0.003 (0.003)	3	0.004 (0.004)	3	0.006 (0.005)	3	0.004 (0.003)	3
Cyclohexene (C_6H_{10})	0.009 (0.010)	3	0.012 (0.012)	3	0.015 (0.016)	3	0.021 (0.021)	3	0.013 (0.013)	3
Other C_6H_{10} (isomer 1)	0.007 (0.006)	3	0.008 (0.007)	3	0.011 (0.010)	3	0.014 (0.013)	3	0.009 (0.008)	3
Other C_6H_{10} (isomer 2)	0.001 (0.001)	3	0.001 (0.001)	3	0.001 (0.001)	3	0.001 (0.002)	3	0.001 (0.001)	3
Other C_6H_{10} (isomer 3)	0.001 (0.001)	3	0.001 (0.001)	3	0.002 (0.002)	3	0.002 (0.003)	3	0.002 (0.002)	3
2-Methylfuran (C_5H_6O)	0.007 (0.007)	3	0.008 (0.009)	3	0.011 (0.011)	3	0.015 (0.015)	3	0.009 (0.010)	3
Other C_6H_{10} (isomer 5)	0.003 (0.003)	3	0.004 (0.004)	3	0.005 (0.005)	3	0.006 (0.007)	3	0.004 (0.004)	3
1-Methylpyrazole ($C_4H_6N_2$)	0.001 (0.001)	3	0.002 (0.002)	3	0.002 (0.002)	3	0.003 (0.003)	3	0.002 (0.002)	3
2-Methyl-1-Pentene (C_6H_{12})	0.035 (0.033)	3	0.043 (0.040)	3	0.057 (0.052)	3	0.077 (0.068)	3	0.049 (0.045)	3
1-Hexene (C_6H_{12})	0.036 (0.035)	3	0.045 (0.043)	3	0.060 (0.055)	3	0.080 (0.073)	3	0.051 (0.048)	3
Cyclohexene (C_6H_{12})	0.001 (0.001)	3	0.002 (0.002)	3	0.002 (0.002)	3	0.003 (0.003)	3	0.002 (0.002)	3
Hexenes (sum of 3 isomers, C_6H_{12})	0.040 (0.048)	3	0.049 (0.058)	3	0.066 (0.076)	3	0.088 (0.101)	3	0.056 (0.065)	3

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
cis-2-Hexene (C_6H_{12})	0.013 (0.017)	3	0.016 (0.021)	3	0.021 (0.028)	3	0.028 (0.037)	3	0.018 (0.024)	3
2,2-Dimethylbutane (C_6H_{14})	0.000 (–)	3	0.000 (–)	3	0.000 (–)	3	0.000 (–)	3	0.000 (–)	3
n-Hexane (C_6H_{14})	0.012 (0.003)	7	0.024 (0.030)	3	0.032 (0.040)	3	0.042 (0.053)	3	0.027 (0.006)	12
3-Methylpentane (C_6H_{14})	0.003 (0.001)	7	0.004 (0.005)	3	0.005 (0.007)	3	0.007 (0.009)	3	0.018 (0.004)	12
Phenol (C_6H_5OH)	0.282 (0.349)	1	0.391 (0.258)	14	0.800 (0.410)	9	0.865 (0.431)	14	0.473 (0.279)	14
2-Ethylfuran (C_6H_8O)	0.009 (0.006)	7	0.015 (0.017)	3	0.020 (0.022)	3	0.027 (0.030)	3	0.017 (0.019)	3
2,5-Dimethylfuran (C_6H_8O)	0.031 (0.014)	7	0.027 (0.030)	3	0.036 (0.040)	3	0.048 (0.053)	3	0.031 (0.034)	3
n-Hexanal ($C_6H_{12}O$)	0.023 (0.027)	3	0.028 (0.032)	3	0.038 (0.042)	3	0.051 (0.056)	3	0.032 (0.036)	3
3-Hexanone ($C_6H_{12}O$)	0.018 (0.017)	3	0.022 (0.021)	3	0.029 (0.027)	3	0.039 (0.036)	3	0.025 (0.023)	3
2-Hexanone ($C_6H_{12}O$)	0.007 (0.007)	3	0.009 (0.009)	3	0.012 (0.012)	3	0.016 (0.015)	3	0.010 (0.010)	3
2-Ethylpyrazine ($C_6H_8N_2$)	0.004 (0.005)	3	0.005 (0.006)	3	0.007 (0.008)	3	0.010 (0.010)	3	0.006 (0.007)	3
Resorcinol ($C_6H_6O_2$)	1.009 (0.964)	3	1.233 (1.171)	3	1.647 (1.516)	3	2.206 (2.005)	3	1.402 (1.308)	3
Toluene ($C_6H_5CH_3$)	0.199 (0.030)	7	0.172 (0.157)	3	0.229 (0.202)	3	0.307 (0.267)	3	0.240 (0.060)	12
Heptadiyne (isomer 1,C_7H_8)	0.001 (0.001)	3	0.001 (0.001)	3	0.002 (0.002)	3	0.002 (0.003)	3	0.001 (0.002)	3
Heptadiyne (isomer 2,C_7H_8)	0.000 (0.000)	3	0.000 (0.000)	3	0.000 (0.001)	3	0.000 (0.001)	3	0.000 (0.000)	3
1-Methylcyclohexene (C_7H_{12})	0.006 (0.006)	3	0.007 (0.008)	3	0.010 (0.010)	3	0.013 (0.013)	3	0.008 (0.008)	3

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
1-Heptene (C_7H_{14})	0.025 (0.025)	7	0.034 (0.034)	3	0.045 (0.044)	3	0.060 (0.058)	3	0.038 (0.038)	3
1-Methylcyclohexane (C_7H_{14})	0.003 (0.003)	3	0.003 (0.003)	3	0.004 (0.004)	3	0.006 (0.006)	3	0.004 (0.004)	3
n-Heptane (C_7H_{16})	0.008 (0.005)	7	0.020 (0.021)	3	0.026 (0.028)	3	0.035 (0.037)	3	0.024 (0.004)	12
Benzenenitrile (C_7H_5N)	0.038 (0.042)	3	0.047 (0.051)	3	0.062 (0.066)	3	0.084 (0.088)	3	0.053 (0.057)	3
Benzaldehyde (C_7H_6O)	0.168 (0.173)	3	0.205 (0.210)	3	0.274 (0.273)	3	0.367 (0.362)	3	0.233 (0.235)	3
Ethynyl Benzene (C_8H_6)	0.004 (0.003)	3	0.004 (0.004)	3	0.006 (0.005)	3	0.008 (0.007)	3	0.005 (0.005)	3
Styrene (C_8H_8)	0.040 (0.004)	7	0.052 (0.046)	3	0.069 (0.059)	3	0.093 (0.077)	3	0.059 (0.051)	3
Ethylbenzene (C_8H_{10})	0.039 (0.039)	7	0.042 (0.047)	3	0.056 (0.061)	3	0.075 (0.081)	3	0.025 (0.009)	12
m,p-Xylenes (C_8H_{10})	0.080 (0.080)	7	0.108 (0.122)	3	0.144 (0.160)	3	0.193 (0.212)	3	0.060 (0.008)	12
o-Xylene (C_8H_{10})	0.025 (0.011)	7	0.038 (0.043)	3	0.050 (0.057)	3	0.068 (0.076)	3	0.027 (0.003)	12
Octadiene (C_8H_{14})	0.018 (0.017)	3	0.022 (0.021)	3	0.029 (0.028)	3	0.039 (0.036)	3	0.024 (0.024)	3
1-Octene (C_8H_{16})	0.022 (0.003)	7	0.034 (0.037)	3	0.046 (0.048)	3	0.061 (0.063)	3	0.039 (0.041)	3
n-Octane (C_8H_{18})	0.008 (0.010)	7	0.017 (0.018)	3	0.023 (0.024)	3	0.031 (0.032)	3	0.020 (0.020)	3
BenzofuranPIT (C_8H_6O)	0.083 (0.074)	3	0.101 (0.090)	3	0.135 (0.116)	3	0.181 (0.153)	3	0.115 (0.100)	3
Indene (C_9H_8)	0.012 (0.013)	3	0.015 (0.016)	3	0.020 (0.021)	3	0.027 (0.028)	3	0.017 (0.018)	3
Indane (C_9H_{10})	0.004 (0.004)	3	0.005 (0.005)	3	0.007 (0.006)	3	0.009 (0.008)	3	0.006 (0.005)	3

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
1-Propenylbenzene (C_9H_{10})	0.001 (0.002)	3	0.002 (0.002)	3	0.002 (0.003)	3	0.003 (0.004)	3	0.002 (0.002)	3
alpha-Methylstyrene (C_9H_{10})	0.002 (0.002)	3	0.003 (0.003)	3	0.003 (0.003)	3	0.004 (0.005)	3	0.003 (0.003)	3
3-Methylstyrene (C_9H_{10})	0.010 (0.012)	3	0.013 (0.014)	3	0.017 (0.019)	3	0.023 (0.025)	3	0.015 (0.016)	3
2-Methylstyrene (C_9H_{10})	0.006 (0.007)	3	0.008 (0.008)	3	0.010 (0.011)	3	0.013 (0.015)	3	0.009 (0.009)	3
2-Propenylbenzene (C_9H_{10})	0.004 (0.004)	3	0.005 (0.005)	3	0.006 (0.006)	3	0.008 (0.008)	3	0.005 (0.005)	3
4-Methylstyrene (C_9H_{10})	0.005 (0.006)	3	0.007 (0.008)	3	0.009 (0.010)	3	0.012 (0.013)	3	0.008 (0.009)	3
1-Ethyl-3-,4-Methylbenzene (C_9H_{12})	0.021 (0.023)	3	0.025 (0.028)	3	0.033 (0.036)	3	0.045 (0.048)	3	0.029 (0.031)	3
1,2,4-Trimethylbenzene (C_9H_{12})	0.071 (0.027)	7	0.027 (0.030)	3	0.036 (0.039)	3	0.048 (0.051)	3	0.015 (0.002)	12
1-Ethyl-2-Methylbenzene (C_9H_{12})	0.006 (0.007)	3	0.008 (0.009)	3	0.010 (0.012)	3	0.014 (0.015)	3	0.009 (0.010)	3
1,2,3-Trimethylbenzene (C_9H_{12})	0.047 (0.030)	7	0.025 (0.030)	3	0.033 (0.040)	3	0.044 (0.053)	3	0.025 (0.003)	12
Isopropylbenzene (C_9H_{12})	0.001 (0.001)	7	0.004 (0.005)	3	0.006 (0.006)	3	0.008 (0.008)	3	0.005 (0.005)	3
n-Propylbenzene (C_9H_{12})	0.005 (0.002)	7	0.008 (0.007)	3	0.010 (0.010)	3	0.014 (0.013)	3	0.009 (0.004)	12
1,3,5-Trimethylbenzene (C_9H_{12})	0.020 (0.020)	7	0.011 (0.012)	3	0.015 (0.016)	3	0.020 (0.021)	3	0.003 (0.001)	12
Nonadiene (C_9H_{16})	0.002 (0.002)	3	0.003 (0.003)	3	0.003 (0.004)	3	0.004 (0.005)	3	0.003 (0.003)	3
1-Nonene (C_9H_{18})	0.008 (0.009)	3	0.009 (0.011)	3	0.013 (0.015)	3	0.017 (0.019)	3	0.011 (0.013)	3
Nonane (C_9H_{20})	0.019 (0.030)	7	0.010 (0.012)	3	0.014 (0.016)	3	0.019 (0.021)	3	0.012 (0.014)	3

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
Methylbenzofuran (isomer 1,C_9H_8O)	0.008 (0.011)	3	0.010 (0.013)	3	0.013 (0.017)	3	0.018 (0.022)	3	0.011 (0.014)	3
Methylbenzofuran (isomer 2,C_9H_8O)	0.014 (0.019)	3	0.017 (0.023)	3	0.023 (0.031)	3	0.031 (0.041)	3	0.020 (0.026)	3
Methylbenzofuran (isomer 3,C_9H_8O)	0.020 (0.028)	3	0.025 (0.034)	3	0.033 (0.045)	3	0.044 (0.060)	3	0.028 (0.039)	3
Naphthalene ($C_{10}H_8$)	0.199 (0.192)	3	0.243 (0.234)	3	0.325 (0.303)	3	0.435 (0.401)	3	0.277 (0.261)	3
1-,3-MethylIndene ($C_{10}H_{10}$)	0.000 (0.000)	3	0.000 (0.000)	3	0.000 (0.000)	3	0.000 (0.000)	3	0.000 (0.000)	3
1,2-Dihydronaphthalene ($C_{10}H_{10}$)	0.004 (0.006)	3	0.005 (0.007)	3	0.007 (0.010)	3	0.009 (0.013)	3	0.006 (0.008)	3
1,3-Dihydronaphthalene ($C_{10}H_{10}$)	0.005 (0.006)	3	0.006 (0.008)	3	0.008 (0.010)	3	0.010 (0.014)	3	0.007 (0.009)	3
1-Butenylbenzene ($C_{10}H_{14}$)	0.002 (0.003)	3	0.002 (0.004)	3	0.003 (0.005)	3	0.004 (0.007)	3	0.002 (0.004)	3
Methylbenzofuran (isomer 4,C_9H_8O)	0.000 (–)	3	0.000 (–)	3	0.000 (–)	3	0.000 (–)	3	0.000 (–)	3
Ethylstyrene ($C_{10}H_{12}$)	0.002 (0.004)	3	0.003 (0.005)	3	0.004 (0.006)	3	0.005 (0.008)	3	0.003 (0.005)	3
1-Methyl-1-Propenylbenzene ($C_{10}H_{12}$)	0.009 (0.012)	3	0.011 (0.014)	3	0.015 (0.019)	3	0.020 (0.025)	3	0.013 (0.016)	3
p-Cymene ($C_{10}H_{14}$)	0.002 (0.001)	7	0.062 (0.086)	3	0.083 (0.114)	3	0.111 (0.151)	3	0.071 (0.097)	3
$C_{10}H_{14}$ non-aromatic	0.002 (0.003)	3	0.003 (0.004)	3	0.004 (0.006)	3	0.005 (0.007)	3	0.003 (0.005)	3
Isobutylbenzene ($C_{10}H_{14}$)	0.005 (0.006)	3	0.006 (0.008)	3	0.008 (0.010)	3	0.011 (0.014)	3	0.007 (0.009)	3
Methyl-n-Propylbenzene (isomer 1,$C_{10}H_{14}$)	0.006 (0.007)	3	0.007 (0.008)	3	0.009 (0.011)	3	0.012 (0.015)	3	0.008 (0.009)	3
Methyl-n-Propylbenzene (isomer 2,$C_{10}H_{14}$)	0.005 (0.006)	3	0.006 (0.007)	3	0.008 (0.009)	3	0.010 (0.013)	3	0.007 (0.008)	3

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
n-Butylbenzene ($C_{10}H_{14}$)	0.008 (0.009)	3	0.009 (0.011)	3	0.012 (0.015)	3	0.017 (0.019)	3	0.011 (0.013)	3
1,4-Diethylbenzene ($C_{10}H_{14}$)	0.002 (0.003)	3	0.002 (0.004)	3	0.003 (0.005)	3	0.004 (0.007)	3	0.002 (0.004)	3
Ethyl Xylene (isomer 1 ,$C_{10}H_{14}$)	0.006 (0.008)	3	0.007 (0.010)	3	0.009 (0.013)	3	0.012 (0.017)	3	0.008 (0.011)	3
Ethyl Xylene (isomer 2,$C_{10}H_{14}$)	0.003 (0.004)	3	0.004 (0.005)	3	0.005 (0.007)	3	0.007 (0.009)	3	0.004 (0.006)	3
Monoterpenes ($C_{10}H_{16}$)	0.253 (0.251)	3	0.309 (0.304)	3	0.413 (0.395)	3	0.553 (0.523)	3	0.351 (0.341)	3
beta-Pinene ($C_{10}H_{16}$)	0.052 (0.013)	7	0.019 (0.027)	3	0.026 (0.036)	3	0.035 (0.048)	3	0.720 (0.090)	12
D-Limonene ($C_{10}H_{16}$)	0.060 (0.084)	3	0.073 (0.102)	3	0.097 (0.134)	3	0.131 (0.179)	3	0.083 (0.115)	3
Myrcene ($C_{10}H_{16}$)	0.002 (0.004)	7	0.003 (0.004)	3	0.004 (0.005)	3	0.006 (0.007)	3	0.004 (0.004)	3
3-Carene ($C_{10}H_{16}$)	0.009 (0.012)	3	0.011 (0.015)	3	0.015 (0.020)	3	0.020 (0.026)	3	0.013 (0.017)	3
gamma-Terpinene ($C_{10}H_{16}$)	0.001 (0.002)	3	0.001 (0.002)	3	0.002 (0.003)	3	0.002 (0.004)	3	0.001 (0.003)	3
Terpinolene ($C_{10}H_{16}$)	0.003 (0.004)	3	0.004 (0.005)	3	0.005 (0.007)	3	0.007 (0.009)	3	0.004 (0.006)	3
alpha-Pinene ($C_{10}H_{16}$)	0.094 (0.021)	7	0.039 (0.072)	3	0.052 (0.096)	3	0.070 (0.128)	3	0.810 (0.100)	12
Camphene ($C_{10}H_{16}$)	0.008 (0.011)	7	0.021 (0.045)	3	0.028 (0.059)	3	0.038 (0.079)	3	0.024 (0.051)	3
iso-Limonene ($C_{10}H_{16}$)	0.003 (0.005)	3	0.004 (0.006)	3	0.006 (0.007)	3	0.008 (0.010)	3	0.005 (0.006)	3
1-Decene ($C_{10}H_{20}$)	0.011 (0.014)	3	0.014 (0.017)	3	0.018 (0.022)	3	0.024 (0.029)	3	0.015 (0.019)	3
n-Decane ($C_{10}H_{22}$)	0.019 (0.039)	7	0.010 (0.013)	3	0.014 (0.017)	3	0.018 (0.022)	3	0.012 (0.014)	3

Table A.1 Continued

Species	Prescribed Fire Southeast Conifer Forest EF	note	Prescribed Fire Southwest Conifer Forest EF	note	Prescribed Fire Northwest Conifer Forest EF	note	Wildfire Northwest Conifer Forest EF	note	Wildfire Boreal Forest EF	note
C11 Aromatics	0.084 (0.077)	3	0.103 (0.093)	3	0.138 (0.120)	3	0.184 (0.159)	3	0.117 (0.104)	3
1-Undecene ($C_{11}H_{22}$)	0.014 (0.020)	3	0.017 (0.025)	3	0.023 (0.033)	3	0.030 (0.043)	3	0.019 (0.028)	3
n-Undecane ($C_{11}H_{24}$)	0.016 (0.020)	3	0.019 (0.024)	3	0.025 (0.032)	3	0.034 (0.043)	3	0.022 (0.028)	3
Sesquiterpenes ($C_{15}H_{24}$)	0.050 (0.077)	3	0.061 (0.094)	3	0.082 (0.124)	3	0.110 (0.166)	3	0.070 (0.106)	3

Notes for Table A.1

1. Average of fire average values from the airborne measurements of Burling et al. (2011) (North Carolina fires) and Akagi et al. (2013).
2. Average of fire average values from the airborne measurements of Burling et al. (2011) (North Carolina fires), Akagi et al. (2013), and Yokelson et al. (1999).
3. Estimated based on MCE using regression equation derived from the laboratory data of Yokelson et al. (2013), see Sect. 2.1.
4. Average of fire average values from the airborne measurements of Burling et al. (2011) (North Carolina fires) and Akagi et al. (2013) and the tower based measurements of Urbanski et al. (2009) (southeast US conifer forest fires).
5. Average of fire average values from the airborne measurements of Burling et al. (2011) (North Carolina fires), Akagi et al. (2013), and Yokelson et al. (1999) and the tower based measurements of Urbanski et al. (2009) (southeast US conifer forest fires).
6. Average of fire average values from the airborne measurements of Akagi et al. (2013) and the tower based measurements of Urbanski et al. (2009) (southeast US conifer forest fires).
7. Average of the airborne measurements of Akagi et al. (2013).
8. Average of Arizona fires from tower based study of Urbanski et al. (2009).
9. Average of fire average values from the airborne measurements of Burling et al. (2011) (California fires).
10. Average of fire average values from the airborne measurements of Burling et al. (2011) (California fires) and the tower based measurements of Urbanski et al. (2009) (Montana, Oregon, and British Columbia conifer forest fires).
11. Average of the tower based measurements of Urbanski et al. (2009) (Montana, Oregon, and British Columbia conifer forest fires).
12. Airborne measurements of Simpson et al. (2011).
13. Glycolaldehyde EF based on EF vs. MCE regression of airborne field measurements of Burling et al. (2011) and Akagi et al. (2013). Regression statistics: slope = -12.06 (3.28), intercept = 11.56 (3.05), residual standard error =0.227, R^2 = 0.57, n = 12.
14. Phenol EF based on EF vs. MCE regression of airborne field measurements of Burling et al. (2011) and Akagi et al. (2013). Regression statistics: slope = -11.52 (2.38), intercept = 11.04 (2.21), residual standard error =0.163, R^2 = 0.75, n = 10.

Table A.2. Estimated EF (g kg^{-1}) for non-methane organic compounds for RSC prone fuels. Numbers in parentheses are estimated uncertainty (see Sect 2.1).

	Stumps and Logs		Temperate Forest Duff/Organic Soil		Boreal Forest Duff/Organic Soil	
Species	EF	Note	EF	Note	EF	Note
Hydrogen Cyanide (HCN)	0.723 (0.380)	1	1.519 (0.293)	5	2.457 (1.825)	7
Formaldehyde (HCHO)	2.124 (0.645)	1	3.343 (3.443)	5	1.610 (1.238)	7
Methanol (CH_3OH)	3.517 (2.136)	1	6.307 (4.272)	5	3.048 (1.290)	7
Isocyanic Acid (HNCO)	0.293 (0.191)	3	0.271 (0.271)	8	0.271 (0.271)	8
FormicAcid (HCOOH)	0.000 (0.000)	1	1.456 (1.094)	5	0.733 (0.827)	7
Ethyne (C_2H_2)	0.207 (0.042)	1	0.205 (0.130)	5	0.109 (0.059)	7
Ethene (C_2H_4)	1.398 (0.503)	2	1.683 (0.475)	5	1.246 (0.248)	7
Ethane (C_2H_6)	2.723 (2.633)	1	2.080 (2.212)	6	2.160 (0.591)	9
Acetonitrile (CH_3CN)	0.406 (0.624)	1	0.739 (0.739)	8	0.739 (0.739)	8
Acetaldehyde (CH_3CHO)	1.546 (1.382)	1	2.700 (2.700)	8	2.700 (2.700)	8
Ethanol (CH_3CH_2OH)	0.019 (0.015)	1	0.495 (0.495)	8	0.495 (0.495)	8
Acetic Acid (CH_3COOH)	1.837 (1.285)	1	8.836 (6.424)	2	5.963 (2.653)	8
Glycolaldehyde ($C_2H_4O_2$)	0.000 (0.000)	1	5.024 (8.162)	5	2.416 (2.263)	7
Methyl Formate ($C_2H_4O_2$)	0.044 (0.035)	3	0.049 (0.049)	8	0.049 (0.049)	8
1,1-Dimethylhydrazine ($C_2H_8N_2$)	0.063 (0.129)	3	– (–)	8	– (–)	8
Glycolic Acid ($C_2H_4O_3$)	0.091 (0.097)	3	0.090 (0.090)	8	0.090 (0.090)	8
Propyne (C_3H_4)	0.019 (0.011)	4	0.042 (0.042)	8	0.042 (0.042)	8
Propylene (C_3H_6)	1.060 (0.818)	2	1.814 (8.162)	5	1.767 (0.671)	7
Propane (C_3H_8)	0.802 (0.793)	4	0.797 (0.797)	8	0.797 (0.797)	8
Acrylonitrile (C_3H_3N)	0.027 (0.020)	4	0.151 (0.151)	8	0.151 (0.151)	8
Propanenitrile (C_3H_5N)	0.023 (0.027)	3	0.024 (0.024)	8	0.024 (0.024)	8
Acrolein (C_3H_4O)	0.472 (0.444)	4	0.590 (0.590)	8	0.590 (0.590)	8
Acetone (C_3H_6O)	1.548 (1.451)	4	1.390 (1.390)	8	1.390 (1.390)	8
Propanal (C_3H_6O)	0.286 (0.260)	3	0.353 (0.353)	8	0.353 (0.353)	8
Carbonsuboxide (C_3O_2)	0.002 (0.003)	3	0.004 (0.004)	8	0.004 (0.004)	8
Acrylic Acid ($C_3H_4O_2$)	0.093 (0.072)	3	0.153 (0.153)	8	0.153 (0.153)	8
Ethyl Formate ($C_3H_6O_2$)	0.017 (0.019)	3	0.024 (0.024)	8	0.024 (0.024)	8

Table A.2 Continued

Species	Stumps and Logs		Temperate Forest Duff/Organic Soil		Boreal Forest Duff/Organic Soil	
	EF	Note	EF	Note	EF	Note
Methyl Acetate ($C_3H_6O_2$)	0.069 (0.056)	4	0.277 (0.277)	8	0.277 (0.277)	8
Pyruvic Acid ($C_3H_4O_3$)	0.045 (0.054)	3	0.269 (0.269)	8	0.269 (0.269)	8
1,3-Butadiyne (C_4H_2)	0.002 (0.002)	3	0.009 (0.009)	8	0.009 (0.009)	8
Butenyne (C_4H_4)	0.007 (0.007)	3	0.018 (0.018)	8	0.018 (0.018)	8
1,3-Butadiene (C_4H_6)	0.147 (0.089)	2	0.293 (0.293)	8	0.293 (0.293)	8
1,2-Butadiene (C_4H_6)	0.004 (0.005)	3	0.000 (0.000)	8	0.000 (0.000)	8
1-,2-Butyne (C_4H_6)	0.008 (0.006)	3	0.014 (0.014)	8	0.014 (0.014)	8
trans-2-Butene (C_4H_8)	0.112 (0.094)	4	0.125 (0.125)	8	0.125 (0.125)	8
1-Butene (C_4H_8)	0.248 (0.210)	4	0.311 (0.311)	8	0.311 (0.311)	8
2-Methylpropene (C_4H_8)	0.171 (0.201)	3	0.246 (0.246)	8	0.246 (0.246)	8
cis-2-Butene (C_4H_8)	0.089 (0.073)	4	0.098 (0.098)	8	0.098 (0.098)	8
i-Butane (C_4H_{10})	0.069 (0.087)	4	0.238 (0.238)	8	0.238 (0.238)	8
n-Butane (C_4H_{10})	0.195 (0.209)	4	0.479 (0.479)	8	0.479 (0.479)	8
Pyrrole (C_4H_5N)	0.021 (0.027)	3	0.051 (0.051)	8	0.051 (0.051)	8
Furan (C_4H_4O)	0.855 (0.575)	2	1.460 (0.082)	6	1.070 (0.070)	9
Methacrolein (C_4H_6O)	0.081 (0.079)	4	0.102 (0.102)	8	0.102 (0.102)	8
Methyl Vinyl Ketone (MVK,C_4H_6O)	0.194 (0.161)	4	0.421 (0.421)	8	0.421 (0.421)	8
Crotonaldehyde (C_4H_6O)	0.588 (0.525)	3	0.494 (0.494)	8	0.494 (0.494)	8
2,5-Dihydrofuran (C_4H_6O)	0.003 (0.007)	3	– (–)	8	– (–)	8
n-Butanal (C_4H_8O)	0.048 (0.040)	4	0.114 (0.114)	8	0.114 (0.114)	8
Methyl Ethyl Ketone (MEK,C_4H_8O)	0.323 (0.256)	4	0.422 (0.422)	8	0.422 (0.422)	8
2-Methylpropanal (C_4H_8O)	0.114 (0.152)	4	0.092 (0.092)	8	0.092 (0.092)	8
Tetrahydrofuran (C_4H_8O)	0.001 (0.001)	3	0.006 (0.006)	8	0.006 (0.006)	8
1-Butanol ($C_4H_{10}O$)	0.204 (0.261)	3	1.180 (1.180)	8	1.180 (1.180)	8
Cyclopentenone (C_5H_6O)	0.013 (0.013)	3	0.201 (0.201)	8	0.201 (0.201)	8
2,3-Butadione ($C_4H_6O_2$)	0.540 (0.520)	3	0.694 (0.694)	8	0.694 (0.694)	8
Vinyl Acetate ($C_4H_6O_2$)	0.000 (–)	3	– (–)	8	– (–)	8

Table A.2 Continued

Species	Stumps and Logs		Temperate Forest Duff/Organic Soil		Boreal Forest Duff/Organic Soil	
	EF	Note	EF	Note	EF	Note
Methyl Acrylate ($C_4H_6O_2$)	0.015 (0.012)	3	0.045 (0.045)	8	0.045 (0.045)	8
2,3-Dihydro-1,4-Dioxin ($C_4H_6O_2$)	0.005 (0.006)	3	0.016 (0.016)	8	0.016 (0.016)	8
Methyl Propanoate ($C_4H_8O_2$)	0.010 (0.010)	3	0.002 (0.002)	8	0.002 (0.002)	8
1,3-CyclopentadienePIT (C_5H_6)	0.090 (0.105)	3	0.125 (0.125)	8	0.125 (0.125)	8
Pentenyneisomers (C_5H_6)	0.005 (0.006)	3	0.012 (0.012)	8	0.012 (0.012)	8
Isoprene (C_5H_8)	0.374 (0.646)	2	0.079 (0.079)	8	0.079 (0.079)	8
trans-1,3-Pentadiene (C_5H_8)	0.052 (0.048)	3	0.054 (0.054)	8	0.054 (0.054)	8
cis-1,3-Pentadiene (C_5H_8)	0.032 (0.030)	3	0.036 (0.036)	8	0.036 (0.036)	8
Cyclopentene (C_5H_8)	0.070 (0.066)	4	0.060 (0.060)	8	0.060 (0.060)	8
Pentadieneisomer (C_5H_8)	0.007 (0.007)	3	0.012 (0.012)	8	0.012 (0.012)	8
Cyclopentane (C_5H_{10})	0.007 (0.008)	3	0.012 (0.012)	8	0.012 (0.012)	8
1-Pentene (C_5H_{10})	0.065 (0.055)	4	0.083 (0.083)	8	0.083 (0.083)	8
2-Methyl-1-Butene (C_5H_{10})	0.046 (0.044)	4	0.026 (0.026)	8	0.026 (0.026)	8
trans-2-Pentene (C_5H_{10})	0.040 (0.035)	4	0.033 (0.033)	8	0.033 (0.033)	8
3-Methyl-1-Butene (C_5H_{10})	0.025 (0.026)	4	0.010 (0.010)	8	0.010 (0.010)	8
cis-2-Pentene (C_5H_{10})	0.021 (0.017)	4	0.049 (0.049)	8	0.049 (0.049)	8
2-Methyl-2-Butene (C_5H_{10})	0.072 (0.085)	4	0.027 (0.027)	8	0.027 (0.027)	8
2,2-Dimethylpropane (C_5H_{12})	0.001 (0.003)	3	0.005 (0.005)	8	0.005 (0.005)	8
i-Pentane (C_5H_{12})	0.030 (0.038)	4	0.136 (0.136)	8	0.136 (0.136)	8
n-Pentane (C_5H_{12})	0.095 (0.108)	4	0.212 (0.212)	8	0.212 (0.212)	8
1-Methylpyrrole (C_5H_7N)	0.008 (0.010)	3	0.015 (0.015)	8	0.015 (0.015)	8
3-Methylfuran (C_5H_6O)	0.059 (0.055)	3	0.073 (0.073)	8	0.073 (0.073)	8
Other C_6H_{10} (isomer 4)	0.436 (0.470)	3	0.008 (0.008)	8	0.008 (0.008)	8
1-Methylcyclopentane (C_6H_{12})	0.189 (0.174)	3	0.015 (0.015)	8	0.015 (0.015)	8
Pentenone (C_5H_8O)	1.028 (0.945)	3	3.780 (3.780)	8	3.780 (3.780)	8
Cyclopentanone (C_5H_8O)	0.281 (0.327)	3	0.199 (0.199)	8	0.199 (0.199)	8
2-Methyl-2-Butenal (C_5H_8O)	0.240 (0.236)	4	0.023 (0.023)	8	0.023 (0.023)	8

Table A.2 Continued

Species	Stumps and Logs		Temperate Forest Duff/Organic Soil		Boreal Forest Duff/Organic Soil	
	EF	Note	EF	Note	EF	Note
2-Methylbutanal ($C_5H_{10}O$)	0.083 (0.111)	3	0.092 (0.092)	8	0.092 (0.092)	8
3-Methyl-2-Butanone ($C_5H_{10}O$)	0.062 (0.056)	4	0.039 (0.039)	8	0.039 (0.039)	8
2-Pentanone ($C_5H_{10}O$)	0.072 (0.070)	3	0.097 (0.097)	8	0.097 (0.097)	8
3-Pentanone ($C_5H_{10}O$)	0.060 (0.062)	3	0.065 (0.065)	8	0.065 (0.065)	8
Methyl Diazine (isomer1,$C_5H_6N_2$)	0.028 (0.029)	3	0.044 (0.044)	8	0.044 (0.044)	8
Methyl Diazine (isomer2,$C_5H_6N_2$)	0.011 (0.011)	3	0.009 (0.009)	8	0.009 (0.009)	8
Methyl Diazine (isomer3,C_5H_6N2)	0.006 (0.012)	3	– (–)	8	– (–)	8
3-Furaldehyde ($C_5H_4O_2$)	0.043 (0.048)	3	0.059 (0.059)	8	0.059 (0.059)	8
2-Furaldehyde ($C_5H_4O_2$)	0.067 (0.082)	4	0.647 (0.647)	8	0.647 (0.647)	8
Cyclopentenedione ($C_5H_4O_2$)	0.023 (0.034)	3	0.019 (0.019)	8	0.019 (0.019)	8
Methyl Methacrylate ($C_5H_8O_2$)	0.070 (0.068)	3	0.076 (0.076)	8	0.076 (0.076)	8
Methyl Butanoate ($C_5H_{10}O_2$)	0.035 (0.077)	3	0.004 (0.004)	8	0.004 (0.004)	8
Benzene (C_6H_6)	0.803 (0.791)	4	0.586 (0.586)	8	0.586 (0.586)	8
Divinylacetylene (C_6H_6)	0.005 (0.005)	3	0.016 (0.016)	8	0.016 (0.016)	8
Methyl Cyclopentadiene (isomer 1,C_6H_8)	0.019 (0.026)	3	0.028 (0.028)	8	0.028 (0.028)	8
Methyl Cyclopentadiene (isomer 2,C_6H_8)	0.019 (0.026)	3	0.031 (0.031)	8	0.031 (0.031)	8
Hexenyne (C_6H_8)	0.008 (0.011)	3	0.021 (0.021)	8	0.021 (0.021)	8
cis-1,3-Hexadiene (C_6H_{10})	0.004 (0.004)	3	0.004 (0.004)	8	0.004 (0.004)	8
trans-1,3-Hexadiene (C_6H_{10})	0.012 (0.015)	3	0.008 (0.008)	8	0.008 (0.008)	8
1-Methylcyclopentene (C_6H_{10})	0.009 (0.008)	3	0.019 (0.019)	8	0.019 (0.019)	8
Cyclohexene (C_6H_{10})	0.031 (0.032)	3	0.015 (0.015)	8	0.015 (0.015)	8
Other C_6H_{10} (isomer 1)	0.021 (0.020)	3	0.001 (0.001)	8	0.001 (0.001)	8
Other C_6H_{10} (isomer 2)	0.002 (0.003)	3	0.004 (0.004)	8	0.004 (0.004)	8
Other C_6H_{10} (isomer 3)	0.004 (0.004)	3	0.016 (0.016)	8	0.016 (0.016)	8
2-Methylfuran (C_5H_6O)	0.646 (0.551)	4	0.537 (0.537)	8	0.537 (0.537)	8
Other C_6H_{10} (isomer 5)	0.009 (0.010)	3	0.004 (0.004)	8	0.004 (0.004)	8
1-Methylpyrazole ($C_4H_6N_2$)	0.004 (0.005)	3	0.028 (0.028)	8	0.028 (0.028)	8

Table A.2 Continued

Species	Stumps and Logs EF	Note	Temperate Forest Duff/Organic Soil EF	Note	Boreal Forest Duff/Organic Soil EF	Note
2-Methyl-1-Pentene (C_6H_{12})	0.114 (0.107)	3	0.117 (0.117)	8	0.117 (0.117)	8
1-Hexene (C_6H_{12})	0.118 (0.113)	3	0.011 (0.011)	8	0.011 (0.011)	8
Cyclohexene (C_6H_{12})	0.004 (0.005)	3	0.006 (0.006)	8	0.006 (0.006)	8
Hexenes (sum of 3 isomers, C_6H_{12})	0.130 (0.154)	3	0.010 (0.010)	8	0.010 (0.010)	8
cis-2-Hexene (C_6H_{12})	0.041 (0.057)	3	0.005 (0.005)	8	0.005 (0.005)	8
2,2-Dimethylbutane (C_6H_{14})	0.000 (–)	3	0.002 (0.002)	8	0.002 (0.002)	8
n-Hexane (C_6H_{14})	0.061 (0.060)	4	0.110 (0.110)	8	0.110 (0.110)	8
3-Methylpentane (C_6H_{14})	0.011 (0.014)	3	0.014 (0.014)	8	0.014 (0.014)	8
Phenol (C_6H_5OH)	0.150 (0.036)	4	4.236 (2.329)	8	1.045 (0.395)	7
2-Ethylfuran (C_6H_8O)	0.036 (0.033)	4	0.048 (0.048)	8	0.048 (0.048)	8
2,5-Dimethylfuran (C_6H_8O)	0.194 (0.194)	4	0.076 (0.076)	8	0.076 (0.076)	8
n-Hexanal ($C_6H_{12}O$)	0.075 (0.086)	3	0.159 (0.159)	8	0.159 (0.159)	8
3-Hexanone ($C_6H_{12}O$)	0.059 (0.055)	3	0.054 (0.054)	8	0.054 (0.054)	8
2-Hexanone ($C_6H_{12}O$)	0.023 (0.024)	3	0.010 (0.010)	8	0.010 (0.010)	8
2-Ethylpyrazine ($C_6H_8N_2$)	0.014 (0.016)	3	0.021 (0.021)	8	0.021 (0.021)	8
Resorcinol ($C_6H_6O_2$)	3.273 (3.120)	3	2.690 (2.690)	8	2.690 (2.690)	8
Toluene ($C_6H_5CH_3$)	0.579 (0.332)	4	0.488 (0.488)	8	0.488 (0.488)	8
Heptadiyne (isomer 1,C_7H_8)	0.003 (0.004)	3	0.005 (0.005)	8	0.005 (0.005)	8
Heptadiyne (isomer 2,C_7H_8)	0.001 (0.001)	3	0.002 (0.002)	8	0.002 (0.002)	8
1-Methylcyclohexene (C_7H_{12})	0.019 (0.020)	3	0.010 (0.010)	8	0.010 (0.010)	8
1-Heptene (C_7H_{14})	0.089 (0.089)	3	0.088 (0.088)	8	0.088 (0.088)	8
1-Methylcyclohexane (C_7H_{14})	0.009 (0.009)	3	0.009 (0.009)	8	0.009 (0.009)	8
n-Heptane (C_7H_{16})	0.043 (0.039)	4	0.048 (0.048)	8	0.048 (0.048)	8
Benzenenitrile (C_7H_5N)	0.124 (0.135)	3	0.101 (0.101)	8	0.101 (0.101)	8
Benzaldehyde (C_7H_6O)	0.544 (0.559)	3	0.583 (0.583)	8	0.583 (0.583)	8
Ethynyl Benzene (C_8H_6)	0.072 (0.037)	4	0.043 (0.043)	8	0.043 (0.043)	8
Styrene (C_8H_8)	0.064 (0.035)	4	0.117 (0.117)	8	0.117 (0.117)	8

Table A.2 Continued

Species	Stumps and Logs EF	Note	Temperate Forest Duff/Organic Soil EF	Note	Boreal Forest Duff/Organic Soil EF	Note
Ethylbenzene (C_8H_{10})	0.111 (0.124)	3	0.104 (0.104)	8	0.104 (0.104)	8
m,p-Xylenes (C_8H_{10})	0.286 (0.326)	3	0.178 (0.178)	8	0.178 (0.178)	8
o-Xylene (C_8H_{10})	0.072 (0.065)	4	0.101 (0.101)	8	0.101 (0.101)	8
Octadiene (C_8H_{14})	0.057 (0.056)	3	0.050 (0.050)	8	0.050 (0.050)	8
1-Octene (C_8H_{16})	0.066 (0.055)	4	0.087 (0.087)	8	0.087 (0.087)	8
n-Octane (C_8H_{18})	0.036 (0.034)	4	0.039 (0.039)	8	0.039 (0.039)	8
BenzofuranPIT (C_8H_6O)	0.268 (0.240)	3	0.908 (0.908)	8	0.908 (0.908)	8
Indene (C_9H_8)	0.040 (0.043)	3	0.051 (0.051)	8	0.051 (0.051)	8
Indane (C_9H_{10})	0.013 (0.013)	3	0.010 (0.010)	8	0.010 (0.010)	8
1-Propenylbenzene (C_9H_{10})	0.005 (0.006)	3	0.001 (0.001)	8	0.001 (0.001)	8
alpha-Methylstyrene (C_9H_{10})	0.007 (0.007)	3	0.004 (0.004)	8	0.004 (0.004)	8
3-Methylstyrene (C_9H_{10})	0.034 (0.038)	3	0.034 (0.034)	8	0.034 (0.034)	8
2-Methylstyrene (C_9H_{10})	0.020 (0.022)	3	0.019 (0.019)	8	0.019 (0.019)	8
2-Propenylbenzene (C_9H_{10})	0.012 (0.013)	3	0.009 (0.009)	8	0.009 (0.009)	8
4-Methylstyrene (C_9H_{10})	0.018 (0.020)	3	0.013 (0.013)	8	0.013 (0.013)	8
1-Ethyl-3-,4-Methylbenzene (C_9H_{12})	0.067 (0.074)	3	0.043 (0.043)	8	0.043 (0.043)	8
1,2,4-Trimethylbenzene (C_9H_{12})	0.124 (0.135)	4	0.056 (0.056)	8	0.056 (0.056)	8
1-Ethyl-2-Methylbenzene (C_9H_{12})	0.020 (0.023)	3	0.012 (0.012)	8	0.012 (0.012)	8
1,2,3-Trimethylbenzene (C_9H_{12})	0.167 (0.228)	4	0.029 (0.029)	8	0.029 (0.029)	8
Isopropylbenzene (C_9H_{12})	0.006 (0.007)	4	0.006 (0.006)	8	0.006 (0.006)	8
n-Propylbenzene (C_9H_{12})	0.031 (0.035)	4	0.012 (0.012)	8	0.012 (0.012)	8
1,3,5-Trimethylbenzene (C_9H_{12})	0.025 (0.020)	4	0.021 (0.021)	8	0.021 (0.021)	8
Nonadiene (C_9H_{16})	0.007 (0.008)	3	– (–)	8	– (–)	8
1-Nonene (C_9H_{18})	0.025 (0.030)	3	0.023 (0.023)	8	0.023 (0.023)	8
Nonane (C_9H_{20})	0.034 (0.035)	4	0.023 (0.023)	8	0.023 (0.023)	8
Methylbenzofuran (isomer 1,C_9H_8O)	0.027 (0.034)	3	0.024 (0.024)	8	0.024 (0.024)	8
Methylbenzofuran (isomer 2,C_9H_8O)	0.046 (0.062)	3	0.038 (0.038)	8	0.038 (0.038)	8

Table A.2 Continued

Species	Stumps and Logs EF	Note	Temperate Forest Duff/Organic Soil EF	Note	Boreal Forest Duff/Organic Soil EF	Note
Methylbenzofuran (isomer 3,C_9H_8O)	0.066 (0.092)	3	0.052 (0.052)	8	0.052 (0.052)	8
Naphthalene ($C_{10}H_8$)	0.645 (0.623)	3	0.815 (0.815)	8	0.815 (0.815)	8
1-,3-MethylIndene ($C_{10}H_{10}$)	0.000 (0.001)	3	0.002 (0.002)	8	0.002 (0.002)	8
1,2-Dihydronaphthalene ($C_{10}H_{10}$)	0.014 (0.019)	3	0.006 (0.006)	8	0.006 (0.006)	8
1,3-Dihydronaphthalene ($C_{10}H_{10}$)	0.015 (0.021)	3	0.007 (0.007)	8	0.007 (0.007)	8
1-Butenylbenzene ($C_{10}H_{14}$)	0.005 (0.010)	3	0.002 (0.002)	8	0.002 (0.002)	8
Methylbenzofuran (isomer 4,C_9H_8O)	0.000 (–)	3	– (–)	8	– (–)	8
Ethylstyrene ($C_{10}H_{12}$)	0.008 (0.012)	3	0.002 (0.002)	8	0.002 (0.002)	8
1-Methyl-1-Propenylbenzene ($C_{10}H_{12}$)	0.030 (0.038)	3	0.005 (0.005)	8	0.005 (0.005)	8
p-Cymene ($C_{10}H_{14}$)	0.422 (0.502)	4	0.059 (0.059)	8	0.059 (0.059)	8
$C_{10}H_{14}$ non-aromatic	0.007 (0.011)	3	– (–)	8	– (–)	8
Isobutylbenzene ($C_{10}H_{14}$)	0.017 (0.021)	3	0.008 (0.008)	8	0.008 (0.008)	8
Methyl-n-Propylbenzene (isomer 1,$C_{10}H_{14}$)	0.018 (0.022)	3	0.002 (0.002)	8	0.002 (0.002)	8
Methyl-n-Propylbenzene (isomer 2,$C_{10}H_{14}$)	0.015 (0.019)	3	0.002 (0.002)	8	0.002 (0.002)	8
n-Butylbenzene ($C_{10}H_{14}$)	0.025 (0.030)	3	0.013 (0.013)	8	0.013 (0.013)	8
1,4-Diethylbenzene ($C_{10}H_{14}$)	0.005 (0.011)	3	0.002 (0.002)	8	0.002 (0.002)	8
Ethyl Xylene (isomer 1 ,$C_{10}H_{14}$)	0.018 (0.026)	3	0.003 (0.003)	8	0.003 (0.003)	8
Ethyl Xylene (isomer 2,$C_{10}H_{14}$)	0.010 (0.013)	3	0.002 (0.002)	8	0.002 (0.002)	8
Monoterpenes ($C_{10}H_{16}$)	0.820 (0.811)	3	0.695 (0.695)	8	0.695 (0.695)	8
beta-Pinene ($C_{10}H_{16}$)	0.316 (0.300)	4	0.092 (0.092)	8	0.092 (0.092)	8
D-Limonene ($C_{10}H_{16}$)	2.647 (2.681)	4	0.085 (0.085)	8	0.085 (0.085)	8
Myrcene ($C_{10}H_{16}$)	0.058 (0.053)	4	0.036 (0.036)	8	0.036 (0.036)	8
3-Carene ($C_{10}H_{16}$)	0.030 (0.040)	3	0.023 (0.023)	8	0.023 (0.023)	8
gamma-Terpinene ($C_{10}H_{16}$)	0.003 (0.006)	3	0.004 (0.004)	8	0.004 (0.004)	8
Terpinolene ($C_{10}H_{16}$)	0.010 (0.014)	3	0.007 (0.007)	8	0.007 (0.007)	8
alpha-Pinene ($C_{10}H_{16}$)	2.650 (3.223)	4	0.084 (0.084)	8	0.084 (0.084)	8
Camphene ($C_{10}H_{16}$)	0.361 (0.333)	4	0.081 (0.081)	8	0.081 (0.081)	8

Table A.2 Continued

Species	Stumps and Logs EF	Stumps and Logs Note	Temperate Forest Duff/Organic Soil EF	Temperate Forest Duff/Organic Soil Note	Boreal Forest Duff/Organic Soil EF	Boreal Forest Duff/Organic Soil Note
iso-Limonene ($C_{10}H_{16}$)	0.011 (0.015)	3	0.002 (0.002)	8	0.002 (0.002)	8
1-Decene ($C_{10}H_{20}$)	0.036 (0.044)	3	0.022 (0.022)	8	0.022 (0.022)	8
n-Decane ($C_{10}H_{22}$)	0.027 (0.024)	4	0.027 (0.027)	8	0.027 (0.027)	8
C11 Aromatics	0.274 (0.248)	3	0.228 (0.228)	8	0.228 (0.228)	8
1-Undecene ($C_{11}H_{22}$)	0.045 (0.066)	3	0.036 (0.036)	8	0.036 (0.036)	8
n-Undecane ($C_{11}H_{24}$)	0.050 (0.065)	3	0.043 (0.043)	8	0.043 (0.043)	8
Sesquiterpenes ($C_{15}H_{24}$)	0.163 (0.250)	3	0.095 (0.095)	8	0.095 (0.095)	8

Notes

1. Average of ground-based measurements of Akagi et al. (2013) and Burling et al. (2011) (CL – unit ME samples 1-4).
2. Average of ground-based measurements of Akagi et al. (2013), Burling et al. (2011) (CL – unit ME samples 1-4), and Hao and Babbitt (2007) (logs and stumps from Southeast and West).
3. Estimated based on MCE using regression equation derived from the laboratory data of Yokelson et al. (2013), see Sect. 2.1.
4. Average of ground-based measurements of Akagi et al. (2013).
5. Average of laboratory data of Bertschi et al. (2003) (fires Lolo 1, 2, and 3) and Yokelson et al. (1997) (forest floor, FF, fuels).
6. Laboratory data of Bertschi et al. (2003) (fires Lolo 1, 2, and 3).
7. Average of laboratory data of Yokelson et al. (2013) (Organic Soil), Bertschi et al. (2003) (fires NWT 1 and 2), and Yokelson et al. (1997) (forest floor, FF, fuels).
8. Laboratory data of Yokelson et al. (2013) (Organic Soil) with uncertainty estimated as 100%.
9. Average of laboratory data of Yokelson et al. (2013) (Organic Soil) and Bertschi et al. (2003) (NWT 1 and 2).