# Smoke Produced from Residual Combustion

Final Report (98-1-9-01)

To

The Joint Fire Science Program

Submitted by

Wei Min Hao and Ronald E. Babbitt
US Forest Service, Rocky Mountain Research Station
Fire Sciences Laboratory, Missoula, Montana

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## Executive Summary

Considerable research has been carried out to estimate the chemical composition and the amount of trace gases and particulate matter emitted during short-duration flaming and smoldering combustion of fuels in the fire-prone forest and grassland ecosystems. For other forest ecosystems, where long-duration residual smoldering combustion (RSC) significantly reduces forest fuels, errors in estimating total emissions have likely existed due to the lack of information, both on the extent and chemical compounds of these emissions. This research, funded by the Joint Fire Sciences Program (JFSP), investigates the smoke emissions produced by RSC, which may persist for hours or even days after the passage of the flame front. This project is the first large scale study to determine the emissions of important trace gases from common RSC prone fuel components such as logs, stumps, and duff. Studies were conducted in Alaska and the Southeastern and Western Regions of the US. Based on these measurements, combustion efficiencies and emission factors for the important carbon-containing trace gases have been calculated. Modified Combustion Efficiency (MCE) in this study was found to be significantly lower than those previously reported for flaming and short-duration smoldering phases of a wildland fire. The lower MCE is primarily the result of increased CO emissions. Emission factors for $CH_4$ were also found to be generally higher, but no empirical relationships were found between the emission factors of $CH_4$ and the emission factors of CO or MCE. Emissions of non-methane hydrocarbons (NMHC) were not correlated with CO and $CH_4$ emissions, and were found to be about equal or lower than NMHC emission factors for the flaming and short-duration smoldering phases. Since prior estimates of RSC emissions were based on short-duration smoldering data, this new information will provide a more accurate estimate of the total emissions released from a wildland fire.

The other project under this JFSP award includes a contract with Dr. Robert Yokelson of the University of Montana to study RSC emissions using Open Path-Fourier Transform Infrared Spectroscopy. This work provides emission factors for additional compounds, including PM2.5, during residual smoldering combustion. [Appendices 3, 4 and 5]

## 1. Introduction

Smoke from biomass burning has long been recognized as an important source of atmospheric pollutants, greenhouse gases, and particulate matter [Crutzen and Andreae, 1990]. About $6 \times 10^{15}$ g of biomass were burned annually from forest, savanna and agricultural fires worldwide [*Hao and Ward,* 1993; *Hao and Liu*, 1994]. Since the 1970s, there have been numerous studies to quantify the emissions of trace gases and aerosol particles from biomass fires in tropical, subtropical, temperate, and boreal ecosystems. Most of the emission measurements were carried out during flaming and short-duration smoldering combustion. For the fuel types that contain a high percentage of fine, flash fuels, the majority of emissions are produced during these two phases of combustion. However, if there is a significant amount of large diameter woody debris, old stumps, and/or duff, the emissions produced from the long-duration smoldering combustion of these fuels, or residual smoldering combustion (RSC), can be a significant part of the total emissions. In some forest ecosystems, such as in the boreal zone, residual

smoldering combustion can account for more than 50% of the total fuel consumption [*Sandburg*, 1983*; Kasischke et al*., 1999] due to the deep moss/duff layer. In pastures in the Amazon basin, *Kauffman et al*., [1998] found that long-duration smoldering of large diameter logs remaining after initial deforestation fires can account for 38% - 44% of the total fuel consumed.

*Wade and Lunsford* [1989] defined residual smoldering combustion to be the smoldering combustion process that is no longer influenced by strong convection associated with a flame front. Since RSC occasionally includes flaming combustion at a fixed location, we define RSC to be the long-duration process of smoldering and/or flaming combustion that may persist for several hours or several days following the passage of the flame front. During RSC, smoldering usually accounts for the majority of the biomass burned; however under certain conditions, such as high winds, the amount of biomass burned during flaming combustion can be significant.

In addition to potentially being a major source of atmospheric trace gases and particulate matter, RSC emissions can have a significant impact on the public health of the local communities as the drift smoke produced during RSC often remains close to the ground, instead of being lofted from the fire front during flaming combustion to the upper atmosphere. Firefighters are also exposed to high levels of RSC emissions during the mop-up stage of fire suppression.

The two primary objectives of this project were to determine (1) the modified combustion efficiencies and (2) the emission factors of major atmospheric pollutants during the period of residual smoldering combustion for different types of RSC prone fuels. The modified combustion Efficiency (MCE) is defined to be the ratio of emitted $CO_2$ concentrations to emitted $CO_2$ and CO concentrations. The flaming combustion of a fire is more efficient than the smoldering combustion. Hence, the MCE are in a range of 95% - 98% for most of the flaming combustion and in a range of 86% - 94% for the short-duration smoldering combustion. The emission factor (EF) (g $kg^{-1}$) is defined as the amount of a particular compound emitted per kg of dry biomass burned.

## 2. Methods

### 2.1 Field Sites

The experimental sites covered a variety of common smoldering fuels in the Southeast and West in the continental US and Alaska. Table 1 summarizes the locations, dominant vegetation and smoldering fuel types, and the experimental dates. The Southeastern sites included the Eglin Air Force Base (eg) in Florida, Francis Marion National Forest (fm) in South Carolina, the Hitciti National Forest (hi) in Georgia, and the Piedmont National Wildlife Refuge (pi) in Georgia. The Western sites included the Baker City Watershed (bc) in Oregon and three other sites within 100 km of Missoula, Montana: the late Dr. Keeling's Ranch (ke), the University of Montana's Lubrecht Experimental Forest (lu), and Seeley Lake (se). The two sites of Erickson wildfire (ek, ek2) and Chena Lakes (clf) were located within 200 km of Fairbanks, Alaska.

In Southern and Western US, measurements were carried out primarily on smoldering logs, stumps, and basal duff following understory prescribed fires in pine forests. In Alaska, measurements focused on emissions of residual smoldering combustion from moss and duff following a wildfire and a prescribed fire in Black Spruce boreal forests. Prescribed burning to forested land has been widely practiced in the Southeast. Hence, the amount of above ground biomass of RSC prone fuels in the Southeast are usually lower than that found in the West or Alaska.

**Table 1.** Experimental Locations, Vegetation and Smoldering Fuel Types, and Dates

| Location | Vegetation - Smoldering Fuel Types | Burn Date |
|---|---|---|
| Eglin Air Force Base, FL | Sandhill Pine- logs, stumps, duff | 04/24/2002 |
| Francis Marion National Forest, SC | Mixed Pine - Hurricane blowdown large logs | 05/09/2000 |
| Hitchiti Forest, GA | Oak and Pine - small logs, duff | 05/03/2000 |
| Piedmont Wildlife Refuge, GA | Oak, Pine, Grass- small logs, stumps, duff | 05/02/2000 |
| Baker City, OR | Large mature Ponderosa Pine, Douglas Fir – downed woody materials, stumps, and duff | 05/31/2002 |
| Keeling Ranch, MT | Lodgepole Pine – stumps, logs, branches, duff | 09/14/1998 |
| University of Montana, Lubrecht Experimental Forest, MT | Mixed Ponderosa Pine and Douglas Fir - downed woody materials, stumps, and duff | 05/02/2002 |
| Seeley Lake, MT | Ponderosa Pine, Douglas Fir - duff, stumps, logs, branches | 09/29/2003 |
| Erickson wildfires, AK | Black Spruce - Smoldering Feather Moss, wildfire conditions | 06/22/2003 |
| Chena Lakes, AK | Black Spruce - Smoldering Feather Moss, prescribed fire conditions | 06/25/2003 |

## 2.2 Sampling

To derive the modified combustion efficiency and the emission factors of trace gases, it is necessary to measure the primary carbon-containing trace gases released at a certain time interval during the entire period of the residual smoldering combustion process.

We have developed an open-bottom sample chamber that was tightly placed over a smoldering fuel, such as a stump, to capture the emitted trace gases. This portable system consisted of two main components: a sample chamber and a backpack containing gas sampling instruments to capture the emissions from the smoldering fuel. The sample chamber was a 1 m x 1 m x 1m aluminum frame made of ½" (O.D.) conduit, in which the top and three sides were covered with a fire shelter material. A small aluminum plate with two gas sampling ports and a thermocouple port were attached to the top of the chamber. A small battery powered muffin fan was housed on the top inside of the chamber to improve mixing gases in the chamber. Two Teflon sampling lines connected the chamber to the $CO_2$ instrument and grab sample pumps. The aluminum frame

backpack held a non-dispersive infrared (NDIR) $CO_2$ analyzer [Li-Cor, Model LI-800], a 2 LPM sampling pump, a data logger [Campbell Scientific, Model CR10X], and another 2 LPM pump to collect grab samples into 250 ml glass bottles. The backpack could hold up to 12 sample bottles. The data logger recorded site identification information, time, battery voltage, temperature from a type K thermocouple, $CO_2$ sample pressure, and the real-time $CO_2$ level. The sample chamber was briefly placed over the smoldering fuel once every two hours during the duration of residual smoldering combustion. The sampling period lasted about 1-3 minutes each time, depending on the rate of increase of $CO_2$ concentrations in the chamber. In addition to monitoring the $CO_2$ increase, grab bottle samples were taken periodically, ranging from several seconds to several minutes, in the sample chamber. The higher the rate of $CO_2$ concentration increases, the shorter the sampling time. Also, the rate of $CO_2$ increase is substantially higher during the early phase of combustion than the rate of increase in the later phase of combustion.

### 2.3 Analytical techniques

Sample bottles and canisters collected in the field were analyzed at the Analytical Chemistry Laboratory of the Fire Sciences Laboratory. The samples were analyzed for $CO_2$, CO, $CH_4$, and $C_2$- $C_3$ aliphatic compounds with a Hewlett Packard model 5890 Series II gas chromatograph. The $CO_2$ and CO analysis used a 1-mL sample loop to inject the sample, a 1/8" (O.D) x 6 ft. Carbosphere (Alltech) column to separate $CO_2$, CO, and air, with helium carrier gas at a flow rate of 16 ml $min^{-1}$. After separation in the column, the sample entered a methanizer (375$^oC$) that converted $CO_2$ and CO to methane, which was detected by the flame ionization detector at 350$^o$ C. The oven temperature was held isothermal at 100$^oC$. The $C_1$ -$C_3$ hydrocarbon analyses were performed using a 0.25-mL sample loop, a 0.53 mm x 30 m GS-Q column (J&W Scientific), with helium carrier gas at a flow rate of 6 mL $min^{-1}$ and a makeup helium gas at a flow rate of 14 mL $min^{-1}$, and the FID at 300$^oC$. The oven temperature program for this analysis was 30$^oC$ for 6 min, increasing by 10$^oC$ $min^{-1}$ to reach the final temperature of 90$^oC$.

Chromatogram data was collected from the gas chromatograph and processed by Hewlett Packard ChemStation II software. A set of trace gas concentration standards bracketing the sample concentrations were analyzed with each set of samples to construct a standard curve for each compound. Based on the integrated peak areas, the sample concentrations were calculated from the standard curves and written into an Excel spreadsheet.

Figure 1 shows the increase of $CO_2$ concentrations with time in the sample chamber of burning duff at the Hitchiti National Forest, Georgia, on 12:55 PM, 3:10 PM, and 8:05 PM, May 3$^{rd}$, 2000. Carbon dioxide concentrations were measured continuously every second by the Li-Cor instrument during the sampling period, while grab bottle samples were taken every 30, 60, or 120 seconds.

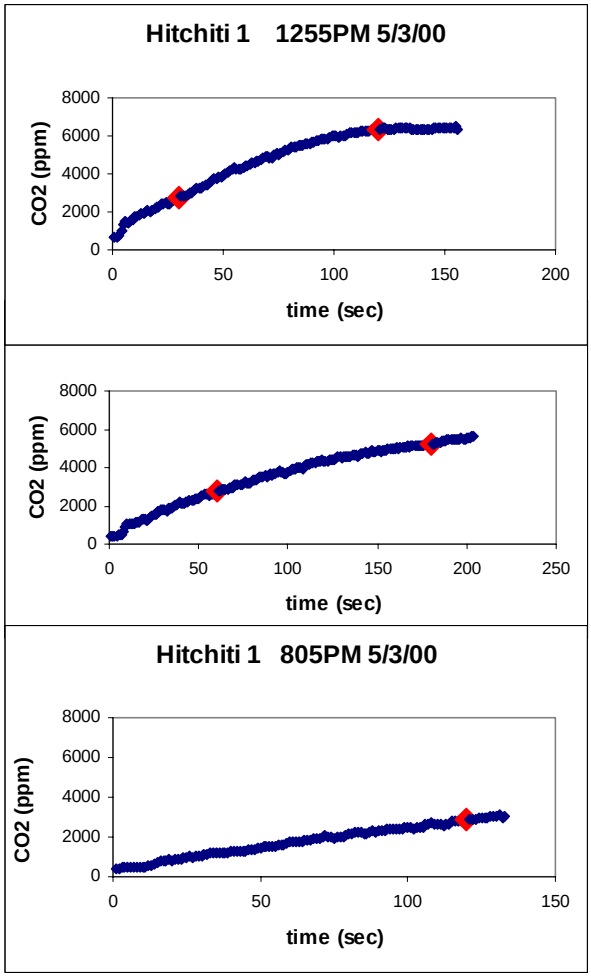



**Figure 1.** Real-time (♦) and grab sample (♦) $CO_2$ concentrations in the sample chamber for smoldering duff, at Hitchiti National Forest, Georgia, May 3rd, 2000.

The $CO_2$ concentrations measured by two different methods are quite consistent. The $CO_2$ levels would initially increase at a constant rate and then reach a maximum level in the sample chamber.

## 3. Results and Discussion

### 3.1 Emission Factors and Modified Combustion Efficiency

Emission Factors for $CO_2$, CO, $CH_4$, and NMHC were calculated for most of the residual smoldering combustion of various fuels using the carbon mass balance method [*Ward and Radke*, 1993]. Table 2 summarizes the emission factors and the modified combustion efficiency in the Southeast, West, and Alaska. Emission factors of residual smoldering combustion for different fuel types at each site in each region are given in Appendix 1. The Southeastern Region had the lowest MCE and the highest emission factors of CO of the three regions, probably because of the high fuel moisture content in the Southeast.

**Table 2.** Average Emission Factors and MCE of RSC by Region

| Site | Number of Samples | $EFCO_2$ (g $kg^{-1}$) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | $EFC_2H_4$ (g $kg^{-1}$) | $EFC_3H_6$ (g $kg^{-1}$) | EFNMHC (g $kg^{-1}$) | MCE |
|---|---|---|---|---|---|---|---|---|
| Southeast | | | | | | | | |
| Eglin Air Force Base, FL | 12 | 1305 | 314 | 10.6 | 1.06 | 0.74 | 1.80 | 0.73 |
| Francis Marion NF, SC | 9 | 1366 | 287 | 6.3 | | | | 0.75 |
| Hitchiti Forest, GA | 7 | 1337 | 298 | 10.4 | | | | 0.74 |
| Piedmont, GA | 7 | 1348 | 286 | 13.3 | | | | 0.75 |
| Average | | 1339 | 296 | 10.1 | 1.06 | 0.74 | 1.80 | 0.74 |
| West | | | | | | | | |
| Baker City, OR | 12 | 1446 | 226 | 14.7 | 1.65 | 1.41 | 3.06 | 0.80 |
| Keeling Ranch, MT | 11 | 1524 | 205 | | | | | 0.83 |
| Lubrecht, MT | 12 | 1431 | 229 | 15.5 | | | | 0.80 |
| Seeley Lake, MT | 9 | 1428 | 229 | 13.5 | 1.44 | 1.24 | 2.68 | 0.80 |
| Average | | 1457 | 222 | 14.6 | 1.55 | 1.32 | 2.87 | 0.81 |
| Alaska | | | | | | | | |
| Erickson wildfire | 5 | 1425 | 244 | 6.3 | 1.35 | 1.04 | 1.35 | 0.79 |
| Erickson2 wildfire | 6 | 1463 | 247 | 8.5 | 0.88 | 0.69 | 0.88 | 0.81 |
| Chena Lake | 6 | 1419 | 240 | 10.1 | 1.49 | 1.24 | 1.86 | 0.79 |
| Average | | 1436 | 244 | 8.4 | 1.23 | 0.99 | 1.37 | 0.80 |

To compare the RSC emission factors with previous results, we compiled and grouped regional flaming and short-duration smoldering emissions data from prescribed fires and wildfires. The Southeastern and Western data have been collected from the ground-based experiments using the Fire Atmosphere Sampling System (FASS) in the past 15 years by the Fire Sciences Laboratory [*Susott et al*., 1991; Hao et al., 1996]. For Alaska data, samples were collected with an aircraft and represent a mixture of flaming and smoldering combustion, although it is most likely weighted heavily by flaming emissions [*Goode et al*., 2000]. Table 3 shows the average emission factors of flaming and short-duration smoldering combustion and MCE for fires in the Southeast, West, and Alaska. The major vegetation and fuel types in each region in the previous studies are very similar to the ones for the residual smoldering combustion experiments.

**Table 3.** Emission Factors of Flaming and Short-duration Smoldering Combustion by Region

| Phase | $EFCO_2$ (g $kg^{-1}$) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | EFNMHC (g $kg^{-1}$) | EFPM2.5 (g $kg^{-1}$) | MCE |
|---|---|---|---|---|---|---|
| Southeast | | | | | | |
| Flaming | 1681 | 73 | 2.0 | 2.4 | 11.7 | 0.94 |
| Short-duration Smoldering | 1618 | 108 | 3.1 | 4.0 | 11.6 | 0.90 |
| West | | | | | | |
| Flaming | 1648 | 91 | 3.5 | 2.9 | 13.4 | 0.92 |
| Short-duration Smoldering | 1563 | 133 | 5.8 | 3.9 | 15.6 | 0.88 |
| Alaska | | | | | | |
| Mixed (aircraft) | 1660 | 89 | 2.8 | 2.3 | | 0.92 |

For all regions, the RSC MCE is significantly lower than the average flaming and short-duration smoldering MCE. The average short-duration smoldering EFCO of 108 g $kg^{-1}$ and 133 g $kg^{-1}$ are much lower than the RSC values of 296 g $kg^{-1}$ and 222 g $kg^{-1}$ for the Southeast and West, respectively. Similarly, the emission factors of $CH_4$ for the RSC are higher than the $CH_4$ emissions from prescribed fires and wildfires in the three regions. However, the emission factors of non-methane hydrocarbons for RSC do not follow the same trend, and are either lower or similar to the non-methane hydrocarbon emissions for the flaming and short-duration smoldering combustion.

Figure 2 shows the negative linear relationship between $EFCH_4$ and MCE for flaming and short-duration smoldering combustion in all Western and Southeastern Regions. Almost all of the previous work has reported a strong linear correlation between MCE and $EFCH_4$ for flaming and short-duration smoldering phases [e.g., Hao and Ward, 1993; Hao et al., 1996; Yokelson et al., 2003]. However, there is no linear correlation between the $CH_4$ emission factors and MCE for residual smoldering combustion in the Southeast, West, and Alaska [Fig. 3], because the $CH_4$ emissions for RSC vary in a narrow range with MCE in comparison to the flaming or short-duration smoldering phases. Therefore, the modified combustion efficiency cannot be used to estimate $CH_4$ emissions from residual smoldering combustion. Smoldering combustion is a different process from flaming combustion, which occurs at a much higher temperature. For most fires there is a transition phase as combustion temperatures decrease from flaming to smoldering combustion, which ultimately affects the emissions of trace gases and particulate matter [*Yokelson et al*., 1996, 1997; *Bertschi et al.*, 2003].

**Figure 2.** $EFCH_4$ v MCE for Flaming and Short-duration Smoldering Combustion in the Southeast and West

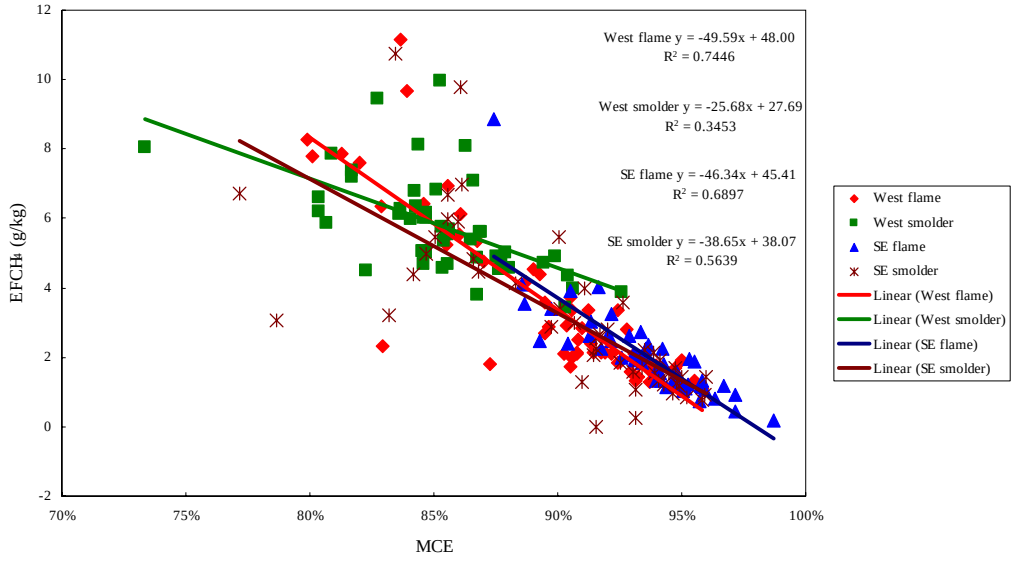
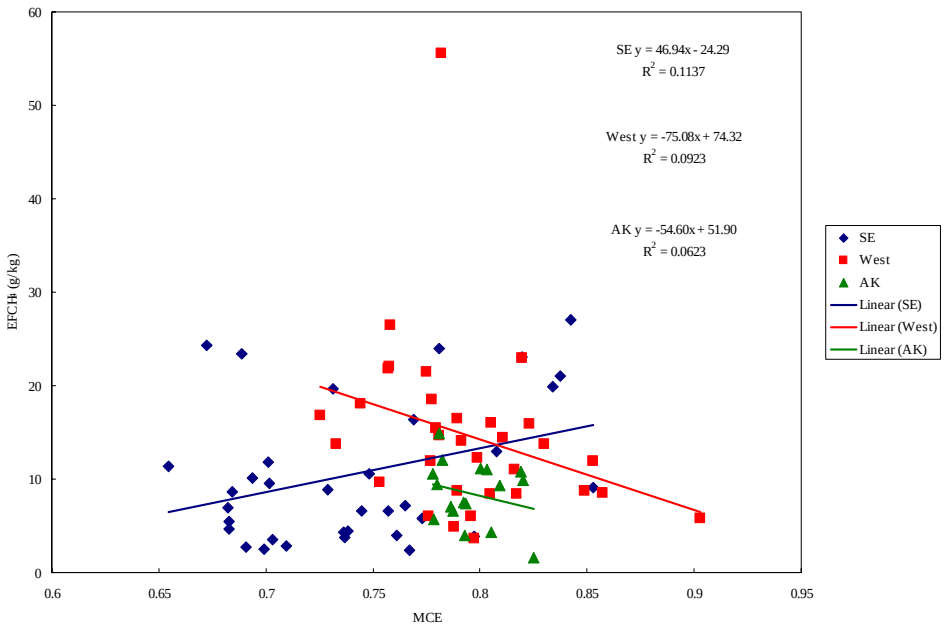
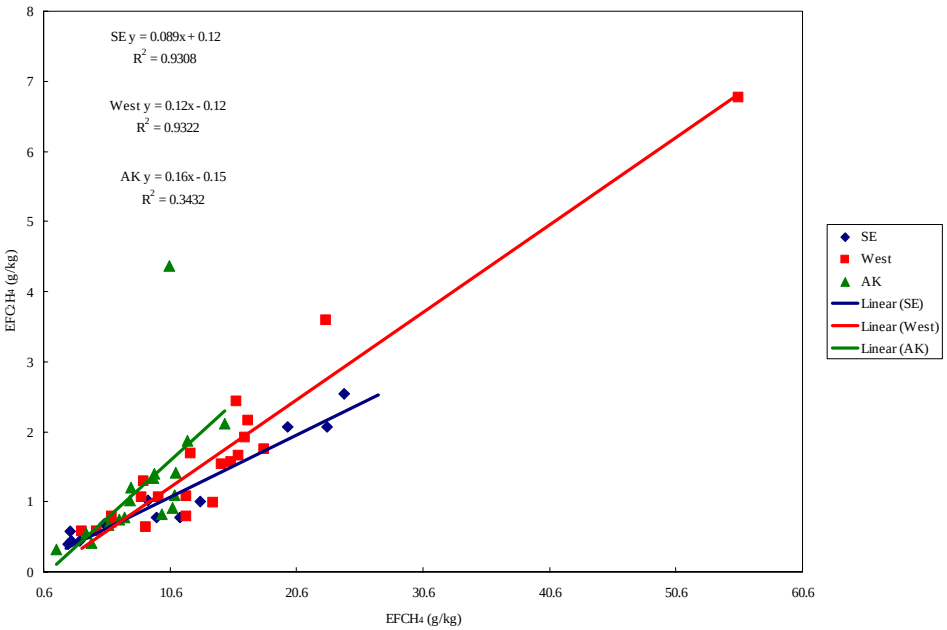


**Figure 3.** $EFCH_4$ vs. MCE fore Residual Smoldering Combustion in the Southeast, West, and Alaska



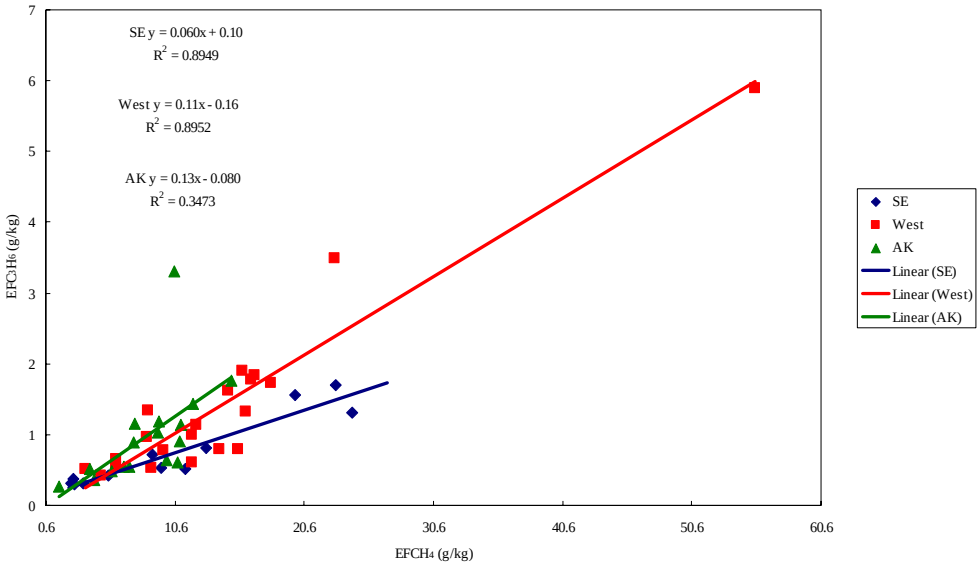

The emissions of $C_2H_4$ and $CH_4$ for residual smoldering combustion are strongly correlated linearly in the Southeast and West [Figure 4]. The linear correlation would be more significant in Alaska, if the outlier point of $C_2H_4$ emission factor of about 4.2 g $kg^{-1}$ is removed from the calculation.

**Figure 4.** Relationship between $C_2H_4$ and $CH_4$ Emissions in Different Regions



In a similar way, the emissions of $C_3H_6$ and $CH_4$ are also strongly correlated in the Southeast and West, but not in Alaska because of the same outlier point [Figure 5]. As with the $EFCH_4$, both $EFC_2H_4$ and $EFC_3H_6$ are weakly correlated with the modified combustion efficiency in all regions.

**Figure 5.** Relationship between $C_3H_6$ and $CH_4$ Emissions in Different Regions




## 3.2 Emission Factors by Fuel Component

Table 4 summarizes the emission factors and modified combustion efficiency by fuel component. Emission factors and modified combustion efficiency by fuel component for each site are given in Appendix 2. There are no emission factors data for $C_2H_4$ or $C_3H_6$ for rotten wood as not all samples were analyzed for non-methane hydrocarbons, and only one rotten stump sample was analyzed for C-2 and C-3 alkanes and alkenes.

**Table 4.** Average Emission Factors and Modified Combustion Efficiency by Fuel Component

| Fuel Component | Number of Samples | $EFCO_2$ (g $kg^{-1}$) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | $EFC_2H_4$ (g $kg^{-1}$) | $EFC_3H_6$ (g $kg^{-1}$) | EFNMHC (g $kg^{-1}$) | MCE |
|---|---|---|---|---|---|---|---|---|
| Woody Materials | 19 | 1378 | 255 | 17.8 | 2.17 | 1.81 | 3.99 | 0.77 |
| Stump | 26 | 1415 | 248 | 14.1 | 1.41 | 1.06 | 2.47 | 0.78 |
| Duff | 15 | 1446 | 234 | 11.0 | 1.40 | 1.21 | 2.61 | 0.80 |
| Basil duff | 9 | 1348 | 299 | 5.1 | 0.52 | 0.37 | 0.89 | 0.74 |
| Alaska Moss | 18 | 1436 | 244 | 8.4 | 1.23 | 0.99 | 1.37 | 0.80 |
| Rotten Wood | 7 | 1352 | 295 | 6.6 | | | | 0.74 |
| Rotten Stump | 3 | 1397 | 254 | 12.4 | 1.68 | 1.15 | 2.83 | 0.78 |
| Average | | 1396 | 261 | 10.8 | 1.40 | 1.10 | 2.36 | 0.77 |

The modified combustion efficiency of residual smoldering combustion ranged from 0.74 for basal duff and rotten wood to 0.8 for duff and Alaska moss with an average of 0.77 for burning 96 residual fuel samples. The MCE values are similar to those used in the FOFEM (41) program (0.76) for smoldering combustion of duff and wood larger than 7.6 cm in diameter. The MCE was reported to be 0.79 for smoldering Ponderosa Pine wood in a laboratory experiment [McKenzie *et al*., 1995]. *Bertschi et al*. [2003] reported the MCE of 0.85 – 0.90 for residual smoldering combustion of duff/organic soil, softwood debris, and large diameter (> 30 cm) hardwood logs in laboratory fires.

The average emission factor of CO was 261 g $kg^{-1}$ for these experiments, which is significantly higher than the CO emission factors for flaming combustion or short-duration smoldering phases of wildland fires. There are no significant differences in the CO emission factors for burning different types of residual fuels. The CO emission factors in the EPA AP-42 are 166 g $kg^{-1}$ for short-duration smoldering of long needles in the conifer forest and 226 g $kg^{-1}$ for smoldering of short needles. The CO emission factors used in FOFEM for fuels > 7.6 cm range from 87 g $kg^{-1}$ for dry fuel to 103 g $kg^{-1}$ for wet fuel [*Reinhardt et al.,* 1997]. The CONSUME [*Ottmar et al*., 2000] program uses 183 g $kg^{-1}$ as the CO emission factor for smoldering combustion following a broadcast burn of Ponderosa pine forest. *Bertschi et al*. [2003] reported an average CO emission factor of 146 g $kg^{-1}$ from smoldering combustion of residual fuels in the northwestern U.S., Canada, and Zambia in western Africa.

There is considerable variability in the $CH_4$ emission factors for various fuel components, with the woody fuels and stumps having higher values than duff, basal buff, or dead moss. *Bertschi et al*., [2003] reported $CH_4$ emission factors ranging between 2.4 g $kg^{-1}$ for softwood debris and 23.2 g $kg^{-1}$ for large diameter logs with an average of 12 g $kg^{-1}$. There is no apparent correlation between the $CH_4$ emission factors and modified combustion efficiency for residual smoldering combustion [Fig. 6]. The results are contradictory to all the published results, in which the $CH_4$ emission factors are linearly correlated negatively with the modified combustion efficiency.

Figures 7 and 8 show the relationship between the emission factors of $C_2H_4$ and $C_3H_6$ versus the emission factors of $CH_4$, respectively, by fuel category. Emissions of $C_2H_4$ and $C_3H_6$ and emissions of $CH_4$ are strongly correlated linearly with for woody fuels and stumps, moderately correlated linearly for the duff and basal duff, and weakly correlated for the Alaska moss. There were insufficient data to determine if a correlation exists between non-methane hydrocarbons and methane emission factors for rotten wood and stumps.

**Figure 6.** Emissions of $CH_4$ vs. MCE by Fuel Component

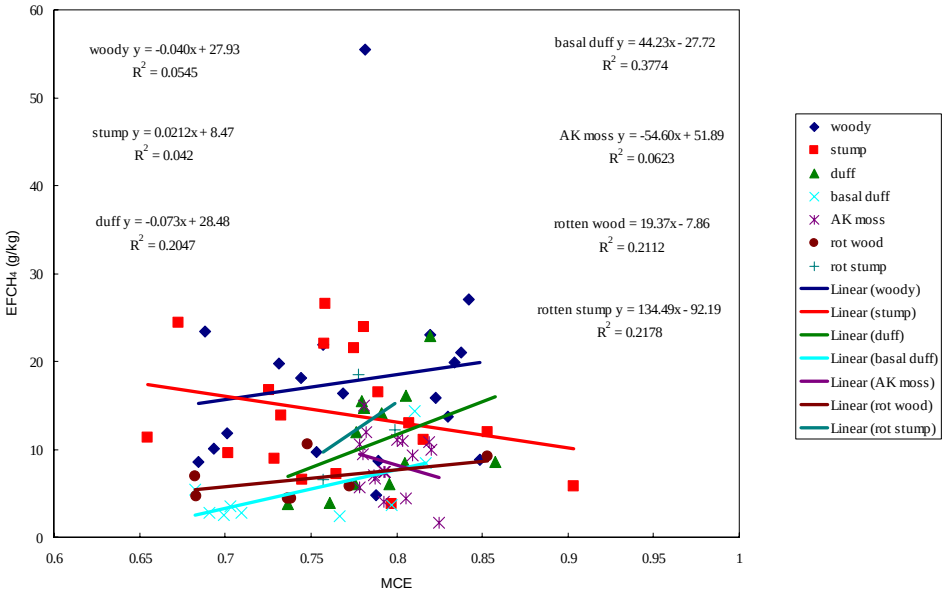



**Figure 7.** Relationship between $C_2H_4$ and $CH_4$ Emissions by Fuel Component

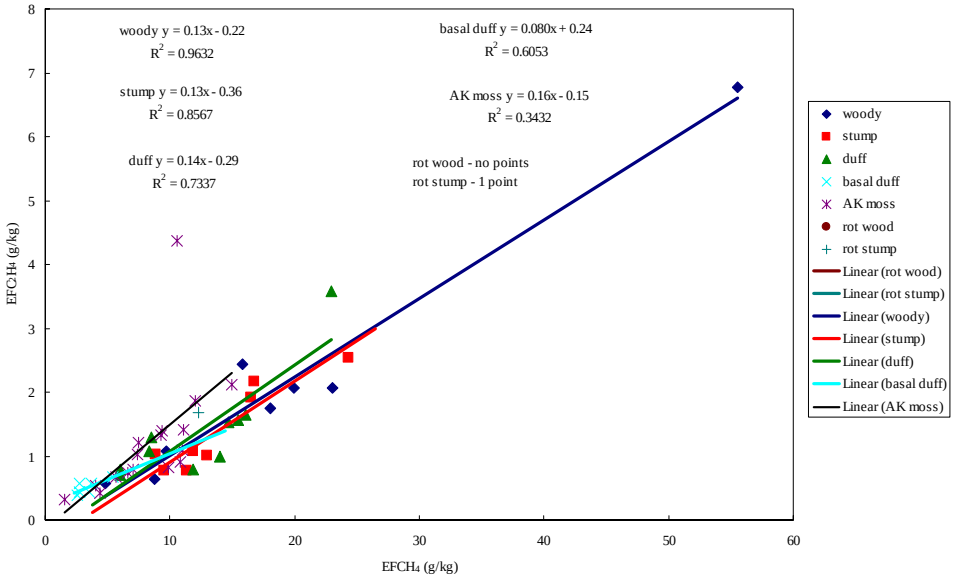
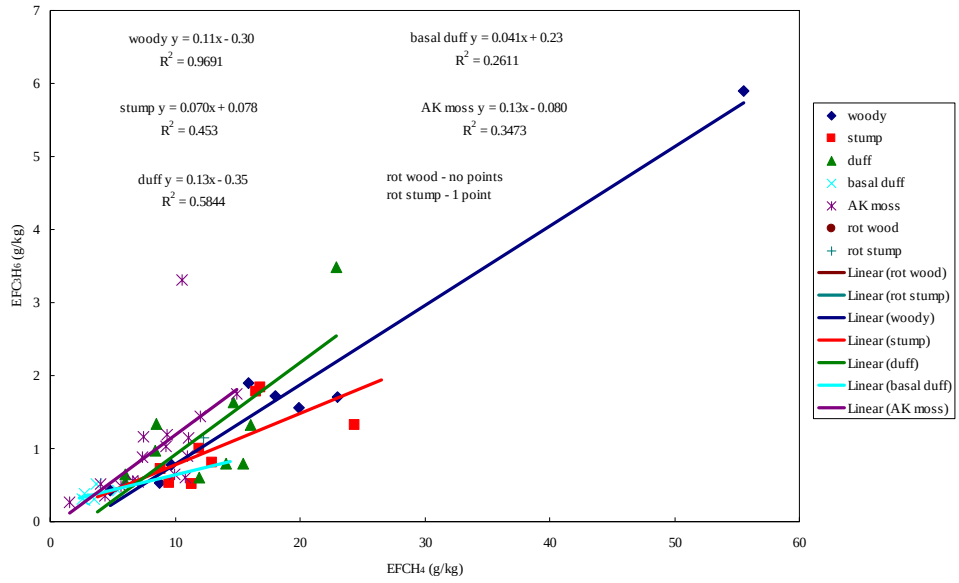
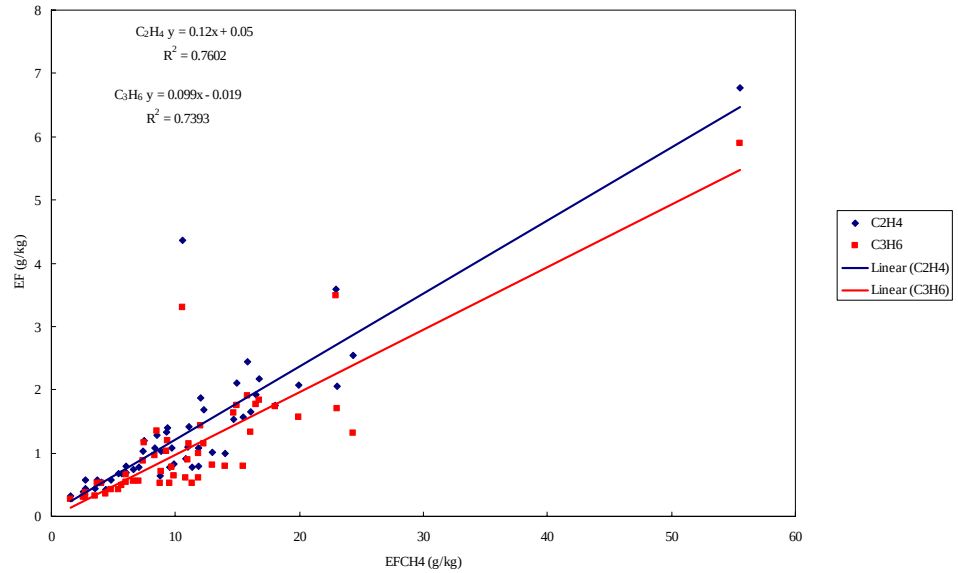


**Figure 8.** Relationship between $C_3H_6$ and $CH_4$ Emissions by Fuel Component




Although the linear relationships between the $C_2H_4$ and $C_3H_6$ emissions and the $CH_4$ emissions may vary for different fuel components, there are reasonably strong linear correlations between the emissions of $C_2H_4$ and $C_3H_6$ and the emissions of $CH_4$ when the results of residual smoldering combustion of all the fuel samples were combined in Figure 9.

**Figure 9.** Relationship between $C_2H_4$ and $C_3H_6$ emissions and $CH_4$ emissions for all fuel samples



## 4. Conclusions

Information collected during this study will be useful in updating models currently used by land managers to determine the modified combustion efficiency and the emission factors of atmospheric pollutants emitted during residual smoldering combustion for a variety of fuel types in the Southeast, West, and Alaska.

The CO emissions relative to the $CO_2$ were significantly higher than had been previously measured for the short-duration smoldering phase that follows the passage of the flame front. The result of this higher CO to $CO_2$ ratio is a lower MCE. This finding has a significant impact on calculations of emission factors of other compounds which are based on the MCE.

The $CH_4$ emissions did not show any strong correlation to the CO emissions or MCE for any of the RSC fuel components measured. The emission factors for $C_2H_4$ and $C_3H_6$ were both lower than for the flaming and short-duration phases, and both emissions were correlated linearly with the $CH_4$ emissions.

## 5. References

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**6. Deliverables**

| ***Proposed*** | ***Accomplished/ Status*** |
|---|---|
| Annual progress reports | Annual progress reports completed |
| Develop the technology to measure residual smoldering emissions in the field. | The construction and deployment of a portable sampling system for residual smoldering emissions completed. This system includes an instrument package and a field chamber for sampling RSC. |
| Produce emission factors for inputs into models such as the EPM. | RSC emission factors developed for individual smoldering fuel components in Southeast, West, and Alaska. |
| Linkage to other projects | Roger D. Ottmar, 2004. *Forest Floor Consumption and Smoke Characterization in Boreal Forested Fuelbed Types of Alaska.* The objective of this project is to provide a fuel consumption module for implementation into fuel consumption and fire effects software tools such as Consume 3.0, EPM, and FOFEM 5.0. We characterized the smoke emissions from RSC in Alaska in 2003 and 2004 using our sampling methodology and produced RSC emission factors for Alaska fuels. |
| Publication | 1) *Smoldering Limits of Alaska Duff*. James Reardon, Fires Sciences Laboratory (in progress). A laboratory investigation of the relationship of moisture and mineral content to the ignition probability and consumption characteristics of Alaskan duff. The samples were collected in 2003.<br><br>2) Appendices 3, 4 and 5 |
| Publication | Mafoko, G. Jomo. 2003. *Variation of specific gravity (bulk density) in conifer stumps with reference to sampling technique and decay class*. Masters thesis, University of Montana, |
| Presentation | Babbit, R. 2004. Residual Smoldering Fire Emissions and Fuel Consumption Overview. National Fire Emissions Technical Workshop. New Orleans |

| ***Proposed*** | ***Accomplished/ Status*** |
|---|---|
| Data Base | RSC emission factors for smoldering components including stumps, downed wood, and duff for the Southeast, West and Alaska. |
| Workshop | Residual Smoldering Combustion Workshop, University of Montana. May 2001. This workshop included 20 participants from the fields of air quality management, fire emissions research, and local land managers. |

**7. Appendices**

Appendix 1 - Emission Factors and MCE for Each Fuel Component at Each Site

Appendix 2 - Emission Factors and MCE by Fuel Component

Appendix 3 - Bertschi, I.T., R.J. Yokelson, J. G. Goode, D.E. Ward, R.E. Babbitt, R. A. Susott, J.G. Goode, and W.M. Hao, Trace gas and particle emissions from fires in large-diameter and belowground biomass fuels, *J. Geophys. Res.*, *108*, 8472, doi:10.1029/2002JD002100, 2003.

Appendix 4 - Christian, T.J., B. Kleiss, R.J. Yokelson, R. Holzinger, P.J. Crutzen, W.M. Hao, B.H. Saharjo, and D. E. Ward, Comprehensive laboratory measurements of biomass-burning emissions: 1. Emissions from Indonesian, African, and other fuels, *J. Geophys. Res.*, *108*, 4719, doi:10.1029/2003JD003704, 2003.

Appendix 5 - Christian, T.J., B. Kleiss, R.J. Yokelson, R. Holzinger, P.J. Crutzen, W.M. Hao, T. Shirai, and D.R. Blake, Comprehensive laboratory measurements of biomass-burning emissions: 2, First intercomparison of open-path FTIR, PTR-MS, GC-MS/FID/ECD, *J. Geophys. Res.*, *109*, D02311, doi:10.1029/2003JD003874, 2004.

## Appendix 1. Emission Factors and MCE for Each Fuel Component at Each Site

Table A1-1. RSC Emission Factors and MCE in the Southeast

| Site | Fuel type | Fuel Code | $EFCO_2$ (g $kg^{-1}$) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | $EFC_2H_4$ (g $kg^{-1}$) | $EFC_3H_6$ (g $kg^{-1}$) | EFNMHC (g/$kg^{-1}$) | MCE |
|---|---|---|---|---|---|---|---|---|---|
| eg1 | basal duff | 4 | 1294.3 | 336.7 | 2.79 | 0.44 | 0.30 | 0.73 | 0.71 |
| eg2 | log | 1 | 1441.8 | 201.3 | 23.04 | 2.06 | 1.70 | 3.76 | 0.82 |
| eg3 | stump | 2 | 1192.9 | 357.2 | 24.35 | 2.54 | 1.32 | 3.86 | 0.67 |
| eg4 | basal duff | 4 | 1238.9 | 366.5 | 5.44 | 0.68 | 0.42 | 1.10 | 0.68 |
| eg5 | stump | 2 | 1265.4 | 342.1 | 9.55 | 0.78 | 0.53 | 1.31 | 0.70 |
| eg6 | basal duff | 4 | 1280.7 | 344.1 | 3.49 | 0.44 | 0.32 | 0.75 | 0.70 |
| eg7 | stump&log | 1 | 1474.0 | 186.6 | 19.92 | 2.07 | 1.56 | 3.63 | 0.83 |
| eg8 | basal duff | 4 | 1259.4 | 358.5 | 2.74 | 0.57 | 0.38 | 0.95 | 0.69 |
| eg9 | basal duff | 4 | 1275.3 | 349.3 | 2.55 | 0.39 | 0.31 | 0.70 | 0.70 |
| eg10 | stump | 2 | 1177.3 | 395.0 | 11.37 | 0.77 | 0.51 | 1.29 | 0.65 |
| eg11 | 12" stump | 2 | 1314.9 | 310.9 | 8.88 | 1.02 | 0.71 | 1.74 | 0.73 |
| eg12 | 9" stump | 2 | 1447.4 | 219.2 | 12.98 | 1.00 | 0.81 | 1.82 | 0.81 |
| fm1 | 11 in stump | 2 | 1453 | 235 | 3.8 | | | | 0.80 |
| fm3 | 80% rotten 7 in log | 6 | 1404 | 263 | 5.8 | | | | 0.77 |
| fm5 | 90% rotten 5 in log | 6 | 1344 | 303 | 4.4 | | | | 0.74 |
| fm6 | rotten (70%) log | 6 | 1243 | 367 | 4.7 | | | | 0.68 |
| fm7 | large chunk-rotten (80%) wood | 6 | 1341 | 306 | 4.4 | | | | 0.74 |
| fm8 | 90% rotten 5 in log | 6 | 1238 | 367 | 7.0 | | | | 0.68 |
| fm9 | chunk rotten 9 in wood | 6 | 1350 | 289 | 10.6 | | | | 0.75 |
| fm10 | stump (50% rotten) | 7 | 1375 | 280 | 6.5 | | | | 0.76 |
| fm11 | 90% rotten 5 in log | 6 | 1542 | 169 | 9.1 | | | | 0.85 |
| hi1 | duff | 3 | 1343 | 305 | 3.8 | | | | 0.74 |
| hi2 | duff | 3 | 1387 | 277 | 3.9 | | | | 0.76 |
| hi3 | log end | 1 | 1375 | 263 | 16.4 | | | | 0.77 |
| hi4 | stump | 2 | 1352 | 295 | 6.6 | | | | 0.74 |
| hi5 | log | 1 | 1263 | 343 | 11.8 | | | | 0.70 |
| hi6 | log | 1 | 1302 | 304 | 19.7 | | | | 0.73 |
| hi7 | log | 1 | 1218 | 351 | 23.4 | | | | 0.69 |
| pi1 | stump | 2 | 1388 | 271 | 7.1 | | | | 0.77 |
| pi2 | 6 in log | 1 | 1239 | 363 | 8.6 | | | | 0.68 |
| pi3 | basal duff | 4 | 1401 | 271 | 2.3 | | | | 0.77 |
| pi4 | log | 1 | 1252 | 352 | 10.1 | | | | 0.69 |
| pi5 | log | 1 | 1487 | 184 | 21.0 | | | | 0.84 |
| pi6 | stump | 2 | 1380 | 247 | 23.9 | | | | 0.78 |
| pi7 | log | 1 | 1482 | 176 | 27.0 | | | | 0.84 |
| Average | | | 1338 | 296 | 10.5 | 1.06 | 0.74 | 1.80 | 0.74 |
| Standard Deviation | | | 93 | 63 | 7.6 | 0.74 | 0.51 | 1.23 | 0.05 |

Table A1-2. RSC Emission Factors and MCE in the West

| Site | Fuel Type | Fuel Code | $EFCO_2$ (g $kg^{-1}$) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | $EFC_2H_4$ (g $kg^{-1}$) | $EFC_3H_6$ (g $kg^{-1}$) | EFNMHC (g $kg^{-1}$) | MCE | Fuel Consumed (kg $m^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| bc-1 | large log | 1 | 1289 | 224 | 55.5 | 6.8 | 5.9 | 12.7 | 0.78 | |
| bc-2 | large log | 1 | 1462 | 200 | 15.9 | 2.4 | 1.9 | 4.3 | 0.82 | |
| bc-3 | 10"X24" wood | 1 | 1322 | 287 | 18.1 | 1.8 | 1.7 | 3.5 | 0.74 | 41.7 |
| bc-4 | duff tree | 4 | 1448 | 236 | 3.7 | 0.6 | 0.5 | 1.1 | 0.80 | 5.4 |
| bc-5 | stump | 2 | 1403 | 238 | 16.5 | 1.9 | 1.8 | 3.7 | 0.79 | 17.4 |
| bc-6 | woody end | 1 | 1431 | 245 | 4.8 | 0.6 | 0.4 | 1.0 | 0.79 | 18.6 |
| bc-7 | 9" rotten wood | 7 | 1430 | 229 | 12.3 | 1.7 | 1.1 | 2.8 | 0.80 | 17.7 |
| bc-8 | wood piece | 1 | 1356 | 283 | 9.7 | 1.1 | 0.8 | 1.8 | 0.75 | 10.7 |
| bc-9 | duff | 3 | 1442 | 235 | 6.0 | 0.8 | 0.7 | 1.4 | 0.80 | 9.8 |
| bc-10 | duff | 3 | 1545 | 163 | 8.5 | 1.3 | 1.3 | 2.6 | 0.86 | 4.8 |
| bc-11 | huge stump | 2 | 1287 | 310 | 16.8 | 2.2 | 1.8 | 4.0 | 0.73 | |
| bc-12 | woody pieces | 1 | 1426 | 242 | 8.7 | 0.6 | 0.5 | 1.2 | 0.79 | 10.6 |
| ke2 | Stump fragment | 2 | 1506 | 208 | | | | | 0.82 | 3.4 |
| ke3 | Stump | 2 | 1473 | 229 | | | | | 0.80 | 3.0 |
| ke4 | Stumphole | 2 | 1628 | 131 | | | | | 0.89 | 7.8 |
| ke5 | Small stump | 2 | 1638 | 124 | | | | | 0.89 | 10.9 |
| ke6 | Double stump | 2 | 1477 | 227 | | | | | 0.81 | 3.6 |
| ke7 | DF Duff | 3 | 1557 | 176 | | | | | 0.85 | 7.6 |
| ke8 | DF Duff | 3 | 1525 | 196 | | | | | 0.83 | 4.5 |
| ke9 | DF Duff | 3 | 1572 | 257 | | | | | 0.86 | 3.9 |
| ke10 | Stumphole | 2 | 1504 | 209 | | | | | 0.82 | 23.0 |
| ke11 | Stumphole | 2 | 1420 | 263 | | | | | 0.77 | 6.1 |
| ke12 | Stumphole | 2 | 1469 | 232 | | | | | 0.80 | 12.3 |
| lu1 | 18" stump | 2 | 1471 | 211 | 11.0 | | | | 0.82 | 7.6 |
| lu2 | log & small stump | 1 | 1535 | 174 | 8.8 | | | | 0.85 | 22.8 |
| lu3 | basal duff | 4 | 1454 | 216 | 14.4 | | | | 0.81 | 10.8 |
| lu4 | 1.5 ft. log | 1 | 1343 | 274 | 21.8 | | | | 0.76 | 0.7 |
| lu5 | stump | 2 | 1343 | 273 | 22.0 | | | | 0.76 | 39.0 |
| lu6 | large stump | 2 | 1375 | 254 | 21.5 | | | | 0.77 | 49.2 |
| lu7 | 2.5 ft. log | 1 | 1491 | 194 | 13.8 | | | | 0.83 | 1.5 |
| lu8 | basal duff | 4 | 1479 | 211 | 8.4 | | | | 0.82 | 2.6 |
| lu9 | rotten low stump | 7 | 1387 | 252 | 18.5 | | | | 0.78 | 23.7 |
| lu10 | 28" stump | 2 | 1316 | 305 | 13.8 | | | | 0.73 | 4.1 |
| lu11 | 28" stump | 2 | 1336 | 270 | 26.5 | | | | 0.76 | 13.8 |
| lu12 | stump | 2 | 1642 | 111 | 5.8 | | | | 0.90 | 5.1 |
| sl1 | Larch duff | 3 | 1452 | 224 | 8.4 | 1.1 | 1.0 | 2.0 | 0.80 | 10.7 |
| sl2 | Larch duff | 3 | 1390 | 250 | 15.5 | 1.6 | 0.8 | 2.4 | 0.78 | 10.9 |
| sl3 | Larch duff | 3 | 1393 | 248 | 14.7 | 1.5 | 1.6 | 3.2 | 0.78 | 3.4 |
| sl4 | Larch duff | 3 | 1395 | 255 | 11.9 | 0.8 | 0.6 | 1.4 | 0.78 | 11.9 |
| sl5 | Larch duff | 3 | 1407 | 258 | 6.0 | 0.7 | 0.5 | 1.2 | 0.78 | 5.0 |
| sl6 | Larch duff | 3 | 1415 | 238 | 14.0 | 1.0 | 0.8 | 1.8 | 0.79 | 6.9 |
| sl7 | Larch duff | 3 | 1433 | 221 | 16.0 | 1.7 | 1.3 | 3.0 | 0.81 | 2.4 |
| sl8 | Larch duff | 3 | 1433 | 201 | 22.9 | 3.6 | 3.5 | 7.1 | 0.82 | 1.4 |
| sl9 | Stump | 2 | 1530 | 168 | 11.9 | 1.1 | 1.0 | 2.1 | 0.85 | 16.9 |
| Average | | | 1446 | 226 | 14.7 | 1.6 | 1.4 | 3.1 | 0.80 | 11.5 |
| Standard Deviation | | | 87 | 44 | 9.3 | 1.4 | 1.3 | 2.6 | 0.04 | 11.0 |

Table A1-3. RSC Emission Factors and MCE in Alaska

| Site | Fuel Type | Fuel Code | $EFCO_2$ (g/kg) | EFCO (g/kg) | $EFCH_4$ (g/kg) | $EFC_2H_4$ (g/kg) | $EFC_3H6$ (g/kg) | EFNMHC (g/kg) | MCE |
|---|---|---|---|---|---|---|---|---|---|
| ek1 | duff/dead moss | 5 | | | | | | | |
| ek2 | duff/dead moss | 5 | 1385 | 251 | 10.6 | 4.36 | 3.31 | 4.36 | 0.78 |
| ek3 | duff/dead moss | 5 | 1442 | 240 | 4.00 | 0.54 | 0.52 | 0.54 | 0.79 |
| ek4 | duff/dead moss | 5 | 1464 | 225 | 4.37 | 0.41 | 0.35 | 0.41 | 0.81 |
| ek5 | duff/dead moss | 5 | 1412 | 256 | 5.71 | 0.67 | 0.49 | 0.67 | 0.78 |
| ek6 | duff/dead moss | 5 | 1424 | 246 | 7.04 | 0.78 | 0.55 | 0.78 | 0.79 |
| ek21 | duff/dead moss | 5 | 1507 | 204 | 1.59 | 0.31 | 0.27 | 0.31 | 0.82 |
| ek22 | duff/dead moss | 5 | 1443 | 225 | 11.0 | 1.09 | 0.90 | 1.09 | 0.80 |
| ek23 | duff/dead moss | 5 | 1474 | 207 | 10.8 | 0.91 | 0.60 | 0.91 | 0.82 |
| ek24 | duff/dead moss | 5 | 1478 | 206 | 9.92 | 0.82 | 0.65 | 0.82 | 0.82 |
| ek25 | duff/dead moss | 5 | 1449 | 397 | 11.1 | 1.41 | 1.14 | 1.41 | 0.80 |
| ek26 | duff/dead moss | 5 | 1425 | 246 | 6.62 | 0.75 | 0.55 | 0.75 | 0.79 |
| clf1 | duff/dead moss | 5 | 1433 | 238 | 7.38 | 1.02 | 0.88 | 1.02 | 0.79 |
| clf2 | duff/dead moss | 5 | 1431 | 238 | 7.48 | 1.20 | 1.16 | 1.20 | 0.79 |
| clf3 | duff/dead moss | 5 | 1402 | 247 | 12.0 | 1.87 | 1.44 | 1.87 | 0.78 |
| clf4 | duff/dead moss | 5 | 1404 | 252 | 9.39 | 1.40 | 1.19 | 2.59 | 0.78 |
| clf5 | duff/dead moss | 5 | 1457 | 219 | 9.27 | 1.33 | 1.02 | 2.36 | 0.81 |
| clf6 | duff/dead moss | 5 | 1390 | 248 | 14.93 | 2.11 | 1.75 | 2.11 | 0.78 |
| Average | | | 1436 | 244 | 8.4 | 1.23 | 0.99 | 1.37 | 0.80 |
| Standard Deviation | | | 33 | 43 | 3.4 | 0.94 | 0.72 | 1.03 | 0.02 |

## Appendix 2. Emission Factors and MCE by Fuel Component

Table A2-1. RSC Emission Factors and MCE for Woody Fuels

| Site | Fuel Type | Fuel Code | $EFCO_2$ (g $kg^{-1}$) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | $EFC_2H_4$ (g $kg^{-1}$) | $EFC_3H_6$ (g $kg^{-1}$) | EFNMHC (g $kg^{-1}$) | MCE |
|---|---|---|---|---|---|---|---|---|---|
| bc-1 | large log | 1 | 1289 | 224 | 55.5 | 6.77 | 5.90 | 12.67 | 0.78 |
| bc-12 | woody pieces | 1 | 1426 | 242 | 8.7 | 0.64 | 0.52 | 1.16 | 0.79 |
| bc-2 | large log | 1 | 1462 | 200 | 15.9 | 2.44 | 1.90 | 4.34 | 0.82 |
| bc-3 | 10"X24" wood | 1 | 1322 | 287 | 18.1 | 1.75 | 1.73 | 3.48 | 0.74 |
| bc-6 | woody end | 1 | 1431 | 245 | 4.8 | 0.58 | 0.43 | 1.01 | 0.79 |
| bc-8 | wood piece | 1 | 1356 | 283 | 9.7 | 1.07 | 0.78 | 1.85 | 0.75 |
| eg2 | log | 1 | 1442 | 201 | 23.0 | 2.06 | 1.70 | 3.76 | 0.82 |
| eg7 | stump&log | 1 | 1474 | 187 | 19.9 | 2.07 | 1.56 | 3.63 | 0.83 |
| hi3 | log end | 1 | 1375 | 263 | 16.4 | | | | 0.77 |
| hi5 | log | 1 | 1263 | 343 | 11.8 | | | | 0.70 |
| hi6 | log | 1 | 1302 | 304 | 19.7 | | | | 0.73 |
| hi7 | log | 1 | 1218 | 351 | 23.4 | | | | 0.69 |
| lu2 | log & small stump | 1 | 1535 | 174 | 8.8 | | | | 0.85 |
| lu4 | 1.5 ft. log | 1 | 1343 | 274 | 21.8 | | | | 0.76 |
| lu7 | 2.5 ft. log | 1 | 1491 | 194 | 13.8 | | | | 0.83 |
| pi2 | 6 in log | 1 | 1239 | 363 | 8.6 | | | | 0.68 |
| pi4 | log | 1 | 1252 | 352 | 10.1 | | | | 0.69 |
| pi5 | log | 1 | 1487 | 184 | 21.0 | | | | 0.84 |
| pi7 | log | 1 | 1482 | 176 | 27.0 | | | | 0.84 |
| Average | | | 1378 | 255 | 17.8 | 2.17 | 1.81 | 3.99 | 0.77 |
| Standard Deviation | | | 100 | 65 | 11.1 | 1.98 | 1.75 | 3.73 | 0.06 |

Table A2-2. RSC Emission Factors and MCE for Stump

| Site | Fuel Type | Fuel Code | $EFCO_2$ (g $kg^{-1}$) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | $EFC_2H_4$ (g $kg^{-1}$) | $EFC_3H_6$ (g $kg^{-1}$) | EFNMHC (g $kg^{-1}$) | MCE |
|---|---|---|---|---|---|---|---|---|---|
| bc-11 | huge stump | 2 | 1287 | 310 | 16.8 | 2.17 | 1.84 | 4.00 | 0.73 |
| bc-5 | stump | 2 | 1403 | 238 | 16.5 | 1.92 | 1.78 | 3.70 | 0.79 |
| eg10 | stump | 2 | 1177 | 395 | 11.4 | 0.77 | 0.51 | 1.29 | 0.65 |
| eg11 | 12" stump | 2 | 1315 | 311 | 8.9 | 1.02 | 0.71 | 1.74 | 0.73 |
| eg12 | 9" stump | 2 | 1447 | 219 | 13.0 | 1.00 | 0.81 | 1.82 | 0.81 |
| eg3 | stump | 2 | 1193 | 357 | 24.3 | 2.54 | 1.32 | 3.86 | 0.67 |
| eg5 | stump | 2 | 1265 | 342 | 9.5 | 0.78 | 0.53 | 1.31 | 0.70 |
| fm1 | 11 in stump | 2 | 1453 | 235 | 3.8 | | | | 0.80 |
| hi4 | stump | 2 | 1352 | 295 | 6.6 | | | | 0.74 |
| ke10 | Stumphole | 2 | 1504 | 209 | | | | | 0.82 |
| ke11 | Stumphole | 2 | 1420 | 263 | | | | | 0.77 |
| ke12 | Stumphole | 2 | 1469 | 232 | | | | | 0.80 |
| ke2 | Stump fragment | 2 | 1506 | 208 | | | | | 0.82 |
| ke3 | Stump | 2 | 1473 | 229 | | | | | 0.80 |
| ke4 | Stumphole | 2 | 1628 | 131 | | | | | 0.89 |
| ke5 | Small stump | 2 | 1638 | 124 | | | | | 0.89 |
| ke6 | Double stump | 2 | 1477 | 227 | | | | | 0.81 |
| lu1 | 18" stump | 2 | 1471 | 211 | 11.0 | | | | 0.82 |
| lu10 | 28" stump | 2 | 1316 | 305 | 13.8 | | | | 0.73 |
| lu11 | 28" stump | 2 | 1336 | 270 | 26.5 | | | | 0.76 |
| lu12 | stump | 2 | 1642 | 111 | 5.8 | | | | 0.90 |
| lu5 | stump | 2 | 1343 | 273 | 22.0 | | | | 0.76 |
| lu6 | large stump | 2 | 1375 | 254 | 21.5 | | | | 0.77 |
| pi1 | stump | 2 | 1388 | 271 | 7.1 | | | | 0.77 |
| pi6 | stump | 2 | 1380 | 247 | 23.9 | | | | 0.78 |
| sl9 | Stump | 2 | 1530 | 168 | 11.9 | 1.08 | 0.99 | 2.08 | 0.85 |
| Average | | | 1415 | 248 | 14.1 | 1.41 | 1.06 | 2.47 | 0.78 |
| Standard Deviation | | | 123 | 69 | 7.0 | 0.69 | 0.53 | 1.17 | 0.06 |

Table A2-3. RSC Emission Factors and MCE for Duff

| Site | Fuel Type | Fuel Code | $EFCO_2$ (g/kg) | EFCO (g/kg) | $EFCH_4$ (g/kg) | $EFC_2H_4$ (g/kg) | $EFC_3H_6$ (g/kg) | EFNMHC (g/kg) | MCE |
|---|---|---|---|---|---|---|---|---|---|
| bc-10 | duff | 3 | 1545 | 163 | 8.5 | 1.29 | 1.34 | 2.63 | 0.86 |
| bc-9 | duff | 3 | 1442 | 235 | 6.0 | 0.79 | 0.65 | 1.44 | 0.80 |
| hi1 | duff | 3 | 1343 | 305 | 3.8 | | | | 0.74 |
| hi2 | duff | 3 | 1387 | 277 | 3.9 | | | | 0.76 |
| ke7 | DF Duff | 3 | 1557 | 176 | | | | | 0.85 |
| ke8 | DF Duff | 3 | 1525 | 196 | | | | | 0.83 |
| ke9 | DF Duff | 3 | 1572 | 257 | | | | | 0.86 |
| sl1 | Larch duff | 3 | 1452 | 224 | 8.4 | 1.07 | 0.97 | 2.04 | 0.80 |
| sl2 | Larch duff | 3 | 1390 | 250 | 15.5 | 1.56 | 0.80 | 2.36 | 0.78 |
| sl3 | Larch duff | 3 | 1393 | 248 | 14.7 | 1.54 | 1.63 | 3.17 | 0.78 |
| sl4 | Larch duff | 3 | 1395 | 255 | 11.9 | 0.80 | 0.61 | 1.40 | 0.78 |
| sl5 | Larch duff | 3 | 1407 | 258 | 6.0 | 0.70 | 0.54 | 1.24 | 0.78 |
| sl6 | Larch duff | 3 | 1415 | 238 | 14.0 | 1.00 | 0.79 | 1.79 | 0.79 |
| sl7 | Larch duff | 3 | 1433 | 221 | 16.0 | 1.66 | 1.33 | 2.98 | 0.81 |
| sl8 | Larch duff | 3 | 1433 | 201 | 22.9 | 3.58 | 3.49 | 7.07 | 0.82 |
| Average | | | 1446 | 234 | 11.0 | 1.40 | 1.21 | 2.61 | 0.80 |
| Standard Deviation | | | 70 | 38 | 5.8 | 0.84 | 0.88 | 1.70 | 0.04 |

Table A2-4. RSC Emission Factors and MCE for Basal Duff

| Site | Fuel Type | Fuel Code | $EFCO_2$ (g $kg^{-1}$) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | $EFC_2H_4$ (g $kg^{-1}$) | $EFC_3H_6$ (g $kg^{-1}$) | EFNMHC (g $kg^{-1}$) | MCE |
|---|---|---|---|---|---|---|---|---|---|
| bc-4 | duff tree | 4 | 1448 | 236 | 3.7 | 0.57 | 0.52 | 1.09 | 0.80 |
| eg1 | basal duff | 4 | 1294 | 337 | 2.8 | 0.44 | 0.30 | 0.73 | 0.71 |
| eg4 | basal duff | 4 | 1239 | 367 | 5.4 | 0.68 | 0.42 | 1.10 | 0.68 |
| eg6 | basal duff | 4 | 1281 | 344 | 3.5 | 0.44 | 0.32 | 0.75 | 0.70 |
| eg8 | basal duff | 4 | 1259 | 359 | 2.7 | 0.57 | 0.38 | 0.95 | 0.69 |
| eg9 | basal duff | 4 | 1275 | 349 | 2.5 | 0.39 | 0.31 | 0.70 | 0.70 |
| lu3 | basal duff | 4 | 1454 | 216 | 14.4 | | | | 0.81 |
| lu8 | basal duff | 4 | 1479 | 211 | 8.4 | | | | 0.82 |
| pi3 | basal duff | 4 | 1401 | 271 | 2.3 | | | | 0.77 |
| Average | | | 1348 | 299 | 5.1 | 0.52 | 0.37 | 0.89 | 0.74 |
| Standard Deviation | | | 96 | 65 | 4.0 | 0.11 | 0.09 | 0.18 | 0.06 |

Table A2-5. RSC Emission Factors and MCE for Duff and Dead Moss in Alaska

| Site | Fuel Type | Fuel Code | $EFCO_2$ (g kg-1) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | $EFC_2H_4$ (g $kg^{-1}$) | $EFC_3H_6$ (g $kg^{-1}$) | EFNMHC (g $kg^{-1}$) | MCE |
|---|---|---|---|---|---|---|---|---|---|
| clf1 | duff/dead moss | 5 | 1433 | 238 | 7.4 | 1.02 | 0.88 | 1.02 | 0.79 |
| clf2 | duff/dead moss | 5 | 1431 | 238 | 7.5 | 1.20 | 1.16 | 1.20 | 0.79 |
| clf3 | duff/dead moss | 5 | 1402 | 247 | 12.0 | 1.87 | 1.44 | 1.87 | 0.78 |
| clf4 | duff/dead moss | 5 | 1404 | 252 | 9.4 | 1.40 | 1.19 | 2.59 | 0.78 |
| clf5 | duff/dead moss | 5 | 1457 | 219 | 9.3 | 1.33 | 1.02 | 2.36 | 0.81 |
| clf6 | duff/dead moss | 5 | 1390 | 248 | 14.9 | 2.11 | 1.75 | 2.11 | 0.78 |
| ek1 | duff/dead moss | 5 | | | | | | | |
| ek2 | duff/dead moss | 5 | 1385 | 251 | 10.6 | 4.36 | 3.31 | 4.36 | 0.78 |
| ek21 | duff/dead moss | 5 | 1507 | 204 | 1.6 | 0.31 | 0.27 | 0.31 | 0.82 |
| ek22 | duff/dead moss | 5 | 1443 | 225 | 11.0 | 1.09 | 0.90 | 1.09 | 0.80 |
| ek23 | duff/dead moss | 5 | 1474 | 207 | 10.8 | 0.91 | 0.60 | 0.91 | 0.82 |
| ek24 | duff/dead moss | 5 | 1478 | 206 | 9.9 | 0.82 | 0.65 | 0.82 | 0.82 |
| ek25 | duff/dead moss | 5 | 1449 | 397 | 11.1 | 1.41 | 1.14 | 1.41 | 0.80 |
| ek26 | duff/dead moss | 5 | 1425 | 246 | 6.6 | 0.75 | 0.55 | 0.75 | 0.79 |
| ek3 | duff/dead moss | 5 | 1442 | 240 | 4.0 | 0.54 | 0.52 | 0.54 | 0.79 |
| ek4 | duff/dead moss | 5 | 1464 | 225 | 4.4 | 0.41 | 0.35 | 0.41 | 0.81 |
| ek5 | duff/dead moss | 5 | 1412 | 256 | 5.7 | 0.67 | 0.49 | 0.67 | 0.78 |
| ek6 | duff/dead moss | 5 | 1424 | 246 | 7.0 | 0.78 | 0.55 | 0.78 | 0.79 |
| Average | | | 1436 | 244 | 8.4 | 1.23 | 0.99 | 1.37 | 0.80 |
| Standard Deviation | | | 33 | 43 | 3.4 | 0.94 | 0.72 | 1.03 | 0.02 |

Table A2-6. RSC Emission Factors and MCE for Rotten Wood

| Site | Fuel Type | Fuel Code | $EFCO_2$ (g $kg^{-1}$) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | $EFC_2H_4$ (g $kg^{-1}$) | $EFC_3H_6$ (g $kg^{-1}$) | EFNMHC (g $kg^{-1}$) | MCE |
|---|---|---|---|---|---|---|---|---|---|
| fm11 | 90% rotten 5 in log | 6 | 1542 | 169 | 9.1 | | | | 0.85 |
| fm3 | 80% rotten 7 in log | 6 | 1404 | 263 | 5.8 | | | | 0.77 |
| fm5 | 90% rotten 5 in log | 6 | 1344 | 303 | 4.4 | | | | 0.74 |
| fm6 | rotten (70%) log | 6 | 1243 | 367 | 4.7 | | | | 0.68 |
| fm7 | large chunk-rotten (80%) wood | 6 | 1341 | 306 | 4.4 | | | | 0.74 |
| fm8 | 90% rotten 5 in log | 6 | 1238 | 367 | 7.0 | | | | 0.68 |
| fm9 | chunk rotten 9 in wood | 6 | 1350 | 289 | 10.6 | | | | 0.75 |
| Average | | | 1352 | 295 | 6.6 | | | | 0.74 |
| Standard Deviation | | | 103 | 68 | 2.5 | | | | 0.06 |

Table A2-7. RSC Emission Factors and MCE for Rotten Stump

| Site | Fuel Type | Fuel Code | $EFCO_2$ (g $kg^{-1}$) | EFCO (g $kg^{-1}$) | $EFCH_4$ (g $kg^{-1}$) | $EFC_2H_4$ (g $kg^{-1}$) | $EFC_3H_6$ (g $kg^{-1}$) | EFNMHC (g $kg^{-1}$) | MCE |
|---|---|---|---|---|---|---|---|---|---|
| bc-7 | 9" rotten wood | 7 | 1430 | 229 | 12.3 | 1.68 | 1.15 | 2.83 | 0.80 |
| fm10 | stump (50% rotten) | 7 | 1375 | 280 | 6.5 | | | | 0.76 |
| lu9 | rotten low stump | 7 | 1387 | 252 | 18.5 | | | | 0.78 |
| Average | | | 1397 | 254 | 12.4 | 1.68 | 1.15 | 2.83 | 0.78 |
| Standard Deviation | | | 29 | 26 | 6.0 | | | | 0.02 |