



AIR SCIENCES INC.

FINAL REPORT:

**CEREAL-GRAIN RESIDUE
OPEN-FIELD BURNING
EMISSIONS STUDY**

Prepared for and funded by:

**WASHINGTON DEPARTMENT OF
ECOLOGY**

**WASHINGTON ASSOCIATION OF
WHEAT GROWERS**

**U.S. ENVIRONMENTAL PROTECTION
AGENCY, REGION 10**

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PROJECT No. 152-02
JULY 2003

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Funding

This project was funded in part by the following United States Environmental Protection Agency grants:

- Persistent Bioaccumulation Toxics (PBT) Program Grant: 2000
- Region 10/Regional Priority 105 Grant: 2002

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EXECUTIVE SUMMARY

A field emissions study was performed in eastern Washington to investigate the opportunities for reducing the emissions of ten pollutant species, including PM_{2.5}, PM₁₀, carbon monoxide, and six polycyclic aromatic hydrocarbon species, from open-field burning of cereal-crop residue. The quantity of emissions from open field burning is a function of the residue consumption per acre, the pollutant emission factors, and the number of acres burned. This study relates changes in proportion of residue consumed (residue consumption) and emissions to changes in several fuel bed and fire variables, including pre-burn residue loading level (low: 6,000 to 8,000 lbs per acre, high: greater than 8,000 lbs per acre), fire ignition pattern (mass ignition, head fire, strip head fire, backing fire), and season of burn (spring, fall). The early study design included pre-burn tillage and pre-burn baling as additional residue treatments. This study was not able to evaluate either pre-burn tillage or baling and therefore makes no conclusions about these two treatments.

The study results show that absolute residue consumption in cereal crops is positively correlated with the pre-burn residue loading ($R^2=0.71$). The higher the pre-burn residue loading, the higher is the absolute residue consumption. Thus, the measured pre-burn loading may be used to predict residue consumption, although small increases (decreases) in the pre-burn loading may not always result in an increase (decrease) in residue consumption. Practical methods for estimating the pre-burn residue loading have not yet been developed and are not part of this study.

No statistically significant differences in the absolute or relative residue consumption were found among any of the alternative ignition patterns, nor between the spring and fall seasons. Thus, no reduction in residue consumption can be ascribed to any particular fire type or season of burn.

The mean PM_{2.5} emission factors (that is, the mass of PM_{2.5} emission per mass of residue consumed) for spring and fall were, respectively, 5.3 and 9.8 lbs PM_{2.5} per ton of residue consumed. These emission factors are lower than the equivalent PM_{2.5} emission factor reported in AP-42 (USEPA, 1995) of 17.6 lbs PM_{2.5} per ton of residue consumed for head fires.¹ The differences between the spring and fall PM_{2.5} emission factors are statistically significant at the 95 percent confidence level, driven almost entirely by differences in the residue moisture content between spring and fall. The residue moisture contents during the fall 2000 burns were significantly higher than during the spring 2000 burns. Although not measured in this study, we believe that the higher recorded moisture contents in the fall are attributable to the amount of “green up” (i.e., germinating seed) that occurred following the precipitation, and are not necessarily a reflection of higher moisture contents in the dead-and-down residue lying on the soil surface.

¹ That is, 22 lbs PM₁₀ per ton \times 0.8 = 17.6 lbs PM_{2.5} per ton, assuming that 80 percent of PM₁₀ is composed of PM_{2.5}.

No statistically significant differences in the PM_{2.5} emission factors were found among most of the alternative ignition patterns studied, nor were statistically significant differences found between the high loading (that is, greater than 8,000 lbs of residue per acre) and low loading (that is, 6,000 to 8,000 lbs of residue per acre) units. The mean PM_{2.5} emission factor for the spring backing fires was lower (statistically significant, 98-percent confidence level) than the mean PM_{2.5} emission factor for the fall baseline fires, but this difference may be driven more by differences in moisture content than by differences in the ignition pattern (the fall baseline fires are believed to have had more “green up” present than the spring backing fires).

INTRODUCTION

Direct seeding is an important crop management system used by cereal-grain growers in the inland Pacific Northwest. Under this system, cereal crops are seeded directly into the soil with little or no pre-seeding tillage. Fields that are direct-seeded have been shown to have greater soil organic matter, water-stable aggregates, microbial biomass, and dehydrogenase activity in the near-surface layer than in conventionally managed fields (McCool et al., 2001). Direct seeding is considered an excellent cropping system for minimizing soil erosion and for maintaining overall soil quality on highly erodible fields.

Seed management systems that require little or no tillage also require specialized and expensive machinery for seeding into heavy residues. Burning the fields prior to planting, however, can reduce the high residue loadings and eliminate the need for specialized equipment. Burning has the added benefits of controlling or eliminating fungal diseases, weed seeds, and insect pest eggs. Fire also quickly recycles potassium, phosphorus, and other minerals back to the soil, thereby reducing the quantity of agro-chemicals that are needed on fields.

The effects of open field burning are not all positive. Biomass burning emits large quantities of CO, CO₂, fine particulate matter, and volatile hydrocarbons into the air, and somewhat lesser amounts of oxides of nitrogen and oxides of sulfur. These emissions could adversely affect human health and regional visibility if present in high enough concentrations.

In 1998 and 1999, the cereal-grain growers in Washington State burned over 200,000 acres of residue. Public concern over smoke emissions from all forms of field burning in the Washington State, not just the burning of cereal-grain residues, led the Washington Association of Wheat Growers to seek and obtain a memorandum of understanding with the Washington Department of Ecology to voluntarily reduce the total emissions over a five-year period. According to the memorandum, the signatories agreed to reduce total emissions by 50 percent from baseline levels by June 30, 2006. The methods for achieving this reduction were not specified in the agreement, but may be achieved either by a reduction in the acreage burned annually, by reducing the residue consumption, or by reducing the pollutant emission factors. Although reducing the acreage burned annually may seem most expedient, there may be equal or greater opportunities for reducing the residue consumption or emission factors by modifying the current residue management or fire management practices (e.g., the residue loading or type of firing pattern used to burn fields). This requires an understanding of the influence of residue management and fire management practices on residue consumption and emission in cereal-grain residues that, prior to this study, did not exist.

The scientific literature contains a great amount of information on the emissions of atmospheric pollutants from burning in various vegetation types worldwide. Estimates of emission factors for

carbon species emitted from biomass burning have been published for cereal and agricultural wood residues (Jenkins and Turn, 1994; Turn et al., 1997), for savanna ecosystems in Australia and southern Africa (Cachier et al., 1995; Hurst et al., 1994a, 1994b; Shea et al., 1996; Ward et al., 1996; Yamasoe et al., 2000), for cereal residues in Spain (Ortiz de Zarate et al., 2000), for wildfires in forested ecosystems in the western United States (Ward and Hardy, 1991; Ward et al., 1992a), and for Cerrado parklands in central Brazil (Ward et al., 1992b). Emission factors for volatile organic compounds, including many polycyclic aromatic hydrocarbon (PAH) species, are also available for cereal residues (Jenkins et al., 1996b; Ramdahl and Moller, 1983), for agricultural wood residues (Jenkins et al., 1996b), and for forest wood residues (Jenkins et al., 1996b). These studies reveal the range of emission factors produced in different fuel types, but offer little information on the expected benefits of alternative residue management or fire management practices in reducing residue consumption, emissions factors, and ultimately, total emissions.

A study was initiated to investigate the opportunities for reducing the residue consumption or emission factors through changes in residue management or fire management practices. The study objectives were as follows:

1. Determine the baseline (i.e., control) fuel consumption, emission factors, and unit-area emissions for open-field burning of cereal-grain residues at dry land sites in eastern Washington, U.S.A. The baseline values will serve as the basis for the comparison between alternative residue reduction and fire management treatments. In this study, baseline conditions were selected to mimic conditions under which local growers have historically performed burns; that is, high-residue-loading fields (i.e., greater than 8,000 pounds of residue per acre) burned in fall using mass ignition firing techniques.
2. Determine changes (relative to baseline conditions) in fuel consumption, emission factors, and total unit-area emissions following a change in the residue treatment.

The treatments consisted of various combinations of: pre-burn residue loading (low loading, high loading), season of burn (spring 2000, fall 2000), and fire ignition pattern (mass ignition, head fire, strip head fire, and backing fire). The early study design included pre-burn tillage and pre-burn bailing as additional residue treatments. This study was not able to evaluate either pre-burn tillage or bailing and therefore makes no conclusions about these two treatments. The pollutant species under consideration were: CO, particulate matter less than 2.5 micrometers in aerodynamic diameter (PM_{2.5}), particulate matter less than 10 micrometers in aerodynamic diameter (PM₁₀), benzo(a)pyrene (BaP), and six additional BaP-equivalent carcinogens including benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, and idenol(1,2,3-cd)pyrene. Two other carbon species--methane, CH₄, and carbon dioxide, CO₂--were included in the investigation because they were required in the calculation of emission factors using the carbon mass balance method.

The experimental plan stated that the capability to measure real-time nitric oxide (NO) concentrations would be included with the Fire Atmosphere Sampling System apparatus. However, the FASS apparatus used in this field study did not come equipped with real-time NO sensors.

METHODS

2.1 Study Locations and Design

The field investigation included 27 burn units located within a 20-mile radius of the town of Dayton, Columbia County, Washington (Figure 2.1). Fifteen of the burn units were sampled during April 2000 (spring burns), and 12 were sampled during October 2000 (fall burns). The 15 spring burn units comprised five different treatments with three replications each. The treatments included²: backing fire under low-residue loading, head fire under low-residue loading, backing fire under high-residue loading, strip head fire under high-residue loading, and head fire under high-residue loading. The 12 fall burn units comprised four treatments with three replications each. The treatments included³: head fire under low-residue loading, backing fire under high-residue loading, strip head fire under high-residue loading, and mass ignition fire under high-residue loading. The emissions from the mass ignition units were used to determine baseline conditions. In one of the fall units (Jones #3), both sampling towers malfunctioned and so none of the data from this site was useable in the analysis. This reduced the number of available fall burn units from 12 to 11, and the total number of burn units from 27 to 26.

Each burn unit consisted of a square area measuring 600 feet on a side and was surrounded by 30-foot-wide fuel breaks plowed to mineral soil. The baseline burn units were approximately 40-acre square fields ($\frac{1}{4}$ mile on a side) and also surrounded by 30-foot-wide plowed fuel breaks. Larger fields were needed for the baseline burns in order to better simulate the mass ignition firing technique favored by local cereal-grain growers. All of the fields, and the treatment units within the fields, were selected based on the predicted pre-burn loading and the uniformity of the pre-burn loading conditions and physiographic characteristics (aspect and slope), as well as proximity to other burn units. The physiographic characteristics of each burn unit are summarized in Table 2.1.

Prior to lighting the fires, sampling to determine the pre-burn residue loading and residue moisture content was performed in each unit, and the emissions sampling equipment was erected. The sampling procedures that were used are described in Section 2.2, Sampling Procedures, and a description of the sampling apparatus is presented in Section 2.2.3, Combustion Emissions. The host grower was responsible for igniting each unit using the instruction on timing and fire pattern provided by the principal investigator. The meteorological and residue moisture conditions at the time of each burn are summarized in Tables 2.2 and 2.3, respectively.

² The last treatment listed (head fire under high-residue loading) is unique to the spring burns; all other treatments were evaluated in the fall burns.

³ The last treatment listed (mass ignition under high-residue loading) is unique to the fall burns; all other treatments were evaluated in the spring burns.

Figure 2.1. Geographic Location of Study Area (Dayton, Columbia County, Washington, U.S.A.)

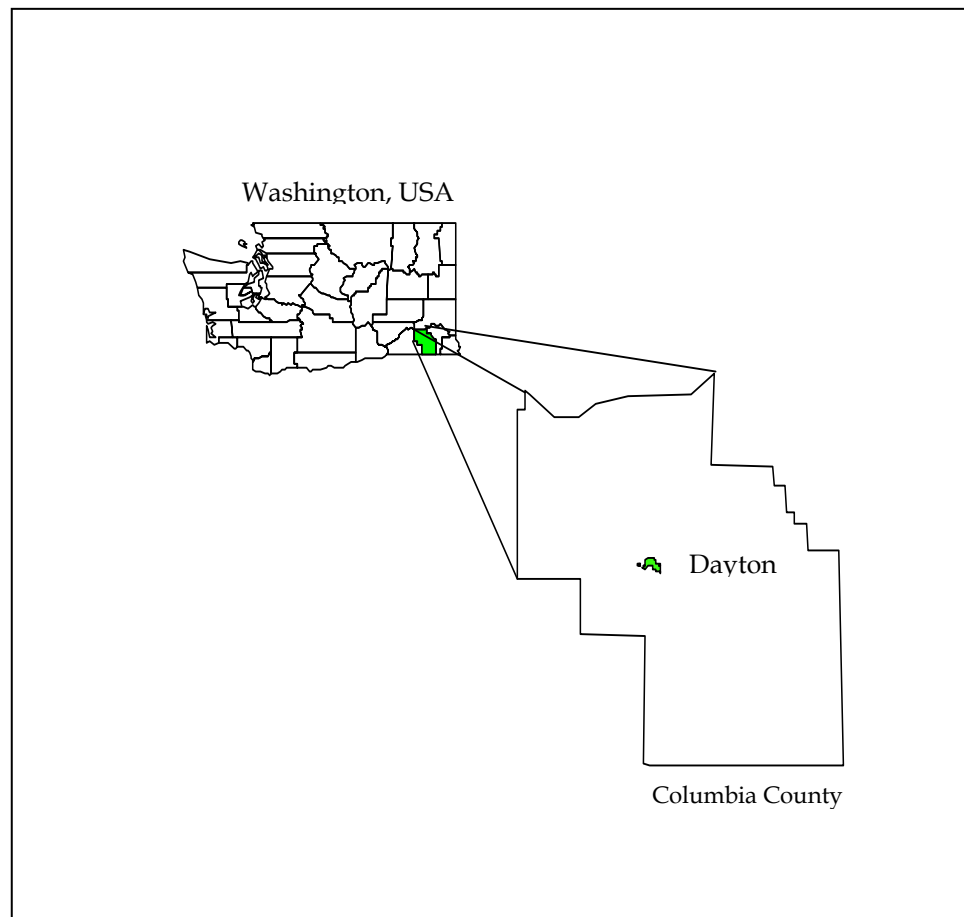


Table 2.1. Physiographic Descriptions of Fall and Spring Burn Units

Unit Name	Ignition Type and Planned Loading	Slope (percent)	Aspect	Elevation (feet above msl)
Spring Burns				
Beard #1	Backing-Low Load	5-10	NW	2,130
Beard #2	Head-Low Load	0-5	NW	2,100
Beard #3	Backing-Low Load	5-10	NW	2,060
Beard #4	Head-Low Load	0-5	NW	2,030
Beard #5	Backing-Low Load	0-5	NW	2,020
Beard #6	Head-Low Load	10-15	80%NW 20%SE	2,170
Covello #1	Backing-High Load	0-5	SW	2,530
Covello #2	Head-High Load	5-10	SW	2,530
Covello #3	Strip-High Load	5-10	W	2,540
Covello #4	Head-High Load	5-10	SW	2,510
Covello #5	Backing-High Load	5-10	W	2,500
Harting #1	Strip Head-High Load	5-10	NW	2,265
Harting #2	Backing-High Load	5-10	NW	2,300
Harting #3	Head-High Load	5-15	NW	2,240
Harting #5	Strip Head-High Load	10-20	NW	2,300
Fall Burns				
Fletcher #1	Head-Low Load	0	-	1,400
Fletcher #2	Head-Low Load	0	-	1,400
Fletcher #3	Head-Low Load	0	-	1,400
Jones #1	Back-High Load	0	-	2,000
Jones #2	Strip Head-High Load	0	-	2,000
Jones #3 [†]	Strip Head-High Load	0-5 (25%) Flat (75%)	S	2,000
Jones #4	Back-High Load	5-10 (50%) Flat (50%)	SE	2,010
McGee #1	Mass-Baseline	0-5	NE	2,920
McGee #2	Mass-Baseline	15-20	NW	2,875
McGee #3	Mass-Baseline	15 (NW) 0-5 (SE)	35%NW 65%SE	2,945
Turner #1	Back-High Load	5-10	S	2,180
Turner #2	Strip Head-High Load	5-15	SW	2,370

[†]Due to an equipment malfunction, the data from this unit were not useable in the subsequent analysis

To determine the pre-burn loading level, the Washington State University Agricultural Extension Service (WSU-AES)'s rule-of-thumb of 100 pounds of residue per bushel of grain harvested was used (Dr. Roland Schirman, WSU-AES, personal communication). Low-loading units were selected from those with a predicted pre-burn residue loading of 6,000 to 8,000 pounds per acre. High-loading units were selected from those with a predicted pre-burn residue loading of greater than 8,000 pounds per acre. During the analysis phase, the 27 experimental burn units were re-stratified according to their *measured* (not predicted) pre-burn residue loading level. The re-stratification resulted in a substantially different number of replications in each treatment than was targeted originally (Section 3.1; range of one to five replications per treatment).

Four different ignition patterns were investigated in order to determine if the pattern of ignition significantly affected the fuel consumption and resulting emissions through some change in residence time and rate of spread of the fire. The ignition patterns included: head fire, strip head fire, backing fire, and mass ignition. A *head fire* is one that is ignited at the upwind edge of the unit to be burned and pushed across the unit by the wind. Head fires are typically fast moving, and the forward "lean" of the fire over the unburned residue creates forward heating of the fuels and a correspondingly wider fire line front (i.e., greater width of burning fuels). A *strip head fire* is a head fire that is ignited in strips, starting at the downwind side of the unit to be burned and proceeding upwind. By igniting in strips, the downwind distance the fire is allowed to burn is restricted. Each strip runs into the previously burned strip, which causes it to be extinguished. Strip head fires are a safer method for igniting fires than a head fire and are much less prone to escape beyond the intended fire boundary. *Backing fires* are the opposite of head fires. A *backing fire* is one that is ignited at the downwind edge of the unit to be burned such that the fire spreads, or *backs*, into the wind. Backing fires are typically slower moving than head fires, and the backward "lean" of the flames over the already burned residues produces relatively little pre-heating of fuels and a narrow fire front. *Mass ignition* is a variation of the head fire technique. With this technique, the unit to be burned is encircled by fire as quickly as possible, typically using drip torches carried on all-terrain vehicles. Usually employed under relatively low wind speeds, this lighting pattern creates a convection column that draws air—and the fire front—inward from all sides of the unit toward the center. This ignition pattern generally produces the fastest rates of fire spread and the highest fire line intensities of any of the four methods examined.

2.2 Sampling Procedures

2.2.1 Residue Loading

Pre- and post-burn residue loading was sampled in order to accurately assess the total residue consumption following each test burn. Within each burn unit, ten sampling locations, laid out on a 30-meter grid upwind from the twin FASS towers (Section 2.2.3), were established to characterize the pre- and post-burn residue loading. At each sampling location two 0.25-square-

meter plots were sampled, spaced roughly 0.5 meters apart, to determine the pre-burn loading and the post-burn loading, respectively.

Table 2.2. Wind Speed, Temperature, and Relative Humidity as a Function of Season and Ignition Type.

Values shown are means \pm 1 standard error (SE).

Season and Ignition Type	Wind Speed (miles per hour)	Temperature (degree F)	Relative Humidity (%)
Spring			
Backing Fire ($n=6$)	8.3 ± 1.5	64.1 ± 2.1	29 ± 5
Head Fire ($n=6$)	9.6 ± 1.0	60.1 ± 3.3	31 ± 3
Strip Head Fire ($n=3$)	9.4 ± 2.8	62.5 ± 0.5	35 ± 4
All ($n=15$)	9.1 ± 0.9	62.2 ± 1.6	31 ± 2
Fall			
Baseline ($n=3$)	10.1 ± 3.4	58.0 ± 3.1	33 ± 4
Backing Fire ($n=3$)	6.4 ± 1.3	58.3 ± 2.5	22 ± 4
Head Fire ($n=3$)	4.2 ± 0.3	69.0 ± 1.7	22 ± 2
Strip Head Fire ($n=2$)	6.5 ± 0.7	58.8 ± 0.9	33 ± 4
All ($n=11$)	6.8 ± 1.1	61.2 ± 1.8	25 ± 2

Table 2.3. Fuel and Soil Moisture Content, Expressed as Percent H₂O per g Over Dry Weight, as a Function of Season, Ignition Type, and Pre-Burn Fuel Loading.

Values shown are means \pm SE.

Season and Ignition Type	Entire Residue Layer (%)	Upper Residue Layer (%)	Lower Residue Layer (%)	Standing Stubble (%)	Soil Layer (%)
Spring by Ignition Type					
Backing Fire	10.0 \pm 0.9 (<i>n</i> =6)	4.6 \pm 0.5 (<i>n</i> =3)	12.5 \pm 1.7 (<i>n</i> =3)	6.0 \pm 0.3 (<i>n</i> =6)	26.1 \pm 1.1 (<i>n</i> =6)
Head Fire	9.2 \pm 0.6 (<i>n</i> =6)	5.4 \pm 0.3 (<i>n</i> =2)	12.6 \pm 1.7 (<i>n</i> =2)	7.4 \pm 0.6 (<i>n</i> =5)	26.0 \pm 2.1 (<i>n</i> =6)
Strip Head Fire	11.1 \pm 1.6 (<i>n</i> =3)	No data.	No data.	8.8 \pm 1.0 (<i>n</i> =3)	26.1 \pm 2.0 (<i>n</i> =4)
<i>All</i>	9.9 \pm 0.5 (<i>n</i> =15)	5.0 \pm 0.3 (<i>n</i> =5)	12.5 \pm 1.1 (<i>n</i> =5)	7.1 \pm 0.4 (<i>n</i> =14)	26.0 \pm 1.0 (<i>n</i> =15)
Fall by Ignition Type					
Baseline	28.1 \pm 9.3 (<i>n</i> =3)	13.6 \pm 4.0 (<i>n</i> =3)	41.6 \pm 11.8 (<i>n</i> =3)	11.7 \pm 2.8 (<i>n</i> =3)	20.5 \pm 2.8 (<i>n</i> =2)
Backing Fire	26.4 \pm 6.7 (<i>n</i> =3)	10.6 \pm 2.8 (<i>n</i> =3)	60.6 \pm 18.4 (<i>n</i> =3)	11.9 \pm 1.4 (<i>n</i> =3)	30.3 \pm 1.6 (<i>n</i> =2)
Head Fire	13.5 \pm 1.8 (<i>n</i> =3)	No data.	No data.	10.8 \pm 1.6 (<i>n</i> =3)	22.9 \pm 2.7 (<i>n</i> =3)
Strip Head Fire	28.7 \pm 7.7 (<i>n</i> =2)	8.0 \pm --- (<i>n</i> =1)	24.7 \pm --- (<i>n</i> =1)	9.95 \pm 0.1 (<i>n</i> =2)	27.0 \pm 2.8 (<i>n</i> =2)
<i>All</i>	23.8 \pm 3.5 (<i>n</i> =11)	11.5 \pm 2.0 (<i>n</i> =7)	47.3 \pm 9.8 (<i>n</i> =7)	11.2 \pm 0.8 (<i>n</i> =11)	24.9 \pm 1.7 (<i>n</i> =9)
Spring by Pre-Burn Fuel Loading					
Low Loading	10.0 \pm 0.8 (<i>n</i> =10)	5.3 \pm --- (<i>n</i> =1)	14.8 \pm --- (<i>n</i> =1)	7.3 \pm 0.6 (<i>n</i> =10)	27.4 \pm 1.2 (<i>n</i> =10)
High Loading	9.5 \pm 0.6 (<i>n</i> =5)	4.8 \pm 0.4 (<i>n</i> =4)	12.0 \pm 1.1 (<i>n</i> =4)	6.7 \pm 0.7 (<i>n</i> =4)	23.2 \pm 0.4 (<i>n</i> =5)
Fall by Pre-Burn Fuel Loading					
Low Loading	13.5 \pm 1.3 (<i>n</i> =4)	5.1 \pm --- (<i>n</i> =1)	25.4 \pm --- (<i>n</i> =1)	10.4 \pm 1.2 (<i>n</i> =4)	24.3 \pm 2.4 (<i>n</i> =4)
High Loading	29.7 \pm 4.0 (<i>n</i> =7)	12.6 \pm 2.0 (<i>n</i> =6)	10.7 \pm 50.1 (<i>n</i> =6)	11.6 \pm 1.2 (<i>n</i> =7)	25.4 \pm 2.5 (<i>n</i> =5)

The pre-burn sampling protocol is summarized as follows:

1. First, the pre-burn sample plot locations were marked on the ground with a metal (*rebar*) rod tipped with high-temperature white paint. The southeast corner of the pre-burn sample plot was found by measuring 0.5 meters north and west of the rebar rod.
2. All standing stubble and vertically-oriented residues within the pre-burn plot were clipped and placed in large paper grocery bags marked with the burn number, the plot number, and the words “pre-burn/standing” for subsequent oven drying. Standing material included all straw, with or without seed heads, and all incidental weeds. The bags were crimped and sealed with three staples.

3. All loose material and all attached but horizontally layered vegetation was collected and placed in large paper grocery bags marked with the burn number, the plot number, and the words “pre-burn/surface” for subsequent oven-drying. This included all chaff, seeds and seed heads, straw, and incidental weeds. Because some of the fields had undergone pre-burn tillage during previous cropping cycles, considerable care was taken to keep dirt out of the sample bags and to avoid “excavating” un-decomposed vegetative material that would not otherwise be consumed during a fire. The bags were crimped and sealed with three staples.

Following the burn, the post-burn sampling protocol was as follows:

4. The northwest corner of the post-burn sample plot was found by measuring 0.5 meters south and east of the rebar rod.
5. If any was found, all standing stubble and vertically-oriented residues were clipped and placed in large paper grocery bags marked with the burn number, the plot number, and the words “post-burn/standing” for subsequent oven-drying. However, no standing stubble was collected in any of the post-burn sample plots because all of this material was consumed by fire.
6. Next, all loose material and all attached but horizontally layered vegetation was collected and placed in large paper grocery bags marked with the burn number, the plot number, and the words “post-burn/surface” for subsequent oven-drying. This included all ash and unburned chaff, seeds and seed heads, straw, and incidental weeds. As in the pre-burn sampling, considerable care was taken to keep dirt out of the sample bags and to avoid “excavating” vegetative material from the soil. The bags were crimped and sealed with three staples.

The post-burn loading determination was performed within two hours following the end of each burn to ensure that the ash and unburned straw was collected before any material was blown into or out of the measurement plots. In some cases, plastic boxes measuring slightly greater than 0.5-meters on a side were placed over the plots to prevent disturbance by the wind or the field crew.

All of the pre- and post-burn sample bags were placed in large plastic debris bags marked with the burn unit name and number, and transported to Dr. Bill Johnston’s laboratory at Washington State University, Pullman, for subsequent drying, dirt extraction, weighing, and recording.

In the laboratory, the sample bags were opened and the contents oven-dried at a temperature of 140°F for at least 48 hours and then weighed. The samples were then screened to remove any dirt that entered the bag during field collection. The weight of the dirt was then subtracted from the

oven-dry weight of each sample bag from which it was taken. The net sample weights were then determined by subtracting the oven-dry bag weights.

Pre-burn and post-burn loading for each test unit were calculated according to:

$$L_{\text{Pre-Burn}} \text{ or } L_{\text{Post-Burn}} (\text{kg ha}^{-1}) = \frac{(W_{\text{OD; Surface}} + W_{\text{OD; Standing}})(10,000 \text{ m}^2 \text{ ha}^{-1})}{(1000 \text{ g kg}^{-1})} \quad (1)$$

In Equation (1), $L_{\text{Pre-Burn}}$ and $L_{\text{Post-Burn}}$ are the pre-burn and post-burn loadings (kg dry biomass ha^{-1}), respectively. W_{OD} is the oven-dry sample weight (g m^{-2} ; measured to 1/100th of a gram), and the subscripts “surface” and “standing” refer to loose materials lying on the surface and standing stubble, respectively. $L_{\text{Pre-Burn}}$ and $L_{\text{Post-Burn}}$ were calculated for each test unit by taking the averages of all ten sub-samples. Fuel loading units were expressed as kg ha^{-1} in the emission factor calculations, but were summarized as tons acre^{-1} .

2.2.2 Residue Moisture Content

Moisture sampling of soil and residue strata was performed to assist in explaining any variation in residue consumption and emissions that occurred. Higher residue moisture may be expected to produce lower residue consumption and combustion efficiencies, and higher CO and particulate matter emission factors. The sampling protocol was as follows:

1. Within each burn unit, ten randomly located samples were taken during the 30-minute period preceding the start of ignition. At all ten moisture plots, from one to three different samples were collected depending on the thickness of the residue layer. If the residue layer was more than about 2 inches deep, then three different samples were collected: a stratified sample from the upper part of the layer (“upper”), a stratified sample from the lower part of the layer in contact with the soil surface (“lower”), and a bulk sample from the entire layer (“entire”). If the residue layer was less than 2 inches deep, then only an entire residue sample was collected.
2. All chaff, seeds and seed heads, and straw were collected. The volume of sample taken was roughly 2,000 cubic centimeters, or 35 to 100 grams depending on the moisture content of the sample. Because some of the fields had undergone pre-burn tillage during previous cropping cycles, considerable care was taken to keep dirt out of the sample bags and to avoid “excavating” un-decomposed vegetative material that would not otherwise be consumed during a fire.
3. At three of the ten plots, standing stubble and soil samples were also taken. The volume of each sample was roughly 2,000 cubic centimeters. The soil (sampled to a typical depth of 2 inches) and residue samples were placed in small paper bags marked with the burn number, the plot number, date, and sample name. The bags were

crimped and sealed with three staples. The bags were immediately weighed to determine fresh or field weight (W_{Field}). All bags were placed in large plastic debris bags marked with the burn unit name and number, and transported to Dr. Bill Johnston's laboratory at Washington State University, Pullman, for subsequent drying, weighing, and recording.

In the laboratory, the sample bags were oven-dried at a temperature of 140°F for at least 48 hours and then weighed to determine the dry weight (W_{OD}). The relative residue moisture contents of the three residue layer strata, the soil layer, and the standing stubble fractions were calculated according to:

$$\text{RMC (\%)} = \left[\frac{(W_{\text{Field}} - W_{\text{OD}})}{W_{\text{OD}}} \right] \cdot 100 \quad (2)$$

where RMC is the residue moisture content, W_{Field} the fresh weight of the samples (g), and W_{OD} is the oven-dried weight (g).

2.2.3 Combustion Emissions

The USDA Forest Service's Missoula Fire Sciences Laboratory's Fire Atmosphere Sampling System (FASS) was used to measure the emissions of carbon species (ie., CO_2 , CO, CH_4 , and $\text{PM}_{2.5}$) and other fire-related parameters such as temperature and combustion efficiency, in real time (Ward et al., 1992b; Susott et al., 1991). Combustion efficiency is the proportion of total carbon emissions (including all carbon species such as CO_2 , CO, CH_4 , and others) that is emitted as CO_2 . The more *complete* the combustion, the greater the fraction of total carbon emitted as CO_2 , and the higher the combustion efficiency.

The field sampling procedure involved setting up two FASS packages 30 meters apart on the downwind side of the residue sampling area. To avoid edge effects, the tower pairs were placed at least 70 meters from the unit edge. Each FASS package was triggered independently and switched from a background mode to a sampling mode when the temperature at the sampling head exceeded 67°C (153°F). Each sampling package was programmed to switch from sampling of flaming combustion to smoldering combustion depending on the expected fire residence time for the ignition pattern being tested.

2.3 Laboratory Analysis

2.3.1 Canister Gas Samples

The canister gas samples and filters were analyzed at the Intermountain Fire Sciences Laboratory in Missoula, Montana, U.S.A. Canister samples were analyzed for CO_2 , CO, CH_4 , and hydrocarbons using gas chromatography (Hewlett Packard Model 5890 Series II). The canisters were pressurized with sample gas to approximately 20 pounds per square inch absolute (psia).

Two columns and two chromatography systems were used, one for CO₂ and CO, and another for CH₄ and carbon-2 (C₂) and carbon-3 (C₃) gases. The CO₂ and CO analysis was performed using a 1-milliliter (ml) sample loop filled directly from the canister. The column used in the analysis consisted of a 6-foot-long, 1/8-inch diameter Carbosphere (Alltech) carbon molecular sieve with helium carrier gas (flow rate of 16 ml per minute) passing through a methanizer and FID at 300 degrees Celsius (°C). CO and CO₂ were analyzed in separate isothermal runs, with CO run at 30°C and CO₂ run at 100°C.

The CH₄, C₂, and C₃ analysis was performed with a 0.53-millimeter (mm) diameter by 35-m long GS-Q (J&W Scientific) megabore column with a 0.53-mm diameter by 6-foot long HP-1 pre-column. The sample is directly injected from the canister into a 0.25-ml sample loop. The carrier gas was helium (flow rate of 4 ml/min), with an FID at 200°C and helium makeup gas. The temperature was programmed at 30°C for six minutes, then increasing at a rate of 10°C/min to a final temperature of 90°C.

Chromatogram data were collected and processed using Hewlett-Packard ChemStation II software connected via a computer link to the gas chromatograph. The ChemStation II software also controlled the operating parameters of the gas chromatograph and performed the integration of the peaks of the chromatograms. Three gas standards were analyzed with each set of samples in order to construct a standard curve for each gas based on integrated peak area, from which sample concentrations are calculated.

2.3.2 Teflon Filter Samples

The Teflon filters used in the PM_{2.5} determination were conditioned and weighed in a controlled-environment room at 68°F and 50-percent relative humidity. Prior to weighing, the filters were conditioned for at least 24 hours to stabilize the particulate matter weights and to reduce the effects of static electricity on the weighing process. Each filter was weighed three times on a Mettler M4 microbalance to a precision of one microgram (µg). The balance was linked to a software program that collects and stores the weights and room condition. Filters were re-weighed until weights were reproducible to within 5 µg. The balance was tarred (zeroed) before each weighing. A calibration weight was used once every five filters to verify the accuracy and calibration of the microbalance. Each filter was pre-weighed prior to sample collection using this procedure, and then again after field collection. Control filters were used to correct for environmental and handling variability in the filter weights. The control filters were handled in the same way as the treatment filters.

PM_{2.5} concentrations were based on the final particulate matter weights (post-weight minus pre-weight) and the volume of air drawn through the filter at about 2 liters per minute during the emission sampling. A small subset of the Teflon filters was selected for PAH analysis. The PAH sample analysis was performed at the Southwest Research Institute, San Antonio, Texas, U.S.A.

2.4 Data Analysis

2.4.1 Fuel Consumption

The absolute residue consumption, referred to as the fuel consumption (FC), was calculated as:

$$FC_{\text{Absolute}} (\text{kg ha}^{-1}) = L_{\text{Pre-Burn}} - L_{\text{Post-Burn}} \quad (3)$$

where FC_{Absolute} is the biomass burned (kg ha^{-1}), and $L_{\text{Pre-Burn}}$ and $L_{\text{Post-Burn}}$ are the residue loadings (kg ha^{-1}) for each of the test units. The relative fuel consumption, FC_{Relative} , was calculated according to:

$$FC_{\text{Relative}} (\% \text{ Consumed}) = \frac{FC_{\text{Absolute}}}{L_{\text{Pre-Burn}}} \quad (4)$$

2.4.2 Pollutant-Specific Emission Factors

Pollutant-specific emission factors were calculated using the carbon mass balance equation (Radke et al., 1990; Ward et al., 1979). The carbon balance is expressed as:

$$C_{\text{Pre-Burn}} - C_{\text{Post-Burn}} = C_{\text{CO}_2} + C_{\text{CO}} + C_{\text{CH}_4} + C_{\text{PM}_{2.5}} \quad (5)$$

where $C_{\text{Pre-Burn}}$, $C_{\text{Post-Burn}}$, C_{CO_2} , C_{CO} , C_{CH_4} , and $C_{\text{PM}_{2.5}}$ represent the carbon mass in the pre-burn biomass, the post-burn biomass, and in emissions of CO_2 , CO , CH_4 , and $\text{PM}_{2.5}$, respectively (kg C). Typically, the hydrocarbon content of emissions from vegetation burning is considerably less than 5 percent of the total emissions (Ward et al., 1992). For this reason, the contribution from hydrocarbons was not considered in Equation (5). The carbon mass, C , of the burned and unburned residue is the product of the average residue loading, the area burned, and the fractional carbon content:

$$C_{\text{Pre-Burn}} (\text{kg C}) = L_{\text{Pre-Burn}} \times A \times f_{\text{Pre-Burn}} \quad (6a)$$

$$C_{\text{Post-Burn}} (\text{kg C}) = L_{\text{Post-Burn}} \times A \times f_{\text{Post-Burn}} \quad (6b)$$

where C is the carbon mass (kilograms C); A is the area burned (ha); L is the fuel load (kg ha^{-1}); and f is the fractional carbon content. The subscripts “Pre-Burn” and “Post-Burn” refer to the fuel loading before and after the fire, respectively (kg ha^{-1}). For $f_{\text{Pre-Burn}}$ a value representative for cereal-grains and grasses was used, i.e., 0.50 grams of carbon per gram of dry biomass (e.g., Hurst et al., 1994; Turn et al., 1997; Hughes et al., 2000). Although the value of $f_{\text{Post-Burn}}$ is dependent on the weight fractions of ash and unburned residue after the fire (e.g., KuhlBusch and Crutzen, 1995) a constant value of 0.50 grams carbon per kilogram of dry biomass was used since the effect of ash weight on $f_{\text{Post-Burn}}$ was negligible (maximum: up to 5 percent of the total post-burn residue).

For gaseous compounds, the carbon mass is expressed as:

$$C_x \text{ (kg C)} = M_{\text{Air}} \times \chi_x \times \kappa_x \times \frac{12}{MM_x} \quad (7)$$

In Equation (7), M_{Air} is the mass of air sampled (kg air), χ the measured volume concentration (ppmv), κ a constant to convert volume concentration to mass concentration (ppmv to kg pollutant kg air⁻¹), MM_x the molar weight of the gaseous compounds, and the ratio $12/MM_x$ a conversion factor from total mass to carbon mass. The subscript x refers to the gaseous compound under consideration, i.e., CO₂, CO or CH₄. M_{air} was calculated from the sampled air volume, air pressure, and temperature. Air volume and ambient temperature were monitored in the field. Air pressure was derived from sea-level air pressure on the day of the first burn in each season. Sea-level air pressure was adjusted to the elevation of the calibration site using a rule-of-thumb of 1 mbar per 8 meters of ascent. Calibrations were performed in Dayton and Walla Walla, Washington, for the spring and fall burns, respectively.

The carbon mass in the PM_{2.5}, $C_{\text{PM2.5}}$, is defined as follows:

$$C_{\text{PM2.5}} \text{ (kg C)} = M_{\text{PM2.5}} \times 10^{-3} \times f_{\text{PM2.5}} \quad (8)$$

where $M_{\text{PM2.5}}$ is the mass of particulate matter <2.5 μm in diameter captured on the filter (g); $f_{\text{PM2.5}}$ is the fractional carbon content of the particulate matter (grams carbon per gram total mass of PM_{2.5}); and 10^{-3} is a conversion factor from grams to kilograms. A typical value of $f_{\text{PM2.5}}$ for particulate emissions from burning of cereal crops and grass is 0.66 (Turn et al., 1997). Substituting (6a), (6b), (7), and (8) into (5), and rearranging the terms, yields:

$$[(L_{\text{Pre-Burn}} \times f_{\text{Pre-Burn}}) - (L_{\text{Post-Burn}} \times f_{\text{Post-Burn}})] A = [C_{\text{gaseous, total}} \times M_{\text{Air}}] + [M_{\text{PM2.5}} \times 10^{-3} \times f_{\text{PM2.5}}] \quad (9)$$

where $C_{\text{gaseous, total}}$ is the total emitted carbon mass from the gaseous compounds (kilograms carbon per kilogram of air):

$$C_{\text{gaseous, total}} = \left(\chi_{\text{CO}_2} \times \kappa_{\text{CO}_2} \times \frac{12}{MM_{\text{CO}_2}} \right) + \left(\chi_{\text{CO}} \times \kappa_{\text{CO}} \times \frac{12}{MM_{\text{CO}}} \right) + \left(\chi_{\text{CH}_4} \times \kappa_{\text{CH}_4} \times \frac{12}{MM_{\text{CH}_4}} \right) \quad (10)$$

Solving for A and expressing the total pollutant-specific emissions as a fraction of total carbon, yields the following equation for the emission factor of PM_{2.5}:

$$EF_{\text{PM2.5}} \text{ (g kg fuel}^{-1}\text{)} = \frac{M_{\text{PM2.5}} [(L_{\text{Pre-Burn}} \times f_{\text{Pre-Burn}}) - (L_{\text{Post-Burn}} \times f_{\text{Post-Burn}})]}{[L_{\text{pre-Burn}} - L_{\text{Post-Burn}}] [(C_{\text{gaseous, total}} \times M_{\text{Air}}) + (M_{\text{PM2.5}} \times 10^{-3} \times f_{\text{PM2.5}})]} \quad (11)$$

The emission factor for PM₁₀ was estimated by dividing EF_{PM2.5} by a scaling factor of 0.8 (Magliano et al., 1999; Purvis et al., 2000). For the gaseous compounds the emission factor is defined as:

$$EF_x \text{ (g kg fuel}^{-1}\text{)} = \frac{(M_{\text{Air}} \times \chi_x \times \kappa_x \times 10^3) [(L_{\text{Pre-Burn}} \times f_{\text{Pre-Burn}}) - (L_{\text{Post-Burn}} \times f_{\text{Post-Burn}})]}{[L_{\text{Pre-Burn}} - L_{\text{Post-Burn}}] [(C_{\text{gaseous, total}} \times M_{\text{Air}}) + (M_{\text{PM2.5}} \times 10^{-3} \times f_{\text{PM2.5}})]} \quad (12)$$

where the 10³ in the numerator is a constant to convert from kilograms per cubic meter to grams per cubic meter, and the subscript x stands for the gaseous compound considered, i.e., CO₂, CO or CH₄. Both the emission factors for the gaseous compounds and for particulate matter are based on grams of pollutant emitted per kilograms of dry fuel burned.

If the carbon fractions in the pre- and post-burn samples are equal (f_{Pre-Burn} and f_{Post-Burn} in Equations 6a, 6b, 9, 11, and 12) and set equal to 0.5, then Equation (12) reduces to the following approximate equation:

$$EF_x \text{ (g kg fuel}^{-1}\text{)} \cong \frac{\chi_x|_{\text{Fire}} (1,000 \text{ g kg}^{-1})}{2.0 \cdot (\chi_{\text{C-CO}_2}|_{\text{Fire}} + \chi_{\text{C-CO}}|_{\text{Fire}} + \chi_{\text{C-CH}_4}|_{\text{Fire}} + \chi_{\text{C-PM2.5}}|_{\text{Fire}})} \Bigg|_j \quad (13)$$

In this equation, χ_x is the air concentration of pollutant species x (where x = CO₂, CO, CH₄, or PM_{2.5}) in milligrams per cubic meter (mg m⁻³), and j is the combustion phase (j = 1, flaming phase; j = 2, smoldering phase).

Using the assumptions expressed in the lead-in paragraph to Equation (13), Equation (13) produced PM_{2.5} emission factors that were within 1/100th of a percent of the values produced using Equation (11).

The emission factors for selected PAH species was scaled to the PM_{2.5} emission factor by calculating the ratio of the specific-PAH mass to the total fine-particle mass measured on the filters:

$$EF_{\text{PAH}} \text{ (g kg fuel}^{-1}\text{)} = \left(\frac{M_{\text{PAH}}}{M_{\text{PM2.5}}} \right) \cdot EF_{\text{PM2.5}} \quad (14)$$

where M is the filter-based mass (PM_{2.5} or PAH-specific, g), and EF_{PM2.5} is the fine-particulate emission factor calculated from Equation (12) (grams per kilograms of residue consumed).

The FASS units are specifically designed to make the measurements needed in each combustion phase. Although fuel loading could be measured only before and after the fire, fuel consumption

in the flaming and smoldering phase was estimated from the FASS data (Personal communication, Ron Babbitt). A summary of the fractions used to calculate a weighted average emission factor over the two fire phases is shown in Table 2.4.

Table 2.4. Weighting Factors Used to Calculate Emission Factors for the Flaming and Smoldering Combustion Phases.

Shown are the percent of carbon mass emitted in the flaming phase and the sample size (± 1 Standard Error).

Ignition Type	Percent of Carbon Emitted in Flaming Phase	Number of Towers with FASS Data
Spring		
Backing Fire	68.0 ± 7.7	6 (10)
Head Fire	99.7 ± 0.2	9 (12)
Strip Head Fire	46.6 ± 10.8	5 (6)
Fall		
Baseline Fire	99.0 ± 0.3	12 (15)
Backing Fire	84.0 ± 5.3	5 (6)
Heading Fire	94.7 ± 2.9	3 (6)
Strip Head Fire	74.8 ± 10.0	4 (4)

2.4.3 Statistical Analysis

Statistical analyses of the data set were carried out in SYSTAT 10 (SPSS Inc., 2000). All statistical analyses were based on mean values for the test units. Thus, when multiple sub-samples were taken (for example, in the case of fuel loadings [10 to 30 sub-samples per unit], moisture contents [3 to 5 sub-samples per unit] and pollutant emissions [2 to 5 sub-samples-), the sub-samples were averaged to obtain a value for the unit as a whole. These values were then used to test for statistical differences in fuel consumption, emission factors, and total emissions based on the season of burning, ignition type, and pre-burn fuel loading. If data were approximately normally distributed two-sample t-tests or analysis of variance was used, indicated as indicated as “t degrees of freedom (df) = t-value, P = significance level” and “ $F_{df \text{ between }, df \text{ error term }} = F\text{-statistic, } P=\text{significance level,}$ ” respectively. To distinguish between different combinations of treatments, a Bonferonni post-hoc test (i.e., a statistical test used to determine difference between more than two sample means) was used within ANOVA. A non-parametric Kruskal-Wallis test was used when criteria for a normal distribution of the data were not met. Basically, all of the above tests indicate whether two (t-test or Kruskal-Wallis) or multiple groups (ANOVA) were statistically different for a particular parameter. The tested parameters were “continuous” variables, such as residue loading, residue moisture content, and emission factors. The grouping variables were categorical, i.e., pre-burn residue loading (high vs. low), ignition type (4 categories), or season (spring vs. fall). The most important value for interpretation is the P-value. This value indicates the probability that an observed difference is due to random chance rather than due to patterns of

variation in the tested variables. A minimum P-value of 0.05 was used to consider differences between groups that are statistically different. This P-value represents a 5 percent chance of the observed difference being due to random variation in the data, rather than a "real" difference between categories.

It is important to characterize the data for the presence of *outliers*, or extreme values. The presence of outliers can cause the distribution of data to deviate substantially from a normal distribution. This is an undesired effect because normality of data distributions is one of the underlying assumptions of the statistical techniques described above. When the normality criterion is not met the results from t-tests and ANOVA are not reliable, and these techniques cannot be used. Statistical outliers were identified based on t-tests of the *studentized* (i.e., normalized) residual in SYSTAT 10 (SPSS Inc., 2000).

In the final analysis, four extreme emission factor values were removed from the spring data set (Appendix C). Summaries of the complete data and the screened data are provided in Appendix B. The statistical analysis was based on the screened data only.

2.5 Quality Assurance and Quality Control Measures

This section provides a brief description of the quality assurance and quality control (QA/QC) measures that were taken to ensure a consistent, high quality data set. Included is a discussion of the following: site selection and unit layout criteria, number of replications, pre- and post-burn residue sampling, weather conditions at time of burning, recording of moisture fresh weights (scale resolution, duplicate weighing), extraction of dirt from samples, data handling including chain of custody, screening criteria used by Missoula Fire Science Laboratory to identify unsuitable data, statistical evaluation of data and identification of outliers, check of SYSTAT results against Excel spreadsheet, and calculation of emission factors using two independent calculation methods. This section describes what QA/QC procedures were used but does not include a description of the specific QA/QC results that were found, or an assessment of how well the QA/QC objectives were met.

All the study fields and units within the fields were selected based on the predicted pre-burn residue loading level, uniformity of pre-burn residue loading and site physiographic conditions, and proximity to other burn units (see Tables 2.1 and 2.2). Large (80-acre+) fields with uniform site conditions and predicted residue loading within the appropriate range were first chosen by Dr. Roland Schirman, Columbia County Extension Service. Later, Air Sciences selected the locations of individual 8-acre burn units within the fields. The locations of individual treatment units were selected to, as closely as possible, ensure the same site conditions within all three replications (burn units) of a treatment (see Table 2.1 for a listing of the treatments).

Pre- and post-burn residue loading was sampled in order to accurately assess the total residue consumption following each test burn. Within each burn unit, ten sampling locations were laid

out on a 30-meter grid upwind from expected locations of the twin FASS towers. At each sampling location, two 0.25-square-meter plots were sampled, spaced roughly 0.5 meters apart, to determine the pre-burn loading (N=10 per unit) and the post-burn loading (N=10 per unit), respectively (Section 2.3). Considerable care was taken to keep dirt out of the sample bags, and to avoid "excavating" vegetative material from the ground surface. All sample bags were clearly labeled with the field and unit name, date, treatment description, and type of sample (e.g., pre-burn residue), and folded and sealed using three staples. All the sample bags from a particular field (e.g., Beard) were assembled in one or more 30-gallon leaf bags, labeled with the field name, and then transported to WSU in Pullman, Washington. There, the bags were dried (>48 hours at 140°F), and weighed to determine oven-dried weight (duplicate weighing to 1/100th gram resolution). The oven-dried bag weight was subtracted from the total weight to obtain the true sample weight. In the laboratory, each sample bag was screened for dirt, and final weight adjusted to correct for any dirt weight.

The pre-burn loading was sampled within the two-week period prior to each burn, and the post-burn sampling was conducted immediately following each burn (usually beginning within 30 minutes following the end of flaming combustion). To avoid possible disturbance of the post-burn sample plots, a plastic box measuring slightly more 20 inches on a side was placed over the post-burn sample plot.

Residue moisture was sampled at randomly selected locations on the field (N=10). At each location several of the following moisture samples were taken depending on the thickness of residue layer (Section 2.2.2): entire layer (spring: N=10; fall: N=10), upper residue layer (spring: N=10; fall: N=3), lower residue layer (spring: N=10; fall: N=3), stubble (spring: N=3; fall: N=3), and upper soil layer (spring: N=3; fall: N=3). Fresh weight of the sample bags was determined in the field immediately after collection, with duplicate weighing to 1/100th gram resolution. All moisture samples were collected within the one-hour period preceding the ignition time. All sample bags were clearly labeled as discussed above, and folded and sealed using three staples. The sampled volume was ~2,000 cubic cm, varying from 35-100 g in weight, depending the moisture content. Bags were then transported to WSU in Pullman, where bags were dried (>48 hours at 140°F), and weighed to determine oven-dried weight (duplicate weighing to 1/100th g resolution).

The weather conditions were kept as similar as possible between burns by selecting burn days with comparable meteorological conditions. Wind speed, temperature and relative humidity were monitored before, during, and after the burns using a 2-meter-tall meteorological tower (Table 2.2).

The Intermountain Fire Sciences Laboratory in Missoula, MT analyzed the atmospheric concentration data collected by the FASS towers. In the laboratory, data from the FASS towers were processed and the canister- and filter data analyzed. Data were screened for internal

consistency (Personal communication, R. Susott). The consistency checks including the following procedures. First, FASS data and canister data for CO₂ and CO emissions were compared. If results from these two methods agreed, then the samples were maintained in the database. If on the other hand, a discrepancy existed between the two methods, the samples were given a closer look in order to discover the reason for the difference. Discrepancies due to mislabeling of samples and canisters were fixed and samples maintained in the database. If a discrepancy could not be explained, the samples were deleted from the database. Potential error sources leading to the deletion of sample data included: air leaks in the field equipment, electrical failure of the field equipment, and laboratory errors that occurred during analysis of the canisters (Personal communication, R. Susott). Second, filter data were checked for internal consistency against CO concentrations. CO concentrations and PM_{2.5} mass should approximately track each other, as both are products of incomplete fuel combustion. If a large discrepancy existed between the two values, samples were given a closer look. Again, samples with large discrepancies that could not be explained or fixed were deleted from the database (Personal communication, R. Susott).

A complete set of data on residue loading and residue moisture content was provided to Air Sciences by WSU. Air Sciences processed the meteorological data. The Intermountain Fire Sciences Laboratory provided Air Sciences with the screened atmospheric concentration data (April 2001). Emission factors of all atmospheric species were calculated in MS Excel. Data for all the units were summarized at the sample level to obtain mean values for each unit. The unit averages were then used in subsequent statistical analysis. Both at the sample and at the unit level, statistical procedures were used to identify outliers and extreme values. Based on this analyses PM_{2.5} data for four FASS towers were excluded from the statistical analyses (Appendix C). Summaries by unit for both the complete and the screened database are summarized in Appendix B. The calculation of the emission factors for the PAH compounds was checked for accuracy by both Air Sciences (Maarten Schreuder) and the Missoula Intermountain Fire Sciences Laboratory (Steve Baker).

Statistical analyses were performed in SYSTAT 10 (SPSS, 2000). The database in SYSTAT was carefully checked against the database in MS Excel, to assure that no errors occurred in the data transfer between the two software packages. Only the screened data were used in the final statistical analysis.

RESULTS

3.1 Planned Versus Actual Residue Loading

During site selection, the pre-burn fuel loading was categorized as either high or low based on the WSU-AES rule-of-thumb of 100 pounds of residue per bushel of yield and a threshold loading of 4 tons per acre (8,000 lbs per acre). The fall burns showed good agreement between the actual and predicted residue loadings (Figure 3.1). However, the spring units showed poor agreement between the actual and predicted fuel loadings with the predicted “low” loadings measuring high and the predicted “high” loadings measuring low. For this reason, data were summarized based on the actual pre-burn fuel loading rather than the predicted fuel loading. Pre-burn fuel loading was significantly higher in the re-stratified high-loading units than in the re-stratified low-loading units (Table 3.1, $t_{24}=7.12$, $P<0.001$).

Figure 3.1. Actual Pre-Burn Fuel Load Versus Planned Fuel Load

The line indicates the cutoff value of 4.0 tons/acre. The data points represent the experimental units. The seasons are indicated as fall (F) and spring (S), and the planned fuel loading as baseline (C), high fuel loading (H), and low fuel loading (L).

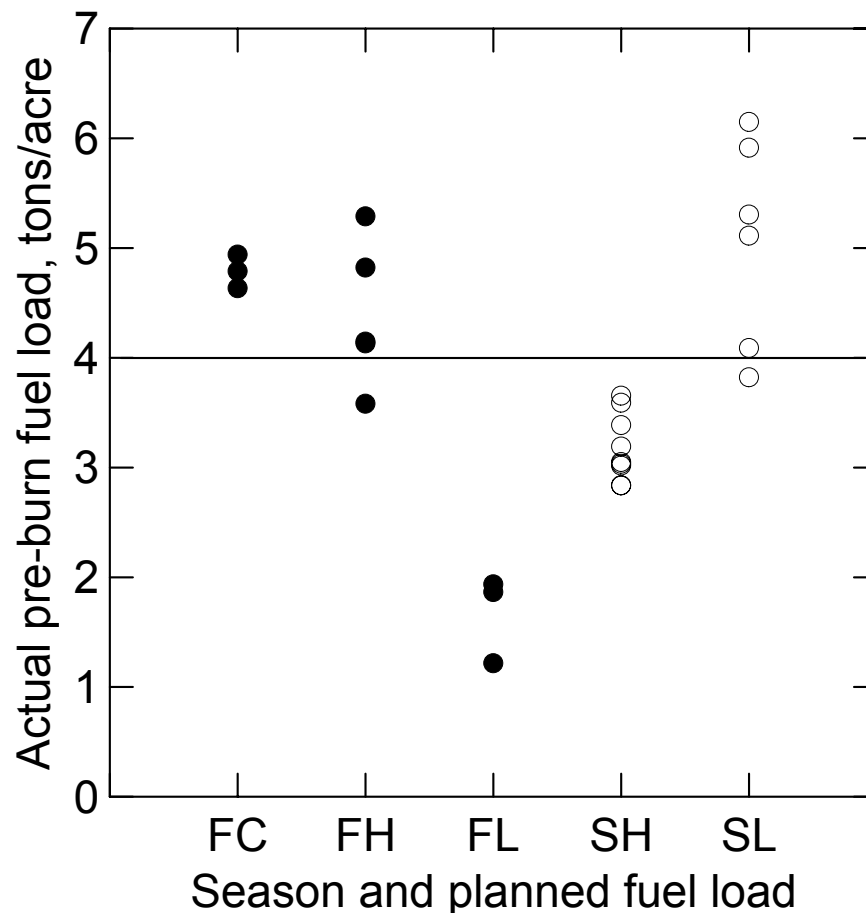


Table 3.1. Fuel Loading and Residue Consumption as a Function of Season, Ignition Type, and Pre-Burn Fuel Loading

Values shown are means \pm SE. Statistically different means based on high and low pre-burn fuel loading are indicated with different letter (T-test, "***" $p < 0.05$, "****" $p < 0.001$).

Season and Ignition Type	Pre-Burn Residue Loading (tons/acre)	Post-Burn Residue Loading (tons/acre)	Residue Consumption (tons/acre)	Residue Consumption (%)
Spring¹				
Backing Fire ($n=6$)	4.1 ± 0.5	1.5 ± 0.3	2.6 ± 0.3	65 ± 6
Head Fire ($n=6$)	4.2 ± 0.5	1.7 ± 0.3	2.5 ± 0.4	59 ± 6
Strip Head Fire ($n=3$)	3.0 ± 0.1	1.6 ± 0.4	1.4 ± 0.3	47 ± 12
All ($n=15$)	3.9 ± 0.3	1.6 ± 0.2	2.3 ± 0.2	59 ± 4
Fall²				
Baseline ($n=3$)	4.8 ± 0.1	1.7 ± 0.3	3.1 ± 0.4	64 ± 7
Backing Fire ($n=3$)	4.2 ± 0.4	1.6 ± 0.4	2.6 ± 0.7	59 ± 13
Head Fire ($n=3$)	1.7 ± 0.2	0.8 ± 0.2	0.9 ± 0.1	56 ± 7
Strip Head Fire ($n=2$)	4.7 ± 0.5	1.7 ± 0.3	3.0 ± 0.9	62 ± 12
All ($n=11$)	3.8 ± 0.4	1.4 ± 0.2	2.3 ± 0.4	60 ± 4
Spring and Fall				
Low Pre-Burn Loading ($n=14$)	2.9 ± 0.2 a ***	1.2 ± 0.2 a *	1.7 ± 0.2 a ***	58 ± 4
High Pre-Burn Loading ($n=12$)	4.9 ± 0.2 b	1.9 ± 0.2 b	3.0 ± 0.3 b	62 ± 4

¹ Generally the "low-moisture" group of burn units

² Generally the "high-moisture" group of burn units

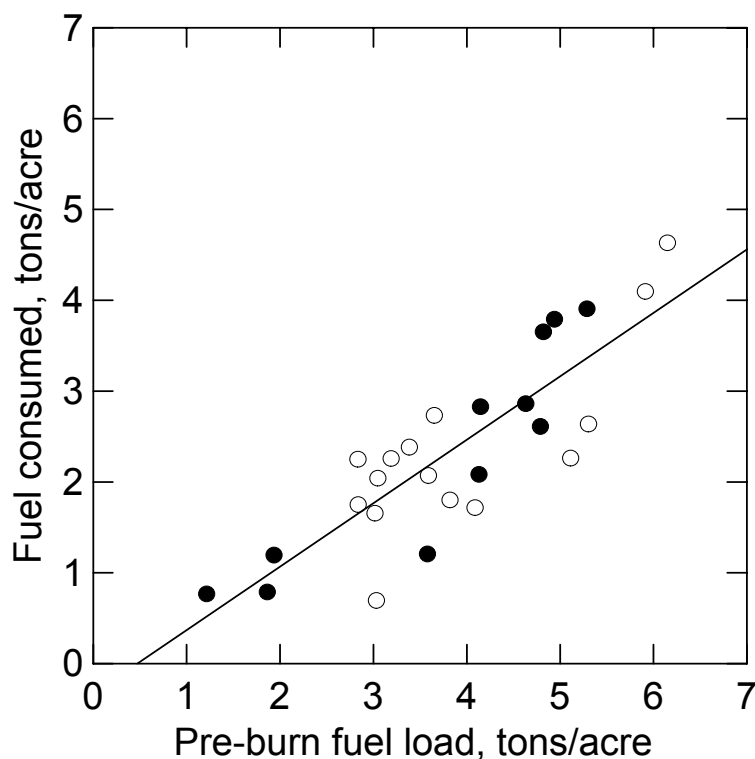
3.2 Residue Consumption

Both pre-burn fuel loading and post-burn fuel loading were lower on the re-stratified low-loading units compared to the high-loading units (Table 3.1). Fuel consumption was expressed in both absolute and relative terms using Equations (3) and (4). Absolute fuel consumption was significantly higher in those units with high pre-burn fuel loading than in those with low pre-burn fuel loading (Table 3.1; $t_{24}=4.57$, $P < 0.001$). That is, the higher the pre-burn fuel loading the higher the absolute fuel consumption. Moreover, there was a strong overall relationship between the absolute fuel consumption and the pre-burn fuel loading (Figure 3.2; $R^2=0.71$, $F_{1,24}=60.85$, $P < 0.001$). However, absolute fuel consumption was not affected by season or ignition type.

Relative fuel consumption (that is, the residue consumption expressed as a percentage of the pre-burn loading) did not differ significantly by season, by ignition type, or by pre-burn fuel loading (Table 3.1, $P > 0.05$), nor was it affected by wind speed or residue moisture content ($P > 0.05$).

Figure 3.2. Absolute Fuel Consumption as a Function of Pre-Burn Residue Loading for Spring (Open Circles) and Fall Season (Closed Circles)

The relationship can be described as follows: Fuel consumption = $-0.417 + (0.713 \times \text{Pre-Burn Residue Loading})$, $R^2=0.71$, $F_{1,24}=60.85$, $P<0.001$).



In summary, absolute fuel consumption was most strongly correlated with the pre-burn loading. The higher the pre-burn residue loading, the higher is the residue consumption. This suggests an opportunity for using the pre-burn residue loading to predict the residue consumption for all types of fires and under a wide range of weather conditions. Practical methods for growers (or others) to sample the pre-burn residue loading have yet to be devised, however.

3.3 Emission Factors

3.3.1 PM_{2.5} Emission Factors

Emission factors for particulate matter less than 2.5 μm in aerodynamic diameter ($EF_{PM_{2.5}}$) were higher in the fall than in the spring (Table 3.2; $F_{1,24}=15.48$, $P<0.001$). There were no differences in $EF_{PM_{2.5}}$ based on wind speed or pre-burn residue loading. Although there was a trend towards higher $EF_{PM_{2.5}}$ in the units with a high pre-burn fuel loading, especially in the fall, these differences were not statistically significant (Spring $t_{13}=0.62$, $P=0.548$; Fall $t_9=1.99$, $P=0.078$). In the spring the backing fires had a significantly lower $EF_{PM_{2.5}}$ compared to the head fires (Table 3.2; $F_{2,12}=6.38$, $P=0.013$), and strip head fires had an intermediate $EF_{PM_{2.5}}$ (Table 3.2). In the fall a similar trend was observed, with the highest $EF_{PM_{2.5}}$ for the control burns (high-intensity fires),

and lower $EF_{PM_{2.5}}$ for strip head fires and backing fires. However, in the fall these differences were not statistically significant, due to the large variation in the emission factors. Moreover, fall head fires had the lowest $EF_{PM_{2.5}}$ compared to the other ignition types.

The patterns in $EF_{PM_{2.5}}$ correspond to the opposite patterns in the combustion efficiency (CE; Table 3.2). Thus, higher $EF_{PM_{2.5}}$ correspond to lower CE values (Figure 3.6). Similarly, emission factors of other incomplete combustion products, EF_{CO} and EF_{CH_4} , tended to increase with lower CE (Table 3.2, Figures 3.4 and 3.5), while EF_{CO_2} decreased with lower CE (Table 3.2, Figure 3.3).

Table 3.2. Combustion Efficiency (CE) and Estimated Emission Factors (EF) for CO_2 , CO, CH_4 , $PM_{2.5}$, and PM_{10}

Emission factors for PM_{10} were estimated as $EF_{PM_{2.5}}$ divided by 0.8. Values are means \pm SE.

Season and Ignition Type	Pollutant-Specific Emission Factors (lbs pollutant ton fuel ⁻¹)					
	CE (%)	CO_2	CO	CH_4	$PM_{2.5}$	PM_{10}
Spring¹						
Backing Fire (<i>n</i> =6)	97.2 \pm 0.2	3566 \pm 6	57 \pm 3	1.6 \pm 0.4	3.7 \pm 0.7	4.6 \pm 0.9
Head Fire (<i>n</i> =6)	95.9 \pm 0.3	3517 \pm 12	83 \pm 7	1.9 \pm 0.2	6.9 \pm 0.6	8.6 \pm 0.8
Strip Head Fire (<i>n</i> =3)	97.2 \pm 0.1	3565 \pm 3	55 \pm 0.6	1.1 \pm 0.2	5.5 \pm 1.2	6.9 \pm 1.5
All (<i>n</i> =15)	96.7 \pm 0.2	3546 \pm 8	67 \pm 5	1.6 \pm 0.2	5.3 \pm 0.5	6.8 \pm 0.6
Fall²						
Baseline (<i>n</i> =3)	92.4 \pm 1.8	3388 \pm 67	143 \pm 29	4.8 \pm 1.2	12.3 \pm 3.2	15.4 \pm 4.0
Backing Fire (<i>n</i> =3)	94.3 \pm 0.4	3459 \pm 14	112 \pm 7	3.5 \pm 0.4	9.7 \pm 1.3	12.1 \pm 1.6
Head Fire (<i>n</i> =3)	94.3 \pm 1.0	3460 \pm 36	117 \pm 22	2.7 \pm 0.5	7.2 \pm 1.8	9.0 \pm 2.3
Strip Head Fire (<i>n</i> =2)	95.4 \pm 0.6	3497 \pm 23	87 \pm 17	3.1 \pm 0.3	10.3 \pm 1.9	12.9 \pm 2.4
All (<i>n</i> =11)	94.0 \pm 0.6	3447 \pm 22	117 \pm 11	3.6 \pm 0.4	9.8 \pm 1.1	12.3 \pm 1.4
Spring¹						
Low Pre-Burn Loading (<i>n</i> =10)	96.9 \pm 0.3	3553 \pm 9	63 \pm 5	1.4 \pm 0.2	5.1 \pm 0.7	6.5 \pm 0.8
High Pre-Burn Loading (<i>n</i> =5)	96.3 \pm 0.4	3532 \pm 14	74 \pm 8	2.0 \pm 0.2	5.9 \pm 0.9	7.4 \pm 1.1
Fall²						
Low Pre-Burn Loading (<i>n</i> =4)	94.5 \pm 0.7	3467 \pm 27	113 \pm 16	2.7 \pm 0.4	7.3 \pm 1.3	9.0 \pm 1.6
High Pre-Burn Loading (<i>n</i> =7)	93.7 \pm 0.9	3436 \pm 32	120 \pm 15	4.1 \pm 0.6	11.3 \pm 1.4	14.1 \pm 1.8

¹ Generally the “low-moisture” group of burn units

² Generally the “high-moisture” group of burn units

$EF_{PM_{2.5}}$ were related to the pre-burn moisture content. The highest coefficients of determination (R^2) were found for the relationships between $EF_{PM_{2.5}}$ and the moisture content in the upper and lower residue layers, but significant relationships were also found for moisture content in stubble and in the entire layer (Table 3.3). For example, 79 percent of the variation in $EF_{PM_{2.5}}$ could be explained by variation in the pre-burn moisture content of the upper layer (Table 3.3, $R^2 = 0.79$). Note that including the experimental unit McGee #3 in the regression analysis had a large effect on the percent regression results (Table 3.3). Although this unit was internally consistent, based on the five FASS towers that were present, it represented an extreme outlier in the regression on moisture content. The regression analyses of the emission factors of CO_2 , CO, and CH_4 on fuel moisture content yielded similar R^2 -values as in the case of $PM_{2.5}$ (Table 3.3).

Figure 3.3. Relationship Between Combustion Efficiency and Emission Factor for CO_2 ($R^2=1.00$, $F_{1,24}=2.18$, $P<0.001$)

Shown are Spring (open circles) and Fall units (closed circles).

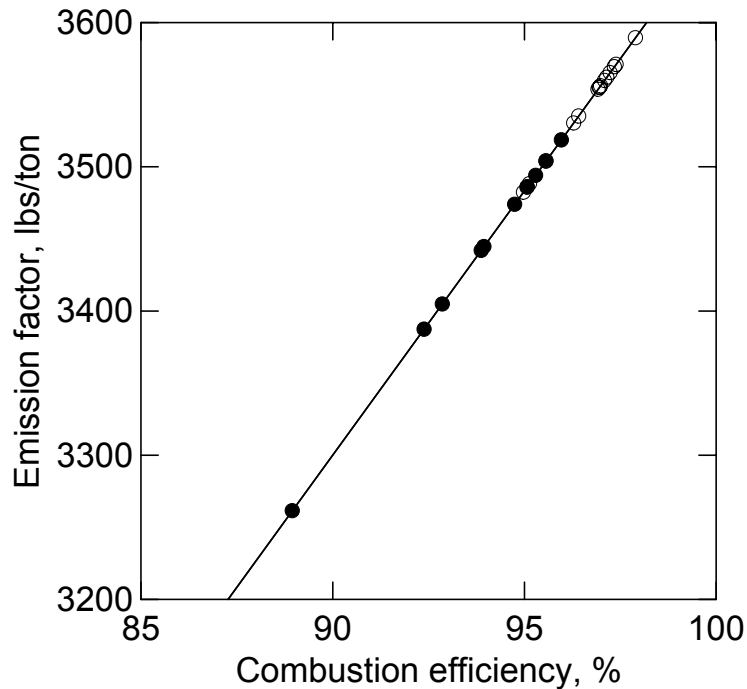


Figure 3.4. Relationship Between Combustion Efficiency and Emission Factor for CO ($R^2=0.98$, $F_{1,24}=1074.45$, $P<0.001$)

Shown are spring (open circles) and fall units (closed circles).

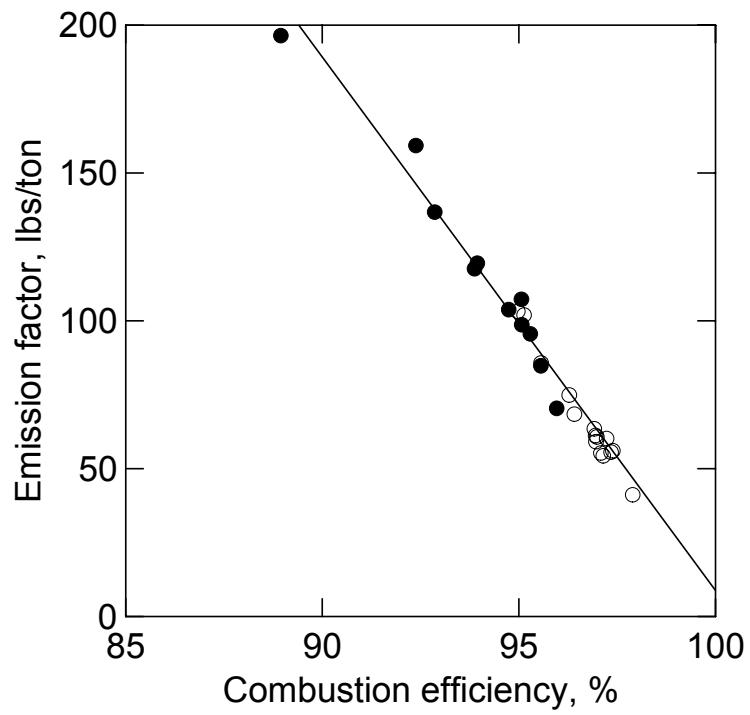


Figure 3.5. Relationship Between Combustion Efficiency and Emission Factor for CH₄ ($R^2=0.87$, $F_{1,23}=162.84$, $P<0.001$)

Shown are spring (open circles) and fall units (closed circles).

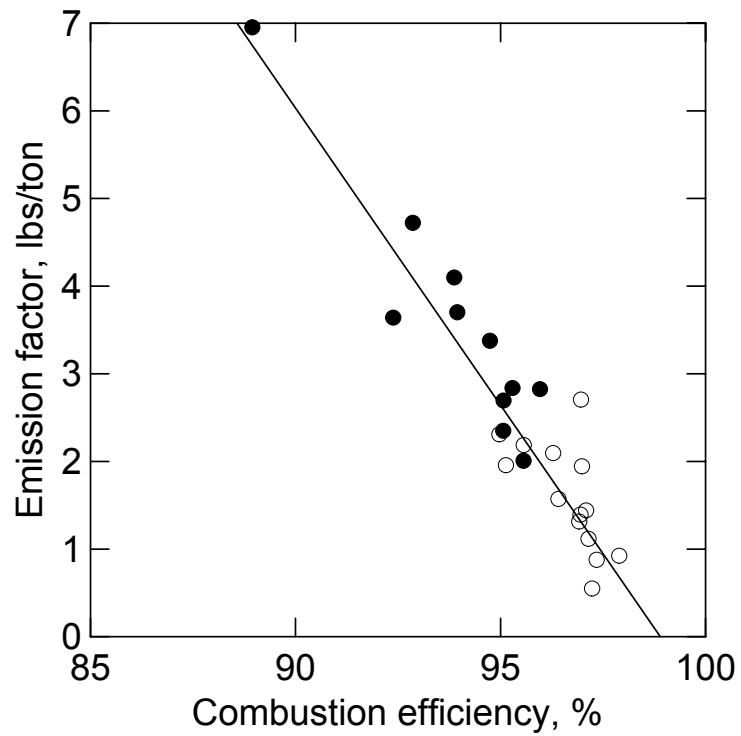


Figure 3.6. Relationship Between Combustion Efficiency and Emission Factor for PM_{2.5} ($R^2=0.61$, $F_{1,24}=39.75$, $P<0.001$)

Shown are spring (open circles) and fall units (closed circles)

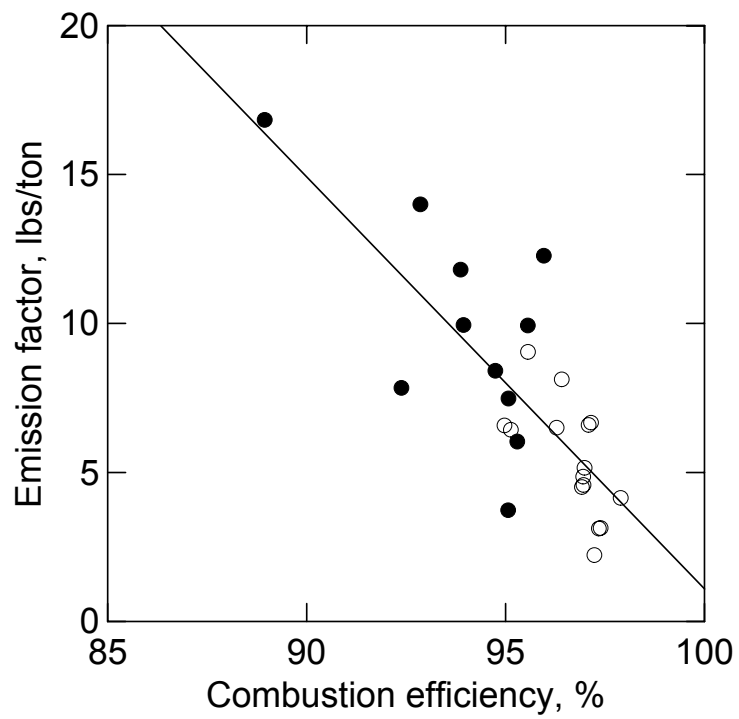


Table 3.3. Relationship Between the Emission Factors and Pre-Burn Residue Moisture Content.

Fuel moisture content is shown for stubble and the upper, lower, and entire surface residue layers. Relationships that are not statistically significant ($P>0.05$) are designated "n.s." All others are statistically significant. Pollutant emission factors were not related to soil moisture content.

Emission Factor/ Fuel Bed		All Units		Without McGee #3 Outlier	
Component	Sign of Slope	R ²	P-Value	R ²	P-value
Emission Factor CO₂					
Stubble	Negative	0.31	0.002	0.59	<0.001
Upper Layer	Negative	0.22	0.068 (n.s.)	0.70	0.001
Lower Layer	Negative	0.25	0.055 (n.s.)	0.63	0.002
Entire Layer	Negative	0.24	0.007	0.36	0.001
Emission Factor CO					
Stubble	Positive	0.32	0.002	0.52	<0.001
Upper Layer	Positive	0.26	0.052 (n.s.)	0.65	0.002
Lower Layer	Positive	0.28	0.045	0.58	0.004
Entire Layer	Positive	0.20	0.012	0.26	0.005
Emission Factor CH₄					
Stubble	Positive	0.28	0.004	0.54	<0.001
Upper Layer	Positive	0.27	0.048	0.67	0.001
Lower Layer	Positive	0.31	0.034	0.65	0.002
Entire Layer	Positive	0.37	0.001	0.58	<0.001
Emission Factor PM_{2.5}					
Stubble	Positive	0.35	0.001	0.50	<0.001
Upper Layer	Positive	0.44	0.012	0.79	<0.001
Lower Layer	Positive	0.48	0.008	0.77	<0.001
Entire Layer	Positive	0.48	<0.001	0.62	<0.001

The mean PM_{2.5} emission factors were *pooled* over all ignition types and summarized for two different moisture content groups (Table 3.4); that is, a "low-moisture" group and a "high-moisture" group. The "low-moisture" group consisted of all the spring units as well as the fall head fires, since the latter had some residue moisture contents that were similar to the spring burns (Table 2.3). The fall head fires (Fletcher #1, #2, and #3) all had unusually low residue loadings (see Table 3.1) and therefore probably dried faster following precipitation than the other fall units. These units were included in the "low-moisture" group. The "high-moisture" group consisted of the remaining fall units. Emission factors and residue moisture content were significantly different between the low- and high-moisture groups (Table 3.4). The 95-percent confidence intervals are provided and indicate the uncertainty in each of these variables.

Table 3.4. Emission Factors for PM_{2.5} and Residue Moisture Content by Moisture Category.
Shown are the sample size (N), arithmetic mean, and the 95-percent confidence interval (95% C.I.). "*" indicates that statistically significant differences exist between the two groups of burn units (t-test, $P \leq 0.01$).

Parameter	Statistic	"Low-Moisture" Group ¹	"High-Moisture" Group ²	Both Groups
EF _{PM2.5} (lbs/ton)*	N	18	8	26
	Mean	5.7	10.8	7.3
	95% C.I.	4.7 – 6.8	7.9 – 13.8	5.8 – 8.8
Moisture Content (% H₂O On A Dry Weight Basis)				
Entire Layer *	N	18	8	26
	Mean	10	28	16
	95% C.I.	9 – 12	18 – 37	12 – 20
Upper Layer *	N	5	7	12
	Mean	5	12	9
	95% C.I.	4 – 6	7 – 16	6 – 12
Lower Layer *	N	5	7	12
	Mean	13	47	32
	95% C.I.	10 – 15	23 – 71	16 – 50
Stubble *	N	17	8	25
	Mean	8	11	9
	95% C.I.	7 – 9	9 – 14	8 – 10
Soil Layer	N	18	6	26
	Mean	25	26	26
	95% C.I.	24 – 27	20 – 31	24 – 27

¹ Generally includes the spring burn units

² Generally includes the fall burn units

The emission factors for particulate matter greater than 10 μm in aerodynamic diameter ($\text{EF}_{\text{PM}_{10}}$) were derived from $\text{EF}_{\text{PM}_{2.5}}$ using a scaling factor of 0.8 (i.e., $\text{EF}_{\text{PM}_{10}} = \text{EF}_{\text{PM}_{2.5}} / 0.8$), and therefore show the same patterns and statistical differences as $\text{EF}_{\text{PM}_{2.5}}$.

In summary, $\text{EF}_{\text{PM}_{2.5}}$ increased with decreasing combustion efficiency (CE) and increasing fuel moisture content. Emission factors of other incomplete combustion products, EF_{CO} and EF_{CH_4} , showed a similar pattern. EF_{CO_2} increased with increasing CE.

3.3.2 PAH Emission Factors

For the spring burns, none of the 30 PAH samples (15 burn units with two samples per unit) were analyzed in the laboratory. Our rationale was that the $\text{PM}_{2.5}$ mass capture on the filters was so low that it was considered unlikely that any of the PAH samples would be above the method detection limit (that is, the minimum concentration in the filter extract that can be measured in the laboratory).⁴

Prior to the fall burns, the FASS packages were retrofitted with high volume pumps in an effort to increase the particulate matter capture on the filters. Following the burns, the four $\text{PM}_{2.5}$ samples (out of 22 possible samples) with the highest mass capture were analyzed for the presence of PAHs, including benzo(a)pyrene (BaP) and six additional BaP-equivalent carcinogens: benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, and idenol(1,2,3-cd)pyrene. In two of the four samples, both taken at Fletcher 2, all PAHs were below the method detection limit. In the other two samples, one from Jones 1 and one from McGee 3, two PAH compounds were found above the method detection limit: dibenzo(a,h)anthracene, and idenol(1,2,3-cd)pyrene. The calculated emission factors for dibenzo(a,h)anthracene were 5.2 and 25.1 milligrams per kilogram of dry residue consumed at Jones 1 and McGee 3, respectively. The calculated emission factors for idenol(1,2,3-cd)pyrene were 3.3 and 15.9 milligram per kilogram of dry residue consumed at Jones 1 and McGee 3, respectively. The PAH emission factors varied depending on the ratio of the PAH to $\text{PM}_{2.5}$ mass, and on the $\text{PM}_{2.5}$ emission factor, at each of the sites (see Equation 14 and Table 3.2).

⁴ Two types of detection limits can be distinguished. The *sampling and analytical detection limit* (expressed as air concentration, in micrograms per liter of air) is simply the *method detection limit* (or minimum detectable PAH concentration in extract) converted to a mass (in micrograms) and divided by the sampled air volume (in liters). The sampling and analytical detection limit only applies to samples that are below the method detection limit. For samples that are below the method detection limit, the higher the sampled air volume, the lower the sampling and analytical detection limit.

3.4 Total Emissions

The total emissions from a proposed burn can be predicted using the following equation:

$$\text{PM}_{2.5} \text{ Emissions (lbs acre}^{-1}\text{)} = (L_{\text{pre}})(\text{FC}_{\text{relative}})(\text{EF}_{\text{PM}_{2.5}}) \quad (15)$$

where L_{pre} is the pre-burn fuel loading (tons per acre), $\text{FC}_{\text{relative}}$ the relative fuel consumption (%), and $\text{EF}_{\text{PM}_{2.5}}$ the emission factor for $\text{PM}_{2.5}$ (lbs per ton). An equivalent formulation is to multiply the emission factor (EF) times the absolute residue consumption (L_{diff}), which also yields total emissions on a per-acre basis.

Figures 3.7 and 3.8 both show the per-acre $\text{PM}_{2.5}$ emissions for the spring and fall seasons, respectively. Although there were no statistically significant differences, units with high pre-burn fuel loading tended to have the highest $\text{PM}_{2.5}$ emissions (Figure 3.7 and 3.8). One exception is the head fires in the spring, where the high and low pre-burn fuel loading treatments had similar emissions. This could be attributed to a fairly small difference in fuel loading for these sites and slightly higher emission factors for the low-loading sites.

Combining both the spring and fall units, the per-acre $\text{PM}_{2.5}$ emissions were expressed as a linear function of the absolute residue consumption, L_{diff} , and the $\text{PM}_{2.5}$ emission factor, $\text{EF}_{\text{PM}_{2.5}}$. These two factors, L_{diff} and $\text{EF}_{\text{PM}_{2.5}}$, explained 95 percent of the variation in the per-acre $\text{PM}_{2.5}$ emissions, corresponding to a coefficient of determination (R^2) of 0.95. L_{diff} and $\text{EF}_{\text{PM}_{2.5}}$ explained roughly equal portions in the variation in per-acre $\text{PM}_{2.5}$ emissions, with R^2 values of 0.43 and 0.48, respectively. Thus, L_{diff} and $\text{EF}_{\text{PM}_{2.5}}$ were important driving variables for the per-acre $\text{PM}_{2.5}$ emissions, based on the combination of the spring and fall units. Similar patterns arose when regression analyses were performed separately for each season. In both the spring and fall seasons, the combination of L_{diff} and $\text{EF}_{\text{PM}_{2.5}}$ explained 98 percent of the variation in the per-acre $\text{PM}_{2.5}$ emissions ($R^2=0.98$). However, within each season, L_{diff} had twice the influence on the per-acre $\text{PM}_{2.5}$ emissions than on $\text{EF}_{\text{PM}_{2.5}}$. In the spring season, L_{diff} and $\text{EF}_{\text{PM}_{2.5}}$ explained 45 and 22 percent of the variation of the per-acre $\text{PM}_{2.5}$ emissions, respectively. In the fall season, L_{diff} and $\text{EF}_{\text{PM}_{2.5}}$ explained 73 and 41 percent of the variation of the per-acre $\text{PM}_{2.5}$ emissions, respectively.

In conclusion, within a season (i.e., moisture regime) the influence of the absolute fuel consumption on the per-acre $\text{PM}_{2.5}$ emissions was about twice as great as on the $\text{PM}_{2.5}$ emission factor. Across both seasons, the two factors were equally important for estimating the per-acre

PM_{2.5} emissions. Moreover, the combination of the two parameters explained almost 100 percent of the variation in the per-acre PM_{2.5} emissions.

Figure 3.7. Total Emission Estimates of PM_{2.5} in Spring (Generally the Low-Moisture Group) as a Function of Ignition Type and Actual Pre-Burn Fuel Load.

The pre-burn fuel loading as high (H) and low (L), and the ignition types are indicated as backing fire (B), head fire (H), and strip head fire (S). The error bars represent one SE.

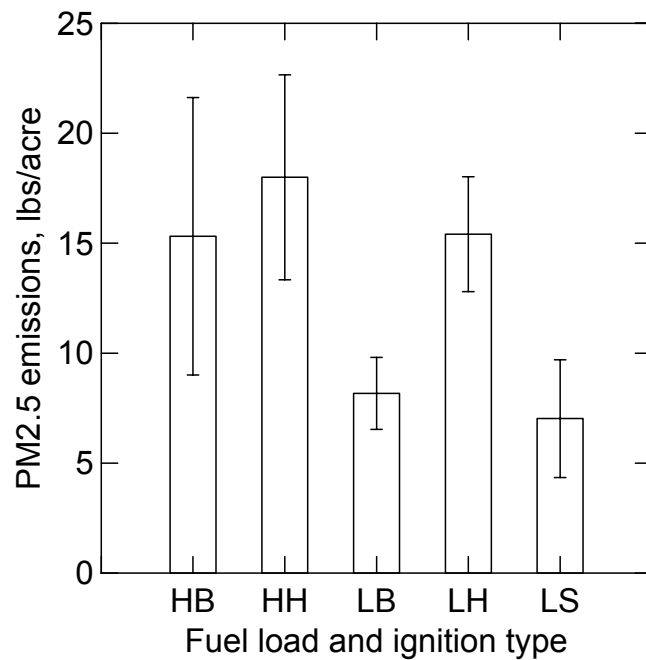
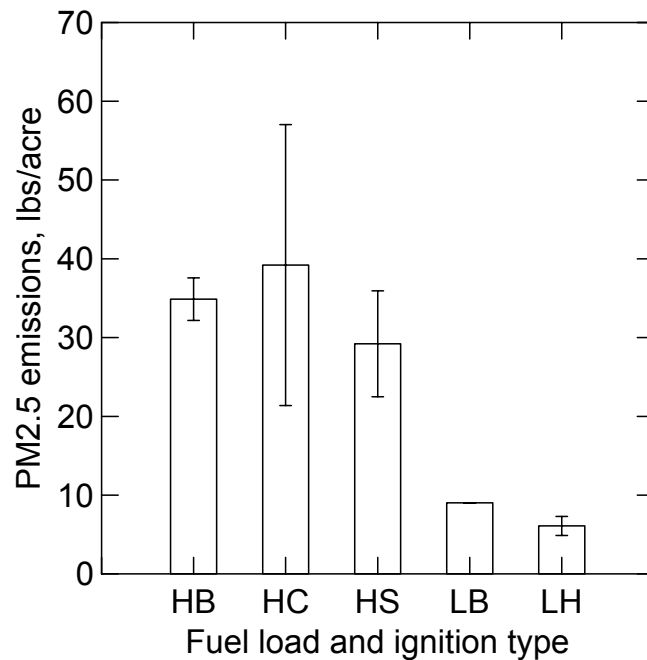


Figure 3.8. Total Emission Estimates of PM_{2.5} in Fall (Generally the High-Moisture Group) as a Function of Ignition Type and Actual Pre-Burn Fuel Load

The pre-burn fuel loading as high (H) and low (L), and the ignition types are indicated as backing fire (B), head fire (H), and strip head fire (S). The error bars represent one SE.



3.5 Comparison of Emission Factors to the Fall Baseline

To explore the implications of these results for management practices, the pollutant-specific emission factors for the treatments were compared with those from the baseline burns (fall mass ignition units).

No statistical differences in emission factors were found between the control burns and the treatment fire ignition types in the fall season (Table 3.5). However, in the spring, $EF_{PM_{2.5}}$ were significantly lower compared to the fall control burns for the back burns (Table 3.5). Although the other ignition types in the spring also had lower emission factors compared to the fall control burns, these differences were not statistically significant (Table 3.5).

On the basis of the carbon balance method, a 67-percent reduction in the PM_{2.5} emissions over the fall baseline burns may be achieved by using backing fires in the spring. However, the lower emission factors observed in the spring can be attributed to differences in fuel moisture content rather than season or ignition type (Section 4.1). Hence the results in Table 3.5 need to be interpreted with caution.

Table 3.5. Emission Factors by Season and Ignition Type as Percent Change Relative to Baseline Emissions

Mean baseline emission factor, i.e., fall season with “mass ignition,” was 12.3 lbs PM_{2.5} per ton of residue consumed. Changes that were statistically different from the baseline are indicated in **BOLD** (Kruskal-Wallis test; df=1; $P \leq 0.05$).

Season and Ignition Type	Change in Emission Factor Relative to the Baseline (%)	P-Value
Spring¹		
Backing Fire ($n=6$)	- 67	0.02
Head Fire ($n=6$)	- 44	0.30
Strip Head Fire ($n=3$)	- 55	0.28
Fall^{2,3}		
Backing Fire ($n=3$)	- 21	0.51
Head Fire ($n=3$)	- 41	0.28
Strip Head Fire ($n=2$)	- 16	0.56

¹ Generally the low-moisture group of burn units

² Generally the high-moisture group of burn units

³ Does not show the fall baseline units ($n=3$) because these units were used as the ‘reference’ units

DISCUSSION

4.1 Residue Consumption

The average relative fuel consumption for all 27 burn units was 60 percent (range 23 to 79 percent). This means that on average 40 percent of the pre-burn residue loading was not consumed by fire. Seed heads, short pieces of mud-covered straw, and green grasses and weeds comprised the majority of the unconsumed material. All standing stubble was consumed; no standing stubble was found on any of the 270 post-burn plots that were sampled.

Absolute fuel consumption did not differ significantly by season, ignition type, or fuel moisture content but was positively correlated with the pre-burn residue loading. The higher the pre-burn loading, the higher was the absolute residue consumption. Considerable variation in the relationship between pre-burn loading and absolute residue consumption was observed (Figure 3.2), attributed to variation in the residue loading, structure, continuity, and moisture content that was not reflected in the unit averages.

The relationship in Figure 3.2 is *statistically significant* at the 99.9 percent level ($P < 0.001$), with a coefficient of determination of 71 percent. This means that 71 percent of the variation in the absolute residue consumption is explained by the variation in the pre-burn residue loading. It also means that 29 percent of the variation is explained by factors other than pre-burn residue loading (residue moisture content, for example). Nonetheless, pre-burn residue loading is a reasonable predictor of the absolute residue consumption on burn units. Given the degree of variation, one cannot say that a small decrease (increase) in the pre-burn residue loading will always produce a decrease (increase) in the absolute residue consumption following the line of “best fit” in Figure 3.2. However, the greater the decrease (increase) in the pre-burn residue loading, the greater is the likelihood that the absolute residue consumption will also be decreased (increased).

4.2 PM_{2.5} Emission Factors

4.2.1 Seasonal Variation and Relationship to Residue Moisture Content

PM_{2.5} emission factors were found to vary by season: significantly lower emission factors were recorded in the spring than in the fall (see Table 3.2). No statistically significant differences in the PM_{2.5} emission factors were found between the different ignition patterns, or between the different pre-burn loading levels. The seasonal differences in the emission factors reflect seasonal differences in the residue moisture content. Residue moisture contents were significantly lower in the spring than in the fall, which resulted in higher combustion efficiencies and lower PM_{2.5} emission factors. Notable exceptions to this pattern were the Fletcher units (fall burns), which had moisture contents similar to those found in the spring.

The PM_{2.5} emission factor is highly sensitive to differences in the combustion efficiency. In this study, a 4-percent decrease in the combustion efficiency between the spring and fall resulted in a near-doubling of the PM_{2.5} emission factor (see Table 3.2).

The relative importance of various environmental factors that influence the PM_{2.5} emission factor was evaluated using the pooled (combined) spring and fall data set. Residue moisture content was found to be the single-most important variable influencing the PM_{2.5} emission factors, with R² values ranging from 0.50 (for the plot of PM_{2.5} emission factor versus stubble moisture content) to 0.79 (for the plot of PM_{2.5} emission factor versus upper-layer moisture content)(see Table 3.3). According to these results, 50 to 79 percent of the variation in the PM_{2.5} emission factors is explained by variation in the residue moisture content, and 21 to 50 percent of the variation is explained by factors *other than* the residue moisture content. Nonetheless, residue moisture content is a reasonable predictor of the PM_{2.5} emission factor.

Statistically significant relationships were also found between the residue moisture content and the emission factors for other species, including CO, CH₄, and CO₂. Positive relationships were found between the CO and CH₄ emission factors and residue moisture content. As expected, a negative relationship was found between CO₂ emission factor and residue moisture content (see Table 3.3).

4.2.2 Seasonal Precipitation Differences

As previously noted, the residue moisture contents were significantly lower in the spring than in the fall. This section discusses the rainfall conditions that existed before and during the spring and fall burns of 2000.

Based on precipitation data from Lewiston, Idaho (located about 80 kilometers east of the project area), the total precipitation for the month of September 2000 was 2.48 inches, or nearly 3.5 times higher than the 50-year average September rainfall total for that station. The total rainfall for March 2000, on the other hand, was approximately the same as the 50-year average (0.95 inches, or 96 percent of the 50-year average). On the basis of the Lewiston rainfall data alone, it would appear that the fall of 2000 was unusually wet and that the spring of 2000 was “average.” But precipitation events in the spring and fall are highly localized, and site-specific precipitation data should be used to provide a more accurate assessment of conditions at the burn sites.

Daily rainfall data for the period from 1987 through 2001 were obtained for six monitoring stations in Columbia County, including: Canright (Harting units), Eslick (Fletcher units), A. Fletcher (Jones units), Neace (Jones units), Takamoura (McGee units), and Turner (Turner units). The monthly precipitation totals at these six stations for year 2000 are summarized in Figure 4.1 along with the 15-year average. The average rainfall total at the six stations during March 2000 was 2.54 inches, or 119 percent of the 15-year average for March of 2.16 inches. The average rainfall total at the six stations during September 2000 was 2.10 inches, or 354 percent of the

Figure 4.1. Year 2000 Precipitation at Six Monitoring Stations in Columbia County.

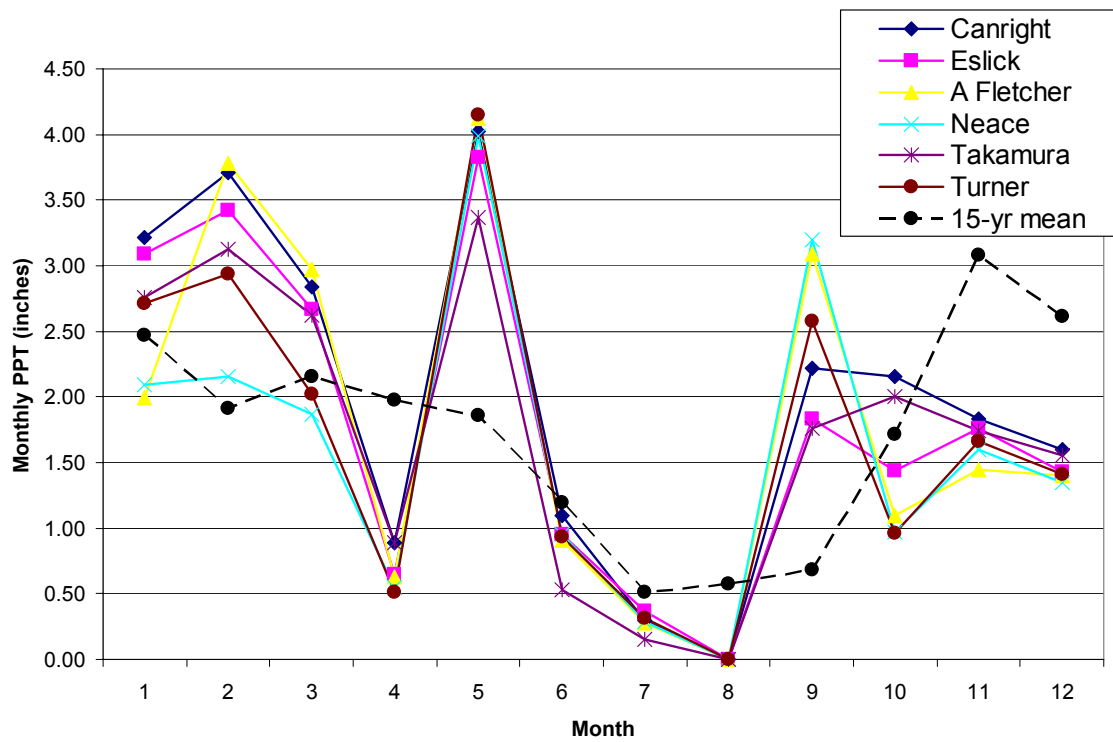
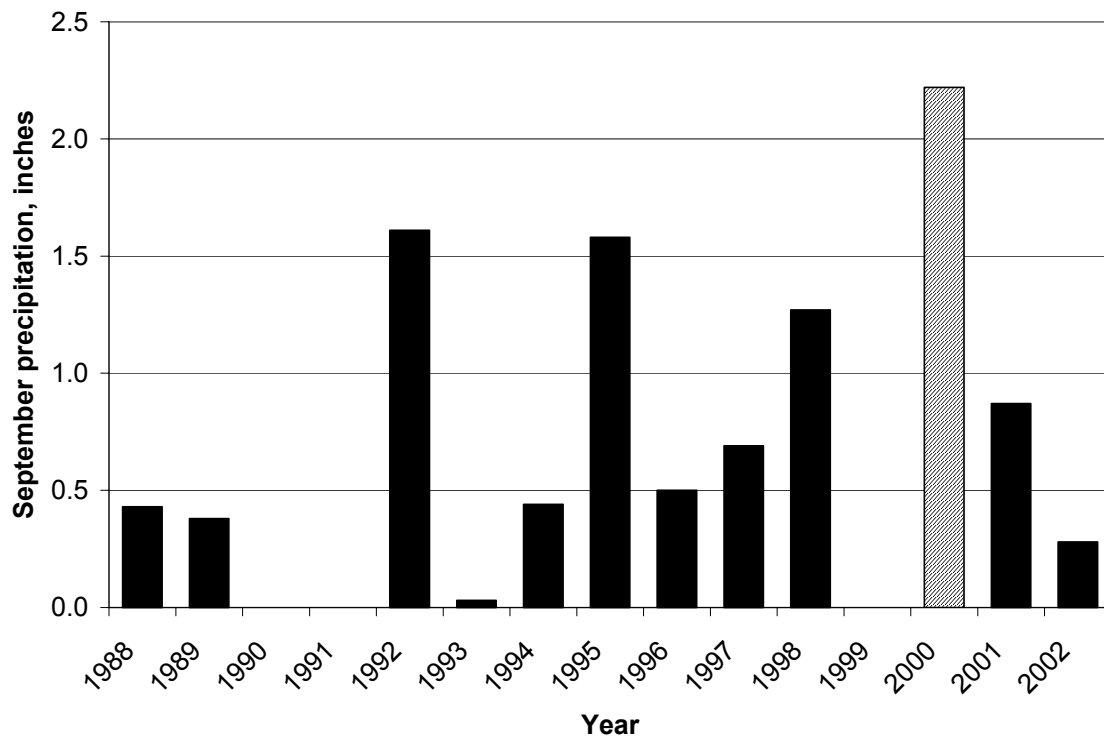


Figure 4.2. Total September Rainfall for Canright (Harting) Monitoring Station, 1988-2002.



15-year-average for September of 0.68 inches. These data suggest that the fall of 2000 was a “wetter than average” fall season. However, it is important to note that the September rainfall was actually *lower* than the March rainfall.

The long-term precipitation record shows that the total precipitation that occurred in the fall of 2000 was not unprecedented. Several years in the last 15 years experienced relatively high precipitation during September, the month preceding the fall burning period (Figure 4.2). However, September 2000 had considerably higher precipitation than any other year in the 15-year record.

The higher observed residue moisture contents in the fall may be related to *timing*, and not to differences in *total precipitation*. The timing of the 27 burns was evaluated by comparing the daily precipitation data with the dates of the individual burns. The spring burns occurred 15 to 19 days after a *significant* rainfall (that is, more than ½ inches of rainfall in 24 hours), whereas the fall burns occurred 5 to 8 days after a significant rainfall. Fewer days following rain means that less time is available for residue drying to occur. This fact could explain why higher residue moisture contents were observed in the fall than in the spring.

The higher moisture contents in the fall may not necessarily be a reflection of higher moisture contents in the dead cereal-grain residue itself. We observed that the highest moisture contents were recorded in burn units with the highest density of green plants (i.e., weeds, grasses, and germinating seed). The pre-burn moisture sampling that was performed did not discriminate between green plants and dead plant material (both were collected together), so the higher residue moisture contents could have come from the green plant material and not from the moisture content in the dead plant residues themselves.

Although a link between the density of green plants and either the total precipitation or the timing of the burns relative to rainfall events is probable, the evidence is circumstantial. The higher densities of green plants in the fall could also have resulted from either no pre-burn spraying, or inadequate spray coverage resulting from the tall, largely intact stubble canopy. The stubble canopy is generally much less dense in the spring, possibly enhancing the effectiveness of the pre-burn spray application.

4.2.3 Variation by Fire Type

Statistical differences between the treatment and the baseline PM_{2.5} emission factors were found for only one ignition type: spring backing fires (see Section 3.4). The difference between the spring backing fires and the fall baseline fires is probably due to a combination of effects, including ignition type and season, where the seasonal differences are driven largely by differences in the residue moisture content. No significant differences *between* seasons (that is, comparing spring and fall within ignition type) were found for any of the other fire types.

Some variation in the PM_{2.5} emission factors was observed for different fire types *within* a season, however. During the spring, the average PM_{2.5} emission factor was significantly higher for head fires than for backing fires (see Table 3.2). This is consistent with the lower combustion efficiencies recorded for the spring head fires (Table 3.2). In the fall, no statistically significant differences in PM_{2.5} emission factors were found between any of the fire types, although PM_{2.5} emission factors generally decreased with decreasing fire intensity: baseline EF_{PM2.5} (highest fire intensity) > head fire EF_{PM2.5} > strip head fire EF_{PM2.5} > backing fire EF_{PM2.5} (lowest fire intensity). The fall head fires (Fletcher units) were the exception to this trend, with the lowest recorded PM_{2.5} emission factors for that season. This deviation could be explained by the substantially lower residue moisture contents found in the fall head fires (see Table 2.3), which apparently resulted in more efficient burns and lower PM_{2.5} emission factors.

4.2.4 Comparison with AP-42 Emission Factors

The EPA's Compilation of Air Pollutant Emission Factors (AP-42) provides an important benchmark for comparing the PM_{2.5} emission factors from agricultural burning operations (USEPA, 1995). For agricultural open-field burning, AP-42 specifies a PM₁₀ emission factor of 22 lbs PM₁₀ per ton of residue consumed. The equivalent PM_{2.5} emission factor, assuming that 80 percent of the PM₁₀ emissions are in the form of PM_{2.5}, is 17.6 lbs PM_{2.5} per ton of residue consumed. In comparison, the mean low-moisture and high-moisture EF_{PM2.5} values in this study (see Table 3.4) were 5.7 and 10.8 lbs PM_{2.5} per ton of residue consumed, which is 35 percent and 67 percent of the AP-42- derived PM_{2.5} emission factor, respectively. The 95-percent confidence intervals for EF_{PM2.5} based on season were also below the AP-42 emission factor (Table 4.1).

4.2.5 Comparison with Other Literature Values

PM_{2.5} Emission Factors

The PM_{2.5} emission factors reported in this study compare favorably with values reported in the literature, especially those for cereal straw burning and savanna fires (see Table 4.1). They also agree well with those reported for the flaming phase of wildfires in the United States, and for wildfires with combustion efficiencies greater than 90 percent. This suggests that the majority of the residue consumed during these wheat residue fires was consumed in the flaming phase rather than the smoldering phase. This was confirmed by the flaming-to-smoldering ratios that were calculated based on the FASS towers in this study (see Table 2.4). Emission factors for the other compounds, CO₂, CO and CH₄, also showed good agreement with those reported in the literature (see Tables 3.2 and 4.1).

The close agreement of the PM_{2.5} emission factor (and the CO₂, CO, and CH₄ emission factors) with those reported for the flaming phase was also in agreement with the high combustion efficiencies found in this study (greater than 92 percent; see Table 3.2). Typically, the flaming phase of the combustion process is characterized by higher combustion efficiencies than the

Table 4.1. Summary of Emission Factors for CO₂, CO, CH₄, and PM_{2.5} Based on This Study and From Other Reports in the Literature

Source	Residue Type	Emission Factor, lbs per ton of residue consumed			
		CO ₂	CO	CH ₄	PM _{2.5}
This Study	Wheat Residue				
	<i>Spring (95% C.I.)</i> ¹	3527 - 3561 (mean 3546)	57 - 77 (mean 67)	1.3 - 2.0 (mean 1.6)	4.0 - 6.9 (mean 5.3)
	<i>Fall (95% C.I.)</i> ²	3396 - 3495 (mean 3447)	93 - 141 (mean 117)	2.6 - 4.5 (mean 3.6)	7.3 - 12.4 (mean 9.8)
	<i>Low-Moisture Group</i> ³ (95% C.I.) ¹				4.7-6.8 (mean 5.7)
	<i>High-Moisture Group</i> ³ (95% C.I.) ²				7.9-13.8 (mean 10.8)
Jenkins & Turn, 1994	Cereal Straw		64 - 198	1.6 - 5.0	6.4 - 15.4
Turn et al., 1997	Cereal Straw				mean ~12.2
Ward et al., 1996	Savanna, Africa	mean ~3500	mean ~90	mean ~1.6	mean ~7.0
Yamasoe et al., 2000	Forest, Brazil				
	<i>Flaming</i> <i>Smoldering</i>				mean ~6.6 mean ~12.2
Ward & Hardy, 1991	Wildfires, U.S.A.				
	<i>CE > 90 %</i>				2 - 12
	<i>CE 74 to 90 %</i>				12 - 40
Ward et al., 1992a	Wildfires, U.S.A.				
	<i>Flaming</i>	3424 - 3518	72 - 116	2.8 - 5.8	4.0 - 12.8
	<i>Smoldering</i>	2472 - 2580	490 - 526	34.8 - 42.8	44.4 - 65.2
Ward et al., 1992b	Cerrado Forest, Brazil				
	<i>Flaming</i>	3380 - 3498	92 - 140	2.0 - 3.2	1.0 - 2.4
	<i>Smoldering</i>	3062 - 3304	182 - 304	8.6 - 18.0	4.8 - 9.8

¹ Generally, the “low moisture” group includes the spring burn units

² Generally, the “high moisture” group includes the fall burn units

³ Based on “entire” layer moisture sample

smoldering phase (e.g., Ward and Hardy, 1991; Cofer III et al., 2000; Ortiz de Zarate et al., 2000). Turn et al. (1997) reported combustion efficiencies of 82 to 92 percent for cereal burned in a wind tunnel. Ward et al. (1996) reported that emission factors of CO, CH₄, and PM_{2.5} from savanna fires in Africa decreased three- to four-fold when combustion efficiencies increased from 90 to 96 percent. In our study these emission factors decreased ~two-fold over the same range of combustion efficiencies. A linear decrease of the PM_{2.5} emission factor with increasing combustion efficiency also has been reported for wildfires in the United States (Ward and Hardy,

1991). Similar relationships between the CO, CH₄, and PM_{2.5} emission factors and combustion efficiency have been reported for savanna fires in Africa (Ward et al., 1996), wildfires in the United States (Ward and Hardy, 1991), and Cerrado forest fires in Brazil (Ward et al., 1992b).

We observed a roughly two-fold difference in CO and CH₄ emission factors between the “wet” (fall) and “dry” (spring) seasons (see Table 3.2). This is in general agreement with Nguyen et al. (1994), who reported a two- to three-fold increase in CO and CH₄ emissions when rice straw was burned during the wet season compared to during the dry season.

PAH Emission Factors

In this study, only 4 samples out of 52 possible samples (that is, 26 burn units with 2 samples per unit) were analyzed for the presence of PAH compounds. None of the 30 spring samples, and only four of the 22 fall samples, were analyzed because the PM_{2.5} mass capture on the filters was so low that it was considered unlikely that any of the PAH concentrations would be above the method detection limit. In two of the four samples analyzed in the fall (both from Fletcher 2), the PAH concentrations were below the method detection limit. In the other two fall samples (one from Jones 1 and one from McGee 3), only two PAH compounds – dibenzo(a,h)anthracene and idenol(1,2,3-cd)pyrene – were found above the method detection limit. The estimated emission factors for these compounds were 5.2 and 25.1 milligrams of dibenzo(a,h)anthracene per kilogram of residue consumed at Jones 1 and McGee 3, respectively, and 3.3 and 15.9 milligrams of idenol(1,2,3-cd)pyrene per kilogram of dry residue consumed at Jones 1 and McGee 3, respectively.

The emission factors for individual PAH species reported in the literature range from less than detection limits to about 20 milligrams per kilogram of dry residue consumed (Ramdahl and Moeller, 1983; Jenkins et al., 1996a and 1996b). The emission factors in this study for dibenzo(a,h)anthracene and idenol(1,2,3-cd)pyrene were higher than those reported for cereal crops by Ramdahl and Moeller (1983; range 0.02 to 0.8 milligrams per kilogram of dry residue consumed), and higher than those reported for cereal straw by Jenkins et al. (1996a and 1996b; range 0.01 to 1.2 milligrams per kilogram of dry residue consumed).

Caution should be exercised in the interpretation and use of these PAH results. The PAH emission factors reported in this study represent only two of the seven PAH compounds selected for evaluation, and are from only two of the 52 possible samples collected in the spring and fall burns. Some of the PAH emission factors reported in the literature (e.g., Jenkins et al., 1996a) represent the arithmetic average of both detected and non-detected samples, which has the effect of lowering the reported average emission factors. In this study, only four of the 52 possible PAH samples were analyzed. Therefore, we did not consider it appropriate to arithmetically average the detected and non-analyzed samples. Therefore, only two of the collected samples could be used in the analysis. While these results may be valid, there are too few PAH samples to represent the true range of variability in PAH emission factors from cereal crop burning.

SECTION 5

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APPENDIX A

List of Symbols

SYMBOL

PARAMETER EXPLANATION

A	Area burned (ha)
$C_{\text{gaseous, total}}$	Carbon mass emitted by burn in gaseous form (kg C)
$C_{\text{Pre-Burn}}$	Carbon load in fuel before burn (kg C)
$C_{\text{Post-Burn}}$	Carbon load in fuel after burn (kg C)
C_{CO_2}	Carbon mass emitted by burn as CO_2 (kg C)
C_{CO}	Carbon mass emitted by burn as CO (kg C)
C_{CH_4}	Carbon mass emitted by burn as CH_4 (kg C)
$C_{\text{PM}_{2.5}}$	Carbon mass emitted by burn as $\text{PM}_{2.5}$ (kg C)
C_x	Carbon mass emitted (kg C) where x stands for CO_2 , CO, CH_4 , or $\text{PM}_{2.5}$
CE	Combustion efficiency
C.I.	Confidence interval [statistics]
EF_x	Emission factor (g kg fuel^{-1}), where x stands for CO_2 , CO, CH_4 , or $\text{PM}_{2.5}$
EF_{PAH}	Emission factor ($\mu\text{g kg fuel}^{-1}$) for polycyclic aromatic hydrocarbons
$\text{FC}_{\text{Absolute}}$	Absolute fuel consumption (kg ha^{-1})
$\text{FC}_{\text{Relative}}$	Relative fuel consumption (%)
$f_{\text{PM}_{2.5}}$	Carbon fraction of $\text{PM}_{2.5}$ ($\text{g C g PM}_{2.5}^{-1}$)
$f_{\text{Pre-Burn}}$	Carbon fraction of residue before burn ($\text{g C g oven dry fuel}^{-1}$)
$f_{\text{Post-Burn}}$	Carbon fraction of residue after burn ($\text{g C g oven dry fuel}^{-1}$)
κ_x	Conversion factor from ppmv to kg pollutant $\times \text{kg air}^{-1}$
χ_x	Measured concentration of pollutant x above background (ppmv)
$\chi_{x, \text{Fire}}$	Measured concentration of pollutant x above background (mg m^{-3})
$\chi_{\text{C-x, Fire}}$	Carbon mass of pollutant x above background (mg m^{-3})
$L_{\text{Pre-Burn}}$	Fuel load before the burn (kg ha^{-1})
$L_{\text{Post-Burn}}$	Fuel load after the burn (kg ha^{-1})
M_{air}	Mass of air sampled by FASS tower (kg)
$M_{\text{PM}_{2.5}}$	Total mass of $\text{PM}_{2.5}$ collected on filter
M_{PAH}	Mass of polycyclic aromatic hydrocarbon species in the $\text{PM}_{2.5}$ fraction
MM_x	Molar weight gaseous pollutants, where x stands for CO_2 , CO, or CH_4
RMC	Residue moisture content (% H_2O per g fresh weight)
W_{Field}	Fresh weight of fuel or soil sample (g)
W_{OD}	Oven-dried weight of fuel or soil sample (g)
$W_{\text{OD;Surface}}$	Oven-dried weight of fuel materials lying loose on the surface (g)
$W_{\text{OD;Standing}}$	Oven-dried weight of fuel materials as standing stubble (g)
x	Subscript used to indicate pollutant species, CO_2 , CO, CH_4 , or $\text{PM}_{2.5}$

APPENDIX B

Summary Data by Burn Unit

Table B1. Fuel Loading and Consumption by Unit for Spring BurnsShown are mean values \pm one standard error (SE).

Unit	Date Burned	Ignition Type	Fuel Loading Category		Actual Loading (tons/acre)		Fuel Consumption	
			Planned	Actual	Pre-Burn	Post-Burn	Absolute	Relative (%)
Beard #1	4/8/2000	Backing	Low	High	5.3 \pm 0.7	2.7 \pm 0.3	2.6	50
Beard #2	4/7/2000	Head	Low	High	4.1 \pm 0.5	2.4 \pm 0.4	1.7	42
Beard #3	4/8/2000	Backing	Low	High	5.9 \pm 0.9	1.8 \pm 0.4	4.1	69
Beard #4	4/5/2000	Head	Low	High	5.1 \pm 0.7	2.8 \pm 0.2	2.3	44
Beard #5	4/7/2000	Backing	Low	Low	3.8 \pm 0.3	2.0 \pm 0.2	1.8	47
Beard #6	4/8/2000	Head	Low	High	6.1 \pm 0.8	1.5 \pm 0.3	4.6	75
Covello #1	4/11/2000	Backing	High	Low	3.2 \pm 0.3	0.9 \pm 0.2	2.3	71
Covello #2	4/10/2000	Head	High	Low	3.4 \pm 0.3	1.0 \pm 0.2	2.4	70
Covello #3	4/10/2000	Strip Head	High	Low	2.8 \pm 0.3	1.1 \pm 0.1	1.8	62
Covello #4	4/11/2000	Head	High	Low	3.6 \pm 0.4	1.5 \pm 0.2	2.1	58
Covello #5	4/11/2000	Backing	High	Low	3.7 \pm 0.3	0.9 \pm 0.2	2.7	75
Harting #1	4/8/2000	Strip Head	High	Low	3.0 \pm 0.3	2.3 \pm 0.2	0.7	23
Harting #2	4/9/2000	Backing	High	Low	2.8 \pm 0.2	0.6 \pm 0.1	2.2	79
Harting #3	4/9/2000	Head	High	Low	3.0 \pm 0.4	1.0 \pm 0.3	2.0	67
Harting #5	4/9/2000	Strip Head	High	Low	3.0 \pm 0.2	1.4 \pm 0.2	1.7	55

Table B2. Fuel Loading and Consumption by Unit for Fall BurnsShown are mean values \pm one standard error (SE).

Unit	Date Burned	Ignition Type	Loading Category		Actual Loading (tons/acre)		Fuel Consumption	
			Planned	Actual	Pre-Burn	Post-Burn	Absolute	Relative (%)
Fletcher #1	10/8/2000	Head	Low	Low	1.9 \pm 0.2	1.1 \pm 0.3	0.8	42
Fletcher #2	10/8/2000	Head	Low	Low	1.2 \pm 0.2	0.4 \pm 0.1	0.8	63
Fletcher #3	10/8/2000	Head	Low	Low	1.9 \pm 0.3	0.7 \pm 0.2	1.2	62
Jones #1	10/5/2000	Backing	High	High	4.1 \pm 0.3	1.3 \pm 0.2	2.8	68
Jones #2	10/5/2000	Strip Head	High	High	4.1 \pm 0.3	2.0 \pm 0.3	2.1	50
Jones #3	10/5/2000	Strip Head	High	Low	3.8 \pm 0.5	1.4 \pm 0.2	2.4	62
Jones #4	10/6/2000	Backing	High	High	4.8 \pm 0.4	1.2 \pm 0.1	3.7	76
McGee #1	10/4/2000	Baseline	Baseline	Baseline	4.8 \pm 0.3	2.2 \pm 0.3	2.6	55
McGee #2	10/9/2000	Baseline	Baseline	Baseline	4.6 \pm 0.4	1.8 \pm 0.2	2.9	62
McGee #3	10/9/2000	Baseline	Baseline	Baseline	4.9 \pm 0.3	1.1 \pm 0.2	3.8	77
Turner #1	10/6/2000	Backing	High	Low	3.6 \pm 0.3	2.4 \pm 0.5	1.2	34
Turner #2	10/6/2000	Strip Head	High	High	5.3 \pm 0.4	1.4 \pm 0.2	3.9	74

Table B3. Fuel Moisture and Meteorological Conditions for Spring Burns

Shown are mean values \pm 1 SE. "ND" indicates no data available. The meteorological conditions are those during the flaming phase of the fire.

"0.0" indicates $SE < 0.05$.

Unit	Fuel and Soil Moisture Content (%)					Meteorological Conditions		
	Entire Layer	Upper Layer	Lower Layer	Stubble	Soil	Wind Speed (miles/hr)	Temperature (Fahrenheit)	Relative Humidity (%)
Beard #1	11.7 \pm 1.6	5.4 \pm 0.5	13.4 \pm 1.3	5.9 \pm 0.1	22.9 \pm 3.8	7.3 \pm 0.2	64.4 \pm 0.2	26.2 \pm 0.2
Beard #2	8.5 \pm 1.2	4.6 \pm 0.7	14.3 \pm 2.0	6.6 \pm 0.2	22.6 \pm 3.0	8.0 \pm 1.0	54.5 \pm 0.3	36.5 \pm 0.3
Beard #3	8.8 \pm 0.7	3.8 \pm 0.2	9.3 \pm 1.0	5.5 \pm 0.0	24.8 \pm 2.2	6.9 \pm 0.3	65.8 \pm 0.2	24.8 \pm 0.2
Beard #4	10.0 \pm 0.5	ND	ND	8.6 \pm 0.5	22.7 \pm 1.9	13.6 \pm 0.6	47.2 \pm 0.1	35.9 \pm 0.2
Beard #5	11.7 \pm 0.7	5.3 \pm 0.7	14.8 \pm 0.9	7.0 \pm 0.1	26.8 \pm 3.5	7.9 \pm 0.1	56.5 \pm 0.1	38.1 \pm 0.3
Beard #6	8.7 \pm 0.7	5.1 \pm 0.8	10.9 \pm 1.0	ND	23.2 \pm 2.0	7.6 \pm 0.3	60.5 \pm 0.1	28.5 \pm 0.3
Covello #1	8.2 \pm 0.2	ND	ND	5.8 \pm 0.3	25.3 \pm 2.2	6.0 \pm 0.1	68.0 \pm 0.1	20.8 \pm 0.4
Covello #2	9.6 \pm 0.6	ND	ND	8.5 \pm 0.6	34.7 \pm 1.7	9.5 \pm 0.3	64.7 \pm 0.4	30.6 \pm 0.6
Covello #3	8.8 \pm 0.6	ND	ND	9.4 \pm 0.3	22.5 \pm 5.9	11.0 \pm 0.3	62.0 \pm 0.1	34.2 \pm 0.4
Covello #4	6.9 \pm 0.4	ND	ND	5.3 \pm 0.2	22.3 \pm 8.0	7.3 \pm 0.4	70.0 \pm 0.2	20.3 \pm 0.4
Covello #5	7.0 \pm 0.5	ND	ND	4.9 \pm 0.1	25.5 \pm 0.1	5.9 \pm 0.1	70.3 \pm 0.1	18.3 \pm 0.2
Harting #1	10.3 \pm 0.8	ND	ND	6.8 \pm 0.2	26.4 \pm 2.4	3.9 \pm 0.2	63.5 \pm 0.1	28.7 \pm 0.2
Harting #2	12.3 \pm 0.9	ND	ND	7.0 \pm 0.3	31.0 \pm 0.9	15.7 \pm 0.2	59.5 \pm 0.2	48.4 \pm 0.3
Harting #3	11.2 \pm 0.8	ND	ND	8.2 \pm 0.0	30.2 \pm 1.7	11.8 \pm 0.2	63.8 \pm 0.1	36.4 \pm 0.4
Harting #5	14.2 \pm 1.7	ND	ND	10.3 \pm 0.2	29.3 \pm 1.2	13.4 \pm 0.2	62.1 \pm 0.1	43.0 \pm 0.2

Table B4. Fuel Moisture and Meteorological Conditions for Fall Burns

Shown are mean values ± 1 SE. "ND" indicates no data available. The meteorological conditions are those during the flaming phase of the fire.

"0.0" indicates $SE < 0.05$.

Unit	Fuel and Soil Moisture Content (%)					Meteorological Conditions		
	Entire Layer	Upper Layer	Lower Layer	Stubble	Soil	Wind Speed (miles/hr)	Temperature (Fahrenheit)	Relative Humidity (%)
Fletcher #1	16.9 \pm 1.5	ND	ND	13.9 \pm 0.1	19.8 \pm 2.0	3.8 \pm 0.3	66.2 \pm 0.3	25.5 \pm 0.6
Fletcher #2	10.6 \pm 1.4	ND	ND	9.1 \pm 0.5	20.6 \pm 1.7	3.9 \pm 0.3	72.0 \pm 0.1	18.0 \pm 0.1
Fletcher #3	13.0 \pm 1.3	ND	ND	9.4 \pm 0.2	28.2 \pm 5.8	4.7 \pm 0.3	68.7 \pm 0.1	22.2 \pm 0.1
Jones #1	35.5 \pm 2.8	12.1 \pm 2.3	87.4 \pm 4.0	13.5 \pm 0.2	31.9 \pm 1.7	5.1 \pm 0.1	58.0 \pm 0.1	14.7 \pm 0.2
Jones #2	36.4 \pm 8.4	ND	ND	9.9 \pm 0.7	29.8 \pm 0.9	7.2 \pm 0.2	57.9 \pm 0.1	16.2 \pm 0.1
Jones #3	42.2 \pm 9.8	7.2 \pm 0.4	55.9 \pm 0.9	11.5 \pm 1.0	27.7 \pm 0.7	4.9 \pm 0.2	58.5 \pm 0.1	13.9 \pm 0.1
Jones #4	30.3 \pm 4.1	14.6 \pm 3.5	69.0 \pm 19.8	13.0 \pm 0.4	ND	5.0 \pm 0.1	54.2 \pm 0.2	29.8 \pm 0.3
McGee #1	46.7 \pm 7.6	21.6 \pm 7.9	62.5 \pm 7.2	17.2 \pm 1.5	ND	7.3 \pm 0.5	58.3 \pm 2.4	31.9 \pm 1.9
McGee #2	17.5 \pm 1.2	9.8 \pm 0.3	21.7 \pm 2.2	8.7 \pm 0.2	23.3 \pm 3.5	6.2 \pm 0.3	63.2 \pm 0.1	27.8 \pm 1.0
McGee #3	20.2 \pm 4.6	9.4 \pm 0.1	40.6 \pm 17.0	9.1 \pm 0.1	17.7 \pm 0.4	17.0 \pm 0.3	52.5 \pm 0.1	40.1 \pm 0.2
Turner #1	13.4 \pm 1.8	5.1 \pm 0.3	25.4 \pm 4.0	9.2 \pm 0.4	28.7 \pm 2.4	9.1 \pm 0.2	62.8 \pm 0.2	22.3 \pm 0.3
Turner #2	21.0 \pm 4.1	8.0 \pm 0.4	24.7 \pm 2.9	10.0 \pm 1.3	24.2 \pm 1.1	5.8 \pm 0.2	59.6 \pm 0.2	26.3 \pm 0.2

Table B5. Emission Factors by Unit for Spring Burns Based on ALL and SCREENED Tower Data

Shown are mean values \pm 1 SE. "ND" indicates no data available, and " \pm ---" a sample size of 1. "0.0" indicates SE<0.05.

Unit	Emission Factor, ALL tower data (lbs/ton)				Emission Factor, SCREENED tower data (lbs/ton)			
	CO ₂	CO	CH ₄	PM _{2.5}	CO ₂	CO	CH ₄	PM _{2.5}
Beard #1	3554 \pm 7	63 \pm 6	1.3 \pm ---	4.5 \pm 0.3	3554 \pm 7	63 \pm 6	1.7 \pm ---	4.5 \pm 0.3
Beard #2	3488 \pm 17	102 \pm 13	2.0 \pm ---	6.4 \pm 0.0	3489 \pm 17	102 \pm 13	2.0 \pm ---	6.4 \pm 0.0
Beard #3	3555 \pm 2	59 \pm 0.2	2.7 \pm 0.1	4.6 \pm 0.7	3556 \pm 2	59 \pm 0.2	2.7 \pm 0.1	4.6 \pm 0.7
Beard #4	3406 \pm 98	139 \pm 53	4.0 \pm 1.8	13.1 \pm 4.0	3506 \pm ---	86 \pm ---	2.2 \pm ---	9.0 \pm ---
Beard #5	3556 \pm 8	61 \pm 6	1.9 \pm ---	5.2 \pm 0.3	3557 \pm 8	61 \pm 6	1.9 \pm ---	5.2 \pm 0.3
Beard #6	3480 \pm 75	97 \pm 36	2.2 \pm 0.8	11.3 \pm 6.4	3555 \pm ---	61 \pm ---	1.4 \pm ---	4.9 \pm ---
Covello #1	3571 \pm ---	56 \pm ---	ND	3.1 \pm ---	3571 \pm ---	56 \pm ---	ND	3.1 \pm ---
Covello #2	3535 \pm 6	68 \pm 4	1.6 \pm 0.2	8.1 \pm 0.4	3536 \pm 6	68 \pm 4	1.6 \pm 0.2	8.1 \pm 0.4
Covello #3	3569 \pm ---	56 \pm ---	0.9 \pm ---	3.1 \pm ---	3570 \pm ---	56 \pm ---	0.9 \pm ---	3.1 \pm ---
Covello #4	3482 \pm 54	103 \pm 28	2.3 \pm 0.6	6.6 \pm 4.0	3483 \pm 54	103 \pm 28	2.3 \pm 0.6	6.6 \pm 4.0
Covello #5	3589 \pm ---	41 \pm ---	0.9 \pm ---	4.1 \pm ---	3590 \pm ---	41 \pm ---	0.9 \pm ---	4.1 \pm ---
Harting #1	3560 \pm 10	55 \pm 6	1.4 \pm 0.4	6.6 \pm 0.2	3561 \pm 10	55 \pm 6	1.4 \pm 0.4	6.6 \pm 0.2
Harting #2	2347 \pm 1218	39 \pm 21	0.7 \pm 0.1	11.6 \pm 1.6	3566 \pm ---	60 \pm ---	0.6 \pm ---	0.6 \pm ---
Harting #3	3530 \pm 31	75 \pm 15	2.1 \pm ---	6.5 \pm 1.8	3531 \pm 31	75 \pm 15	2.1 \pm ---	6.5 \pm 1.8
Harting #5	3530 \pm 32	78 \pm 23	0.6 \pm ---	15.5 \pm 1.3	3563 \pm ---	54 \pm ---	1.1 \pm ---	6.7 \pm ---

Table B6. Emission Factors by Unit for Fall Burns Based on ALL and SCREENED Tower Data

Shown are mean values \pm 1 SE. "ND" indicates no data available, and " \pm ---" a sample size of 1. "0.0" indicates SE<0.05.

Unit	Emission Factor, ALL Tower Data (lbs/ton)				Emission Factors, SCREENED Tower Data (lbs/ton)			
	CO ₂	CO	CH ₄	PM _{2.5}	CO ₂	CO	CH ₄	PM _{2.5}
Fletcher #1	3387 \pm ---	159 \pm ---	3.6 \pm ---	7.8 \pm ---	3388 \pm ---	159 \pm ---	3.7 \pm ---	7.8 \pm ---
Fletcher #2	3504 \pm ---	85 \pm ---	2.0 \pm ---	9.9 \pm ---	3505 \pm ---	85 \pm ---	2.0 \pm ---	9.9 \pm ---
Fletcher #3	3486 \pm 1	107 \pm 0.2	2.4 \pm ---	3.7 \pm 0.9	3486 \pm 1	107 \pm 0.2	2.4 \pm ---	3.7 \pm 0.9
Jones #1	3442 \pm 22	118 \pm 13	4.1 \pm 1.0	11.8 \pm 0.4	3444 \pm 22	118 \pm 13	4.1 \pm 1.0	11.8 \pm 0.4
Jones #2	3519 \pm 2	70 \pm 2	2.8 \pm 0.1	12.3 \pm 0.1	3520 \pm 2	70 \pm 2	2.8 \pm 0.1	12.3 \pm 0.1
Jones #3	NO DATA				NO DATA			
Jones #4	3445 \pm 9	119 \pm 4	3.7 \pm 0.7	9.9 \pm 0.2	3446 \pm 9	119 \pm 4	3.7 \pm 0.7	9.9 \pm 0.2
McGee #1	3405 \pm 31	137 \pm 16	4.7 \pm 0.5	14.0 \pm 1.9	3407 \pm 31	137 \pm 16	4.7 \pm 0.5	14.0 \pm 1.9
McGee #2	3494 \pm 17	96 \pm 8	2.8 \pm 0.4	6.0 \pm 1.9	3494 \pm 17	96 \pm 8	2.8 \pm 0.4	6.0 \pm 1.9
McGee #3	3261 \pm 34	196 \pm 19	7.0 \pm 0.7	16.8 \pm 1.3	3264 \pm 34	197 \pm 19	7.0 \pm 0.7	16.8 \pm 1.3
Turner #1	3486 \pm 9	99 \pm 3	2.7 \pm 0.3	7.5 \pm 1.4	3487 \pm 9	99 \pm 3	2.7 \pm 0.3	7.5 \pm 1.4
Turner #2	3474 \pm 31	104 \pm 16	3.4 \pm 0.7	8.4 \pm 1.7	3475 \pm 31	104 \pm 16	3.4 \pm 0.7	8.4 \pm 1.7

APPENDIX C

List of Statistical Outliers

Table C1. List of Towers Excluded From the Emission Factor Analysis

The mean is based on the data by ignition type for each season, with the outliers included.

Unit and Tower	Emission Factors	Reason for	Outlier Statistics		
	Excluded	Exclusion	Outlier Value	Mean \pm SD	# of SD's
Spring					
Beard #4, Tower #1	CO ₂ , CO, CH ₄ , PM _{2.5}	EF _{PM2.5} extreme outlier	17.13 lbs PM _{2.5} /ton	8.66 \pm 2.85	+3.0
Beard #6, Tower #2	CO ₂ , CO, CH ₄ , PM _{2.5}	EF _{PM2.5} extreme outlier	17.65 lbs PM _{2.5} /ton	8.66 \pm 2.85	+3.2
Harting #2, Tower #2	CO ₂ , CO, CH ₄ , PM _{2.5}	EF _{PM2.5} extreme outlier; smoldering data only	22.63 lbs PM _{2.5} /ton	4.22 \pm 0.70	+4.2
Harting #5, Tower #2	CO ₂ , CO, CH ₄ , PM _{2.5}	EF _{PM2.5} extreme outlier; flaming phase	24.34 lbs PM _{2.5} /ton	4.71 \pm 1.76	+4.5
Fall					
No outliers removed.					