## S1: Supplementary material to "Combustion efficiency and emission factors for wildfire season fires in mixed conifer forests of the northern Rocky Mountains, US"

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### S1.1 Burned area

The primary source of burned area information for the fire events was fire perimeter polygons mapped by incident management teams and made available through the National Fire Interagency Center (ftp://ftp.nifc.gov/). The maps are a digital representation of the fire boundary, derived from airborne infrared imagery or GPS coordinates recorded along the fire perimeter through aerial and/or ground based survey. The fire size and daily growth estimates provided in Table S1 are based on incident fire perimeters supplemented with fire size estimates from the Incident Command System 209 Reports (ICS-209) (ICS209, 2011) when perimeters were not available. The incident perimeter polygons are produced to support fire management activities, not map burned area, and are therefore less than ideal as a reference dataset. The characteristics of the fire perimeter maps must be considered when they are applied for modeling emissions. The maps provide little information regarding the spatial heterogeneity of burned area within the perimeter. The area within a perimeter typically includes unburned areas, the average fraction of unburned to low severity burned area within incident fire perimeters were found to be 28% when compared to high-resolution remote sensing observations (Schwind, 2008).

In addition to lacking information on the spatial heterogeneity of the burned area, the perimeters often have poor temporal coverage. Perimeters are not produced on a regular basis. There may be several days between incident perimeters resulting in a data gap on the daily growth in the burned area boundary. Even when perimeters are available for consecutive days, the area involved in burning during the interim period is not usually limited to the region of perimeter growth. On most days of sampling, we observed wide spread smoldering and regions of active burning (flaming combustion) scattered within the fire perimeter.

## S1.2 Elevation, vegetation involved and fuel loading

Fire elevation was obtained from geospatial overlays of the incident fire perimeters and a digital elevation map (LANDFIRE, 2012). The dominant vegetation cover for the area burned was estimated from a geospatial overlay of the incident fire perimeters with a USDA Forest Service Remote Sensing Application Center (RSAC)/ Forest Inventory Analysis Program (FIA) map of forest type (Ruefenacht et al. 2008; http://fsgeodata.fs.fed.us). The RSAC/FIA forest type map has a resolution of 250 m and assigns a dominant forest type to each pixel identified as forest. The forest types for the fires in this study were primarily Lodgepole Pine, Douglas-Fir, and Engelmann Spruce / Subalpine Fir. Non-forest cover was not a significant portion (> 1%) of the area burned by the fires during this study. The forest types identified using the forest type map have fuel loading models in the reference database of the First Order Fire Effects Model (FOFEM; FOFEM6, 2013), the model used to estimate fuel loading and consumption for the burned areas as described in Sect. S1.3.

We augmented the FOFEM reference database fuel loadings with canopy fuel loading estimates specific to each fire. Canopy fuel loading (CFL; kg $m^{-2}$), which is the canopy fuels likely to be consumed in a fully active crown fire (needles, lichen, moss, and live and dead branch wood less than 6 mm in diameter) (Scott and Reinhardt, 2001), was estimated using canopy geospatial layers (canopy cover (CC; %), canopy height (CH; m), canopy base height (CBH; m), and canopy bulk density (CBD kg $m^{-3}$)) from the LANDFIRE project (LANDFIRE, 2012):

$$\mathrm{CFL} = (\mathrm{CC}/100) \times \mathrm{CBD} \times (\mathrm{CH} - \mathrm{CBH}) \qquad \text{(S1)}$$

In a uniform forest stand, the CBD may be computed as the available canopy fuel load divided by the canopy depth (Keane et al., 1998), so if CH – CBH equals canopy depth, then Eq. S1 might be expected to yield CFL. However, forest stands are generally uniform and the LANDFIRE CBD is intended to represent the maximum value of canopy fuels within a non-uniform stand. Also, the LANDFIRE CBH is defined as the lowest layer in the canopy at which the CBD $\geq 0.012$ kg $m^{-3}$ (Reeves et al., 2006), so CH – CBH may not equal canopy depth. Therefore, our approach has significant deficiencies and provides only a crude estimate of CFL.

**S1.3 Fuel consumption estimates**

Best-guess estimates of daily fuel consumption were derived using the FOFEM. FOFEM includes a forest type specific reference fuel loading database, which we used in our calculations. In addition to fuel loading data, FOFEM requires 10-hr and 100-hr fuel moistures as input. FOFEM simulates the consumption of surface fuels (litter, dead wood, duff), herbs, and shrubs by fuel component (e.g. litter, duff, dead wood size class) but does not model canopy consumption. We assumed 50% canopy consumption. Our best-guess estimates of daily fuel consumption were used to calculate the coarse fuel fraction (CFF, the sum of CWD and duff fuel load consumed divided by the sum of total fuel load consumed) that is provided in Table S1.

**S1.4. Linear regression of EF as a function of MCE for measurements from previous studies**

Since EF for many species are correlated with MCE, previously published field measurements of emissions from fires in similar forest types (temperate mixed conifer forests) may be used to provide rough estimates of EF for species not measured in our study. Measurements from previous studies were used to derive EF – MCE linear relationships for the estimation of EF at our study average MCE of 0.883 (Table 2). Statistics for the linear regression of EF as a function of MCE are given in Table S2. Plots of EF vs. MCE with the best fit regression line are shown in Figures S1 and S2. We include $EFCH_4$ in this analysis for comparison with that measured in our study (Table 2).

In Figure S1 we have plotted $EFPM_{2.5}$ vs. MCE with best fit linear regression lines for four different combinations of data: panel (a) NW airborne only measurements (B11, H96, R91), panel (b) NW airborne and tower-based measurements (B11, H96, R91, U09), panel (c) airborne measurements all regions (B11, H96, R91), and panel (d) airborne and tower-based measurements for all regions (B11, H96, R91, U09). The $EFPM_{2.5}$ predicted at our study average MCE of 0.883 (Table S2) are all in close agreement with one another as well as our best estimate $EFPM_{2.5}$ (23.2 g $kg^{-1}$, Sect. 3.3). Emission factors reported in previous studies (A13, B11, U09, and R91) for four NMOC are plotted vs. MCE in Figure S2 along with best fit linear regression lines. Figure S2 (a) plots $EFC_2H_6$ from the airborne studies of A13 and R91 and the tower-based study of U09. Figure S2 (b) plots $EFC_3H_6$ from the airborne studies of A13, B11, and R91 and the tower-based study of U09. Panels (c) and (d) plot the airborne EF for $CH_3OH$

and HCHO reported by A13 and B11 (R91 and U09 did not measure these compounds). We consider the EF predicted by the EF – MCE regression equations (Table S2) at our study average MCE (0.883) to be best estimate EF for these NMOC for wildfires occurring in mixed conifer forest of the northern Rocky Mountains.

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Table S1. Size, growth, fire activity and fuel moisture conditions of fires on the days they were sampled

| Date | Transport Winds[1] speed (m/s) | Transport Winds[1] direction (degree) | Size (ha) | Growth (ha) | Fuel Moisture[2] (%) 10-hr | Fuel Moisture[2] (%) 1000-hr | Simulated Fuel Consumption[3] CWD + Duff Total | Fire Activity[4] |
|---|---|---|---|---|---|---|---|---|
| North Fork Prescribed Fire | | | | | | | | |
| 2011-08-13 | 7 | 260 | 400 | N/A | 6 | 14 | 0.78 | Prescribed fire with initial ignition on August 12. ICS-209 report not filed. |
| Big Salmon Lake Fire | | | | | | | | |
| 2011-08-17 | 13 | 265 | 900 | N/A | 5 | 14 | 0.72 | Significant spotting up to 0.4 km and sustained crown runs with wind-driven and terrain induced spread. |
| 2011-08-22 | 12 | 245 | 1130 | 20[4] | 5 | 14 | 0.72 | Fire spread rate was low to moderate and involved creeping and smoldering with some single tree torching occurred |
| 2011-08-28 | 5 | 270 | 1330 | 405[4] | 4 | 13 | 0.72 | Fire spread was moderate to high with active ground fire with group torching. |
| Hammer Creek Fire | | | | | | | | |
| 2011-08-22 | 12 | 245 | 550 | 0[4] | 5 | 14 | 0.61 | Fire activity was mostly creeping and smoldering with some isolated single tree and group torching observed along the perimeter. |
| Saddle Complex | | | | | | | | |
| 2011-08-24 | 10 | 250 | 8950 | 774 | 4 | 10 | 0.67 | Bitterroot branch (BR): Fire spread was mostly upslope runs. Salmon-Challis branch (SC): Activity included group torching and short crown runs. |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2011-08-25 | 11 | 260 | 9295 | 345 | 5 | 10 | 0.67 | BR: The activity included backing fire, isolated torching, and moderate spread.<br>SC: Group torching and short crown runs were observed. |
| 2011-08-26 | 10 | 250 | 9530 | 235 | 4 | 10 | 0.67 | BR: Activity included fire backing down slope, upslope crown runs from rolling material. Small columns developed in isolated areas of the fire.<br>SC: Group torching and short crown runs were observed. |
| 2011-08-27 | 10 | 260 | 10010 | 480 | 5 | 9 | 0.67 | BR: Moderate fire spread rate, isolated and group torching, spotting, and crown runs<br>SC: NA |

[1]Transport winds are from the Great Falls, MT 00Z soundings. Wind direction is direction wind is blowing from (270 degree is wind from the west). Data downloaded from University of Wyoming http://weather.uwyo.edu/upperair/sounding.html ; last accessed: 10 April 2013.
[2]Fuel moisture data from fire weather stations archived by the USFS – Wildland Fire Assessment System (WFAS, 2012) available at: http://wfas.net/index.php/search-archive-mainmenu-92; accessed on 06 August, 2012. The observations are from the weather stations: Big Salmon Lake Fire and Hammer Creek Fire - Big Prairie, WIMS# 241596; Saddle Creek Complex – Hell's Half Acre, WIMS# 101019.
[3]CWD (coarse woody debris) is dead wood with diameter > 7.62 cm.
[4]Fire activity from the Incident Command System 209 Reports (ICS-209) available at: http://fam.nwcg.gov/fam-web/hist_209/report_list_209; accessed on 18 March 2012.
[5]Daily burned area growth estimated from ICS-209.

Table S2. Statistics for the linear regression of EF as a function of MCE for combined airborne and tower measurements from previous studies. Values in parentheses represent 1-σ standard deviation. Uncertainty of EF is 95% confidence interval of linear regression fits at MCE = 0.833.

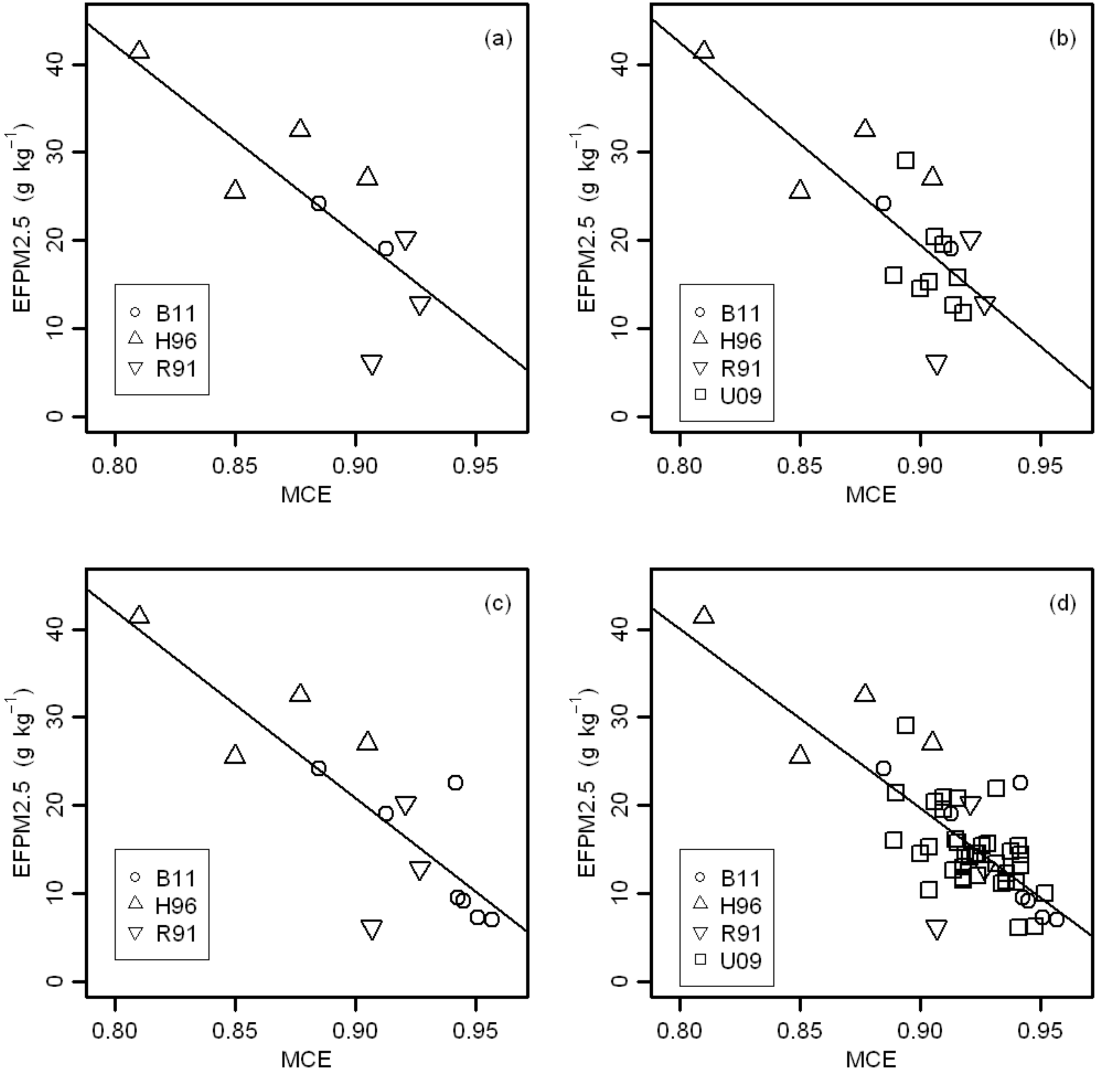
| Species | Number of Samples | Slope | Intercept | $R^2$ | EF (g $kg^{-1}$) at MCE = 0.883 | Data Source |
|---|---|---|---|---|---|---|
| Methane ($CH_4$) | 54 | -105.23 (7.92) | 100.57 (7.30) | 0.76 | 7.65±1.45 | a, b, c, d, e |
| $PM_{2.5}$ | 9 | -214.69 (64.08) | 213.90 (56.97) | 0.62 | 24.3±10.8 | d, e, f |
| $PM_{2.5}$ | 18 | -230.46 (48.63) | 226.91 (43.64) | 0.58 | 23.4±5.3 | d, e, f, g |
| $PM_{2.5}$ | 15 | -212.59 (41.10) | 212.21 (37.42) | 0.69 | 24.5±8.7 | d, e, f |
| $PM_{2.5}$ | 50 | -203.59 (24.51) | 202.92 (22.52) | 0.59 | 23.2±4.3 | b, c, d, e |
| Ethane ($C_2H_6$) | 41 | -12.83 (1.52) | 12.26 (1.40) | 0.65 | 0.93±0.26 | a, c, e |
| Propylene ($C_3H_6$) | 51 | -10.06 (1.09) | 9.82 (1.01) | 0.63 | 0.94±0.20 | a, b, c, e |
| Methanol ($CH_3OH$) | 15 | -35.25 (3.25) | 34.03 (3.04) | 0.90 | 2.19±0.77 | a, b |
| Formaldehyde (HCHO) | 15 | -18.82 (3.15) | 19.25 (2.94) | 0.73 | 2.63±0.74 | a, b |

Data Source: a. Akagi et al., 2013 (A13); b. Burling et al., 2011 (B11); c. Urbanski et al., 2009 (U09); d. Hobbs et al., 1996 (H96); e. Radke et al., 1991 (R91), f. B11 NW fires only, g. U09 NW fires only.

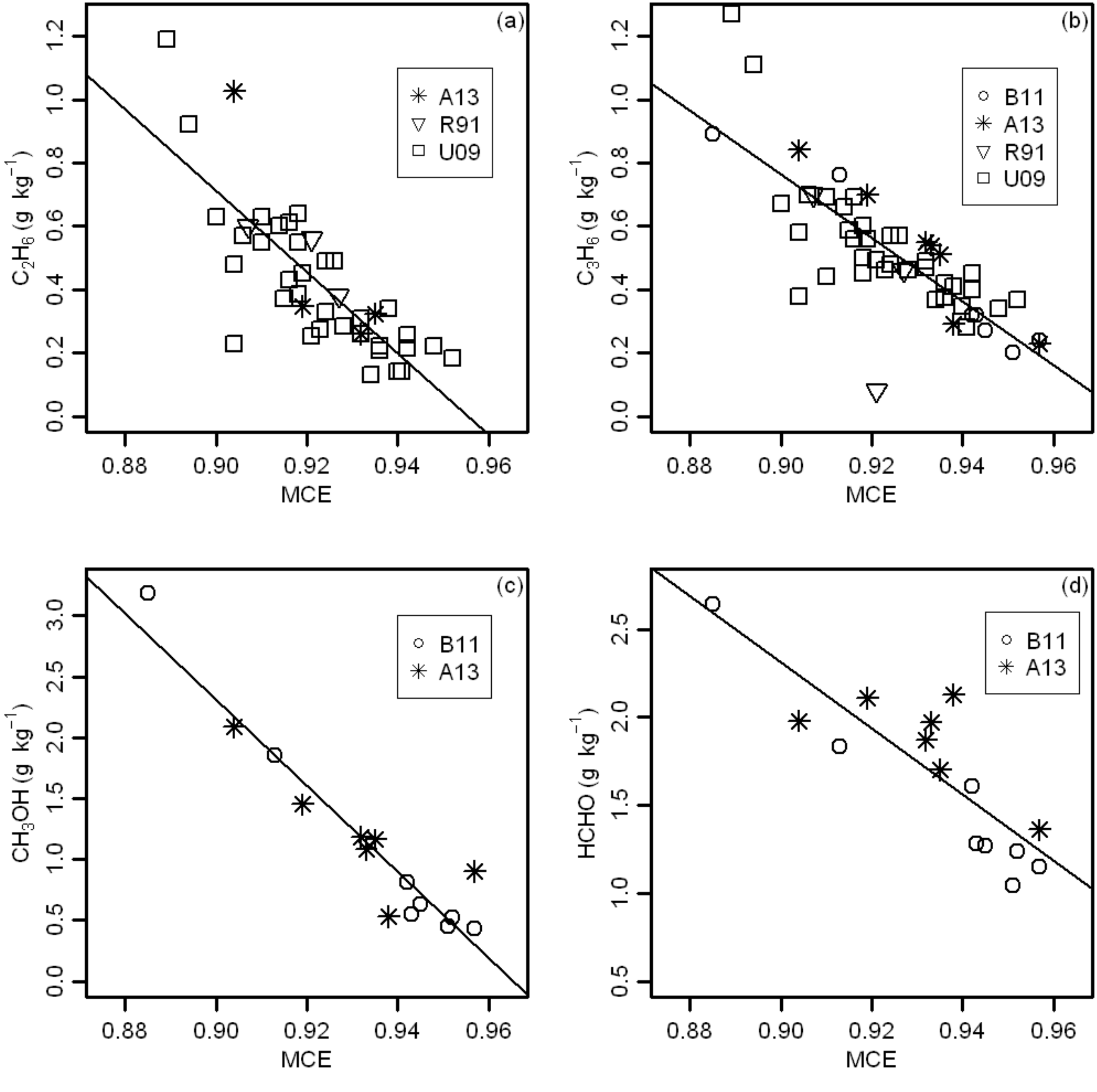
Figure Captions

Figure S1. $PM_{2.5}$ emission factors (g $kg^{-1}$) as a function of MCE for previous studies of a) R91, H96, and B11 (NW burns only), b) R91, H96, B11 (NW burns only), and U09 (NW burns only), c) R91, H96, B11, d) R91, H96, B11, and U09. Regression statistics are shown in Table S2.

Figure S2. Emission factors (g $kg^{-1}$) from previous studies as a function of MCE a) $C_2H_6$, b) $C_3H_6$, c) $CH_3HO$, and d) HCHO. Data are from A13 (Akagi et al., 2013), B11 (Burling et al., 2011), U09 (Urbanski et al., 2009), and R91 (Radke et al., 1991). Regression statistics are shown in Table S2.



(a)
(b)
(c)
(d)
EFPM2.5 (g kg$^{-1}$)
MCE
B11
H96
R91
U09
0
10
20
30
40
0.80
0.85
0.90
0.95



(a)
(b)
(c)
(d)
$C_2H_6$ (g kg$^{-1}$)
$C_3H_6$ (g kg$^{-1}$)
$CH_3OH$ (g kg$^{-1}$)
HCHO (g kg$^{-1}$)
MCE
A13
R91
U09
B11
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.5
1.5
2.0
2.5
3.0
0.88
0.90
0.92
0.94
0.96