Forest Floor Consumption and Smoke Characterization in Boreal Forested Fuelbed Types of Alaska

Final Report
JFSP Project #03-1-3-08
May 25, 2007

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Jim Cronan observing forest floor consumption on the Porcupine Fire in Alaska

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ABSTRACT

The Fire and Environmental Research Applications Team (PNW Research Station) and the Fire Chemistry Project (RM Research Station) have completed the data collection and modeling for fuel consumption and smoke emissions during wildland fires in boreal forested types in Alaska. Forest floor reduction was measured at 24 black and white spruce and birch-aspen sites on 8 wildfires during the 2003 and 2004 fire season. Emissions were measured at 5 wildfires which included 8 of the sites where forest floor consumption was measured. A robust forest floor reduction equation was developed, as well as a set of emission factors for particulate matter, CO, CO_2, CH_4, NMHC. The double parameter forest floor consumption equation uses upper forest floor fuel moisture content and preburn forest floor depth as independent variables. Fuel moisture content of the upper forest floor can be obtained from forest floor samples that are collected, oven dried, and weighed to determine gravimetric fuel moisture content. Preburn forest floor depths require onsite measurements to be collected.

The fuel consumption models and emission factors have been incorporated into Consume version 3.0 (http://www.fs.fed.us/pnw/fera/research/smoke/consume/) which estimates fuel consumption and emissions and was developed with support from the JFSP (Project #98-1-9-06). The models and their implementation into Consume 3.0 are the principle science delivery products for the Rapid Response Joint Fire Science Program-funded project "Forest Floor Consumption and Smoke Characterization in Boreal Forested Fuelbed Types of Alaska" (Project #03-1-3-08).

Fuel consumption models and emission factors developed during this study enable Consume v 3.0 to predict the amount of fuel consumption, emissions, and heat release from the burning of forest floor material during wildland fires in Alaska and other boreal forest regions. Using these predictions, resource managers can determine when and where to conduct a prescribed burn or plan for a wildland fire for use to achieve desired objectives while reducing impacts on other resources.

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Introduction

Fire is recognized as an essential natural process in Alaska, and managers are increasingly expected to use fire as a landscape-level fuel treatment mechanism to improve ecosystem health and wildlife habitat, as well as to reduce the likelihood of catastrophic fires

(Foote 1983, Vierick and Dyrness 1979, Vanderlinden 1996, Boucher 2003). To complete this task, the public has required managers to improve their decision-making processes and use science-based predictive models to meet various regulatory requirements. One of the most critical regulatory requirements is smoke management. Many areas of the boreal forest of Alaska contain deep layers (12+ inches) of moss, duff, and peat, resulting in a large pool of biomass that potentially can burn and smolder for long periods of time. Ground fires in boreal forests can create hazardous smoke episodes for local residents and communities and can also cause undesirable landscape impacts (Vierick and Dyrness 1979, Viereck and Schandelmeier 1980). Research to quantify fuel consumption, flammability thresholds, and smoke production in boreal forest types is critical for effective modeling of fire effects (e.g., smoke emissions, regional haze, carbon accounting, permafrost melting, erosion, and plant succession). Successful landscape management including prescribed burning and wildland fire use depends on reliable fire effects models. Because fuel consumption is one of the key variables to all fire effects including smoke generation, it is imperative scientists develop a forest floor consumption model and refine smoke emission factors for use in fuel consumption, fire effects, fire severity, emission production, and dispersion models that are more applicable to the boreal forest types.

On the average, more than 3 million acres are burned annually (in 2004 alone, over 6 million acres burned) during wildland fires in Alaska, generating thousands of tons of pollutants including CO_2, CO, CH_4, and NMHC, and particulate matter. These pollutants can have widespread impacts on human health, visibility, and regional haze (Barney and Berglund 1974, Ottmar and Sandberg 2003). The pollutants are a direct result of the inefficient combustion of forest fuels including tree crowns, shrub stems, leaves, dead woody debris, litter, and deep forest floor layers composed of lichen, moss, peat, and duff. Although the consumption of the tree crowns, shrub layer, downed woody material, and litter can be a significant source of pollutants, they often represent less than 20 percent of the total fuel available for consumption in the boreal forest ecosystem (Ottmar and Vihnanek 1998). The forest floor has the greatest potential for emitting large masses of pollutants because it may reach depths in excess of 12 inches, resulting in over 100 tons per acre of potentially consumable biomass (Ottmar and Sandberg 2003). In addition, most of the forest floor is consumed during the smoldering phase when combustion efficiency is low and smoke generation is high (Ottmar and Sandberg 2003, Hardy et al. 2001).

Although smoke emitted from burning moss and duff is a major concern, there are other problems associated with the consumption of organic forest floor. The combustion and heat produced during the smoldering period can result in substantial effects on other resources. The removal of the forest floor may melt permafrost, damage soil, increase erosion, and change plant successional patterns (Viereck and Schandelmeier 1980).

Fuel Consumption

There has been a considerable amount of forest floor consumption research completed for understory and clearcut burns in the lower 48 states (Norum 1977, Sandberg 1980, Ottmar et al. 1985, Brown et al. 1991). However, the unique lichen, moss, and duff forest floors typical of the boreal forests of Alaska have received little attention. Viereck and Dyrness (1979) burned four small units at a site near Fairbanks. They observed that the forest floor reduction from the fire was not dependent on consumption of the woody material. Dyrness and Norum (1983) burned seven 2-hectare units between July 19 and August 8, 1978, over a range of conditions typical of most fire seasons in Alaska. Preburn forest floor depth, lower moss (dead moss), fuel moisture, and lower duff moisture were the variables used in regressions to predict forest floor reduction. Lawson et al. (1997) developed a probability curve relating probability of sustained smoldering ignition of the forest floor as a function of duff moisture content. Miyanishi and Johnson (2002) found a positive relationship between duff consumption and moisture content and depth in mixed wood forests of Canada. A small study was carried out in Alaska over the past 10 years by the Fire and Environmental Research Applications Team and results indicate a strong relationship between forest floor consumption, moisture content, and fuelbed depth which shows promise for building predictive models for consumption (Ottmar and Sandberg 2003).

Emissions

Emissions from wildland fires have been measured extensively since about 1970 in contiguous United States. The result is a relatively complete set of emission factors for criteria pollutants and many hazardous air pollutants for most important fuel types (Ward et al. 1989, Environmental Protection Agency 1996, Andreae and Merlot 2001, Hardy et al. 2001, Battye and Battye 2002). Less complete compilations of emission factors are available for emissions in the boreal forest type where deep layers of forest floor and organic matter can consume and smolder for days, weeks and months. This proposal enabled the Fire Chemistry Project to measure emissions during active wildfires in Alaska, providing the knowledge needed to better predict emissions from boreal forest fires.

Project Objectives

The four primary objectives of the boreal forest wildfire study were to:

- Develop a model that predicts forest floor consumption.
- Provide modified combustion efficiency (MCE) for residual smoldering.
- Determine emission factors of major smoldering emission species.
- Determine the rate of carbon release and estimated total fuel consumption for residual smoldering combustion.

In completing this project, we surpassed our original objectives by collecting more data than originally proposed and across a fuel moisture range rarely observed in Alaska. The fuel consumption model and emission factors are implemented into Consume 3.0 (JFSP Project #98-1-9-06) which supports a large number of clients including BlueSky, Fire Effects Tradeoff Model (FETM), Fire Emissions Production Simulator (FEPS), and the Fuel Analysis, Smoke Tracking, and Report Access Computer System (FASTRACS). This research makes Consume 3.0 and other fuel consumption, fire effects, and smoke production models more robust by account for boreal forest fuelbed types, thereby aiding managers, planners, and researchers in developing environmentally, socially, and legally responsible land management plans. This knowledge enables a more effective and informed use of emission production and wildfire/prescribed fire trade-off models which provide improved wildland fire emissions and carbon accounting in the Alaska boreal forest types, and at other local, regional, and global scales.

Tasks

This project was divided into seven major task items:

(1) Coordination and study design
(2) Field data collection and analysis
(3) Data reduction and analysis
(4) Discussion and recommendations
(5) Implementation into Consume 3.0 software
(6) Science documentation
(7) Training

Each task is addressed separately in this section.

Coordination and Study Design

The project was discussed with land managers, scientists and the Alaska Wildland Fire Coordinating Group's science team in May 2003. The BLM Alaska Fire Service, National Park Service, and U.S. Fish and Wildlife Service gave full support to the project and offered Randi Jandt (BLM-AFS) and Jake Dollard (BLM-AFS) as liaisons between the Alaska Wildland Fire Coordinating Group agencies and fire teams. We obtained additional support from several fire ecologists including Jennifer Allen (NPS), and Karen Murphy (FWS). During the coordinating phase an agreement was reached, supplying the project with: (1) in-kind helicopter support; (2) housing, meals, and fire dispatch; (3) logistical support, and (4) training. Two scientists, 2 foresters, and 3 forestry technicians from the Fire and Environmental Research Applications Team were red carded at the arduous level and were on call for dispatch starting on June 1, 2003. The Air Chemistry Group from the Missoula Fire Lab also had five red-carded personnel that were on call. All participates received bear safety training and other pertinent fire and safety training.

Although a sampling technique for measuring fuel consumption and collecting independent variables has been refined over the years from earlier efforts by FERA, improvements were made. An extensive synthesis of the literature and consultations with scientists, other experts and land managers were used to design the study that included protocols for measuring forest floor consumption, monitoring and sampling smoke and collecting weather, fuel moisture, and other independent variables.

Field Data Collection and Analysis

The Fire and Environmental Research Applications Team (FERA) of the Pacific Northwest Research Station's Pacific Wildland Fire Sciences Laboratory, and the Fire Chemistry Project of the Rocky Mountain Research Station's Fire Laboratory, led an aggressive field effort to gather fuel consumption and emissions data on active wildfires in Alaska during the 2003 and

2004 fire season.

Study Area

The study area included all black and white spruce forested areas of Alaska. During the 2003 fire season, field efforts were concentrated on three wildfires: the Erickson Creek wildfire along the Dalton Highway fifty miles northwest of Fairbanks; the Chena Lakes wildfire 10 miles east of Fairbanks; and the Black Hills wildfire, 50 miles east of Tok. During the 2004 fire season we concentrated our efforts on five wildfires including the Chicken, Porcupine, Wall Street, Kings Creek, and Gardiner wildfires 50 to 100 miles north and east of Tok (fig. 1).

Forest Floor Consumption

Forest floor consumption was measured at 24 black spruce and white spruce forested sites on U.S. Fish and Wildlife Service, Alaska State Department of Natural Resources, and Bureau of Land Management sites during 8 wildfires occurring in Alaska in 2003 and 2004 (table 1). Figure 2 displays a higher resolution map with the location of plots inventoried and plots burned on the Porcupine, Chicken, Wall Street, and Gardiner wildfires in 2004.

Forest floor reduction was measured as the dependent variable according to procedures adapted from Beaufait et al. (1977; table 2). Nine to 18 permanent plots were established in an area in front of an active wildfire (fig. 3). Within each plot, 16 forest floor pins were inserted 1.5 feet apart into the forest floor, clipped flush with the lichen, moss, or duff surface around each plot (figs. 4 and 5). Because the forest floor is often very deep, lightweight welding rod >60 cm in length was used as forest floor reduction pins.

Several possible independent variables were measured (table 2). One forest floor plug about 6 inches square down to mineral soil was collected near each permanent plot (fig. 6). Depths of live moss, dead moss, upper duff, and lower duff layers were measured. Each plug was then separated into live moss, dead moss, upper duff, and lower duff layers, and placed into a labeled and sealed plastic bags. To determine fuel moisture, all samples were oven dried at 70 °C for 96 hours and weighed before and after drying. We also collected shrub and grass moisture content samples (fig. 7). Weather data collected before the burn at each site included temperature, wind speed, and relative humidity.

Following the fire front, each plot was relocated, and the depth of the burn was measured at each forest floor reduction pin (fig. 8). A measurement from the top of the pin to mineral soil provided a total forest floor depth.

To develop predictive equations, forest floor reduction was calculated with a regression analysis on several independent variables using SPlus. The data analysis was used to generate coefficients for theoretical and empirical fuel consumption model design for implementation into Consume 3.0 (Prichard et al. 2006).

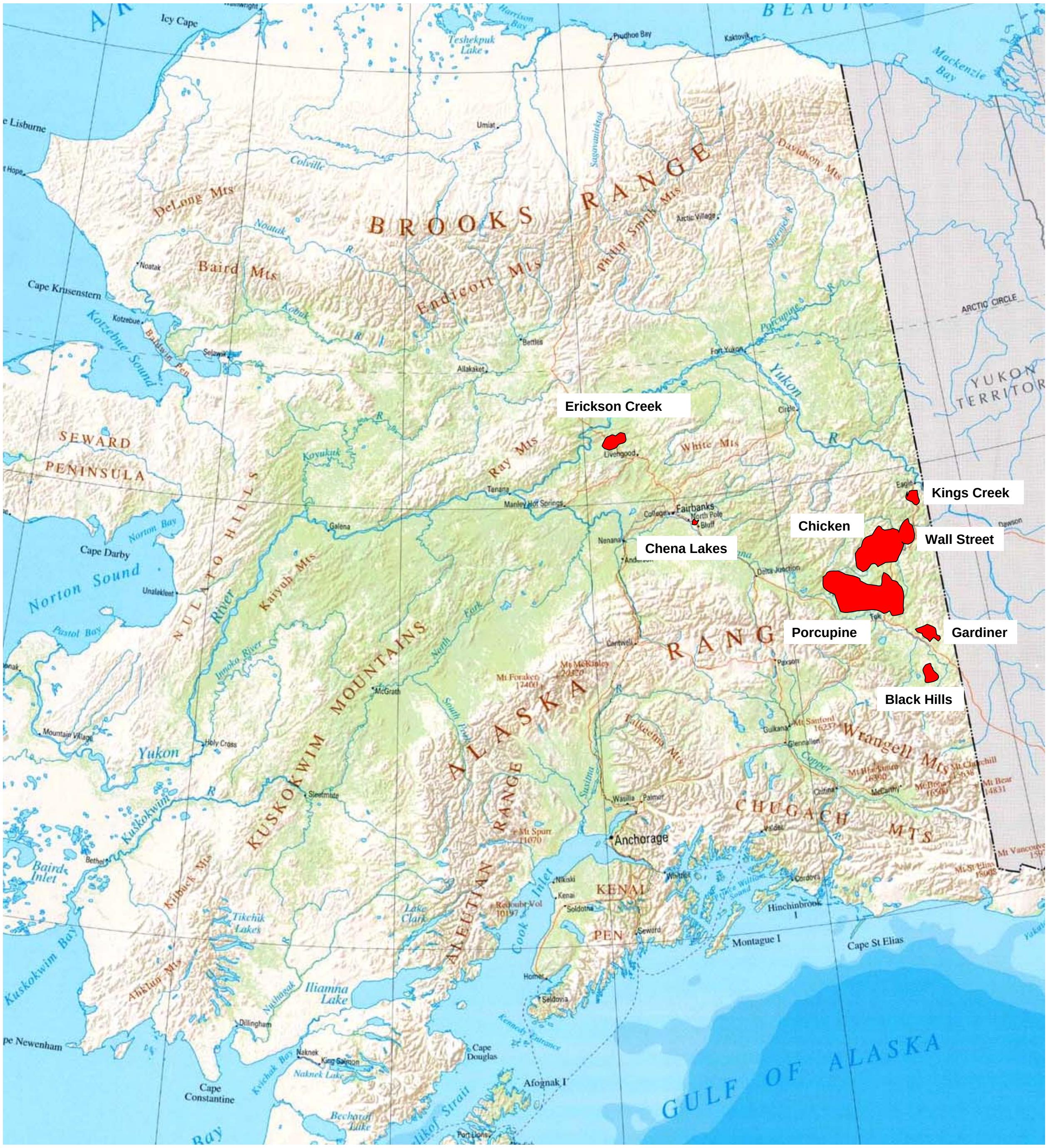


Figure 1. Wildfire locations sampled for forest floor consumption and smoke during 2003 and 2004.

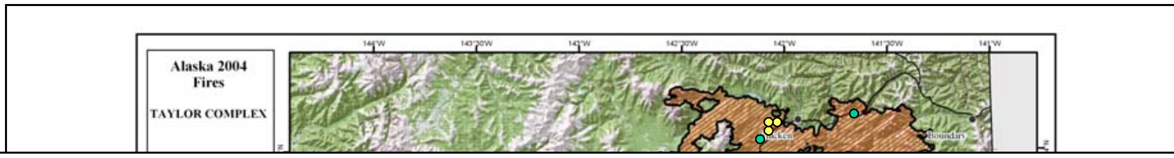
Table 1. Wildfire fuel consumption sites ordered by burn date.

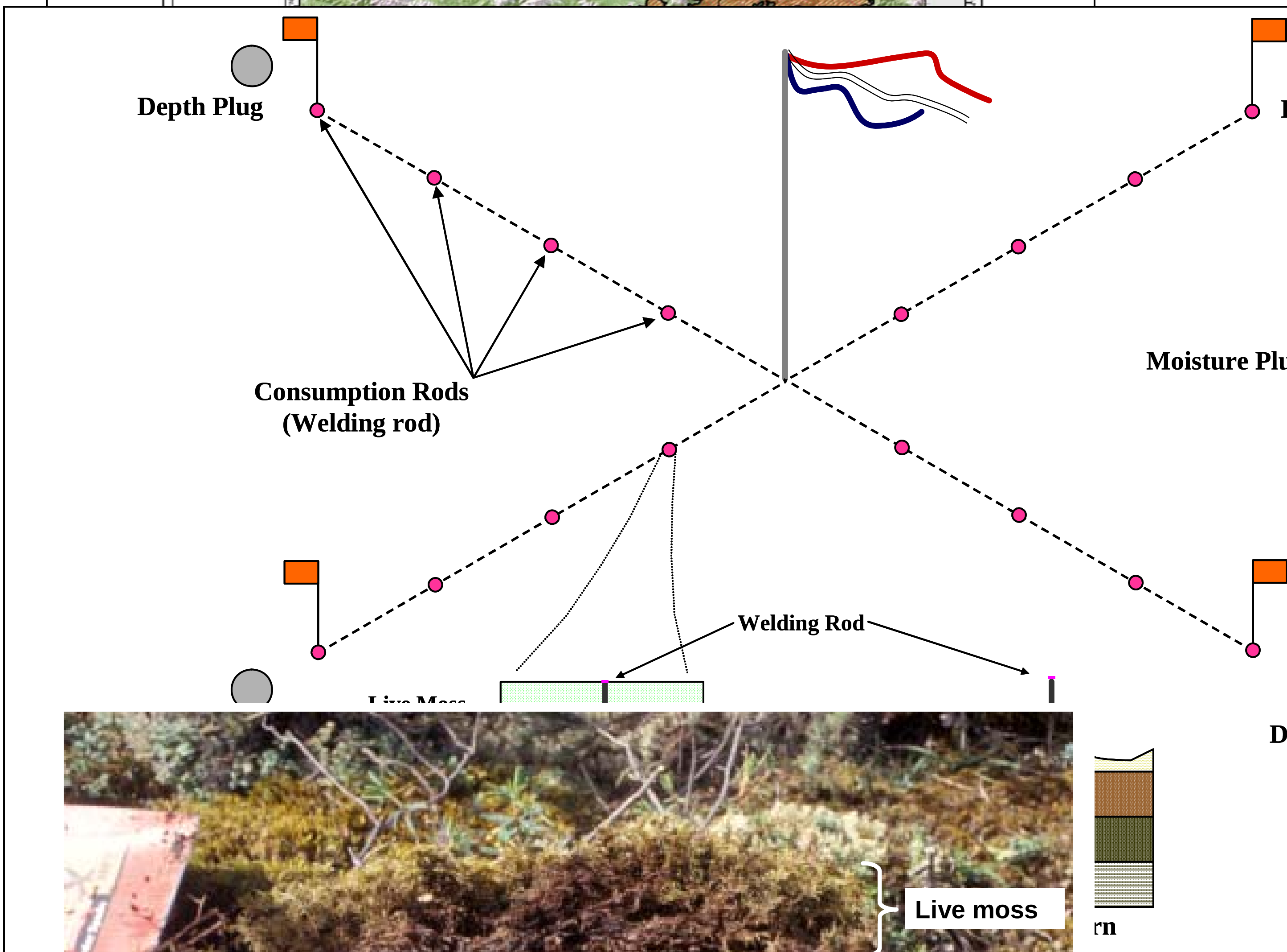
Unit Name	Wildfire Name	Plot Set-Up Date	Burn Date	Forest Floor Consumption Monitoring	Emission Sampling
Erickson Creek A	Erickson Creek	June 21, 2003	June 21, 2003	Yes	Yes
Erickson Creek B	Erickson Creek	June 22, 2003	June 22, 2003	Yes	Yes
Chena Lakes	Chena Lake	June 20, 2003	June 24, 2003	Yes	Yes
Erickson Creek D	Erickson Creek	June 30, 2003	June 30, 2003	Yes	No
Erickson Creek E	Erickson Creek	July 1, 2003	July 1, 2003	Yes	No
Black Hills	Black Hills	August 2, 2003	August 2, 2003	Yes	No
Chicken 04	Chicken	June 23, 2004	June 23, 2004	Yes	Yes
Chicken 05	Chicken	June 24, 2004	June 25, 2004	Yes	No
Chicken 06	Chicken	June 25, 2004	June 25, 2004	Yes	No
Porcupine 01	Porcupine	June 26, 2004	June 27, 2004	Yes	No
Wall Street 01	Wall Street	June 24, 2004	June 27, 2004	Yes	No
Porcupine 02	Porcupine	June 27, 2004	June 29, 2004	Yes	Yes
Porcupine 04	Porcupine	June 29, 2004	June 29, 2004	Yes	Yes
Porcupine 05	Porcupine	June 28, 2004	June 29, 2004	Yes	No
Porcupine 06	Porcupine	June 30, 2004	June 30, 2004	Yes	No
King Creek 01	Kings Creek	July 12, 2004	July 12, 2004	Yes	No
King Creek 02	Kings Creek	July 12, 2004	July 12, 2004	Yes	Yes
Porcupine 10	Porcupine	July 15, 2004	July 15, 2004	Yes	No
Porcupine 11	Porcupine	July 15, 2004	July 15, 2004	Yes	No
Porcupine 12	Porcupine	July 16, 2004	July 16, 2004	Yes	Yes

Porcupine 13	Porcupine	July 16, 2004	July 16, 2004	Yes	No
Porcupine 14	Porcupine	August 25, 2004	August 25, 2004	Yes	No
Gardiner 02	Gardiner	August 27, 2004	August 27, 2004	Yes	No
Gardiner 03	Gardiner	August 27, 2004	August 27, 2004	Yes	No

Table 2. Forest floor consumption trial methods. Independent variables were selected as the most likely variables to influence forest floor consumption. Adapted from Beaufait et al. 1977.

Fuelbed Type	**Independent Variables**	**Method**	**Dependent Variable**	**Method**
Boreal forest	Pre-fire live moss, dead moss, upper duff, and lower duff depth	Pre-fire forest floor inventory with 9-18 plots; forest floor depth measurement	Forest floor reduction	200-300 forest floor pins
	Moisture content	Litter and duff		
	Weather (relative humidity, temperature, days since rain, wind speed)	Weather station or belt weather kit		





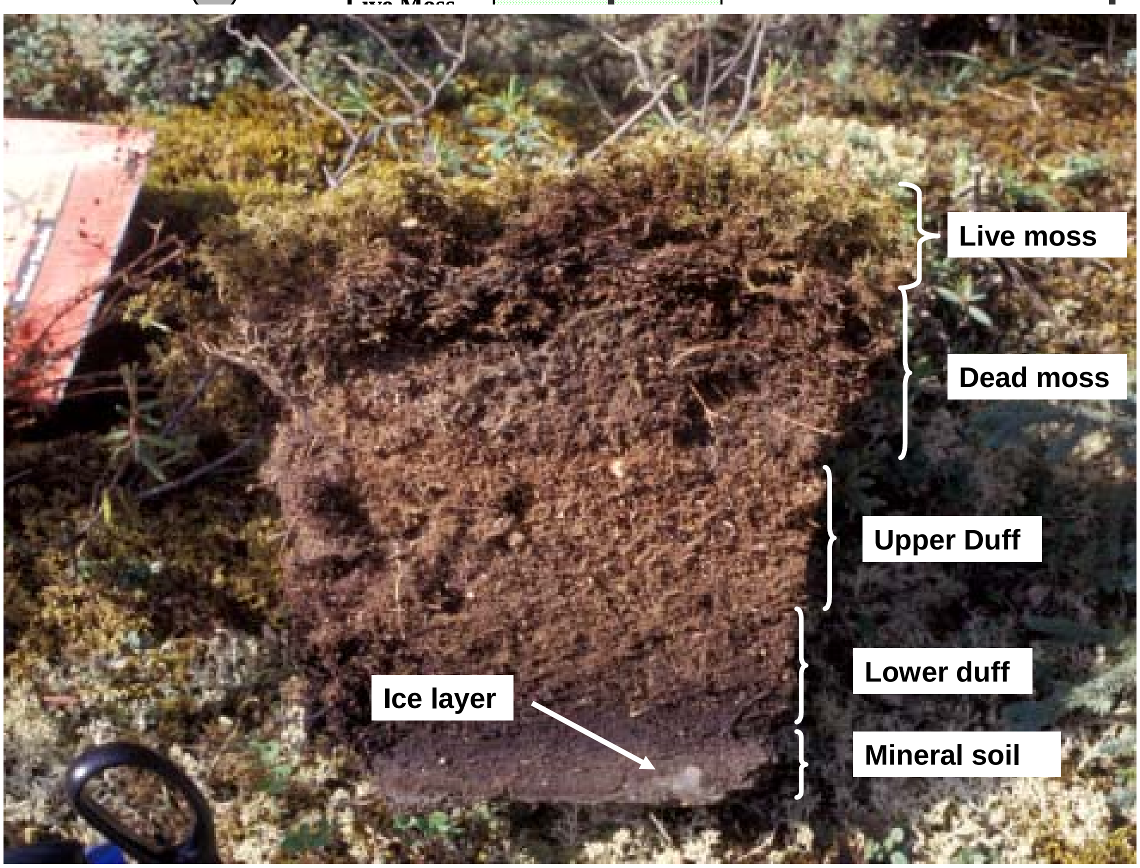


Figure 6. A forest floor moisture plug was collected near each plot. Moisture content was determined for the live moss, dead moss, upper and lower duff. Thickness of each layer was also measure. Note the ice layer at the bottom of the plug

Figure 7. Collecting shrub moisture content samples in front of the active fire front on the Porcupine wildland fire.

Figure 8. Measuring forest floor consumption.

Emissions Sampling

The fire atmosphere sampling system (FASS) (Ward et al. 1992, Hao et al. 1996*a*) was used to collect canister and filter samples and to record temperature, wind speed, CO and CO_2 during the flaming stage as the flaming front passed (figs. 9 and 10). FASS towers were set up a few hours before the flaming front passed by. FASS instrument boxes were set in shallow depressions made on the wet surface and covered with fire shelter material. Ambient air or smoke was drawn from the top of 30-foot high towers. Emissions were collected in 850-ml canisters pressurized to 25 psi. The sample head at the top of the tower contained inlets for the gases as well as cyclone samplers where the aerosols were collected on filters. A set of anemometers to measure air flow in three directions were mounted just below the sample head as was a thermocouple. The sampling times for these fires were set to 5 minutes flaming, 7 minutes intermediate and 10 minutes smoldering. Canisters of background air were collected at each tower before the fire came through.

A portable sample chamber was placed over the fuels to capture trace gases emitted during the smoldering stage following the passage of the flaming front of the wildfire (figs. 9 and 11). This system consisted of two main components: a sample chamber and a backpack containing gas sampling instruments to capture the emissions from smoldering fuels. The sample chamber was a 1m x 1m x 1m aluminum frame made of ½” (outside diameter [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 was attached to the top of the chamber. A small battery-powered fan was housed on the top inside of the chamber to improve mixing the 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 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 300-ml glass bottles. The backpack could hold up to12 sample bottles. The data logger recorded site identification information, time, battery voltage, temperature from a type K thermocouple, CO_2 sample pressure, and real-time CO_2 level. The sample chamber was briefly placed over the smoldering fuel plot during the duration of residual smoldering combustion. A sampling period lasted about 1-3 minutes each time, depending on the rate of increase of CO_2 concentrations in the chamber. In addition, bottle samples of CO_2 were taken from the sample chamber at intervals ranging from 30 seconds to 5 minutes. The rate of CO_2 increase was substantially higher during the early sample times than the rate of increase as the hours progressed and residual smoldering combustion (RSC) slowed down.

At each fire site, four to six plots were selected and staked out at the start of sampling. The objective was to begin taking RSC samples as soon as possible to characterize the initial smoldering rates. Each plot was then revisited, in the same order each time and at intervals of one to four hours. Background samples of the ambient air were collected periodically as well.

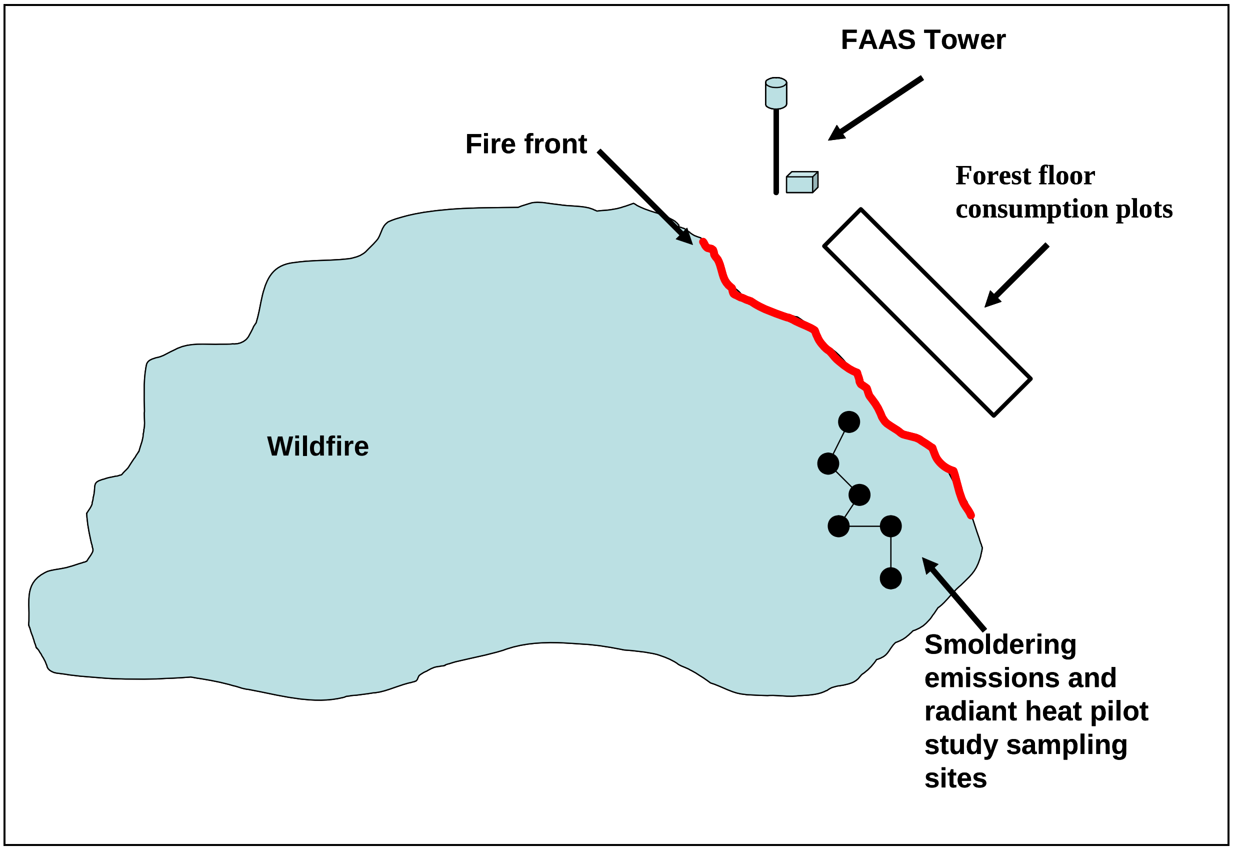


Figure 9. Location of FAAS tower, and the smoldering emissions and radiant heat pilot study sampling areas, in relationship to forest floor consumption plots and active fire front.

Figure 10. FAAS tower on the Chicken fire.

Figure 11. Fire Chemistry Project crew personnel sampling smoldering emissions on the Porcupine fire following the fire front.

Air samples collected in the bottles and canisters were analyzed at the Analytical Chemistry Laboratory of the Fire Sciences Laboratory for CO_2, CO, CH_4, and C_2- C_3 aliphatic compounds using a Hewlett Packard model 5890 Series II gas chromatograph. The CO_2 and CO analysis were performed using 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^{o}C. 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 flame ionization detector at 300^o C. The oven temperature program for this analysis was 30^{o}C for 6 min, increasing by 10^o C min^{-1} to reach the final temperature of 90^{o}C.

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, sample concentrations were calculated from the standard curves and written into an Excel spreadsheet.

Emission factors (EF) for CO_2, CO, CH_4, and NMHC were calculated for residual smoldering combustion using the carbon mass balance method (Ward and Radke 1993). The rate of combustion was computed based on the exponential decrease of the emission rate of carbon-containing compounds with time. The emission rate was derived by the changes of concentrations of carbon-containing compounds with time in the sample chamber for each sample plot. A series of "instantaneous" consumption rates measured over time for the smoldering fuel was used to calculate the overall fuel consumption rate and the amount of fuel consumed. This exponentially declining consumption rate is used by modelers to determine fuel consumption and total emissions at any point from the onset of residual smoldering combustion. In the general form, it is expressed as:

$$dC/dt = \mathrm{A}e^{-kt}$$

where A is the y-intercept and is the rate at time zero (the initial rate), k is the decay constant and t is some time from the start of RSC. In general, the initial rate, A, is heavily dependent on the total fuel available, while the value of k usually depends on the type of fuel and environmental factors affecting the combustion. Values for total fuel consumed and the time constant 1/k, (the time when about 63% of the fuel has been consumed) can be calculated once the exponential decay rate is known. As t goes to infinity, e^{-kt} approaches zero, so a good estimate of the total fuel consumption is given by:

$$\text{Fuel consumption}_{\,total} = 2\mathrm{A} / k$$

By combining total fuel consumption estimates with emission factors it is possible to estimate total emissions quantities per square meter for long-term RSC on these sites.

Data Reduction and Analysis

Forest Floor Consumption

Preburn forest floor depth, upper and lower duff moisture content, and forest floor reduction are presented in table 3. The moisture content of the upper duff layer ranged from 167 percent during the Erickson Creek wildfire in late June to 60 percent on the Gardiner wildfire in late August. The lower duff moisture content ranged from 319 percent on the Wall Street wildfire late in June to around 60 percent on the Porcupine and Gardiner fires in mid-July and late August. Preburn forest floor depths ranged from 5 to nearly 11 inches. Forest floor reduction ranged from 7 inches on the Porcupine wildfire in late August to 2.27 inches on the Wall Street wildfire in late June 2004.

The wide range of moisture contents during the 2004 fire season was extremely rare and provided the opportunity to develop a very robust forest floor consumption data set (fig. 12). In late spring and early summer, the ice layer which formed during the winter months on the forest

Table 3. Summary of moisture content, preburn duff depth, and forest floor reduction for each plot.

Unit Name	Date Burned	Unit Abbreviation	Upper Duff Moisture Content (%)	Lower Duff Moisture Content (%)	Preburn Forest Floor Depth (inches)	Forest Floor Reduction (inches)
Erickson Creek A	June 21, 2003	ECA	154.5	262.3	8.86	2.42
Erickson Creek B	June 22, 2003	ECB	167.0	254.6	9.54	4.90
Chena Lakes	June 24, 2003	CL	129.6	270.2	10.61	3.74
Erickson Creek D	June 30, 2003	ECD	140.7	273.9	9.34	2.37
Erickson Creek E	July 01, 2003	ECE	236.0	298.0	8.85	2.63
Black Hills	Aug. 02, 2003	BH	106.3	199.4	7.72	6.01
Chicken 04	June 23, 2004	C4	147.5	317.8	8.44	3.07
Chicken 05	June 25, 2004	C5	108.1	253.1	7.21	3.68
Chicken 06	June 25, 2004	C6	81.5	137.5	7.60	4.43
Porcupine 01	June 27, 2004	P1	101.6	236.7	8.04	4.23
Wall Street 01	June 27, 2004	W1	141.6	318.7	8.18	2.28
Porcupine 02	June 29, 2004	P2	92.2	208.4	7.45	2.80
Porcupine 04	June 29, 2004	P4	97.5	106.7	7.80	5.23
Porcupine 05	June 29, 2004	P5	100.0	142.5	8.86	5.80
Porcupine 06	June 30, 2004	P6	75.1	176.4	7.29	3.29
King Creek 01	July 12, 2004	K1	73.4	73.8	3.40	2.27
King Creek 02	July 12, 2004	K2	77.3	85.5	4.94	3.86
Porcupine 10	July 15, 2004	P10	113.5	80.1	6.75	4.84
Porcupine 11	July 15, 2004	P11	82.0	82.1	5.42	3.96
Porcupine 12	July 16, 2004	P12	68.2	62.9	4.43	4.11
Porcupine 13	July 16, 2004	P13	73.2	59.8	3.80	3.58
Porcupine 14	Aug. 25, 2004	P14	83.1	161.6	9.94	7.23
Gardiner 02	Aug. 27, 2004	G02	60.7	60.7	6.11	4.30
Gardiner 03	Aug. 27, 2004	G03	76.5	78.6	7.16	5.20

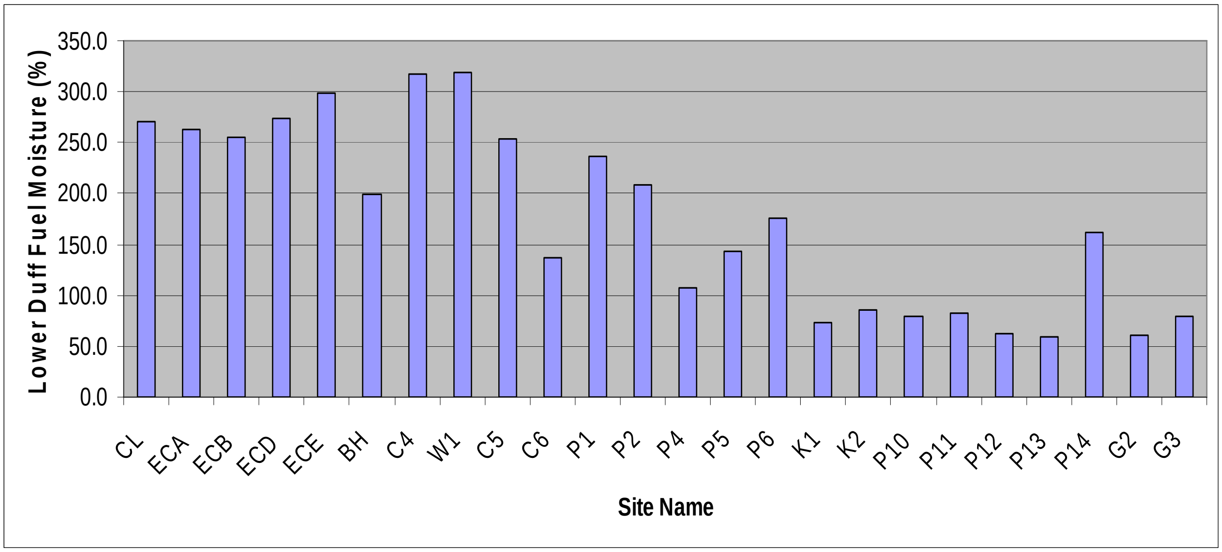


Figure 12. Lower duff fuel moisture content measured for each unit of the study. See table 3 for a key to abbreviations of the site names.

floor begins to melt and the upper layers become ice free. In late June, the upper layers of the mineral soil become ice free and moisture from the forest floor begins to drain. Rapid drying occurs on the forest floor unless rainfall occurs. The 2004 fire season was very dry late in July and August, providing an opportunity to measure forest floor consumption under low fuel moisture contents.

Forest floor consumption generally increased as moisture content decreased and forest floor depth increased. Forest floor consumption for boreal forest fuelbed types in Alaska were predicted by pre-burn forest floor depth and lower duff moisture content. Forest floor depth is important for determining total consumption. Moisture content of the upper duff is the major heat sink, determining total amount of forest floor that will consume. The fuel moisture content of the lower forest floor can be obtained from forest floor samples that are collected, oven dried, and weighed to determine gravimetric fuel moisture content. Preburn forest floor depths require onsite measurements to be collected or using a fuelbed from the Fuel Characteristic Classification System (JFSP Project #98-1-1-06). The equation is summarized in table 4 with the fitted results fig. 13. Further detail is given in the scientific documentation section of the Consume v 3.0 User's Guide (Prichard et al. 2006).

Table 4. Fuel reduction algorithm for forest floor. All loading and consumption units are in tons per acre. Proportion deviance explained refers to the proportion of the null deviance of the consumption data explained by the modeled equation.

Fuelbed Category	Consumption Equation	Sample size (n)	Proportion of Deviation Explained (R^2)	Applicable Region
Total forest floor	Proportion FF Reduction (%/100) = 0.9161 – 0.0020 x Lower Duff FM	24	0.8135	Boreal

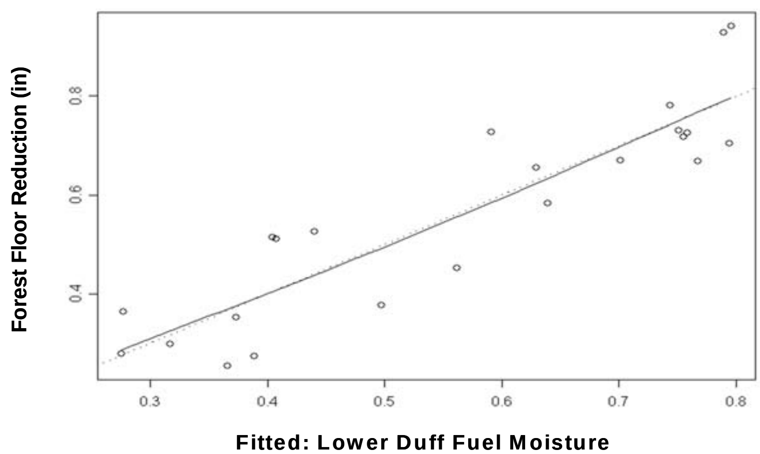


Figure 13. Response variable vs fitted Boreal forest regression model.

Emissions

Comparisons of total CO and CH_4, NMHC, and $PM_{2.5}$ from the FASS tower fire sampling in 2004 are displayed in **figs. 14, 15 and 16.** Carbon monoxide is a good predictor of other fire emission products, and useful in emissions models where CO concentration can be measured or estimated. The plot of CH_4 vs. CO (fig. 14) shows a characteristically high r^2 value for these gases that has been observed for most prescribed and wildland fires measured in the contiguous United States. A similar relationship with CO is also produced for non-methane hydrocarbons, in this study (fig. 15). The r^2 value of 0.98 indicates that variation in CO concentration highly predicts NMHC concentration.

The r^2 for $PM_{2.5}$ vs. CO is also a high 0.87 (fig 16). This is higher than is generally observed on prescribed and wildfires in the contiguous United States (Ward and Radke 1993). This may be due to the wide range of conditions that occurs in the phases of a high intensity crown fire, producing a range of values that result in a highly correlated linear function. More data from boreal fire experiments may demonstrate that CO is an effective predictor of $PM_{2.5}$, for these fires.

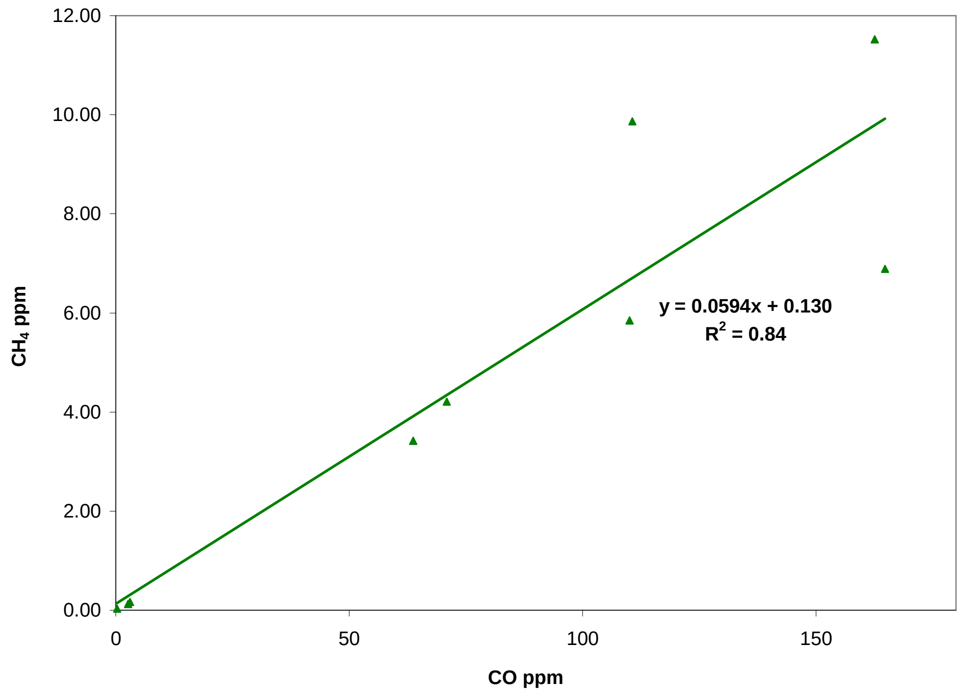


Figure 14. CH_4 vs. CO for FASS canister samples collected during the Chicken and Porcupine 1 fires.

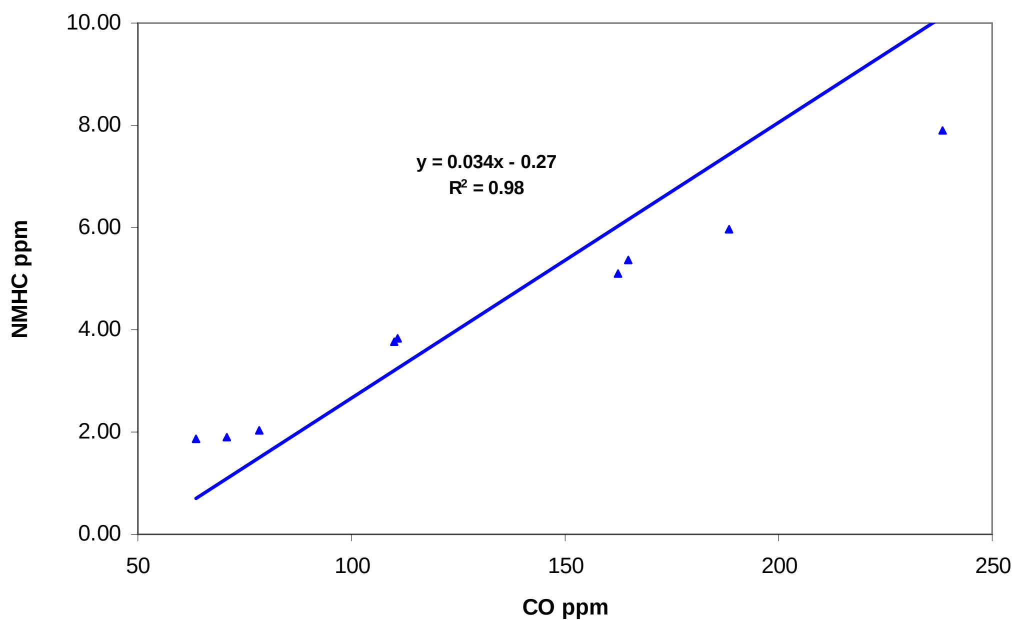


Figure 15. NMHC (non-methane hydrocarbons) vs. CO for FASS canister samples collected during the Chicken, and Porcupine 1 fires.

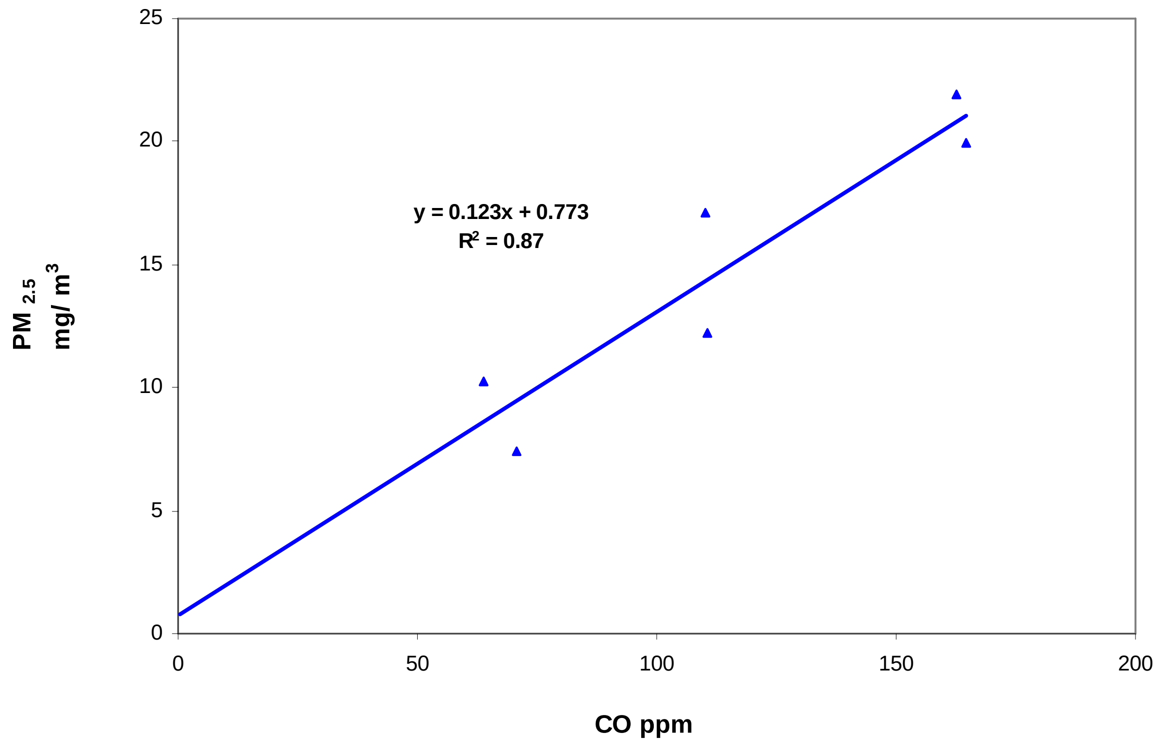


Figure 16. $PM_{2.5}$ vs. CO for Chicken and Porcupine 1 fires.

Flaming emission factors during the passage of the fire front for wildfires sampled in 2004 are presented in table 5. These can be considered representative crown fire emission factors for Alaska boreal forest. The sample towers were directly in the path of the fire as it burned and the high intensity crown fire tested the heat resistance of the sample towers and ground packages (fig. 17). These emission factors can be considered applicable for use in Alaska and other boreal forest sites where emission factors are required as model inputs. The emission factors and MCE values are quite consistent among the three samples.

Table 5. Emission factors for crown fires from the FASS tower canisters during the flaming (F), intermediate (I), and smoldering (S) phases. The averaged weighted emission factors (WEF) for each fire follow the individual phase emission factors. The Modified Combustion Efficiency (MCE) is also presented. NS is no sample collected.

			EFCO_2	**EFCO**	**EFCH_4**	**EFNMHC**	**EF$PM_{2.5}$**	**MCE**
Fire	**Date**	**Phase**	- - - - - - - - - - - - - *g/kg* - - - - - - - - - - - - -					*ratio*
Chicken	6/24/2004	F	1692	68.4	2.08	2.66	5.59	0.940
		I	1612	108.1	4.38	3.94	7.65	0.905
		S	1515	155.5	7.92	6.39	9.02	0.861
		WEF	1616	105.0	4.39	4.06	7.23	0.906
Porcupine 1-1	6/26/2004	F	1734	50.3	1.20	1.83	3.19	0.956
		I	1642	92.6	2.84	3.07	7.82	0.919
		S	1509	165.7	5.62	5.18	9.08	0.853
Porcupine 1-2	6/26/2004	F	1681	82.2	2.66	3.14	1.83	0.929
		I	1553	156.3	6.23	5.84	NS	0.863
		S	1535	168.1	5.94	5.15	0.57	0.853
		WEF	1671	86.0	2.72	3.05	2.97	0.925

Figure 17. FASS tower instrument package burned during the King Creek wildfire.

The crown fire flaming emission factors for the Chicken and Porcupine 1-1 and 1-2 sites were very similar (table 5) and are similar to those measured in previous work done in pine forests in Montana, Arizona, and Oregon (Hardy et al. 2001). Flaming phase Modified Combustion Efficiency (MCE) values for these fires were in the range of 0.90 to 0.95. One difference that was noted however, is that emission factors for pine fires were in the range of 8 to 24 mg/m^3, whereas the boreal forest values were much lower and in a range of 0.6 to 9.1 mg/m^3. This may be a significant indicator or characteristic of crown fire.

The smoldering emission factors reported in table 5 are for short term smoldering- shortly after cessation of flaming phase and the MCE range from 0.85 to 0.86. The MCEs reported in table 6 are for longer term smoldering phase emission factors and are 0.81 or less. The short term smoldering phase produces a lower quantity of atmospheric pollutants compared to longer duration and lower combustion efficiency of the longer term smoldering phase.

The residual smoldering emission factors for the 2003 fires are given in table 6. The Chena Lake site had higher emission factors for CH_4 and NMHC than the two Erickson sites, although they all had very similar CO emission factors (240 to 247 g/kg). In comparison with emission factors from previous RSC studies in the western and southeast United States (table 7), the Alaska boreal forest MCE had lower MCE values. This may be an indication of different fuel moistures or a difference in the smoldering characteristics of the boreal forest fuels, mainly in the duff layer.

During the 2004 wildfires, a strong positive linear relationship between CH_4 and CO (r^2 of 0.70) and NMHC and CO (r^2 of 0.67) for residual smoldering combustion (rsc) was noted (figures 18 and 19). This indicates that CO can be used as a good predictor of these other compounds for residual smoldering combustion in Alaska. Almost all previous work has reported a strong linear correlation between CO, CH_4 and NMHC for flaming and short-duration smoldering phases (Hao and Ward 1993, Hao et al. 1996*a* and **b**, Yokelson et al. 2003).

Table 6. Residual smoldering combustion emission factors of the 2003 fires in Alaska.

Fire	**Date**	**EFCO_2**	**EFCO**	**EFCH_4**	**EFC_2H_4**	**EFC_3H_6**	**EFNMCH**	**MCE**
		- - - - - - - - - - - - - - - - *g/kg* - - - - - - - - - - - - - - - -						*Ratio*
Erickson Wildfire	6/22/03	1425	244	6.3	1.35	1.04	1.35	0.79
Erickson 2 Wildfire	6/22/03	1463	247	8.5	0.88	0.69	0.88	0.81
Chena Lake	6/25/03	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**
Standard deviation		**33**	**43**	**3.4**	**0.94**	**0.72**	**1.03**	**0.02**

Table 7. Emission factors and MCE values of residual smoldering combustion for common smoldering fuel types in the southeastern and western U.S., measurements made in 2002 to 2004 as part of RSC study by Fire Chemistry Project for JFSP.

Fuelbed component	**EFCO_2**	**EFCO**	**EFCH_4**	**EFC_2H_4**	**EFC_3H_6**	**EFNMHC**	**MCE**
	- - - - - - - - - - - - - - - - *(g/kg)* - - - - - - - - - - - - - - - -						*Ratio*
Stumps	1415	248	14.1	1.41	1.06	2.47	0.78
Duff	1446	234	11.0	1.40	1.21	2.61	0.80
Basal duff	1348	299	5.1	0.52	0.37	0.89	0.74
Rotten wood	1352	295	6.6				0.74
Rotten stump	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**

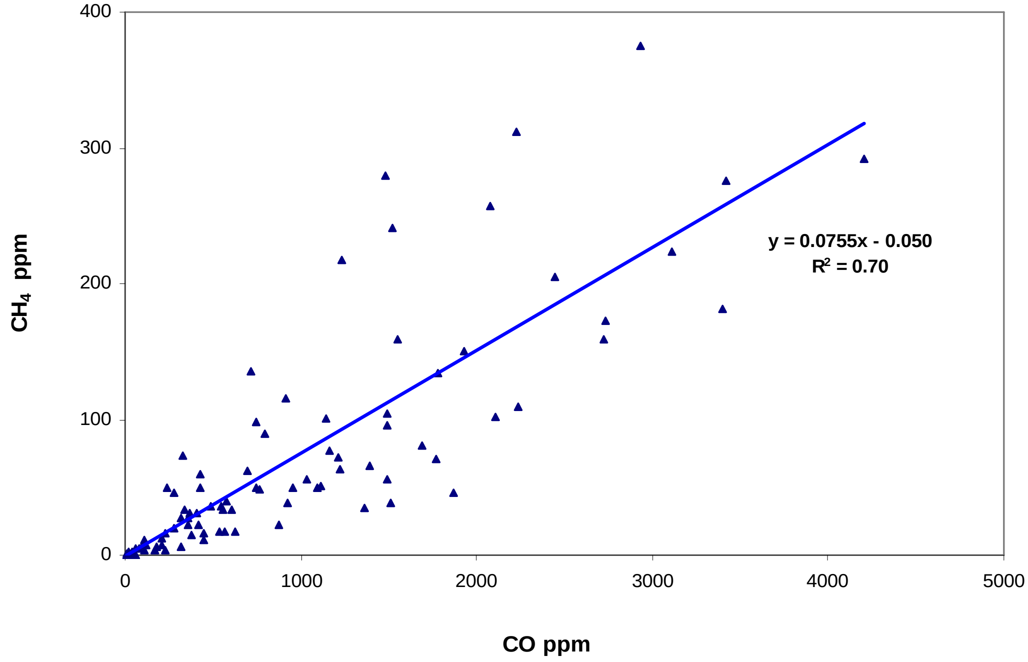


Figure 18. CH_4 vs.CO concentration for residual smoldering combustion samples collected at the 2004 Alaska fires.

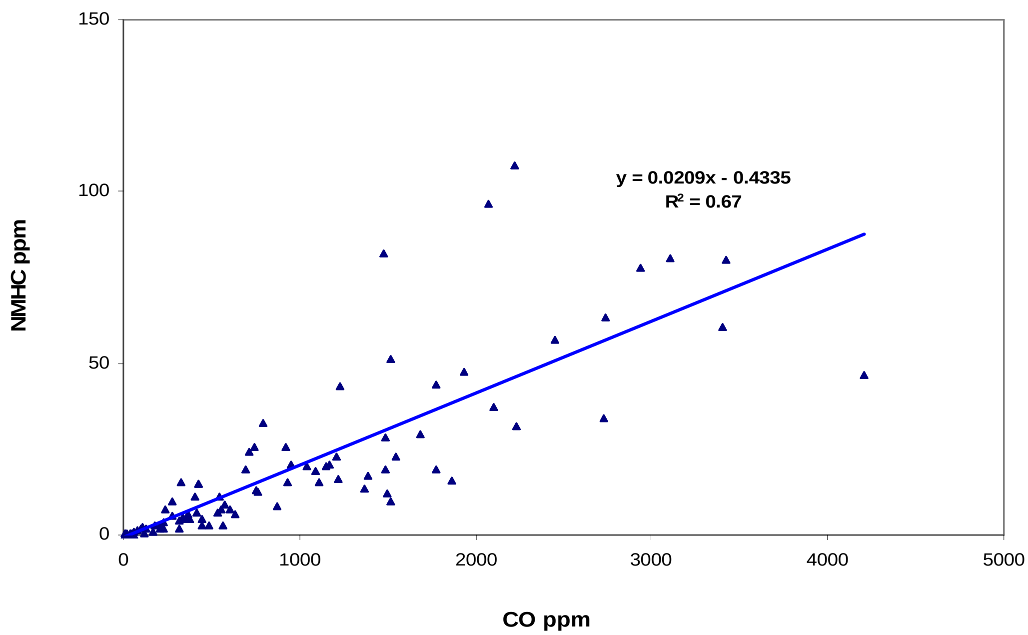


Figure 19. NMHC (non-methane hydrocarbons) vs. CO concentration for residual smoldering combustion samples collected at the 2004 Alaska fires.

Table 8 shows a summary of some 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 **a and b**). The Alaska data presented in the table 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 8. Emission factors of flaming and short-duration smoldering combustion by regions of U.S.

Region	**Phase**	**EFCO_2**	**EFCO**	**EFCH_4**	**EFNMHC**	**EFPM2.5**	**MCE**
		g/kg					*ratio*
Southeast U.S.	Flaming	1681	73	2.0	2.4	11.7	0.94
	Short-duration smoldering	1618	108	3.1	4.0	11.6	0.90
Western U.S.	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 wildfires	Mixed (aircraft)	1660	89	2.8	2.3		0.92

Smoldering emission factors and MCE for the 2004 fires are given in table 9. The average modified combustion efficiency value (MCE) was 0.79 for 2004 (table 9) and 0.80 for 2003 (table 6). These MCE values are lower than those measured in the southeast and western U.S. for smoldering fuels such as forest floor and large pieces of wood.

For the fires sampled in 2004, the Alaska RSC MCE (table 9) is significantly lower than the average flaming and short-duration smoldering MCE from the southeast, western United States, and Alaska wildfires sampled by aircraft (table 8). The average short-duration smoldering EFCO and CH_4 for the southeast and western U.S., respectively, are significantly lower than measured in Alaska during the 2003 and 2004 wildfire season.

Table 9. Residual smoldering emission factors for the 2004 Alaska RSC fires.

		Emission Factors									
		CO_2	**CO**	**CH_4**	**C_2H_4**	**C_2H_2**	**C_2H_6**	**C_3H_6**	**C_3H_8**	**C_3H_4**	**MCE**
Fire	**Date**	*g/kg*									*ratio*
Chicken	6/25/04	1354	288	5.91	1.77	0.07	2.53	1.90	1.35	0.18	0.75
Porcupine 1	6/27/04	1435	228	8.60	2.29	0.09	4.09	2.83	2.33	0.31	0.80
Porcupine 2	6/29/04	1399	245	12.56	2.22	0.10	4.21	2.14	1.92	0.30	0.78
King Creek 2	7/12/04	1330	296	9.41	1.79	0.29	3.57	1.78	1.80	0.27	0.74
Porcupine 12	7/16/04	1584	131	9.32	2.43	0.07	4.83	2.85	2.30	0.70	0.88
Average		**1420**	**237**	**9.16**	**2.10**	**0.12**	**3.85**	**2.30**	**1.94**	**0.35**	**0.79**

Figure 20 displays the set of carbon release curves for the six plots measured on the Chicken wildfire (6/25/04). All six display a characteristic exponential decay curve. This exponentially declining consumption rate is used by modelers to determine fuel consumption and total emissions at any point from the onset of RSC. In general, the initial rate, A, is proportional to the total fuel available, while the value of *k* usually indicative of the type of fuel and environmental factors affecting the combustion. In Plot 1 of figure 20, the RSC consumption rate at time *t* is $2489.3e^{-.5651t}$, where the initial rate is 2489.3 and the *k* value is -0.5651. It can be seen from the curves that the rate of carbon release declined rapidly between 10 and 15 hours after initiation of the residual smoldering phase.

Table 10 presents the fuel consumption components for all plots measured during the 2004 Alaska wildfires. The exponential decay constant *k* is calculated from each sample plot curve. Values for total fuel consumed and the time constant (the time when 63% of the fuel has been consumed) can be calculated from once the exponential decay rate is known. For the Alaska fires there is a range of variation for initial fuel consumption (Y), slope (*k*), and total fuel consumed. Factors such as quantity and type of fuel, fuel moisture, and ignition characteristics are likely to contribute to these variations. The R^2 value was high for most plots, indicating that the exponential decay is a good model of the RSC fuel consumption. The Porcupine 2 fire had the lowest decay rates (*k*), and resulting highest averaged time constant of 17.1 hours. The other time constants ranged from 2.9 hours for the chicken fire to 9.2 hours for the Porcupine 12 fire. The average total fuel consumption estimate based on the emissions rate was for the all fires, 3721 g/m^2, with an associated standard deviation of 2324 g/m^2.

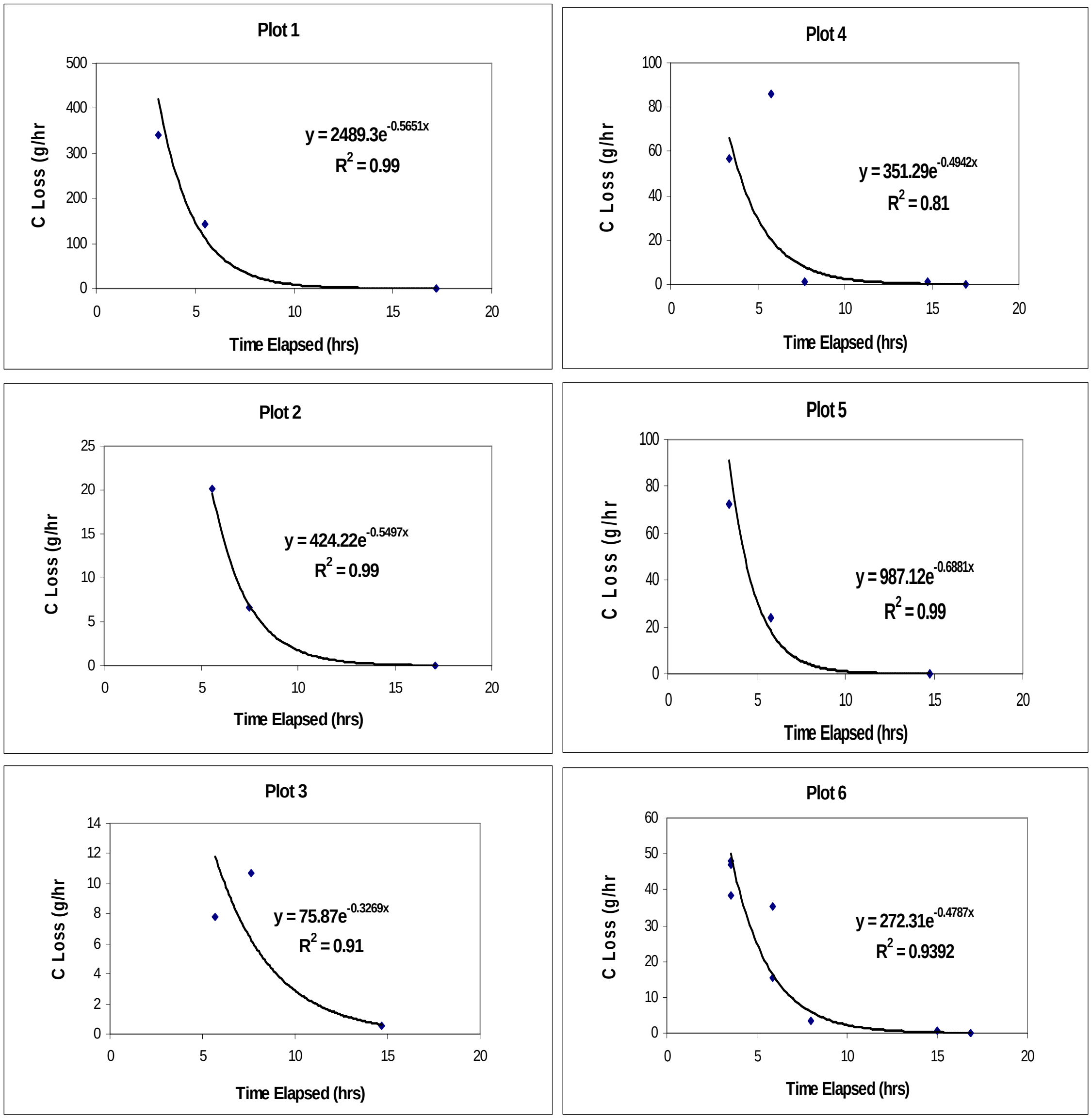


Figure 20. Carbon loss rate graphs for the six sample plots measured on the Chicken fire 6/25/2004.

Table 10. RSC carbon release exponential curve results and total consumption estimates for 2004 Alaska RSC sites.

Fire	**Date**	**Plot #**	**Y-intercept (g/m^2)**	**Decay Constant (k)**	**Time Constant (1 / k) (hours)**	**r^2**	**Total Fuel Consumed (g/m^2)**
Chicken	6/24/04	1	2489	0.565	1.77	1.00	8810
		2	546	0.589	1.70	1.00	1854
		3	76	0.327	3.06	0.91	464
		4	193	0.393	2.55	0.64	983
		5	375	0.473	2.11	1.00	1584
		6	174	0.391	2.56	0.92	892
		Average	642	0.456	2.29		2815
Porcupine 1	6/27/04	1	993	0.281	3.56	0.99	7062
		2	482	0.307	3.26	0.93	3139
		3	504	0.168	5.94	0.95	5995
		4	412	0.275	3.64	0.95	3001
		5	425	0.367	2.73	0.58	2318
		6	217	0.338	2.96	1.00	1283
		Average	505	0.289	3.68		3495
Porcupine 2	6/29/04	1	15	0.043	23.42	0.73	702
		2	138	0.083	12.06	0.59	3324
		3	346	0.235	4.26	0.82	2949
		4	150	0.033	30.77	1.00	9208
		5	220	0.304	3.29	0.21	1445
		6	27	0.035	28.99	1.00	1540
		Average	149	0.122	17.13		2447
King Creek 2	7/12/04	1	323	0.179	5.60	0.95	3618
		3	189	0.311	3.22	1.00	1219
		4	348	0.340	2.94	1.00	2047
		Average	287	0.277	3.92		2075
Porcupine 12	7/16/04	1	507	0.111	9.05	0.98	9170
		3	492	0.125	7.99	0.98	7864
		5	281	0.094	10.66	0.93	5997
		Average	427	0.110	9.23		7771
All Sites		Average	402	0.251	7.25		3721
		Std. dev.	191	0.142	6.12		2324

Pilot Study

A pilot study of the relationship between radiant heat release rate and carbon release rate during smoldering combustion was undertaken at some of the fires. Best results were obtained at the Porcupine 12 study site. A Mikron MikroScan 7200 thermal imaging system was used to measure the spectral radiant energy emitted from Plots 1, 3 and 5. The Mikroscan 7200 has a 320 $\times$ 240 uncooled focal plane array (UFPA) that is sensitive to a longwave bandpass between 8 and 14 μm. The camera was mounted on a modified surveyor tripod at a height of 5 feet to obtain a nadir looking view of the smoldering plots. A wide angle lens (Mikron P/N 18520-1, 19 mm, f/1.37, $\angle 48°$) was used to increase the field of view so that the entire 1m^2 plot was contained within one frame. The dynamic range of the camera was set to “Range 2” which permitted brightness temperatures between 0 and 500 ºC to be measured with an accuracy of ± 2% or 2 ºC of reading. An example of a longwave thermal image of smoldering combustion is presented in fig. 21.

Thermal images were a streamed to a laptop via an IEEE 1394 FireWire interface at 1 frame per second (fps) for 35 seconds before and after the smoldering tent was placed over the plot. The camera was re-positioned over the same area of the plot each time a canister sample was collected. Sampling intervals for each plot ranged from approximately 2 to 6 hours, and weather conditions, including background ambient temperatures, were recorded at each site before sampling.

Brightness temperatures at each image coordinate were converted to bandpass radiance values ($W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$) by integrating Planck’s function over the flat spectral response function of the camera. Bandpass radiance is a unit of measure that expresses the rate at which radiant energy is emitted per unit area, per unit solid angle, and per unit wavelength. The relationship between bandpass radiance measured in the longwave atmospheric window and total emissive power ($W\ m^{-2}$) has not been examined. The mean bandpass radiance was calculated for each image in the pair of sequences collected before and after the canister sample (fig. 22). The grand mean of all 70 images was then correlated to the carbon loss rate determined from the canister analysis (fig. 23).

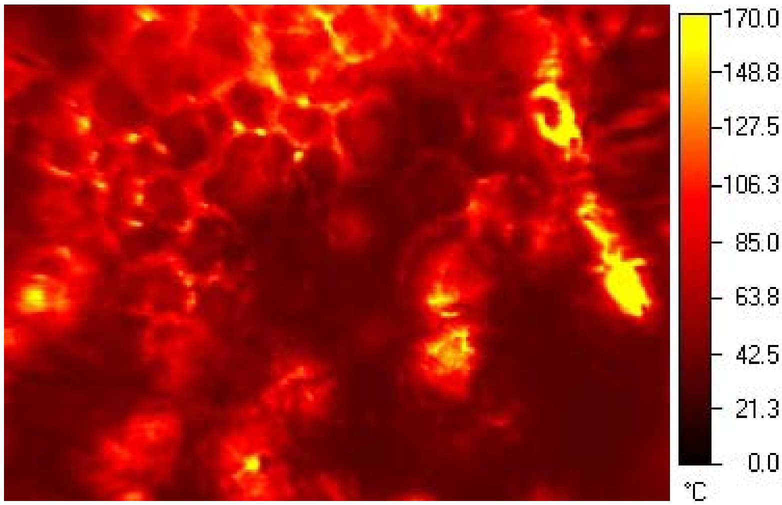


Figure 21. Longwave thermal image of smoldering combustion collected on 16 July 04 at 22:32 local time. The relationship between brightness temperatures measured by the longwave camera, at this spatial resolution, and the true kinetic temperature of the fuel surface has not been examined.

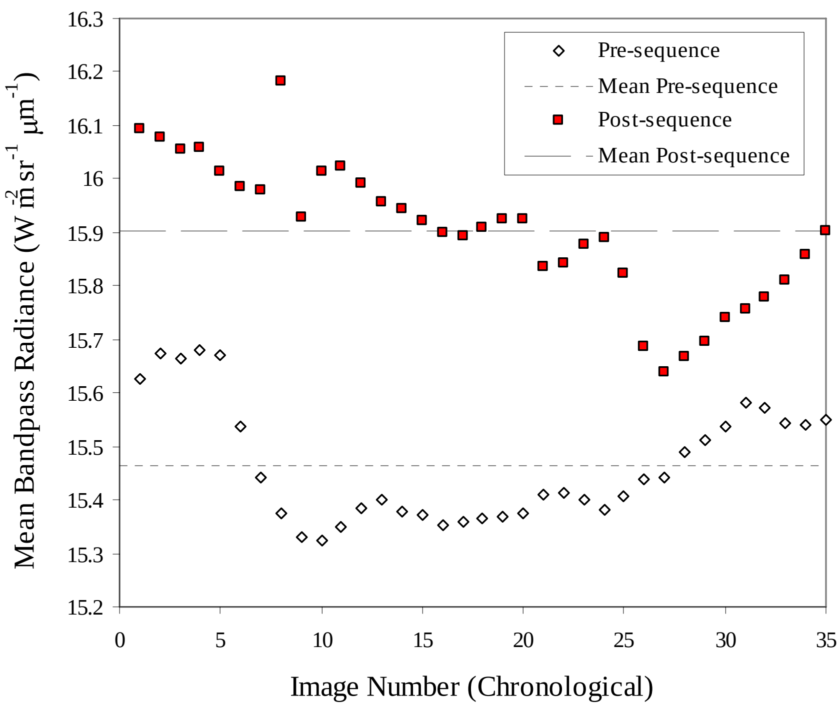


Figure 22. Chronology of bandpass radiance measurements collected before and after the first canister sample of Plot 3. Pre- and post-canister sequences were separated by 5 minutes. Differences between pre- and post- measurements cannot be solely attributed to changes in combustion reaction rates.

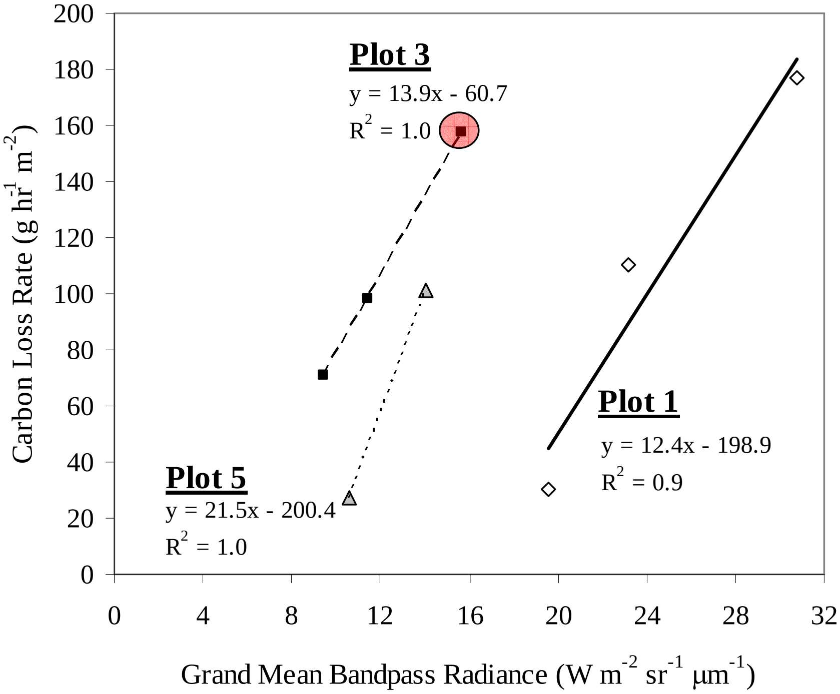


Figure 23. Relationship between the rate of emission of spectral radiant energy and rate of carbon emission for Plots 1, 3, and 5 within the greater “Porcupine 12” study area. The individual point highlighted in Plot 3 corresponds to the data presented in fig. 22.

Discussion and Recommendations

This study reported forest floor consumption and emissions measured from wildfires that occurred during the 2003 and 2004 fire season in Alaska. The proportion of the forest floor reduction is influenced by the lower forest floor moisture content and the pre-burn depth of the forest floor. This relationship holds if the relative humidity is < 40 percent to enable the fire to carry across the surface material of the forest floor and the surface layer is dry enough to sustain combustion to ignite the lower layers of the forest floor (generally < 30 percent moisture content).

Currently, lower forest floor moisture content can be obtained by collecting forest floor plugs, separating into upper and lower forest floor samples, weighing and oven drying to obtain a gravimetric moisture content expressed as a percentage. Ongoing research by Ferguson et al. (2003) is attempting to develop a predictive model to adequately estimate the moisture content of the forest floor found under black spruce and white spruce in Alaska. Forest floor moisture probes and moisture content measuring instruments also are being tested. Both research products will enable managers to determine the upper forest floor moisture content with relative ease. The forest floor depth on the other hand, cannot not be easily predicted and can be obtained only by cutting 10 to 20 plugs from around the unit and measuring the forest floor depth from them.

The forest floor equation resulting from this study has its limitations and should be used only under the conditions it was developed. When rainfall occurs within a few hours after ignition and the smoldering stage is terminated prematurely by the precipitation the equations will most likely over predict the forest floor consumption. In this case, the forest floor consumption was determined more by the occurrence of rain than by the lower forest floor moisture content and pre-burn forest floor depth. Second, when sustained surface winds >10 miles per hour occur, more forest floor is consumed than accounted for by the lower forest floor moisture content and pre-burn forest floor depth.

Only 82 percent of the forest floor variation is explained by the upper forest floor moisture content and pre-burn depth. Other factors such as relative humidity, surface material moisture, wind speed, and upper duff moisture content may influence how much of the forest floor burned. Including these variables in future analysis may improve the predictive capability of the model.

The flaming, smoldering, and combustion phase weighted average emission factors from the FASS tower have been calculated and reported in this report. In addition, the long term smoldering from specifically targeted fuels such as smoldering forest floor, stumps, and logs were presented. These are the first ground sampling emissions data to be collected during active wildfires in the Alaska boreal region and will be important in future smoke production and carbon release calculation.

Since the new forest floor consumption equation and emission factors have been implemented into Consume 3.0, we highly recommend managers, scientists, and State regulatory agencies use Consume 3.0 to estimate fuel consumption and smoke production. This will provide the best science and most up-to-date ability to predict fuel consumption and emissions for fire effects and carbon assessment for the Boreal Forest Region of Alaska. This will require a fuelbed selection, pre-burn forest floor depth, and a lower forest floor moisture content estimation.

Implementation into Consume 3.0 Software

We have implemented into Consume 3.0 the forest floor consumption equation and the emission factors for boreal forest types as well as the corresponding input variable screens. We have modified the user's guide and tutorial to reflect these modifications to the program.

Consume version 3.0 is a user-friendly computer program designed for resource managers with some working knowledge of Microsoft Windows® applications. The software predicts the amount of fuel consumption, emissions, and heat release from the burning of logged units, piled debris, and natural fuels based on weather data, the amount and fuel moisture of fuels, and a number of other factors. Using these predictions, resource managers can determine when and where to conduct a prescribed burn or plan for a wildland fire for use to achieve desired objectives while reducing impacts on other resources. The Fuel Characteristic Classification System (FCCS) was developed in coordination with Consume. Fuel loading values from the FCCS National Fuelbed reference library can be accessed directly in Consume or imported from customized FCCS fuelbeds. With its built-in link to the FCCS, Consume can be used for most forest, shrub and grasslands in North America and may be applicable to other areas of the world.

Scientific Documentation

Scientific documentation is included in the User's Guide for Consume 3.0 and will be submitted as a general technical report. The fuel consumption research and resulting algorithm as well as the emission factors will be submitted as a peer-reviewed scientific paper (expected completion Winter 2008).

Training

The new forest floor consumption model and emissions factors developed from this work has been incorporated into the RX 310 and RX 410 curriculum. It has been presented at two fire management meetings and at RX 310 in Alaska.

Deliverables

The primary deliverable product from this project is an algorithm that can be used to predict forest floor consumption from wildland fires that occur in the boreal forest fuelbed types of Alaska (table 11). The second major deliverable is a table of emission factors that can be used to predict emissions from boreal forest wildland fires. Both deliverables were successfully completed by collecting and analyzing field data from 24 plots established on 8 wildland fires in Alaska during the 2003 and 2004 wildfire seasons. The consumption algorithm and emission factors have been implemented into the software product, Consume 3.0. The user's guide, on-line help, and tutorial that accompany Consume 3.0 have been updated. In addition, the RX 310 and RX 410 curriculum has been modified to account for the new information. Additional products and technology transfer have been completed that exceeded the scope of the project (table 12).

Table 11. Comparison of proposed and actual deliverables.

Proposed	Delivered	Status
SOFTWARE Complete fuel consumption and emissions module and upload onto website for implementation into fuel consumption and fire effects software	http://www.fs.fed.us/pnw/fera/research/smoke/consume/	Done
EQUATION Complete moisture algorithm.	Weather stations and moisture sensors were positioned on the Kenai and east of Tok, Alaska. However, failure of sensors and limited ability to transmit data in remote areas did not enable reliable data collection and this portion of the study was terminated. The remaining effort was directed toward capturing 4 additional forest floor consumption and emissions data sites.	Terminated
SOFTWARE Program into Consume 3.0 and FEPS (EPM vs 2)	http://www.fs.fed.us/pnw/fera/research/smoke/consume/	Done
PUBLICATION Complete moss/duff consumption and emissions paper for submission as a research paper or journal article	Consumption trial data and emissions information have been summarized and analyzed. A PNW research paper, and journal article (*International Journal of Wildland Fire*) on these topics are in preparation and will be forwarded to the Board when complete.	In progress; January 2008
PUBLICATION Complete journal article paper on moisture algorithm and deployment protocols for moisture meter	Weather stations and moisture sensors were positioned on the Kenai and east of Tok, Alaska. However, failure of sensors and limited ability to transmit data in remote areas did not enable reliable data collection and this portion of the study was terminated. The remaining effort was directed toward capturing 4 additional forest floor consumption and emissions data sites.	Terminated
PUBLICATOION JFSP progress reports	JFSP progress reports were completed for each year starting in 2003 and ending in 2005	Done
EQUATION Forest floor consumption algorithm for boreal forest fuelbed types	Developed August 2005. Ottmar, Roger D.; Baker, Stephen P. 2007. Forest floor consumption and smoke characterization in boreal forest fuelbed types of Alaska. Final report to the Joint Fire Science Program.	Done

Table 12. Deliverables exceeding the scope of the JFSP proposal.

Publication	Ottmar, R.D. and Sandberg, D.V. 2003. Predicting forest floor consumption from wildland fire in boreal forests of Alaska – preliminary results. In: Galley, K.E.M.., Klinger, R.C., Sugihara, N.G. (eds). Proceedings of Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. Misc. Pub. 13. Tallahassee, FL: Tall Timbers Research Station: 218-224.
Publication	Joint Fire Science Program. 2005. Rapid response enables additional forest floor consumption and smoke characterization sampling in boreal forests of Alaska. September 2004. http://jfsp.nifc.gov/news/doc/highlight9-04.pdf. (22 January 2007)
Website	Updated Consume User's manual, on-line help, and tutorial
Presentation	Forest floor consumption equation was presented to 20 participants as part of a 3-day train-the-trainer workshop in Fairbanks, AK August 15-17, 2006.
Presentation	Forest floor consumption equation was presented to 60 participants as part of a 4-day RX 310 training session in Fairbanks, AK September 15-17, 2006.
Presentation	The study preliminary results were presented to 120 participants as part of the Alaska Annual Fire Staff meeting, Anchorage, AK October 18, 2004.
Presentation	Ottmar, R.D. 2005. Forest floor consumption and smoke characterization in boreal forest fuelbed types of Alaska. Progress report. Annual Meeting, Joint Fire Science Program, 1–3 November 2005, San Diego, California.
Presentation	Otttmar, Roger D. 2005. Forest floor consumption and smoke characterization in boreal forest fuelbed types of Alaska.. Presentation to the Joint Fire Science Program Governing Board. September.
Presentation	Presentation at the Society of American Foresters annual meeting, Fort Worth Texas, October, 2005 on the study protocols and preliminary results.
Demonstrations	Fifteen Consume 3.0 demonstrations at RX 410 (Smoke Management), RX 300, (Burn Boss), RX 310 (Fire Effects) national and regional training sessions, and at 3 Technical Fire Management modules.

WEB PAGE

A web page describing Consume and including downloads, publications, and contacts was established at http://www.fs.fed.us/pnw/fera/products/consume.html.

PUBLICATIONS

Ottmar, R.D. 2001. Smoke source characteristics. Chapter 5. In Hardy, C.C.; Ottmar, R.D.; Peterson, J.L. [and others]. Smoke management guide for prescribed and wildland fire: 2001 edition. National Wildfire Coordinating Group, Boise, ID. 226 p.

Ottmar, R.D. 2002. Characterization of emissions from fires. Chapter 4. In: Sandberg, D.L.; Ottmar, R.D.; Peterson, J.S.; Core, J.S. Wildland fire in ecosystems: effects on air. General Technical Report RMRS-GTR-42-Vol 5. Ogden, UT U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 70 p.

Ottmar, R.D. and Sandberg, D.V. 2003. Predicting forest floor consumption from wildland fire in boreal forests of Alaska – preliminary results. In: Galley, K.E.M.., Klinger, R.C., Sugihara, N.G. (eds). Proceedings of Fire Conference 2000: The First

National Congress on Fire Ecology, Prevention, and Management. Misc. Pub. 13. Tallahassee, FL: Tall Timbers Research Station: 218-224.

DEMONSTRATIONS

The 3-day train-the-trainer Alaska Regional Fuels workshop (August 15-17, 2006, JFSP Project #04-4-1-19), showcased a modified version of Consume 3.0 with the new forest floor consumption equation and emission factors. The workshop consisted of a series of short presentations, question and answer sessions, a practicum led by the Consume team, and a hands-on use of the system. Questions and comments were collected during the demonstration. These comments were used to improve the Consume software. Four additional workshops (Ohio, Idaho, Southern California, and New Mexico) and two mini workshops at major conferences in California and Florida have been completed and also demonstrated Consume 3.0.

RX CLASS TRAININGS

The principal investigator teaches fuel combustion and consumption classes 12 times a year at national training courses including Rx 300 Burn Boss, Rx 310 Fire Effects, Rx 410 Smoke Management, and Technical Fire Management. The course work includes discussion of new fuel consumption model developed from this study and a demonstration of Consume v 3.0.

CONSULTATIONS

The principle investigator consults with several land managers, regulators, and scientist each year with regard to the best available fuel consumption models for various fuelbed types throughout the country. The principle investigator is also the lead scientist in directing the use of fuel consumption models for a National Wildland Fire Emissions Tracking System being implemented by the EPA. The fuel consumption models from the study will be used by the EPA emissions tracking system.

TUTORIAL

A web-based self-taught tutorial along with an instructor's guide and student workbook for Consume 3.0 has been modified following the inclusion of the boreal forest fuel consumption and emission factors (JFSP Project #04-4-1-19). The Consume 3.0 tutorial can be accessed through a web-browser or down-loaded directly from http://www.fs.fed.us/pnw/fera/research/tutorials/consume.shtml. The final report for this project is in preparation.

Literature Cited

Andreae, M.O. and P. Merlot. 2001. Emissions of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles, 15, 955-966, 2000GB001382.

Barney, R.J. and E. R.Berglund. 1974. Wildfire smoke conditions: interior Alaska. Res. Pap. PNW-178. Portland, OR: U.S. Department of Agriculture, Forest service, Pacific Northwest Forest and Range Experiment Station. 18 p.

Battye, W.B. and R. Battye. 2002. Development of emissions inventory methods for wildland fire. Prepared for Thompson G. Pace, D205-01 of the U. S. Environmental Protection Agency, Final report. [online]. Available from: http://www.epa.gov/ttn/chief/ap42/ch13/related/firerept.pdf [accessed 24 April 2006].

Beaufait, W.R., Hardy, C.E., and W.C. Fischer. 1977. Broadcast burning in larch-fir clearcuts: the Miller Creek–Newman Ridge study. Res. Pap. INT-175. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station. 53 pp.

Boucher, T. V. 2003. Vegetation response to prescribed fire in the Kenai Mountains, Alaska. Res. Pap. PNW-RP-554. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 59 p.

Brown, J.K., E.D. Reinhardt, and W.C. Fischer. 1991. Predicting duff and woody fuel consumption in northern Idaho prescribed fires. Forest Science 37:1550–1566.

Dyrness, C.T. and R. Norum. 1983. The effects of experimental fires on black spruce forest floors in Interior Alaska. Can. J. For. Res. 13:879-893.

Environmental Protection Agency. 1996. Wildfire and prescribes fire emissions. AP-42. U.S. Environmental Protection Agency, Research Triangle Park, NC.13.1.1-14.

Ferguson, SA., J. Rutherford, M. Rorig, and D.V. Sandberg. 2003. Measuring moss moisture dynamics to predict fire severity. Pages 211-217 in K.E.M. Galley, R.C. Klinger, and N.G. Sugihara (eds). Proceedings of Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. Miscellaneous Publication No. 13, Tall Timbers Research Station, Tallahassee, FL.

Foote, J. M. 1983. Classification, description, and dynamics of plant communities after fire in the Taiga of Interior Alaska. Res. Pap. PNW-307. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, 108 p.

Goode, J. G., R. J. Yokelson, D. E. Ward, R. A. Susott, R. E. Babbitt, M. A. Davies, and W. M. Hao. 2000. Measurements of excess O3, CO2, CO, CH4, C2H4, C2H2, HCN, NO, NH3, HCOOH, CH3COOH, HCHO, and CH3OH in 1997 Alaskan biomass burning plumes by airborne Fourier transform infrared spectroscopy (AFTIR). J. Geophys. Res. 105: 22,147-22,166.

Hao, W. M., and D. E. Ward. 1993. Methane production from global biomass burning. Journal of Geophyiscal Research. 98: 20,657–20,661.

Hao, W.M., D.E. Ward, G. Olbu and S.P. Baker. 1996a. Emissions of CO_2, CO, and hydrocarbons from fires in diverse African savanna ecosystems. Journal of Geophysical Research. 101: 23577-23584.

Hao, W.M., D.E. Ward, G. Olbu, S.P. Baker and J.M. Plummer. 1996b. Emissions of trace gases from fires in fallow forests and woodland savannas in Zambia. In: Levine, J.S., ed. Biomass Burning and Global Change. Volume l. Cambridge, MA: MIT Press. 361-369.

Hardy, C. C., R.D. Ottmar, J.L. Peterson, J.E. Core, and P. Seamon. 2001. Smoke management guide for prescribed and wildland fire: 2001 edition. PMS 420-2. Boise, ID: National Wildfire Coordination Group. 226 p.

Lawson, B.D., Frandsen W.H., Hawkes B.C., and G.N. Dalrymple G.N. 1997. Probability of sustained smoldering ignition for some boreal forest duff types. Edmonton, Alberta: Canadian Forest Service, Forest Management Note. 63:11.

Miyanishi, K. and E.A. Johnson. 2002. Process and patterns of duff consumption in the mixedwood boreal forest. Can. J. Forest Res. 32: 1285-1295.

Norum, Rodney A. 1977. Preliminary guidelines for prescribed burning under standing timber in western larch/Douglas-fir forests. Res. Note INT-229. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 15 p.

Ottmar, R.D., S.N. Little, and J. Ohmann. 1985. Predicting duff reduction to reduce smoke from clearcut slash burns in western Washington and western Oregon. Proceedings of the Conference on Fire and Forest Meteorology 8:139–144.

Ottmar, R.D. and R.E. Vihnanek. 1998. Stereo photo series for quantifying natural fuels: volume II: Black spruce and white spruce types in Alaska. PMS 831. NFES 2580. Boise, Idaho: National Wildfire Coordinating Group. National Interagency Fire Center. 65 p.
Ottmar 2005

Ottmar, R.D. and D.V. Sandberg. 2003. Predicting forest floor consumption from wildland fire in boreal forests of Alaska—preliminary results. Pages 218-224 in K.E.M. Galley, R.C. Klinger, and N.G. Sugihara (eds). Proceedings of Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. Miscellaneous Publication No. 13, Tall Timbers Research Station, Tallahassee, FL.

Prichard, S.J.; R.D. Ottmar and G.K. Anderson. 2006. Consume User's Guide v. 3.0. http://www.fs.fed.us/pnw/fera/products/consume/consume30_users_guide.pdf. (10 July 2006).

Sandberg, D.V. 1980. Duff reduction by prescribed burning in Douglas-fir. Research Paper PNW-272, U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range

Experiment Station, Portland, OR.

Susott, R.A., D.E. Ward, R.E. Babbitt, and D.J. Latham. 1991. The measurement of trace emissions and combustion characteristics for a mass fire. In: Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications (J.S. Levine, ed.), 245-257. MIT Press, Cambridge, MA.

Vanderlinden, Larry A. 1996. Applying stand replacement prescribed fire in Alaska. Society for Ecological Restoration Symposium. 1995. 10 pp.

Viereck, L.A. and L.A. Schandelmeier. 1980. Effects of fire in Alaska and adjacent Canada: a literature review. BLM-Alaska Technical Report. BLM/AK/TR-80/06. USDI Bureau of Land Management, Alaska State Office. Anchorage, Alaska. 124 pp.

Viereck, L. A.; Dyrness, C. T. 1979. Ecological effects of the Wickersham Dome Fire near Fairbanks, Alaska. Gen. Tech. Rep. PNW-90. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 71 p.

Ward, D.E., C.C. Hardy, D.V. Sandberg, and T.E. Reinhardt. 1989. Part III-emissions characterization. In: Sandberg, D.V., D.E. Ward, and R.D. Ottmar, comp. eds. Mitigation of prescribed fire atmospheric pollution through increased utilization of hardwoods, piled residues, and long-needled conifers. Final report. U.S. DOE, EPA. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Seattle

Ward, D.E., R. Susott, J. Kauffman, R. Babbitt, B. N. Holben, Y.J. Kaufman, A. Setzer, R. Rasmussen, D. Cumming and B. Dias. 1992. Emissions and burning characteristics of biomass fires for cerrado and tropical forest regions of Brazil - BASE-B experiment. Journal of Geophysical Research. 97, 14601-14619.

Ward, D.E.; Radke, L.F. 1993. Emissions measurements from vegetation fires: a comparative evaluation of methods and results. In: Crutzen, P.J.; Goldammer, J.G., eds. Fire in the environment: the ecological, atmospheric, and climatic importance of vegetation fires. NewYork: John Wiley: 53-76. Chapter 4.

Yokelson, R. J., Bertschi, I. T., Christian, T. J., Hobbs, P. V., Ward, D. E., and Hao, W. M. 2003. Trace gas measurements in nascent, aged, and cloud-processed smoke from African savanna fires by airborne Fourier transform infrared spectroscopy (AFTIR). Journal of Geophysical Research. 108(D13), 8478, doi:10.1029/2002JD00232

Contents of CD I

Final Report:

jfsp_Alaska_Forest_Floor_report_03_1_3_08_ottmar
Final Report JFSP Project #03-1-3-08

CONSUME:

factsheet_consume.pdf (396 kb)
Consume Fact Sheet

Setup.msi (18.2 MB)
Consume software (self extracting)

Consume_user_guide.pdf (2.3 MB)
Consume_User's Guide

Consume_tutorial.zip (16.9 MB)
Consume tutorral

Dotnetfx.exe (23.1 MB)
Microsoft Framework.NET v 1.1

Vjredist.exe (6.6 MB)
Microsoft Visual J# .NET v 1.1

Microsoft_end_user_license_agreement-NET.pDF
User license agreement for dotnetfx.exe and vjredist.exe

Photos

jfsp_03_1_3_08_alaska_forest_floor_consumption_emissions_photos

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