QUANTIFYING POST-HARVEST EMISSIONS FROM BLUEGRASS SEED PRODUCTION FIELD BURNING

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GRASS SEED CROPPING SYSTEMS FOR A SUSTAINABLE AGRICULTURE

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SUMMARY AND CONCLUSIONS

Summary:

Residue Loading. Removal of post-harvest residue by baling significantly reduced the amount of pre-burn residue at all sites. The high (i.e., no residue removed) residue loading and low (i.e., residue removed by baling) residue loading means averaged over all sites were 4.0 and 1.8 tons acre^{-1}, respectively. The low residue loading was similar at all sites (1.7 to 1.9 tons acre^{-1}). Pre-burn residue loading did not influence post-burn residue loading. The high and low pre-burn residue loading at Connell, WA (irrigated) and Worley, ID (dryland) sites burned down to similar post-burn residue loading. However, at Rathdrum, ID (irrigated) both high and low pre-burn residue loading had significantly lower post-burn residue loading relative to the other two sites.

Residue Consumption. Absolute residue consumption ($RC_{Absolute}$) was the same for high residue loading at all sites, approximately 3.2 ton acre^{-1}. The Rathdrum low residue loading treatment was unique and $RC_{Absolute}$ was more than two times greater than at the other two sites. There was a strong positive relationship between $RC_{Absolute}$ and the pre-burn residue loading. The higher the pre-burn residue loading, the higher the $RC_{Absolute}$. Since 89% of the variation in $RC_{Absolute}$ was explained by the variation in pre-burn residue loading, this would suggest that any practice that removes a significant portion of the post-harvest residue from a bluegrass seed production field (e.g., baling) would reduce the amount of residue consumed. Total $PM_{2.5}$ emissions (lbs acre^{-1}) would be reduced by a significant reduction in $RC_{Absolute}$ if the $PM_{2.5}$ emission factor (EF, lbs ton^{-1} of residue consumed) remained constant or did not increase markedly.

Emission Factors for $PM_{2.5}$, CO_2, CO, and CH_4. Since there were no statistical differences in $EF_{PM2.5}$ between Rathdrum and Worley residue loading treatments, $EF_{PM2.5}$ was pooled for these sites. Based on the pooled means, $EF_{PM2.5}$ for Connell high residue loading was greater than Rathdrum and Worley high residue loading. At Rathdrum and Worley, low pre-burn residue loading produced consistently greater $EF_{PM2.5}$ than high residue loading. This relationship could not be assessed at Connell due to a lack of replication (n=1) in the low residue loading treatment.

It should be noted that the $EF_{PM2.5}$ in this study are substantially greater than those reported for most agricultural burns, wildfires, and forest fires (Air Sciences Inc., 2003). The $EF_{PM2.5}$ for the cereal study conducted in eastern Washington (Air Sciences Inc., 2003) had a mean $EF_{PM2.5}$ of 7.4 lbs ton^{-1} of residue consumed while the mean $EF_{PM2.5}$ for this study was 57 lbs ton^{-1} of residue consumed. $EF_{PM2.5}$ was significantly higher for the Connell high residue loading treatment than for high residue loading at Rathdrum and Worley, 109 lbs of $PM_{2.5}$ ton^{-1} of residue consumed. There were no differences in $EF_{PM2.5}$ among the low pre-load residue treatments at Rathdrum or Worley.

There was a strong positive relationship between EF_{CO2} and CE (Combustion Efficiency, %). There also were strong negative relationships between CE and EF_{CO} and EF_{CH4}. These relationships are similar to those reported for other studies (Air Sciences Inc., 2003). Overall CO_2 emissions increased with increased CE while CO and CH_4 emissions decreased with increased CE.

Emission Factors Affected by Residue and Soil Moisture. There was no discernible relationship between residue moisture content (%, oven-dry weight basis) and $EF_{PM2.5}$. EF_{CO2} decreased with increasing residue moisture content, while EF_{CO} and EF_{CH4} increased with increasing residue moisture content. None of the pollutant emission factors was significantly related to soil moisture content.

Emission Factors for Polyaromatic Hydrocarbons (PAHs). Fourteen samples were analyzed for PAHs. Of these, two samples taken at the Worley high residue loading units showed PAH concentrations above the method of analysis detection limit. The emission factors in this study for benzo(a)anthracene and chrysene ranged from 0.39 to 0.42 mg kg^{-1} of residue consumed and were in the range reported in other crops (Ramdahl and Moller, 1983; Jenkins et al., 1996a, 1996b, and 1996c). Similarly, the emission factor for benzo(b)fluoranthene of 1.6 mg kg^{-1} of residue consumed was in the range reported for other crops.

Total $PM_{2.5}$ Emissions. Total $PM_{2.5}$ emissions for the Connell high residue loading treatment were significantly higher than for any other treatment, 350 lbs of $PM_{2.5}$ $acre^{-1}$. The differences in total $PM_{2.5}$ are mostly attributable to differences in $EF_{PM2.5}$ and not $RC_{Absolute}$. The Worley and Connell (n=1) low residue loading treatment produced 30 lbs of $PM_{2.5}$ $acre^{-1}$ and the Rathdrum high residue loading, Rathdrum low residue loading, and Worley high residue loading treatments were intermediate at approximately 100 lbs of $PM_{2.5}$ $acre^{-1}$.

The management practice of baling and burning (propane flaming at Connell and open-field burning at Worley), significantly reduced total $PM_{2.5}$ $acre^{-1}$ at Worley and numerically at Connell (n=1). At Rathdrum, baling followed by burning did not reduce total $PM_{2.5}$ emissions $acre^{-1}$ relative to open-field burning of the high residue load. Higher $RC_{Absolute}$, potentially leading to higher total emissions, was compensated for by a lowered $EF_{PM2.5}$ at the high residue loading at Rathdrum.

$PM_{2.5}$ emissions $acre^{-1}$ was regressed as a linear function to assess the relative contribution of $RC_{Absolute}$ and $EF_{PM2.5}$ to total $PM_{2.5}$ $acre^{-1}$. These two factors combined explained 95% of the total variation in total $PM_{2.5}$ emissions. When regressed individually, $RC_{Absolute}$ and $EF_{PM2.5}$ explained 21 and 45 %, respectively, of the variation in total $PM_{2.5}$ emissions $acre^{-1}$. Independently they are affected by site and residue loading and it is difficult to consider the individual effect of these parameters on total $PM_{2.5}$ emissions $acre^{-1}$. In this study, both the $RC_{Absolute}$ and $EF_{PM2.5}$ were needed to explain the total $PM_{2.5}$ emissions $acre^{-1}$. So, while it is probably valid to attribute the high total emissions for the Connell high residue loading treatment, relative to the other two sites, to a high $EF_{PM2.5}$, and the high total emissions at the Rathdrum low residue loading treatment, relative to the other two sites, to a high $RC_{Absolute}$, one must use caution when discussing cause and effect in this study.

Conclusions:

High pre-burn residue loading had significantly more pre-burn residue on the field than the low loading residue treatment.

Post-burn residue loading was independent of pre-burn residue loading, i.e., the high and low pre-burn residue loading (baled) treatments burned down to the same post-burn residue loading at each site. Following burning the same amount of residue remained on the field regardless of the initial residue loading.

Residue consumption (tons of residue consumed per acre, tons $acre^{-1}$) increased with pre-burn residue loading, i.e., the higher the pre-burn residue loading, the higher the consumption. The implication is that baling is an effective method to reduce residue consumption.

There was no apparent relationship between residue consumption and soil moisture or any environmental factors monitored during the burns.

The residue stratification (residue architecture above the soil surface) and the bulk densities of the residue layers may affect $RC_{absolute}$, $EF_{PM2.5}$, and total $PM_{2.5}$ emissions (pounds per acre, lbs $acre^{-1}$).

Both $RC_{absolute}$ and $EF_{PM2.5}$ are required to predict (together they explained 95% of the variation in the data) total $PM_{2.5}$ emissions (lbs $acre^{-1}$) at any site.

At Rathdrum, baling did not reduced total $PM_{2.5}$ emissions (lbs $acre^{-1}$), while at Worley, baling significantly reduced total $PM_{2.5}$ emissions (lbs $acre^{-1}$) by 66%. At Connell, baling followed by propane flaming of the low residue loading treatment numerically reduced total $PM_{2.5}$ emissions (lbs $acre^{-1}$) by 91%, compared to the high residue open-field burn. Due to lack of replication of the low residue loading treatment, no statistical conclusion can be made for the Connell site.

1. INTRODUCTION

1.1 Statement of Problem

Fire has long been used as a management tool in grass seed production (Burton, 1944; Conklin, 1976; Chilcote et al., 1978; Hardison, 1980; Kamm and Montgomery, 1990; Johnston et al., 1996; Mazzola et al., 1997; Schirman, 1997). However, increasing concerns over the health impact of emissions from open-field burning have pointed to the need for information on grass fire emissions. Although some data are currently available that identify and quantify the various chemical components of grassfire emissions in the Pacific northwest (Boubel et al., 1969; Adams, 1976), and biomass burning (Crutzen and Andreae, 1990; Kuhlbusch et al., 1991; Jenkins et al., 1996a), little research has been performed with residue reduction and burning systems. Because mechanical residue removal is an option growers can use to reduce the residue load on grass fields, emissions from fields where residue has been removed and fields with typical post-harvest residue loads need to be studied.

In a never-completed study, Adams (1976) found indications of higher emissions with open-field burning following residue removal than with open-field burning alone. However, current WSU research with diesel or propane flaming following residue reduction (baling) indicates the possibility of reduced emissions and reduced smoldering while maintaining good seed yield (Felgenhauer, personal communication, 1999). Characterization of particulate-matter emissions from the bale-and-flame system are needed because the combustion efficiencies of these burns may be different from conventional open-field burns, with either higher or lower particulate-matter emissions per mass of residue consumed.

The Washington State Department of Ecology (WDOE), based on statements of concern for public health, in 1996 reduced the acres of Kentucky bluegrass (*Poa pratensis* L.) seed production fields that were burned in Washington State by 33%. In 1997, the number of burned acres were reduced 67% from pre-1996 levels, and in 1998, bluegrass burning was virtually eliminated. Are there options other than a restriction on number of acres burned to reduce emissions? Currently, insufficient research on grassy residues has been conducted to characterize emissions to the degree necessary to resolve this issue. Additional research is needed to establish Best Management Practices (BMPs) under the conditions typically found in open-field burns of dryland and irrigated bluegrass post-harvest residue in eastern Washington and northern Idaho.

Several groups recognized the need for emissions research on post-harvest burning of Kentucky bluegrass seed production fields and provided financial support for this study: Washington Department of Ecology (WDOE), Idaho Department of Environmental Quality (IDEQ), Grass Seed Cropping Systems for a Sustainable Agriculture (GSCSSA), Washington Turfgrass Seed Commission (WTSC), Coeur d'Alene Tribe, and Environmental Protection Agency Region 10. The WTSC stated in a letter to the GSCSSA Administrative Committee (January 28, 2000) that "[this] project will parallel the procedures for emissions data collection and analysis established by the WDOE and Washington Association of Wheat Growers (WAWG) in order to create a reliable baseline for emissions from our industries agricultural burning. Our ability to participate in these studies brings the cost for both industries down and begins to establish a very important body of information for agriculture. Although Washington currently allows no grass seed field burning, Idaho will greatly benefit from these studies." (Lee Morris, WTSC, 2000).

Therefore, this study evaluated emissions generated from grass seed production fields with post-harvest residue reduction compared to those burned without post-harvest residue reduction. The information obtained from this study will help establish appropriate residue management

and burning practices needed to significantly reduce emissions, enhance the scientific database on emissions from grassy residues, and provide data to direct future research.

1.2 Objectives

1. To characterize post-harvest residue and field conditions of Kentucky bluegrass seed production fields at the time of burning.

2. To quantify, under field conditions at dryland and irrigated sites, with and without post-harvest residue removal, the quantity of emissions generated by Kentucky bluegrass field burning and relate these emissions to conditions evaluated in Objective 1.

1.3 Treatments and Emissions Characterization

The planned experimental treatments consisted of two pre-burn residue loads (no residue removed, or high residue load; and baling and removal of post-harvest residues, or low residue load), three locations (Connell, Washington; Worley, Idaho; and Rathdrum, Idaho), and two irrigation practices (irrigated [Connell and Rathdrum], and non-irrigated or dryland [Worley]). The emission species to be characterized were designated by the WDOE as follows:

Carbon monoxide (CO)
Particulate matter less than 2.5 micrometers in diameter ($PM_{2.5}$)
Particulate matter less than 10 micrometers in diameter (PM_{10})
Benzo(a)pyrene (BaP)
Six additional BaP-equivalent carcinogens, including benzo(a)anthracene, benzo(b)fluroanthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, and idenol(1,2,3-cd)pyrene

Two other carbon species, methane (CH_4) and carbon dioxide (CO_2), were included in the investigation because they are required in the calculation of emission factors using the carbon mass balance method.

2 METHODS

2.1 Study Locations and Design

This field investigation included 18 burn units at three locations (6 per location): at Connell in the Columbia Basin of eastern Washington, and at Rathdrum and Worley in northern Idaho (Figure 2.1; Appendix 4). At each location, the six burn units comprised two residue treatments (high residue loading, and low residue loading) with three replications of each treatment (Table 2.1).

All of the burn units were combined up to three weeks prior to burning. On the low-residue-loading units, the residue was also removed (baled) up to three weeks prior to burning (Table 2.1).

Each burn unit consisted of a square area measuring 417 feet on a side (4 acres), surrounded by a fuel break. The fuel break consisted of either a 50-foot-wide area disked to mineral soil, or a 20- to 60-foot-wide area in which the residue was removed (Appendix 4). All of the treatment units within the fields were selected based on uniformity of pre-burn loading conditions.

Prior to igniting the fires, sampling to determine pre-burn residue loading and residue moisture content was performed in each unit (Section 2.2, Sampling Procedures), and the emissions sampling equipment was erected (Section 2.2.4, Emissions). Growers utilized water trucks to wet the border of each burn unit so the burn would be contained to the 4-acre burn unit. The growers performed the ignition of fires at the Rathdrum and Worley locations. The ignition of the fires at the Connell location was performed by WSU personnel. The meteorological and residue moisture conditions at the time of each burn are summarized in Tables 2.2 and 2.3, respectively.

Table 2.1. Combining, harvesting, and burn dates of the experimental units.

Study Site	Irrigation Treatment	Combine Date	Residue Removal (Bale) Date	Burn Date
Connell, WA	Irrigated	July 31, 2001	August 1, 2001	August 7-9, 2001
Rathdrum, ID	Irrigated	July 23, 2001	August 6, 2001	August 21-22, 2001
Worley, ID	Dryland	August 3, 2001	August 6, 2001	August 15-16, 2001

Figure 2.1. Geographic locations of study sites.

The study sites were located at Connell, WA (irrigated); Rathdrum, ID (irrigated); and Worley, ID (dryland).

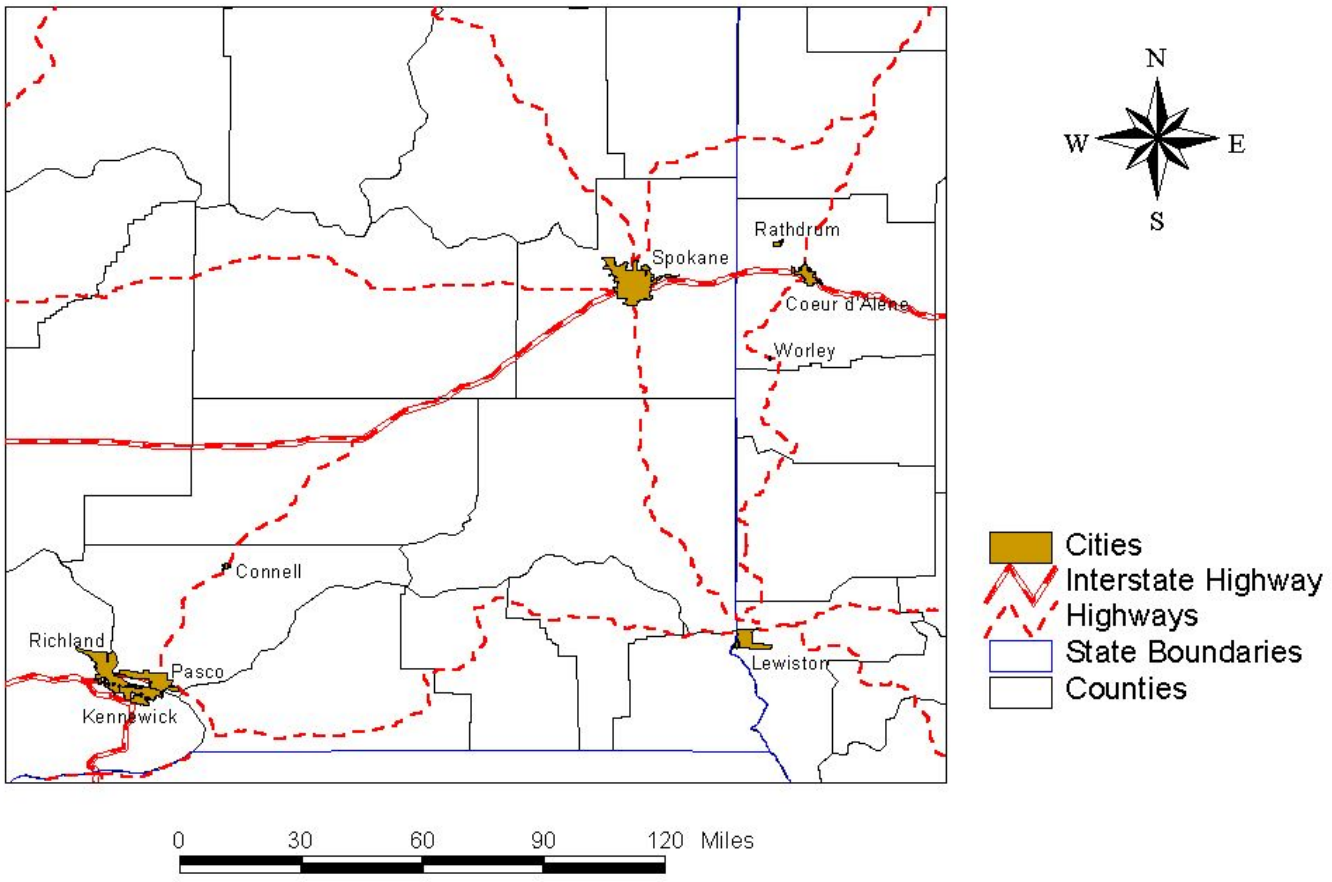


Table 2.2. Meteorology by site and pre-burn residue loading

Values shown are means ± 1 standard error (SE). The sample size varied from 7 to 20 (2-minute means for each unit average).

Study Site and Residue Loading	Wind Speed (mph)	Temperature (^{O}F)	Relative Humidity (%)	Wind Direction (^{O} from true N)
Connell, WA, irrigated				
High loading (*n*=3)	10.0 ± 2.0	88.6 ± 0.6	14 ± 3	274 ± 32
Low loading (*n*=1)	7.8	94.4 ± 0.2	14 ± 0.1	238 ± 24 (n=2)
Rathdrum, ID, irrigated				
High loading (*n*=3)	7.3 ± 1.4	74.2 ± 2.5	31 ± 10	205 ± 8
Low loading (*n*=3)	6.8 ± 0.8	72.1 ± 1.5	33 ± 7	200 ± 9
Worley, ID, dryland				
High loading (*n*=3)	6.5 ± 1.4	87.2 ± 0.6	19 ± 2	147 ± 20
Low loading (*n*=3)	6.3 ± 0.7	91.8 ± 0.3	14 ± 1	130 ± 12
All (n=16)	7.4 ± 0.6	83.5 ± 2.3	22 ± 3	

Table 2.3. Fuel- and soil-moisture percent by site and pre-burn residue loading.

Values are expressed as % H_2O per g dry weight, as a function of study site and residue loading. Values shown are means ± SE. Statistically significant differences (1-way ANOVA with Bonferroni post-hoc test (see Section 2.4.4, Statistical Analysis; $P<0.05$) are indicated with different letters (compare within columns only).

Study Site and Residue Loading	Entire Residue Layer (%)	Upper Residue Layer (%)	Lower Residue Layer (%)	Soil Layer (%)
Connell, WA, irrigated				
High loading (*n*=3)	13.5 ± 5.0 ab	2.8 ± 0.3 a	26.7 ± 7.6	4.7 ± 0.1 a
Low loading (*n*=1)	22.1			4.4
Rathdrum, ID, irrigated				
High loading (*n*=3)	16.2 ± 1.8 ab	6.5 ± 1.2 b	21.7 ± 3.2	8.6 ± 0.6 b
Low loading (*n*=3)	21.6 ± 3.9 a			7.4 ± 0.2 b
Worley, ID, dryland				
High loading (*n*=3)	14.8 ± 2.2 ab	3.6 ± 0.6 ab	22.3 ± 1.0	5.5 ± 0.3 a
Low loading (*n*=3)	9.3 ± 0.8 b			5.0 ± 0.3 a
All (n=7, 9, 9, 17)	16.4 ± 2.9 (Low)	4.3 ± 0.7	23.6 ± 2.5	6.1 ± 0.4
(n=8)	14.8 ± 1.5 (High)			

All fires, except for two units, were ignited as "head fires." 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 residues and a correspondingly wider fireline depth (i.e., greater width of burning residues). The low loading unit #1 (replication 1) at the Connell site was ignited using a head fire pattern, but the fire never developed properly over the whole unit. A post-burn residue loading could not be taken, and the unit was disqualified for the study (data not included in report). Consequently, the low loading units #2 (replication 2) and #3 (replication 3) at the Connell site were ignited using a propane burner, using the pattern of a "strip head fire." 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 limited. Each strip runs into the previously burned strip, which causes it to be extinguished. At the Connell site all the strips did not come together (see Discussion, Section 4.7).

2.2 Sampling Procedures

2.2.1 Residue Load

Pre- and post-burn residue loading was sampled in order to assess the total residue consumption following each test burn. Within each burn unit, eight to 12 sampling locations were randomly chosen throughout each experimental unit, to characterize the pre-burn residue loading (three per unit were taken at Connell for stubble length). Similarly, four sampling locations were randomly chosen throughout each experimental unit, to characterize the post-burn residue loading. At each sampling location a 1-square foot (12 by 12 inches) area was sampled.

The pre-burn sampling protocol is summarized as follows. On each of the high residue units, stratified samples were taken and stored in labeled paper bags for transport to the laboratory at WSU. The upper residue layer was qualified as all those grass residues swathed and combined with post-harvest residue scattered on the field by the combine. This residue rests on top of the stubble that is still attached to the root system. The lower residue layer was all those residues still attached to the root system plus any post-harvest residue that filtered down into the standing stubble. On each of the low residue units an entire layer residue sample was taken, which consisted of standing stubble plus any post-harvest residue remaining following raking and baling. At the flat, irrigated study sites, Connell and Rathdrum, the residue depth of vertically oriented residue was 2 inches and approximately 9 to 10 inches, respectively, and the length of the standing stubble was not affected by residue load (Table 2.4). The dryland Worley site was on rolling terrain with slopes and draws. At Worley, mean standing stubble height with high residue loading was 9.3 inches (slope = 8.3 inches; draw = 10.3 inches). The low residue loading units had standing stubble of approximately 3 to 4 inches (slope = 3.9 inches; draw = 3.1 inches) (Table 2.4).

Table 2.4. Stubble and residue height by site and pre-burn residue loading.

Study Site and Residue Loading	Standing Stubble (inches)	Ground to Top of Residue (inches)	Ground to Residue Layer (inches)	Thickness of Residue Layer (inches)
Connell, WA, irrigated				
High loading	2	6-9 estimated	0	6-7 estimated
Low loading	2			
Rathdrum, ID, irrigated				
High loading	9-10 estimated	7.8 (8.0-10.0)	4.2 (1.5-6.0)	3.7 (3.0-4.0)
Low loading	9.7 (7.3-10.8)			
Worley, ID, dryland				
High loading	8.3 (7.0-9.3) (slope) 10.3 (7.3-12.5) (draw)	6.1 (2.8-8.0)	2.6 (0.0-4.5)	3.5 (2.8-4.5)
Low loading	3.9 (2.5-4.8) (slope) 3.1 (2.0-4.8) (draw)			

Table 2.5. Bulk density of pre-burn residue by site, loading, and residue layer.

Calculated from residue moisture dry weights, n=3. Values are means ± standard error. Statistically significant differences (1-way ANOVA with Bonferroni test (see Section 2.4.4, Statistical Analysis); $P<0.05$) are indicated with different letters to compare within column for each site.

Study Site and Residue Loading	Residue Layer	Bulk Density (lbs ft^{-3})
Connell, WA, irrigated		
High loading	Entire	0.27 ± 0.02 b
High loading	Upper	0.20 ± 0.03 b
High loading	Lower	0.51 ± 0.04 a
Low loading	Entire	0.48 ± 0.00 a
Rathdrum, ID, irrigated		
High loading	Entire	0.26 ± 0.05 a
High loading	Upper	0.24 ± 0.06 a
High loading	Lower	0.28 ± 0.04 a
Low loading	Entire	0.11 ± 0.01 b
Worley, ID, dryland		
High loading	Entire	0.39 ± 0.02 bc
High loading	Upper	0.24 ± 0.03 c
High loading	Lower	0.60 ± 0.05 a
Low loading	Entire	0.30 ± 0.02 bc

At each experimental unit four random samples were taken to determine post-burn residue loading. Only entire residue was determined to assess post-burn residue loading. The post-burn loading determination was performed within 10 minutes following the end of each burn to ensure that the ash and unburned materials were collected before any material was blown into, or out of, the measurement areas.

All of the pre- and post-burn sample bags were placed in large cloth bags marked with the burn unit name and number, and transported to WSU for subsequent drying, weighing, and recording. In the laboratory, the sample bags and the contents were oven-dried at 140^{O}F for five days and then weighed.

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

$$L_{\text{Pre-Burn}} \text{ or } L_{\text{Post-Burn}} \text{ (tons acre}^{-1}) = \frac{(W_{OD})(43560 \text{ feet}^2 \text{ acre}^{-1})}{(907184.8 \text{ g ton}^{-1})} \quad (1)$$

In Equation (1), $L_{\text{Pre-Burn}}$ and $L_{\text{Post-Burn}}$ are the pre-burn and post-burn loadings (tons dry biomass acre^{-1}), respectively. W_{OD} is the oven-dry sample weight (g feet^{-2}; measured to 1/100th of a gram). $L_{\text{Pre-Burn}}$ and $L_{\text{Post-Burn}}$ were calculated for each experimental unit by taking the averages of all sub-samples.

2.2.2 Residue Moisture Content

Moisture sampling of residue strata and soil 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 particulate matter, CO, and CH_4 emission factors. The sampling protocol was as follows. Within each burn unit, four randomly located samples were taken during the 30-minute period preceding the start of ignition, to determine pre-burn residue moisture content. High loading residue moisture samples were stratified, as described under the pre-burn residue loading methodology, into upper, lower, and entire residue layers.

All moisture content samples were placed in 'Ziploc' plastic bags, to seal in moisture, and transported to the laboratory for analysis at WSU at Pullman, WA. In the laboratory, the sample bags were weighed to determine fresh weight (W_{Field}) then oven-dried at a temperature of 140^{O}F for five days and then weighed to determine the dry weight (W_{OD}). The relative residue moisture contents of the three residue layer strata and the soil layer were calculated according to:

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

where RMC is the residue moisture content (relative to dry weight), W_{Field} the fresh weight of the samples (g), and W_{OD} is the oven-dried weight (g). The relative moisture content of the entire layer of the high loading sites was calculated as the weighted average of the RMC of the upper- and lowers residues at each unit (Anderson and Grant, 1993).

2.2.3 Bulk Density of Residue Layers

The bulk density (BD) in lbs ft^{-3} was calculated for each residue layer. High loading-Upper layer, High loading-Lower layer, and Low loading-Entire layer were calculated as:

$$BD_{layer} = \frac{W_{od}}{H_{layer} * (1\,ft^2)} \quad (3)$$

In Equation (3), BD_{layer} is the calculated bulk density of a specific residue layer (lbs ft^{-3}), W_{OD} the oven-dry sample weight (lbs), and H_{layer} the height of the residue layer (feet).

Bulk density for the High loading-Entire layer was calculated as the weighted average of the bulk densities of the upper- and lower-residue layers:

$$BD_{entire} = BD_{upper} * \left(\frac{H_{upper}}{H_{upper} + H_{lower}} \right) + BD_{lower} * \left(\frac{H_{lower}}{H_{upper} + H_{lower}} \right) \quad (4)$$

In Equation (4), BD_{entire}, BD_{upper}, and BD_{lower} represent the bulk densities (lbs ft^{-3}) of the entire layer (high loading units), upper layer, and the lower layer, respectively. H_{upper} and H_{lower} stand for the height (feet) of the upper and lower residues layers, respectively.

2.2.4 Emissions

The USDA Forest Service's Missoula Fire Sciences Laboratory's (MFSL) Fire Atmosphere Sampling System (FASS) was used to measure the emissions of carbon species (i.e., CO_2, CO, CH_4, and $PM_{2.5}$) and other fire-related parameters such as temperature and combustion efficiency, in real time (Ward et al., 1992b; Susott et al., 1991). Combustion efficiency (CE) 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 about 140 feet apart on the downwind side of the residue sampling area. To avoid edge effects, the tower pairs were placed at least 140 feet from the burn unit edge. Each FASS package was triggered independently and switched from a background mode to a sampling mode when CO reached 1000 ppm (Ward et al., 1992a). Each sampling package was programmed to switch from sampling of flaming combustion to smoldering combustion after 3 minutes, which was the expected fire residence time for the ignition determined by MFSL.

2.3 Laboratory Analysis of Emissions

2.3.1 Canister Gases

The canister gas samples and filters were analyzed at the Intermountain Fire Sciences Laboratory at Missoula, Montana (MFSL). 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 CO_2 and CO, and another for CH_4 and carbon-2 (C_2) and carbon-3 (C_3) gases. The CO_2 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 min^{-1}) passing through a methanizer and FID at 300°C. CO and CO_2 were analyzed in separate isothermal runs, with CO run at 30°C and CO_2 run at 100°C.

The CH_4, C_2, and C_3 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^{-1}), 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^{-1} 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 Filters

The Teflon filters used in the $PM_{2.5}$ determination were conditioned and weighed in a controlled-environment room at 68°F and 50% relative humidity at the MFSL at Missoula, MT. 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. Before each weighing the balance tare was zeroed. 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 manner 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 L min^{-1} 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. PAH samples were taken using high volume samplers with a total volume of 30 L for the flaming phase (based on a 3-min sampling period and a flow of 10 L min^{-1}).

2.4 Data Analysis

2.4.1 Fuel Consumption

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

$$RC_{Absolute}\ (\text{tons acre}^{-1}) = L_{Pre\text{-}Burn} - L_{Post\text{-}Burn} \quad (5)$$

where $RC_{Absolute}$ is the residue burned (tons acre^{-1}), and $L_{Pre\text{-}Burn}$ and $L_{Post\text{-}Burn}$ are the residue loadings (tons acre^{-1}) for each of the test units before and after the burn, respectively. The relative residue consumption, $RC_{Relative}$, was calculated according to:

$$RC_{Relative}\ (\%\ \text{Consumed}) = \frac{RC_{Absolute}}{L_{Pre\text{-}Burn}} * 100\% \quad (6)$$

2.4.2 Pollutant-Specific Emission Factors

Pollutant specific emission factors were calculated according to a carbon mass method. This method calculates the pollutant-specific emission factors (lbs pollutant per ton residue consumed) by dividing the concentration of the emission above background by the total airborne carbon concentration times an empirically derived residue mass-to-carbon mass ratio of 2.0:

$$EF_x\ (\text{lbs ton}^{-1}\ \text{fuel}\ ) = \left. \frac{\chi_x \big|_{Fire}\ \left(2{,}000\ \text{lbs ton}^{-1}\right)}{2.0 \cdot \left(\chi_{C\text{-}CO_2}\big|_{Fire} + \chi_{C\text{-}CO}\big|_{Fire} + \chi_{C\text{-}CH_4}\big|_{Fire} + \chi_{C\text{-}PM2.5}\big|_{Fire}\right)} \right|_j \quad (7)$$

Here, χ_x is the air concentration of pollutant species x (where x = CO_2, CO, CH_4, 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).

This method assumes that the carbon content of the residue was the same for the pre- and post-burn residue. A representative value for the pre-burn carbon fraction in cereal-grains and grasses is 50%, i.e., 0.50 grams of carbon per gram of dry biomass (Hurst et al., 1994a and 1994b; Turn et al., 1997; Hughes et al., 2000). Although the carbon fraction after the burn is dependent on the weight fractions of ash and unburned residue after the fire (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 the total post-burn sample weight was considered negligible. The emission factor for PM_{10} was estimated by dividing $EF_{PM2.5}$ by a scaling factor of 0.8 (Magliano et al., 1999; Purvis et al., 2000). Finally, the combustion efficiency (CE), expressed as percent, was calculated as the ratio of the actual CO_2 emission factor (lbs ton^{-1}) over the estimated CO_2 emission factor assuming that 100 percent of the carbon emissions occur as CO_2.

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:

$$EF_{PAH}\ (\text{lbs ton}^{-1}) = \left(\frac{M_{PAH}}{M_{PM2.5}}\right) * Flow\_correction * EF_{PM2.5} \quad (8)$$

where M is the filter-based mass ($PM_{2.5}$ or PAH-specific, g), "Flow_correction" a factor to account for the difference on total flow between the PAH and $PM_{2.5}$ samplers, and $EF_{PM2.5}$ is the fine-particulate emission factor calculated from Equation (7) (lbs ton^{-1}). EF_{PAH} was converted from lbs ton^{-1} residue to μg kg^{-1} residue, since the latter is a more common measure of reporting emission factors for PAHs.

The FASS units are specifically designed to make the measurements needed in each combustion phase. Although residue loading could be measured only before and after the fire, residue consumption in the flaming and smoldering phase was estimated from the FASS data (Ron Babbitt, personal communication, 2003). Since the majority of the fire emissions occurred in the flaming phase, the emission factors were based on the flaming phase only, with the exception of one site (FASS tower #2 at Rathdrum, high loading, replication 1), where the majority of the emissions occurred during the smoldering phase. For this site the smoldering emission factors were used.

2.4.3 Total $PM_{2.5}$ Emissions

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

$$PM_{2.5}\ \text{Total}\ (\text{lbs acre}^{-1}) = (L_{\text{Pre-Burn}})(RC_{\text{relative}})(EF_{PM2.5}) \quad (9)$$

where $L_{Pre\text{-}Burn}$ is the pre-burn residue loading (tons $acre^{-1}$), $RC_{Relative}$ the relative residue consumption (%), and $EF_{PM2.5}$ the emission factor for $PM_{2.5}$ (lbs ton^{-1}). Equation 9 is equivalent to multiplying the emission factor ($EF_{PM2.5}$, lbs ton^{-1}) and the absolute residue consumption ($RC_{Absolute}$, tons $acre^{-1}$), also yielding the total emissions on a per-acre basis:

$$PM_{2.5}\ \text{Total}\ (\text{lbs acre}^{-1}) = (RC_{\text{Absolute}})(EF_{PM2.5}) \quad (10)$$

2.4.4 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, i.e., in the case of residue loadings (4 to 12 sub-samples per unit), moisture contents (4 sub-samples per unit) and pollutant emissions (1 or 2 sub-samples per unit, FASS towers-), 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 residue consumption, moisture contents, emission factors, as well as total emissions based on the site, irrigation treatment, and pre-burn residue loading. If data were approximately normally distributed, then analysis of variance (ANOVA) was used, indicated by "$F_{\text{df between, df error term}}$ = F-statistic, *P*= significance level." 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, indicated by "χ^2=Chi-squared test statistic, *P*= significance level," was used when criteria for a normal distribution of the data were not met. Basically, all of the above tests indicate whether two (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 versus low), or treatment (irrigated versus dryland). An important value in the statistical 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 (i.e., 0.05) represents a 5%chance of the observed difference being due to random variation in the data, rather than a "real" difference between categories. In this study, if the P-value was less than or equal to 0.05, differences were declared to exist between or among 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, one extreme value of pre-burn residue loading was removed from the dataset for the high loading treatment at Connell, i.e., 13.0 tons acre^{-1} (+ 4 standard deviations; mean 4.5 tons acre^{-1} ± 2.2). Since only one of the 12 sub-samples was deleted from the dataset, this experimental unit was still included in the dataset.

Finally, it should be mentioned that the analyses of the residue consumption relationships with moisture were based on 17 sites total, as post-burn loading data was missing for one of the low loading units at Connell. However, the statistical analyses for the emission factors were based on a sample size of 15. This is because the Connell low loading treatment only had one unit with emission factor data. Therefore this site by loading combination lacked replication and was excluded from the emission factor analyses. Also, the field sites are indicated in the summary graphs as follows: Connell as “CO”, Rathdrum as “RA”, and Worley as “WO.”

3. RESULTS

3.1 Residue Consumption

Table 3.1 summarizes the pre-burn residue loading, post-burn residue loading, and residue consumption by study site location and pre-burn residue loading category. Pre-burn residue loading was significantly higher for the high loading sites compared to the low loading sites (Table 3.1; 2-way ANOVA, factors site and loading, $F_{2,1,12}$=202.90, P<0.001). The pre-burn residue loading at the high loading sites at Rathdrum was lower than at the other two locations, but this difference was not statistically different (Table 3.1; 2-way ANOVA, factors site and loading, $F_{2,1,12}$=2.87, P=0.096).

Post-burn residue loading was not influenced by pre-burn residue loading (Table 3.1; 2-way ANOVA, factors site and loading, $F_{2,1,11}$=1.10, P=0.316). Both the Connell and the Worley sites tended to burn down to a similar post-burn residue loading. However, both high and low pre-burn residue loading units at Rathdrum had significantly lower post-burn residue loading compared to the other two study locations (Table 3.1; 2-way ANOVA, factors site and loading, $F_{2,1,11}$=19.32, P<0.001).

Residue consumption was expressed in both absolute and relative terms using Equations (5) and (6). Absolute residue consumption ($RC_{Absolute}$) was significantly higher for the high loading units than for the low loading units at each site (Table 3.1; 2-way ANOVA, factors site and loading, $F_{2,1,11}$=131.32, P<0.001). At Rathdrum, $RC_{Absolute}$ was higher for the low residue loading units compared to the low residue units at the other sites (Table 3.1, 1-way ANOVA, $F_{2,5}$=12.21, P=*0.01*).

Similarly, the relative residue consumption ($RC_{Relative}$) was significantly higher for the high residue loading units compared to the low loading units at each site (Table 3.1; 2-way ANOVA, factors site and loading, $F_{2,1,11}$=59.99, P<0.001). At Rathdrum, $RC_{Relative}$ was higher for the low residue loading units compared to the low residue units at the other sites (Table 3.1; 2-way ANOVA, factors site and loading, $F_{2,1,11}$=59.99, P<0.001).

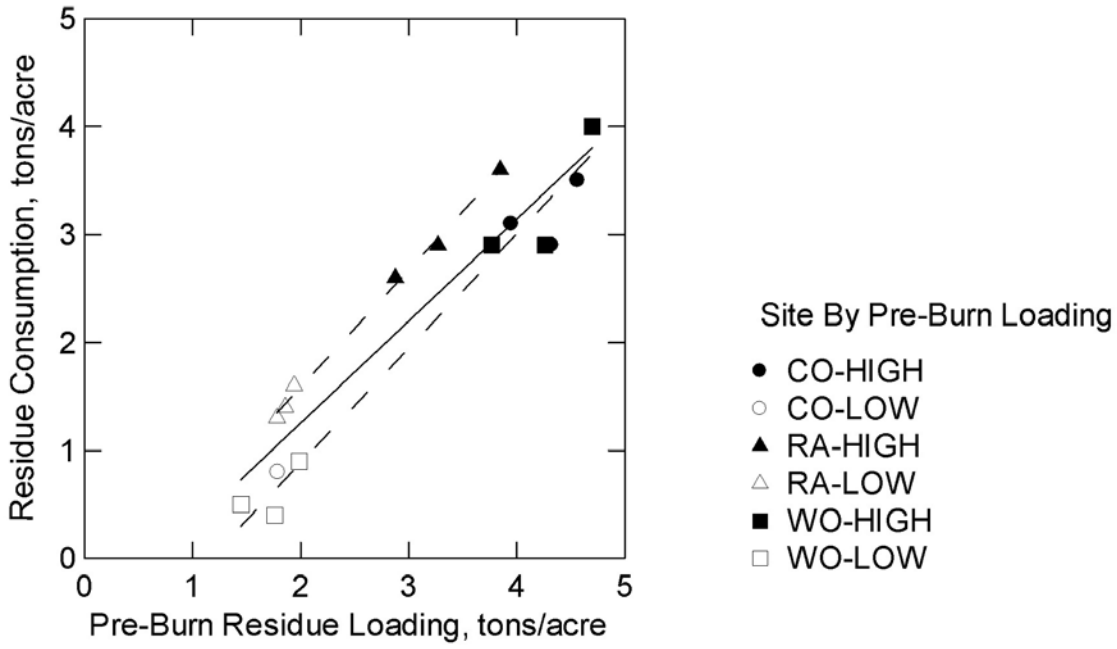
Although $RC_{Relative}$ tended to be higher at the Rathdrum high residue loading units, the differences were not statistically significant at the 95% confidence level.

Table 3.1. Pre-burn residue loading, post-burn residue loading and residue consumption. Values shown are means ± SE. Statistically significant differences are indicated with different letters (compare within columns only).

Study Site and Residue Loading	Pre-burn Residue Loading (tons acre^{-1})	Post-burn Residue Loading (tons acre^{-1})	Residue Consumption Absolute (tons acre^{-1})	Residue Consumption Relative (%)
Connell, WA, irrigated				
High loading (*n*=3)	4.3 ± 0.2	1.1 ± 0.2	3.2 ± 0.2	74 ± 4
Low loading (*n*=2)	1.7 ± 0.1	1.1 ± 0.1	0.6 ± 0.2	32 ± 10
Rathdrum, ID, irrigated				
High loading (*n*=3)	3.3 ± 0.3	0.3 ± 0.04	3.0 ± 0.3	91 ± 2
Low loading (*n*=3)	1.9 ± 0.05	0.4 ± 0.05	1.4 ± 0.1	76 ± 3
Worley, ID, dryland				
High loading (*n*=3)	4.2 ± 0.3	1.0 ± 0.2	3.3 ± 0.4	77 ± 5
Low loading (*n*=3)	1.7 ± 0.2	1.1 ± 0.1	0.6 ± 0.2	33 ± 7
High loading, all (*n*=9)	4.0 ± 0.2 a	0.8 ± 0.1	3.2 ± 0.2 a	81 ± 3 a
Low loading, all (n=8)	1.8 ± 0.1 b	0.9 ± 0.1	0.9 ± 0.2 b	49 ± 9 b

There was a positive relationship between the absolute residue consumption and the pre-burn residue loading (Fig. 3.1; R^2=0.89, $F_{1,15}$=125.24, P<0.001). The R^2 value (coefficient of determination) of 0.89 indicated that almost 90% of the observed variation in absolute residue consumption was explained by the initial pre-burn residue loading. This relationship was even stronger when the regression analyses were carried for Rathdrum and Connell/Worley separately (dashed lines in Fig. 3.1), with R^2 values of 0.99 (n=6) and 0.97 (n=10), respectively. This suggests that the relationship between absolute residue consumption and pre-burn residue loading was site specific. Although relative residue consumption tended to be higher with higher pre-burn residue loading, the relationship between these two variables was not statistically significant. In summary, residue consumption was most strongly correlated with the pre-burn loading: the higher the pre-burn residue loading, the higher the absolute residue consumption.

Figure 3.1 Residue consumption as a function of pre-burn residue loading.
The relationship for all data points can be described as follows:
Residue consumption = -0.75 + (0.97*Pre-Burn Residue Loading), R^2=0.89, $F_{1,15}$=125.24, P<0.001 (intercept with x-axis at ~0.8 tons/acre). Note that the Rathdrum units (triangles) are systematically above the best linear fit line based on the other sites, Connell (circles) and Worley (squares).



3.2 Emission Factors for $PM_{2.5}$, CO_2, CO, and CH_4

Most of the available emission factors were used in the analysis. An exception was the Connell low loading treatment, because of the lack of replication within this treatment (n=1). Emission factors, as well as the combustion efficiency (CE), varied considerably between sites and pre-burn residue loading (Table 3.2). Since the Connell high loading sites had unusually low combustion efficiency and CO_2 emission factors, data summaries are shown with and without this treatment (Table 3.2). However, because of the internal consistency within and between the Connell high loading burn units, these units cannot be considered statistical outliers, but should be treated as real observations.

Table 3.2. Emission factors by site and pre-burn residue loading.
Values shown are means ± SE.

Study Site and Residue Loading	Emission Factors (lbs ton^{-1})					Combustion Efficiency (%)
	CO_2	CO	CH_4	$PM_{2.5}$	PM_{10}*	
Connell, WA, irrigated						
High loading (*n*=3)	2843 ± 30	480 ± 49	53 ± 5	109 ± 25	136 ± 31	78 ± 1
Low loading (*n*=1)**	3207	314	19	50	63	88
Rathdrum, ID, irrigated						
High loading (*n*=3)	3199 ± 74	360 ± 90	24 ± 3	33 ± 3	41 ± 3	87 ± 2
Low loading (*n*=3)	3084 ± 41	369 ± 28	26 ± 3	66 ± 12	82 ± 15	84 ± 1
Worley, ID, dryland						
High loading (*n*=3)	3092 ± 136	429 ± 102	39 ± 13	28 ± 3	35 ± 4	84 ± 4
Low loading (*n*=3)	3320 ± 37	214 ± 14	9.0 ± 2.6	51 ± 9	64 ± 11	91 ± 11
High loading, all (*n*=9)	3044 ± 70	423 ± 45	40 ± 6	56 ± 15	70 ± 19	83 ± 2
High loading, (*n*=6) *(Connell excluded)*	3145 ± 73	394 ± 63	33 ± 8	30 ± 2	38 ± 3	86 ± 2
Low loading, (n=6) *(Connell excluded)*	3202 ± 58	291 ± 37	18 ± 4	58 ± 7	73 ± 9	87 ± 2

* Calculated as: $PM_{10} = PM_{2.5}/0.8$ (Section 2.4.2); ** Data included in table but not in statistical analysis.

Emission factors were only checked for statistical differences in the $PM_{2.5}$ emission factors, $EF_{PM2.5}$, since $PM_{2.5}$ is the main pollutant of interest. The comparisons were based a (non-parametric) Kruskal-Wallis test, since the graphic analysis of the data showed that the normality requirements (Section 2.4.4) were not met. $EF_{PM2.5}$ at the Connell with high residue loading was statistically different than at Rathdrum and Worley high residue loading units (Kruskal-Wallis, χ^2=3.86, *P*=0.05). There were no differences in $EF_{PM2.5}$ between high residue loading at Rathdrum and Worley (Kruskal-Wallis, χ^2=1.19, *P*=0.28). Similarly, there were no differences in $EF_{PM2.5}$ between the low residue loading sites Rathdrum and Worley (Kruskal-Wallis, χ^2=0.43, *P*=0.51). The $EF_{PM2.5}$ at the Rathdrum low residue loading units was statistically greater than at Rathdrum high residue loading units (Kruskal-Wallis, χ^2=3.86, *P*=0.05).

Since there were no statistical differences between the Rathdrum and Worley sites within pre-burn residue loading category, $EF_{PM2.5}$ was pooled for these two sites. Based on the pooled means, $EF_{PM2.5}$ at Connell high residue loading was statistically greater than at Rathdrum and Worley high loading (Kruskal-Wallis, χ^2=5.40, P=0.02). Moreover, at Rathdrum and Worley , the low residue loading units had significantly higher $EF_{PM2.5}$ than the high residue loading units (Kruskal-Wallis, χ^2=6.56, *P*=0.01)

The relationships between the emission factors for CO_2 (EF_{CO2}), CO (EF_{CO}), CH_4 (EF_{CH4}), and $PM_{2.5}$ ($EF_{PM2.5}$) versus the combustion efficiency (CE) were explored based on linear regression analysis. As expected, there was a strong positive relationship between EF_{CO2} and CE (Fig. 3.2, Table 3.3). Also, there were statistically significant negative relationships between EF_{CO} and EF_{CH4} versus CE (Fig. 3.3 and 3.4, Table 3.3). These patterns make sense as the incomplete combustion products (CO and CH_4) decreased with increasing CE (Fig. 3.3 and 3.4), while CO_2 emissions increased with increasing CE (Fig. 3.2). However, even though $PM_{2.5}$ is a product of incomplete combustion, there was no relationship between $EF_{PM2.5}$ and CE (Fig. 3.5, Table 3.3). This relationship was largely driven by the Connell high residue loading units, it was statistically significant (*P*=0.04) with a R^2 of 0.22 (Fig. 3.5, Table 3.3). Moreover, when the Connell high residue loading units were taken out of the analysis the R^2 became 0.00, indicating no relationship at all between these variables (Table 3.3). Therefore, although EF_{CO2}, EF_{CO}, and EF_{CH4} showed relationships with CE consistent with what is known about fire emissions, the $EF_{PM2.5}$ did not correlate with CE.

Similarly, the data were examined for relationships between EF_{CO2}, EF_{CO}, EF_{CH4}, and $EF_{PM2.5}$ versus the residue and soil moisture parameters (Table 3.4). Statistically significant relationships only existed between EF_{CO2}, EF_{CO}, and EF_{CH4} versus the moisture content of the entire surface layer (Table 3.4). However, $EF_{PM2.5}$ did not correlate with any of the moisture content measures (Table 3.4). Furthermore, none of the emission factors were related significantly to the upper or lower residue moistures (high residue loading units) or the soil moistures.

Figure 3.2. Linear regression of the CO_2 emission factor versus the combustion efficiency (CE).
(The CO_LOW unit is included in the graph, but is not included in regression)

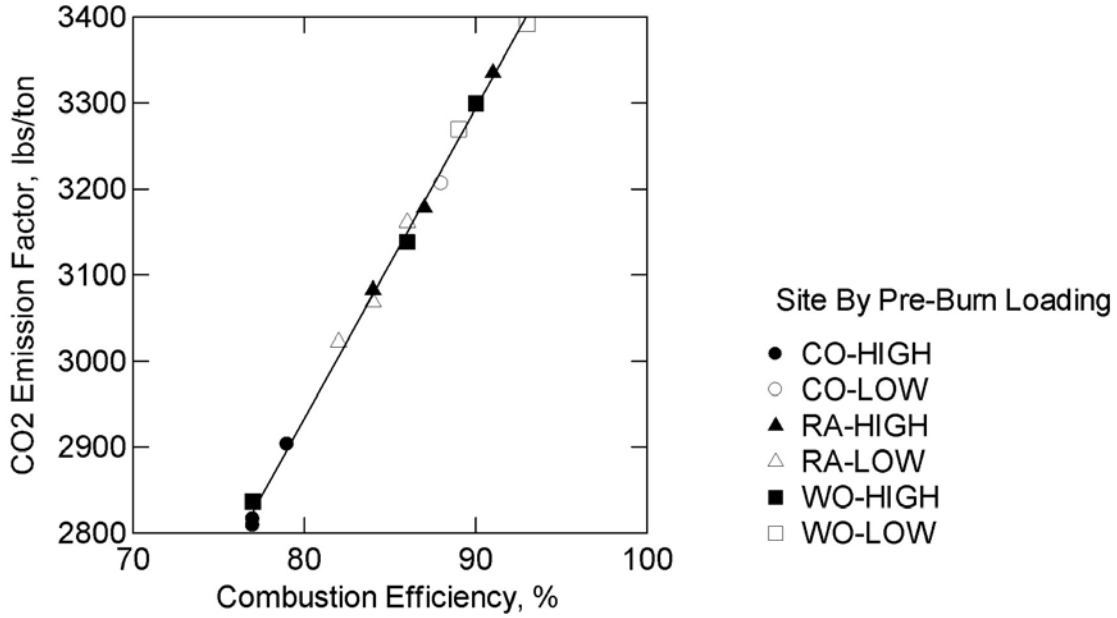


Figure 3.3. Linear regression of the CO emission factor versus the combustion efficiency (CE).
(The CO_LOW unit is included in the graph, but is not included in the regression)

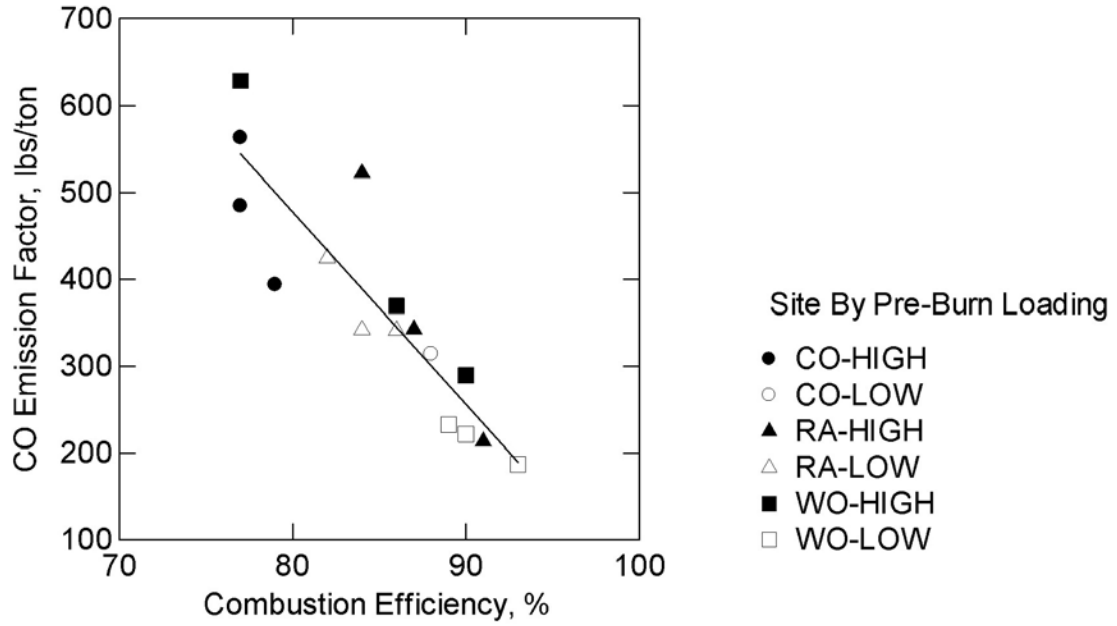


Figure 3.4. Linear regression of the CH_4 emission factor versus the combustion efficiency (CE).
(The CO_LOW unit is included in the graph, but is not included in the regression)

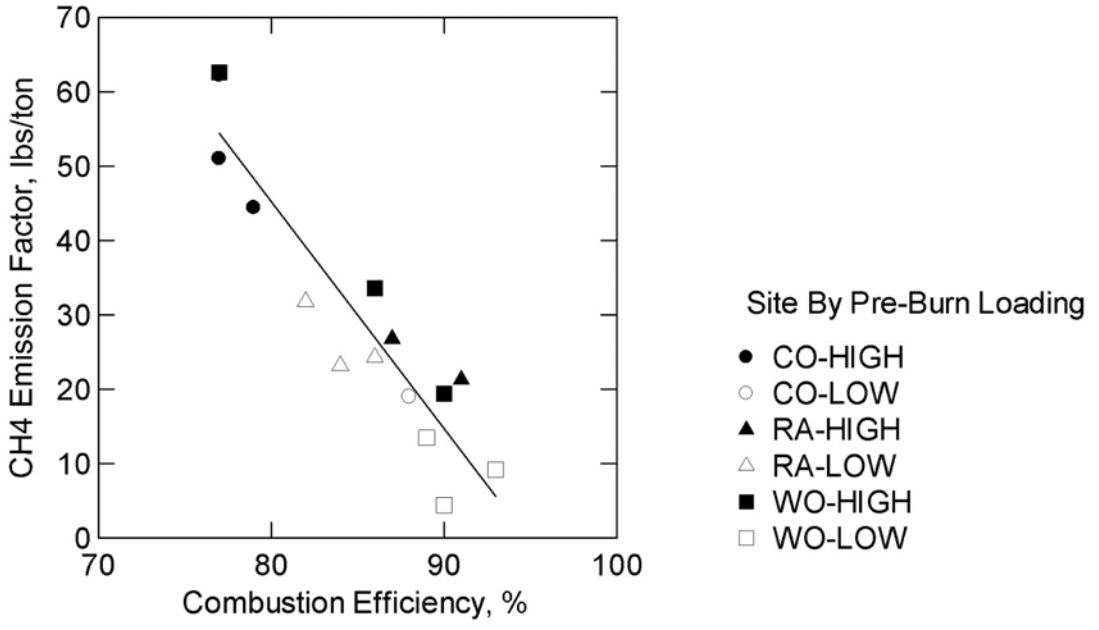


Figure 3.5. Linear regression of the $PM_{2.5}$ emission factor versus the combustion efficiency (CE).
(The CO_LOW unit is included in the graph, but is not included in the regression)

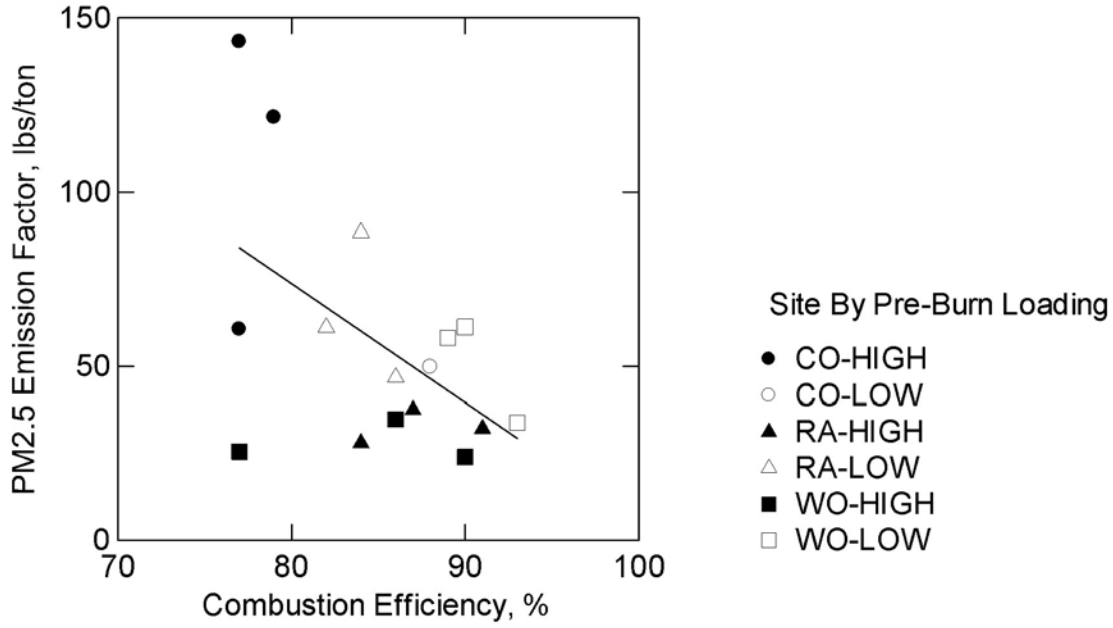


Table 3.3. Relationships between the emission factors and combustion efficiency. Relationships that are statistically significant ($P<0.05$) are shown in **BOLD**. All others are not statistically significant.

Emission Factor	Sign of Slope	All Units	
		R^2	*P*-Value
CO_2	Positive	**1.00**	**<0.005**
CO	Negative	**0.79**	**<0.005**
CH_4	Negative	**0.85**	**<0.005**
$PM_{2.5}$	Negative	**0.22**	**0.04**

Table 3.4. Relationships between emission factors and pre-burn residue moisture content. Fuel moisture content is shown for the entire surface layer (low residue loading units), upper and lower surface layers (high residue loading units), and soil layers (all units). Relationships that are statistically significant ($P<0.05$) are shown in **BOLD**. All others are not statistically significant.

Emission Factor/ Residue Component	Sign of Slope	All Units	
		R^2	*P*-Value
Emission Factor CO_2			
Entire Layer	Negative	**0.75**	**0.02**
Upper Layer	Negative	0.22	0.12
Lower Layer	---	0.00	0.37
Soil	---	0.00	0.43
Emission Factor CO			
Entire Layer	Positive	**0.82**	**0.01**
Upper Layer	---	0.00	0.39
Lower Layer	---	0.00	0.37
Soil	---	0.00	0.99
Emission Factor CH_4			
Entire Layer	Positive	**0.76**	**0.01**
Upper Layer	Positive	0.24	0.12
Lower Layer	Positive	0.07	0.26
Soil	---	0.00	0.40
Emission Factor $PM_{2.5}$			
Entire Layer	---	0.00	0.42
Upper Layer	Positive	0.10	0.21
Lower Layer	---	0.00	0.94
Soil	---	0.00	0.16

3.3 Emission Factors for Polycyclic Aromatic Hydrocarbons (PAH)

The PAH emission factors for the compounds prescribed by WDOE (specifically, benzo(a)pyrene (BaP), and six additional BaP-equivalent carcinogens including benzo(a)anthracene, benzo(b)fluroanthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, and idenol(1,2,3-cd)pyrene) were generally below the method detection limit (the lowest concentration that can be detected by the instrument in the extracted sample). In 12 out of the 14 PAH samples the concentrations were below the detection limit. At two of the high residue loading units at Worley benzo(a)anthracene and chrysene were found, with emission factors of ~410 and ~400 μg kg^{-1}, respectively. In addition, at the high residue loading, replication 2, at Worley benzo(b)fluroanthene was found, with an emission factor of ~1593 μg kg^{-1}.

3.4 Total $PM_{2.5}$ Emissions

The total $PM_{2.5}$ emissions were calculated as a function of the $RC_{Absolute}$ and the $PM_{2.5}$ emission factor, $EF_{PM2.5}$, based in Equation 10). The absolute residue consumption, $EF_{PM2.5}$, and total $PM_{2.5}$ emissions are summarized by site and pre-burn residue loading in Fig. 3.6A and 3.7. Total $PM_{2.5}$ emissions were significantly higher for the Connell high residue loading units compared to the Rathdrum and Worley high residue loading units (Fig. 3.7; Kruskal-Wallis, χ^2=3.86, P=0.05). Also, total $PM_{2.5}$ emissions at the Worley low residue loading units were significantly lower than those at the Worley high residue loading unit as well as the Rathdrum low residue loading unit (Fig. 3.7; Kruskal-Wallis, χ^2=3.86, P=0.05).

Total $PM_{2.5}$ emissions did not differ between the Rathdrum and Worley high residue loading (Fig. 3.7; Kruskal-Wallis, χ^2=0.05, P=0.83). Therefore, the total $PM_{2.5}$ emissions for the Rathrum and Worley high residue loading units were pooled. Based on the pooled data the total $PM_{2.5}$ emissions at the Connell high residue loading units were significantly higher than at the Rathdrum and Worley high residue loading treatments (Figure 3.7; Kruskal-Wallis, χ^2=5.40, P=0.02).

There was no difference in total $PM_{2.5}$ emissions between the high and low residue loading at Rathdrum (Fig. 3.7; Kruskal-Wallis, χ^2=0.05, P=0.83). At this site, higher $RC_{Absolute}$ (Fig. 3.6A), potentially leading to higher total emissions (Fig. 3.7), was compensated by a lower $EF_{PM2.5}$ at the high residue loading units (Fig. 3.6B). A similar pattern was observed at Worley. However, a lower $EF_{PM2.5}$ with high residue loading did not completely compensate for the higher $RC_{Absolute}$, leading to lower total $PM_{2.5}$ emissions with low residue loading (Kruskal-Wallis, χ^2=3.86, P=0.05).

Finally, the total $PM_{2.5}$ emissions were regressed as a linear function of the $RC_{Absolute}$ and the emission factor, $EF_{PM2.5}$, to assess the relative contribution of each of these factors to the total $PM_{2.5}$ emissions. When the Connell high residue loading units were included in the regression, $RC_{Absolute}$ and $EF_{PM2.5}$ combined explained 95% of the variation in the total $PM_{2.5}$ emissions. When regressed individually, $RC_{Absolute}$ and $EF_{PM2.5}$ explained 21 and 71% of the variation in the total $PM_{2.5}$ emissions, respectively. This pattern was influenced mostly by the high $EF_{PM2.5}$ at the Connell high residue loading units. This was confirmed by the regression results without Connell high residue loading units. When based on Rathdrum and Worley only, $RC_{Absolute}$ and $EF_{PM2.5}$ combined explained 89% of the variation in the total $PM_{2.5}$ emissions. However, when regressed individually, $RC_{Absolute}$ and $EF_{PM2.5}$ explained 45 and 0% of the variation in the total $PM_{2.5}$ emissions, respectively. Overall, both the $RC_{Absolute}$ and $EF_{PM2.5}$ are needed to explain the total $PM_{2.5}$ emissions. Moreover, it is difficult to consider the effect of these parameters on the total $PM_{2.5}$ emissions individually.

Figure 3.6. Summary of absolute residue consumption and $PM_{2.5}$ emission factor.
(The CO_LOW unit "*" is included in the figure, but is not included in the statistics)

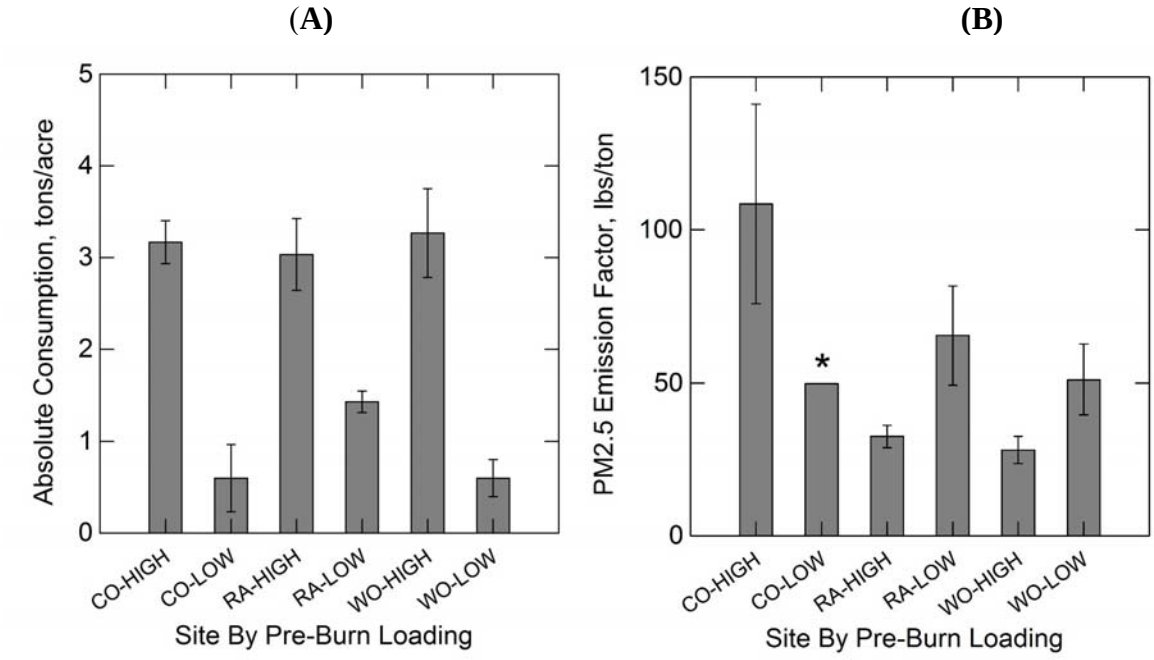
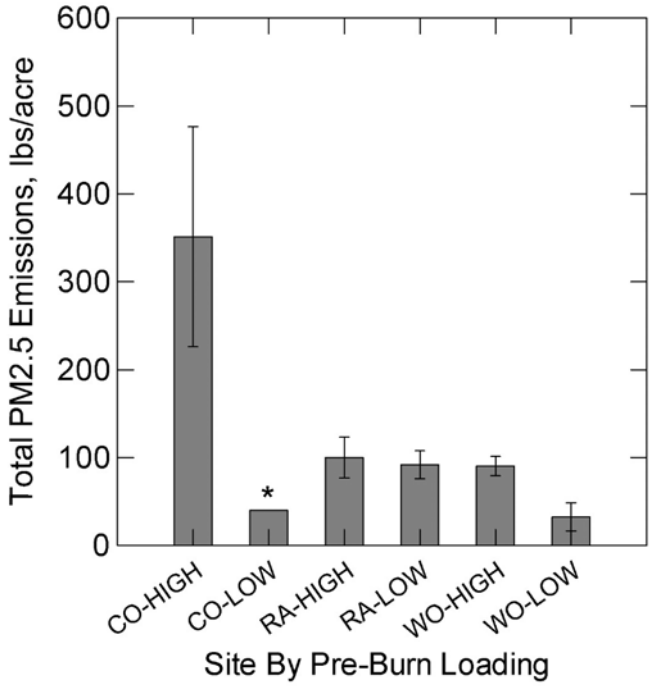


Figure 3.7. Summary of total $PM_{2.5}$ emissions.
(The CO_LOW unit "*" is included in the figure, but is not included in the statistics)



4. DISCUSSION

4.1 Residue Loading

As expected, removal of post-harvest residue by baling (i.e., low residue loading) significantly reduced the amount of pre-burn residue at all sites compared to high residue loading (Table 3.1). The high residue (i.e., no residue removed) loading and low residue (i.e., residue removed by baling) loading means averaged over all sites were 4.0 and 1.8 tons acre^{-1}, respectively. Baling of residue reduced the residue load by 2.2 tons acre^{-1}. Although the pre-burn high residue loading was numerically different among sites, i.e., Rathdrum was lower than the other two locations, statistically they were not different (P=0.096). The low residue loading was very similar at all sites (range of 1.7 to 1.9 tons acre^{-1}).

Post-burn residue loading was not influenced by pre-burn residue loading (Table 3.1). Connell and Worley sites burned down to similar post-burn residue loading. However, at Rathdrum, both high and low pre-burn residue loading had significantly lower post-burn residue loading compared to the other two sites.

4.2 Residue Consumption

There was a positive relationship between the ($RC_{Absolute}$ and the pre-burn residue loading (Figure 3.1; R^2=0.89, P<0.001). An R^2 value (coefficient of determination) of 0.89 indicates that 89% of the observed variation in $RC_{Absolute}$ was explained by the initial pre-burn residue loading. $RC_{Absolute}$ was significantly greater for the high residue loading units than the low residue loading units. Similarly, the $RC_{Relative}$ was significantly greater for the high residue loading units than for the low residue loading units.

The relationship between $RC_{Absolute}$ and pre-burn residue loading was possibly site specific as R^2 values of 0.99 and 0.97 were obtained when regression was performed separately for Rathdrum and for Connell/Worley, respectively (dashed lines in Fig. 3.1). Also, the Rathdrum site was quite unique in that the low residue loading units had higher $RC_{Absolute}$ and higher $RC_{Relative}$ than the low residue loading units at the other locations. The $RC_{Absolute}$ on the high residue loading units was also higher at Rathdrum (91%) than at Connell/Worley, 74 and 77%, respectively (Table 3.1).

The $RC_{Relative}$ was somewhat lower at the low residue loading of bluegrass compared to cereal residue (49 and 58%, respectively), but the $RC_{Relative}$ was much greater for high residue loading of bluegrass compared to cereal (81 and 62%, respectively)(Table 3.1; Air Science Inc., 2003). Some of this response can be explained by residue moisture. For the entire residue layer, moisture at the low residue load treatment was quite similar (Table 2.3), 16% and 10 to 14% for Kentucky bluegrass and cereal (Air Science Inc., 2003), respectively. However, at high residue loading the cereal entire residue layer moisture was 10 to 30% (Air Science Inc., 2003, see Table 2.3 high cereal residue loading), while that of the bluegrass was 15% (Table 2.3). This in part could account for the more complete burns observed in Kentucky bluegrass when a drier high residue load was burned relative to cereal.

In summary, residue consumption was strongly correlated with pre-burn residue loading, i.e., the higher the pre-burn residue loading the higher the $RC_{Absolute}$ (Fig. 3.1). Since 89% of the variation in $RC_{Absolute}$ was explained by the variation in pre-burn residue loading, this would suggest that any practice (e.g., baling) that removes a significant portion of the post-harvest residue from a bluegrass seed production field would reduce the amount of residue consumed. Total $PM_{2.5}$ (lbs acre^{-1}) would be reduced by a significant reduction in $RC_{Absolute}$ if $EF_{PM2.5}$ remained constant or did not increase markedly (Equation 10).

4.3 Emission Factors for $PM_{2.5}$, CO_2, CO, and CH_4

Since $PM_{2.5}$ was the main pollutant of interest, it alone was analyzed for statistical differences due to treatments, and it will be discussed in more detail than the other emission factors. The $EF_{PM2.5}$ for the Connell high residue loading units was higher (P=0.05; P=0.02 when Rathdrum and Worley data were pooled, see below) than $EF_{PM2.5}$ for the high residue loading units at Rathdrum and Worley. At Rathdrum, $EF_{PM2.5}$ was significantly greater for the low residue loading units than for the high residue loading units (P=0.05) (66 and 33 lbs of $PM_{2.5}$ ton^{-1} of residue for low and high loading, respectively, Table 3.2).

Since there were no statistical differences in $EF_{PM2.5}$ between Rathdrum and Worley residue treatments, $EF_{PM2.5}$ was pooled for these sites. Based on the pooled means, $EF_{PM2.5}$ at the Connell high residue loading units was greater than at the Rathdrum/Worley high residue loading units (P=0.02). At Rathdrum/Worley, low pre-burn residue loading produced consistently greater $EF_{PM2.5}$ than high residue loading (P=0.01,Table 3.2, Fig. 3.6B). This relationship could not be assessed at Connell due to a lack of replication (n=1) in the low residue loading treatment.

It should be noted that the $EF_{PM2.5}$ in this study are substantially greater than those reported for most agricultural burns, wildfires, and forest fires (Appendix 3). The $EF_{PM2.5}$ for the Cereal-Grain Open-Field Burning Emissions Study conducted in eastern Washington during 2000 (Air Sciences Inc., 2003) had $EF_{PM2.5}$ means of 6.2 and 8.6 lbs ton^{-1} of residue for low and high pre-burn residue loading, respectively, while the $EF_{PM2.5}$ means for this Kentucky bluegrass study were 56 and 58 lbs ton^{-1} for high residue loading and low residue loading, respectively. The eastern Washington cereal burn also had considerably higher CE and higher EF_{CO2}.

The relationships between emission factors and CE were studied based on linear regression analysis. As expected, there was a strong positive relationship between EF_{CO2} and CE (Fig. 3.2). There also were statistically significant negative relationships between CE and EF_{CO} and EF_{CH4}. These relationships are similar to those reported for other studies (Appendix 3). CO_2 emissions increased with increased CE while CO and CH_4 emissions decreased with increased CE.

Numerically, the highest CE occurred in the low residue loading treatment at Worley (dryland) and the lowest CE was at the Connell (irrigated) high residue loading treatment (Table 3.2). As expected, the lowest CE had the lowest EF_{CO2} and the highest CE had the highest EF_{CO2} (2843 and 3320 lbs ton^{-1} CO_2, respectively).

$PM_{2.5}$ is a product of incomplete combustion; however, there was a poor relationship between $EF_{PM2.5}$ and CE (Table 3.3, Fig. 3.5). Although the trend toward decreased $PM_{2.5}$ with increased CE was consistent with other reports, the relationship in bluegrass (P=0.04, R^2=0.22) was much weaker than in the eastern Washington cereal study (P<0.001, R^2=0.61) (Air Science Inc., 2003). Factors contributing to the poor relationship between CE and $EF_{PM2.5}$ in post-harvest Kentucky bluegrass residue burns are currently unknown. Site locations and/or crop management practices might play some role in the relationship, as described in Section 4.6.

4.4 Emission Factors Affected by Residue and Soil Moisture

There were no relationships between any residue moisture component and $EF_{PM2.5}$ (Table 3.4). It would be expected that $PM_{2.5}$ would increase with increased residue moisture as a result of less efficient combustion. In the eastern Washington cereal study (Air Sciences Inc., 2003), greater $PM_{2.5}$ emission factors were driven almost entirely by the higher residue moisture content in fall cereal residue relative to spring cereal residue moisture content.

In the current Kentucky bluegrass study, residue moisture contents were low, and over a narrow range. There may be a relationship between bluegrass residue moisture and $EF_{PM2.5}$, but it may not be resolvable within such a narrow range of moisture conditions observed in this study.

Statistically significant relationships existed only between EF_{CO2}, EF_{CO}, and EF_{CH4} and percent moisture of the entire residue layer (Table 3.4). EF_{CO2} decreased with increasing residue moisture, while EF_{CO} and EF_{CH4} increased with increasing residue moisture. These relationships are to be expected and it is well documented that moist residue does not burn efficiently.

None of the emission factors were significantly related to soil moisture (Table 3.4). This might be expected as these soils were quite dry (6% moisture as compared to 25% moisture for the eastern Washington cereal study (Air Sciences Inc., 2003)) and varied over a small range (4.5 to 8.6%).

4.5 Emission Factors for Polyaeromatic Hydrocarbons (PAHs)

In this study, 14 samples out of 36 samples possible (18 units x 2 FASS towers per unit) were analyzed for PAHs. Of these samples, two samples, taken at the Worley high residue loading units (replication 2 and 3) showed PAH concentrations above the method of detection limit (i.e., the minimum concentration in the filter extract that can be measured in the laboratory[1]). The samples that were below the detection limit represented all the possible combinations of site and residue loading categories, with up to three replications per combination.

The emission factors for individual PAH species reported in the literature range from less than detection limits to about 20 mg kg^{-1} of residue consumed (Ramdahl and Moeller, 1983; Jenkins et al., 1996a, 1996b, and 1996c). The emission factors in this study for benzo(a)anthracene and chrysene, range 0.39 to 0.42 mg kg^{-1} of residue consumed, were in the range reported for cereal crops by Ramdahl and Moeller (1983; range ~0.4 to 2.1 mg kg^{-1} of residue consumed), and by Jenkins et al. (1996a and 1996b; range 0.04 to ~2.5 mg kg^{-1} residue consumed). Similarly, the emission factor for benzo(b)fluoranthene in this study, 1.6 mg kg^{-1} residue consumed, was in the range reported for cereal crops by Ramdahl and Moeller (1983; range ~0.5 to ~1.0 mg kg^{-1} of residue consumed), and by Jenkins et al. (1996a, 1996b, 1996c; range ~0.011 to ~2.9 mg kg^{-1} of residue consumed).

4.6 Total $PM_{2.5}$ Emissions

Total $PM_{2.5}$ (Fig. 3.7) was calculated as a function of the $RC_{Absolute}$ and $EF_{PM2.5}$ utilizing Equation 10. $RC_{Absolute}$ was the same for high pre-burn residue loading at all sites, approximately 3.2 ton $acre^{-1}$ (Table 3.1). The Rathdrum low residue loading treatment was unique and $RC_{Absolute}$ was more than two times greater than at the other two sites (Table 3.1, Fig. 3.6A).

$EF_{PM2.5}$, 109 lbs of $PM_{2.5}$ ton^{-1} of residue consumed, was significantly higher for the Connell high residue loading treatment than for high residue loading at Rathdrum and Worley (Table 3.2, Fig. 3.6B). There were no differences in $EF_{PM2.5}$ among the low loading pre-burn treatments at Rathdrum or Worley (Connell was numerically similar to Worley, but was omitted from analysis, n=1).

[1] 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.

Total $PM_{2.5}$ emissions for Connell high residue loading were significantly greater than for any other treatment, at 350 lbs of $PM_{2.5}$ $acre^{-1}$ (Fig. 3.7). The Worley and Connell (n=1) low residue loading treatment produced 30 lbs of $PM_{2.5}$ $acre^{-1}$ and the Rathdrum high residue loading, Rathdrum low residue loading, and Worley high residue loading treatments were intermediate at approximately 100 lbs of $PM_{2.5}$ $acre^{-1}$ (Fig. 3.7).

The management practice of post-harvest residue baling and burning (propane flaming at Connell and open-field burning at Worley), significantly reduced total $PM_{2.5}$ $acre^{-1}$ at Worley and numerically at Connell (n=1) (Fig. 3.7). Pre-burn residue loading, post-burn residue loading, $RC_{Absolute}$, and $RC_{Relative}$ where similar for Connell and Worley within residue loading levels (high or low) (Table 3.1).

At Rathdrum, post-harvest residue baling followed by burning did not reduce total $PM_{2.5}$ emissions $acre^{-1}$ compared to open-field burning of the high residue load, i.e., there was no effect of residue loading (P=0.83) on total $PM_{2.5}$ emissions $acre^{-1}$. Higher $RC_{Absolute}$ (Fig. 3.6A), potentially leading to higher total emissions (Fig. 3.7), was compensated for by a lowered $EF_{PM2.5}$ at the high residue loading units.

To assess the relative contribution of $RC_{Absolute}$ and $EF_{PM2.5}$ to total $PM_{2.5}$ $acre^{-1}$, the total $PM_{2.5}$ emissions $acre^{-1}$ were regressed as a linear function of these two factors. $RC_{Absolute}$ and $EF_{PM2.5}$ combined explained 95% of the total variation in total $PM_{2.5}$ emissions (Connell high units included in regression) and 89% of the total variation in total $PM_{2.5}$ emissions (Rathdrum and Worley, only). When regressed individually, $RC_{Absolute}$ and $EF_{PM2.5}$ explained 21 and 71% (Connell high included) and 45 and 0% (Rathdrum and Worley, only), respectively, of the variation in total $PM_{2.5}$ emissions $acre^{-1}$. Independently they are affected by site and residue loading and it is difficult to consider the individual effect of these parameters on total $PM_{2.5}$ emissions $acre^{-1}$. In this study, both the $RC_{Absolute}$ and $EF_{PM2.5}$ are needed to explain the total $PM_{2.5}$ emissions $acre^{-1}$. So, while it is probably valid to attribute the high total $PM_{2.5}$ emissions for the Connell high residue loading treatment relative to the other two sites to a high $PM_{2.5}$ emission factor, and the high total emissions at the Rathdrum low residue loading treatment relative to the other two sites to a high $RC_{Absolute}$, one must use caution when discussing cause and effect in this study given the large variability in these factors among treatments.

Finally, while total emissions of 350 lbs of $PM_{2.5}$ $acre^{-1}$ produced at the high residue loading Connell units was high, other values (30 to 123 lbs of $PM_{2.5}$ $acre^{-1}$) in this Kentucky bluegrass study are also high, compared to other combustion studies (Appendix 3). However, they are within the range of those reported for smoldering emissions measured by Ward et al. (1992a) for forest wildfires in British Columbia, Canada.

4.7 Results Evaluated on a Treatment Basis (Location and Loading)

In this Kentucky bluegrass study, as noted above, burn characteristics were often site and residue loading specific, and did not always conform to emission patterns observed in other studies. To better understand the results, sites and residue loading treatments will be discussed individually, as it was hypothesized that the makeup of the residue loading (residue architecture) had an influence on combustion and emission factors at each site.

Connell irrigated site in the Columbia Basin of eastern Washington – high residue loading:

The Connell, Columbia Basin, high residue loading treatment produced the highest emissions. It also had the lowest CE. Since the high total emissions cannot be attributed to the amount of residue consumed (Table 3.7), other factors must be explored.

The Connell site was very flat and the soil was a sandy loam containing few rocks and the grower was able to swath at a very low height (2 inches). A low swathing height was used because the grower was selling the residue for hay and a high production of hay was desirable, as there was a good market for bluegrass hay in 2001. To maintain high hay quality, the post-harvest bluegrass residue was raked, baled, and hauled off the field shortly after combining the bluegrass seed field.

The high residue load units were not baled, but had the post-harvest residue distributed (scattered) over the field as it came out of the combine. The post-harvest, pre-burn residue architecture (soil surface to top of residue) was 6 to 7 inches of residue over 2 inches of stubble (2 inches was the stubble length, i.e., soil surface to top of stubble when stubble was held erect). In the original experimental design, in this large field (several hundred acre Kentucky bluegrass seed production field) the research area was to be combined first to facilitate drying of the stubble and post-harvest residue (Dave Johnson, personnel communication, 2001). Unfortunately, this did not occur and the research site was the last area at the site to be combined. The grower had some concern that there was a possibility of the research burn escaping into the bluegrass seed production field prior to the end of harvest.

The field prior to burning had a soil moisture content of 4.7%. Due to the low swathing height the post-harvest, overlying residue filtered down into the stubble to the soil surface. The lower residue layer, which consisted of the stubble and post-harvest residue, had a moisture content of 27%. The 6 to 7 inches of overlying residue has a moisture content of 2.8%. The calculated bulk density of the lower and upper residue layers were 0.51 and 0.20 lbs ft^{-3}, respectively (Table 2.5). The entire canopy moisture content was 14% and had a bulk density of 0.27 lbs ft^{-3}. Therefore, there was a very dry layer of residue, approximately 6 to 7 inches thick, over moist stubble that contained a dense post-harvest residue.

It is hypothesized that upon ignition, the upper dry residue layer was rapidly consumed. Then the more moist and dense lower residue layer would begin to burn and smolder. Due to the dense residue in the lower canopy there was probably poor flow of air into and through the remaining residue, which led to the lowest CE of any treatment in the study (Table 3.2). The smoldering phase accounted for 7% of the $PM_{2.5}$ collected, which was the highest percentage for any of the high residue burn treatments in the study (Appendix 5).

Connell irrigated site in the Columbia Basin of eastern Washington – low residue loading:

The low residue loading treatment prior to burning had a soil moisture content of 4.4%, which was slightly lower (but probably not significantly different, n=1) than that of the high residue loading treatment (Table 2.3). A lack of difference in soil moisture due to residue loading is supported by the fact that the level of pre-burn residue loading had no effect on soil moisture at the other sites.

There was 2 inches of standing stubble (erect stubble length=2 inches) that contained some residue following raking and baling; however, there was little, or no, residue layer above the standing stubble. The entire residue layer was at 22% moisture content with a bulk density of 0.48 lbs ft^{-3} (Table 2.5). Thus, there was a moist, dense residue layer that contained stubble and essentially all of the post-baled residue.

This field was combined (July 31) and raked and baled (August 1) a few days prior to burning (August 7); therefore, there was only marginal drying of the field. Since the research plots were in the last area the grower harvested, and the field had to be irrigated quickly by the grower prior to planting a following crop, it was not possible to permit a significant "dry down" of the field.

Predictably, this somewhat green, closely cut field was difficult to burn. When ignition was attempted, by lighting the edge of the field with a propane torch, the residue failed to ignite and carry the fire across the low residue loading treatment. Replication 1 was lost because the field would not burn using an open-field burn head fire.

The remaining two low residue loading units (replications) were burned using a tractor pulling a propane burner with an 18-foot boom. This was essentially the technique utilized by growers in the Columbia Basin when a crop of bluegrass was to be harvested the following year. Also, in the irrigated Rathdrum Prairie of north Idaho, in low, moist draws, the post-harvest residue often will not carry a fire and will be propane or diesel burned by some growers. MFSL was unable to collect data from either of the two FASS towers in replication 2; however, both FASS towers collected data in replication 3, making this a non-replicated treatment (n=1).

The propane burner transversed each burn unit, beginning downwind, creating a series of strip head fires across the burn unit. The flame from the propane burner was essentially "blasted" onto the residue, there was some flaming of the residue, and then the residue began to smolder and was quickly extinguished as the flame front created by the propane burner moved forward. However, the strips did not always coalesce completely.

The CE using the propane burner was 88%, which is numerically greater than the CE of the high residue loading burn. The smolder phase accounted for 29% of the $PM_{2.5}$ collected, which was the highest percent in any of the six treatments (3 sites x 2 pre-burn residue loading levels) in the study (Appendix 5). The high amount of $PM_{2.5}$ captured during the smoldering phase was probably due to the length of time it took to burn the numerous strips (numerous transverses across the burn unit). The FASS setting for a 3-minute flaming phase was exceeded during the multiple passes needed to cover the burn unit. Thus, any flaming emissions captured in passes with the propane burner after the 3-minute setting for the flaming phase were "artificially" added to the smoldering phase. The low $RC_{Absolute}$ combined with an intermediate amount of $PM_{2.5}$ ton^{-1} of residue consumed produced a relatively low total $PM_{2.5}$ emissions for this non-replicated treatment (Fig. 3.6A and B and 3.7). The "bale and flame" technique utilizing strip head fires warrants additional research, as the total $PM_{2.5}$ $acre^{-1}$ was significantly reduced (91%) using this technique compared to open-field burning of the high residue load (Fig. 3.7).

Over all burn units in the study, the percent moisture of the entire canopy was negatively correlated with EF_{CO2} (P=0.02, R^2=0.75) (Table 3.4). As residue moisture content of the entire canopy increased the amount of CO_2 produced decreased, which suggested the burns smoldered more as moisture increased in the entire residue layer.

The Kentucky bluegrass cultivar (variety) at this site may also have affected the burn. Compared to the other cultivars in this study, 'Total Eclipse' is a newer, "elite", turf-type Kentucky bluegrass cultivar. Such bluegrass cultivars typically are low growing, have higher shoot density, and more basal leaves in the lower canopy than the older, taller, more erect "common" cultivars. When swathed low these cultivars could still have a fairly dense, possibly lush, lower canopy. This dense, lower canopy may affect CE when such fields are open-field burned rather than propane burned. Although the CE at this site was quite good utilizing the propane burner, cultivar effects on traditional methods of open-field burning and/or propane flaming could be a possible area of future research.

Rathdrum irrigated site in the Rathdrum Prairie of north Idaho – high residue loading:

The Rathdrum site was unique in this study since total $PM_{2.5}$ emissions were not affected by the level of residue loading (Fig. 3.7). Although total $PM_{2.5}$ ranged from 92 to 123 lbs $acre^{-1}$ and are

intermediate for this study, these levels of total $PM_{2.5}$ are quite high compared to those from other burn studies (Appendix 3). Also unique to the Rathdrum site was the low amount of residue left in the field following burning (Table 3.1).

Unlike the Connell site that was swathed at a height of 2 inches, the Rathdrum site was swathed at 9 to 10 inches (Table 2.4). Several factors contributed to the higher swathing height at Rathdrum. First, due to the gravel soil at this site the grower typically cuts at a high height to reduce the risk of damaging the swather's cutting bar. Second, the grower was not going to market the post-harvest residue as hay, so a low cutting height to maximize hay yield was not necessary. Third, the cultivar 'Alene' at Rathdrum is a taller, more erect growing Kentucky bluegrass that when not lodged can be swathed higher and not reduce seed yield. Fourth, at a higher swathing height less material passes through the combine and combine speed can be increased, which would decrease harvest time.

The high residue loading units were swathed, combined, and the residue was scattered as it came out the back of the combine over the top of the standing stubble. The standing stubble height in the high residue loading treatment was estimated at 9 to 10 inches based on the stubble height in the low residue loading treatment (Table 2.4). The post-harvest residue that was scattered across the field tended to flatten the tall stubble and the height from the soil surface to the top of the residue layer was 7.8 inches. The residue architecture was a 4-inch layer of loose, dry (6.5% moisture content, 0.24 lbs ft^{-3} bulk density) residue suspended approximately 4 inches above the soil surface (Table 2.4 and 2.5). Below the 4-inch layer of suspended dry residue was a lower residue layer that consisted of a more moist stubble and loose post-harvest material (22% moisture content, 0.28 lbs ft^{-3} bulk density).

The field, prior to burning, had a soil moisture content of 8.6%. This was almost twice the percent soil moisture relative to the soil moisture at the hotter, drier, Connell site. It was also significantly greater that the soil moisture at the dryland Worley site (Table 2.1). The temperature and relative humidity at the time of the Rathdrum burns were also much lower and higher, respectively, than at other two sites (Table 2.2). Although there were no statistical relationships shown between soil moisture and emissions factors (Table 3.4), a greater soil moisture content could contribute to a higher residue moisture and higher relative humidity in the lower canopy near the soil surface. Given time, a greater soil moisture content could also contribute to enhanced regrowth of the bluegrass stand. The stubble underlying the residue was observed to be fairly green at Rathdrum. Burning any green residue would lower CE and increase emission factors (Air Sciences Inc., 2003).

Upon ignition, the drier upper residue layer began to burn. Since the lower residue layer in the Rathdrum high residue loading was more loosely packed (bulk density=0.28 lbs ft^{-3}, Table 2.5), relative to the lower residue layer in the high residue loading treatment at Connell or Worley (bulk densities = 0.51 and 0.60 lbs ft^{-3}, respectively), air may have been more easily drawn into the lower canopy at Rathdrum. The burning residue and heated air drove off much of the moisture from the lower residue layer making it conducive to a more efficient burn (CE = 87%). The CE at Rathdrum high residue loading was numerically greater than the high residue loading treatment at the other two sites. There was little residue on the field following burning (0.3 ton $acre^{-1}$, Table 3.1). The post-burn residue in the burn units was essentially black ash.

The plumes at Rathdrum were observed to be lighter in color compared to the plumes from the high residue burns at Connell. $EF_{PM2.5}$ were 109 and 33 lbs ton^{-1} of residue consumed for high residue loading at Connell and Rathdrum, respectively, and the total $PM_{2.5}$ emissions were 349 and 123 lbs of $PM_{2.5}$ $acre^{-1}$ at Connell and Rathdrum, respectively (Table 3.2). The plumes at

Connell also contained approximately 12% less water vapor (12% water content assumed that all the moisture in the entire residue layer was driven off as water vapor).

Rathdrum irrigated site in the Rathdrum Prairie of north Idaho – low residue loading:

The amount of post-harvest residue on the field following combining (i.e., high residue loading) was significantly less than that at the other two sites; however, following baling there was slightly, but not statistically, more pre-burn low residue loading compared to the other two sites (1.9 tons acre^{-1} versus 1.7 ton acre^{-1}, Table 3.1). Baling removed 1.4 tons of post-harvest residue acre^{-1}. Since the low residue loading stubble length was approximately 2 and 3.5 inches at Connell and Worley, respectively, the taller (9.7 inch) residue at Rathdrum may account for the increase in pre-burn residue loading following baling (Table 3.1). Due to the high swathing height, raking and baling were less efficient. Also the stand was observed to be less dense (thinner), which may contribute to the lower amount of biomass initially on the field (Table 3.1).

Soil moisture with low loading was 7.4%, 1.2% less than high residue loading, but this difference was not statistically significant (Table 2.3). Soil moisture content for the irrigated Rathdrum site was significantly greater than at the other sites. Although soil moisture was not correlated with any emission factor (Table 3.4), a higher soil moisture should increase the moisture content of the residue in immediate contact with the soil surface.

Compared to the low residue treatments at Worley and Connell, the low loading treatment at Rathdrum had the highest residue consumption (1.4 tons acre^{-1}, Table 3.1, Fig. 3.7). The high residue consumption was probably the major contributing factor to the higher total $PM_{2.5}$ emissions at Rathdrum compared to those at Connell or Worley (Fig. 3.7). However, as discussed earlier, to more completely explain total $PM_{2.5}$ acre^{-1} the $EF_{PM2.5}$ must also be taken into account in this bluegrass study.

Compared to the low residue loading treatments at Connell or Worley, the low residue loading architecture was quite different at Rathdrum. The residue consisted of a tall (10 inch stubble length), erect stubble with pre-burn residue (1.9 tons acre^{-1}) distributed thorough out the tall, erect stubble. The entire residue layer bulk density was 0.11 lbs ft^{-3} at Rathdrum low residue loading compared to 0.30 and 0.48 lbs ft^{-3} at Worley and Connell, respectively.

Since the low residue treatment had been swathed on July 4, combined on July 23, and raked and baled on August 6, it was anticipated that considerable drying of the standing stubble and loosely packed residue would have occurred prior to field burning on August 21 or 22. However, this was not the case and the entire residue layer moisture content was 22% (Table 2.3).

It was hypothesized that although the entire residue layer was at a moisture content of 22%, there would be a moisture gradient from higher moisture residue (residue that was on the soil surface) to lower moisture residue at the top of the entire residue layer. Upon ignition, the drier material of the upper canopy burned and air was drawn into the loose residue (bulk density=0.11 lbs ft^{-3}). The burning residue and hot air drove off the moisture in the lower residue. The CE was fairly high (84%) and the $RC_{Relative}$ was over two times greater than the low residue loading burns at Connell or Worley (Table 3.1). The low residue loading burn was a very complete burn leaving essentially black ash on the field (0.4 tons acre^{-1}, Table 3.1). It is interesting to note that post-burn residue loading was the same in the high and low residue loading treatments at Rathdrum, i.e., 0.3 and 0.4 tons acre^{-1}, respectively. Although a very complete burn, the low residue loading burn has some smoldering, as indicated by the lower EF_{CO2} (3084 lbs ton^{-1}) and higher $EF_{PM2.5}$ (66 lbs ton^{-1}) compared to the high residue emission factors (Table 3.2). This might be due in part to

the cooler temperature and higher relative humidity that occurred during these burns (Table 2.2). Trace precipitation occurred not long after the final unit was burned on August 22.

Worley dryland site in north Idaho – high residue loading:

The Worley site was the only dryland Kentucky bluegrass seed production field in the study. Unlike the flat Connell and Rathdrum sites, the Worley site was a rolling field. Although residue treatments within a replication were side-by-side (Appendix 4), there was an estimated 50 foot change in elevation within and between some burn units. It was noted that the length of the standing stubble was taller in draws than on slopes (Table 2.4). These variations in stubble length due to topography were taken into account in the pre-burn and post-burn sampling, i.e., if a burn unit had 25% of the area in draws then 25% of the samples for each parameter would be randomly taken in draws.

The site was swathed about July 22 (exact date not recorded but swathing in the Worley area is typically done 10 to 14 days prior to combining). The field was combined on August 3 with the post-harvest residue scattered on the field as it came out of the combine.

The Kentucky bluegrass cultivar at Worley was 'Garfield', which is a "common" bluegrass that has a tall, erect growth habit. The mean (average of slope and draw) stubble length was 9.3 inches (Table 2.4). Like the Rathdrum high residue loading treatment, the post-harvest residue scattered across the field during combining tended to flatten the stubble, as a result, the measured height from the soil surface to the top of the residue layer was 6.1 inches (Table 2.4). The residue high loading architecture was a 3.5-inch layer of dry (3.6% moisture, 0.24 lbs ft^{-3} bulk density) residue suspended 2.6 inches above the soil surface. Below the 3.5-inch layer of suspended residue was a lower residue layer of stubble and post-harvest material with a moisture content of 22% and a bulk density of 0.60 lbs ft^{-3}. The entire residue layer moisture content was 15%, which is very similar to that at Rathdrum or Connell (Table 2.3). Worley and Rathdrum were similar in that post-harvest residue was scattered over a 9 to 10 inch standing stubble. Two noted differences between the sites were that the distance from the soil surface to the suspended residue was 3.9 inches at Rathdrum versus 2.6 inches at Worley, and the soil moisture at the dryland Worley site was, as expected, less than at the irrigated Rathdrum site, soil moisture content=5.5 and 8.6%, respectively (Table 2.3).

It was hypothesized that upon ignition the drier, looser packed, upper residue layer began burning. The heated air caused by the burning upper residue layer drove off moisture. The plumes at Worley, like Rathdrum, were observed to be lighter in color than the plumes from the high residue burns at Connell. The $RC_{Absolute}$ was 77% and the CE was 84% (Table 3.1 and 3.2). Some smoldering was observed, which is alos indicated by the low EF_{CO2} (3092 lbs ton^{-1}, Table 3.2). The high standard errors associated with emission factors and CE at the Worley site (taking both high and low residue loading into account, Table 3.2) indicated more variability among treatments than at the other two sites, which may be due, in part, to variability of the rolling terrain at Worley compared to the flat terrain at the other two sites.

The $RC_{Absolute}$ at Worley was similar to that observed at the other two sites with high residue loading (Fig. 3.6A). $EF_{PM2.5}$ for Worley (28 lbs ton^{-1}) was similar to that for Rathdrum, but significantly less than that for Connell (Table 3.2, Fig. 3.6B). The total lbs of $PM_{2.5}$ emissions $acre^{-1}$ for high residue loading was similar to that seen at Rathdrum and was significantly less than that for the high residue loading at Connell (Fig.3.7).

Worley dryland site in north Idaho – low residue loading:

Following combining on August 3, the low residue loading units were re-swathed and raked on August 5 and baled on August 6. The low residue loading burn units were burned on August 15 or 16, which allowed for good "dry down" and was reflected in the low entire residue layer moisture content, 9.3% (Table 2.3). The $RC_{Relative}$ at 76% was more than two times greater than the $RC_{Relative}$ of the other low residue loading treatments at Connell and Rathdrum, which probably was due to the dryness of the entire residue layer at Worley. There was very little smoldering observed (Appendix 4 and 5). The Worley low residue loading treatment had the highest CE (91%) and the highest EF_{CO2} (3320 lbs $acre^{-1}$) of any treatment in the study. While these values are not as high as those observed in the cereal study in eastern Washington (Air Sciences Inc., 2003), they are very comparable to those seen in the flaming phase of forest fires (Appendix 3). Although the low entire residue layer moisture content was probably the major reason (9% moisture content at Worley versus 22% moisture content at Connell and Rathdrum, respectively) for the efficient burns, other factors may have played some role.

Cultivar growth habit may also have contributed to a more efficient combustion at Worley. At Connell the cultivar was the low growing, denser, elite-type 'Total Eclipse' Kentucky bluegrass, while at Worley the cultivar was 'Garfield', a taller, less dense "common" bluegrass. When swathed at 3.5 inches, 'Garfield' had more stem and less leaf biomass than 'Total Eclipse'. As previously discussed, residue architecture and cultivar effects on burning and emissions are potential areas for future research.

Another factor could be management of Kentucky bluegrass seed fields. Burned fields tend to be thinner and more open, while non-burned field tend to become sod bound, produce fewer seed heads, and leafier biomass. If there is a sufficiently dry residue load to carry a fire, an open stand may enhance air flow into the residue and led to more efficient and cleaner burns. At Connell the stand had not been burned, was two-years-old, in its second harvest, and was a dense stand. In contrast, at Worley and Rathdrum, the stands had been continually burned, so they may have been thinner and more open. The exceptionally high total $PM_{2.5}$, for the high residue loading burns at Connell may be, in part, due to this factor. Total emissions for a bluegrass seed production field burned year after year could possible be less over time. Future research should address this issue.

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APPENDIX 1: LIST OF SYMBOLS

BD	Bulk density (lbs ft^{-3})
CO	Connell site in Columbia Basin of eastern Washington
CE	Combustion efficiency (%)
EF_x	Emission factor (lbs ton^{-1} of residue); x stands for CO_2, CO, CH_4, or $PM_{2.5}$
EF_{PAH}	Emission factor (lbs ton^{-1} of residue) for polyaromatic hydrocarbons
$EF_{PM2.5}$	Emission factor (g kg^{-1} of residue or lbs ton^{-1} of residue) for $PM_{2.5}$
Flow_correction	Factor to correct for air flow difference in PAH and $PM_{2.5}$ samples (dimensionless)
χ_x	Measured concentration of pollutant x above background (ppmv)
$\chi_{x, Fire}$	Measured concentration of pollutant x above background (mg m^{-3})
$\chi_{C\text{-}x, Fire}$	Carbon mass of pollutant x above background (mg m^{-3})
$L_{Pre\text{-}Burn}$	Fuel load before the burn (tons $acre^{-1}$)
$L_{Post\text{-}Burn}$	Fuel load after the burn (tons $acre^{-1}$)
$M_{PM2.5}$	Mass of $PM_{2.5}$ collected on filter (g)
M_{PAH}	Mass of polyaromatic hydrocarbon species in the $PM_{2.5}$ fraction (g)
PAH	Polyaromatic hydrocarbons
$PM_{2.5}$ Total	Total $PM_{2.5}$ emissions on a per acre basis (lbs $acre^{-1}$)
RA	Rathdrum, ID site
RMC	Residue moisture content (% H_2O per g dry weight)
$RC_{Absolute}$	Absolute residue consumption (tons $acre^{-1}$)
$RC_{Relative}$	Relative residue consumption (% of pre-burn residue loading, $L_{Pre\text{-}Burn}$)
W_{field}	Fresh weight of residue or soil sample (g)
W_{OD}	Oven dried weight of residue or soil sample (g)
WO	Worley, ID site
X	Subscript used to indicate pollutant species, CO_2, CO, CH_4, or $PM_{2.5}$

APPENDIX 2:SUMMARY OF PHYSICAL SITE DATA, BY BURN UNIT

Summary Physical Site Data, By UNIT 6/2/2003 **0=NO DATA**

Site_Load_Unit	Parameter	tons/acre Pre_Load	tons/acre Post_Load	% H2O_tot	% H2O_up	% H2O_low	% H2O_soil	lbs/ton CO2	lbs/ton CO	lbs/ton CH4	lbs/ton PM2.5	% CE
CB_LOW_1	N of cases	11	0	4	0	0	4	0	0	0	0	0
CB_LOW_1	Minimum	1.1	.	23.5	.	.	4.1	.	.	.	.	
CB_LOW_1	Maximum	2.5	.	45.0	.	.	5.1	.	.	.	.	
CB_LOW_1	Mean	1.6	.	35.5	.	.	4.6	.	.	.	.	
CB_LOW_1	Std. Error	0.1	.	4.8	.	.	0.2	.	.	.	.	
CB_HIGH_1	N of cases	12	4	0	4	4	4	1	1	1	1	1
CB_HIGH_1	Minimum	1.6	1.1	.	2.0	18.7	3.4	2817	562.8	62.2	60.7	0.77
CB_HIGH_1	Maximum	8.9	1.7	.	4.4	64.1	5.6	2817	562.8	62.2	60.7	0.77
CB_HIGH_1	Mean	4.3	1.4	.	3.3	40.3	4.9	2817	562.8	62.2	60.7	0.77
CB_HIGH_1	Std. Error	0.6	0.2	.	0.7	11.4	0.5	.	.	.	.	
CB_LOW_2	N of cases	10	3	4	0	0	4	0	0	0	0	0
CB_LOW_2	Minimum	1.1	1.0	6.8	.	.	4.3	.	.	.	.	
CB_LOW_2	Maximum	2.8	1.5	58.8	.	.	5.2	.	.	.	.	
CB_LOW_2	Mean	1.7	1.3	23.1	.	.	4.8	.	.	.	.	
CB_LOW_2	Std. Error	0.2	0.1	12.1	.	.	0.2	.	.	.	.	
CB_HIGH_2	N of cases	11	4	0	4	4	4	2	2	1	2	2
CB_HIGH_2	Minimum	2.1	0.8	.	2.0	11.5	3.6	2746	461.2	51.0	130.2	0.75
CB_HIGH_2	Maximum	7.1	1.5	.	4.9	61.8	5.4	2872	507.8	51.0	156.1	0.78
CB_HIGH_2	Mean	4.6	1.1	.	2.9	25.7	4.7	2809	484.5	51.0	143.2	0.77
CB_HIGH_2	Std. Error	0.4	0.2	.	0.7	12.1	0.4	63	23.3	.	12.9	0.02
CB_LOW_3	N of cases	12	4	4	0	0	4	2	2	1	2	2
CB_LOW_3	Minimum	0.9	0.8	9.1	.	.	3.9	3197	308.8	19.0	39.9	0.87
CB_LOW_3	Maximum	3.2	1.4	40.9	.	.	4.9	3216	319.2	19.0	59.7	0.88
CB_LOW_3	Mean	1.8	1.0	22.1	.	.	4.4	3207	314.0	19.0	49.8	0.88
CB_LOW_3	Std. Error	0.2	0.1	7.5	.	.	0.2	10	5.2	.	9.9	0.01
CB_HIGH_3	N of cases	12	4	0	4	4	4	1	1	1	1	1
CB_HIGH_3	Minimum	2.0	0.4	.	1.9	7.0	3.8	2903	393.6	44.4	121.5	0.79
CB_HIGH_3	Maximum	6.8	1.1	.	3.1	24.4	5.1	2903	393.6	44.4	121.5	0.79
CB_HIGH_3	Mean	3.9	0.9	.	2.4	14.1	4.6	2903	393.6	44.4	121.5	0.79
CB_HIGH_3	Std. Error	0.4	0.2	.	0.3	3.7	0.3	.	.	.	.	
WO_LOW_1	N of cases	7	3	4	0	0	4	2	2	1	2	2
WO_LOW_1	Minimum	1.1	1.0	4.2	.	.	4.4	3290	200.6	4.4	52.4	0.90
WO_LOW_1	Maximum	2.7	1.2	13.5	.	.	6.5	3308	242.8	4.4	70.2	0.90
WO_LOW_1	Mean	2.0	1.1	8.6	.	.	5.0	3299	221.7	4.4	61.3	0.90
WO_LOW_1	Std. Error	0.2	0.1	2.2	.	.	0.5	9	21.1	.	8.9	0.00
WO_HIGH_1	N of cases	8	4	0	4	4	4	1	1	1	1	1
WO_HIGH_1	Minimum	2.7	1.0	.	1.7	18.2	4.4	2837	628.6	62.6	25.5	0.77
WO_HIGH_1	Maximum	5.5	2.2	.	3.3	29.6	7.7	2837	628.6	62.6	25.5	0.77
WO_HIGH_1	Mean	4.3	1.3	.	2.4	24.3	5.4	2837	628.6	62.6	25.5	0.77
WO_HIGH_1	Std. Error	0.3	0.3	.	0.4	3.1	0.8	.	.	.	.	
WO_LOW_2	N of cases	7	3	4	0	0	4	2	2	2	2	2
WO_LOW_2	Minimum	1.0	0.9	6.6	.	.	4.8	3268	220.6	11.8	52.3	0.89
WO_LOW_2	Maximum	1.9	1.0	10.6	.	.	6.2	3271	244.2	15.2	64.1	0.89
WO_LOW_2	Mean	1.4	1.0	8.5	.	.	5.5	3270	232.4	13.5	58.2	0.89
WO_LOW_2	Std. Error	0.1	0.0	1.0	.	.	0.3	2	11.8	1.7	5.9	0.00
WO_HIGH_2	N of cases	8	4	0	4	4	4	1	1	1	1	1
WO_HIGH_2	Minimum	2.0	0.8	.	3.4	8.8	4.6	3139	369.2	33.6	34.8	0.86
WO_HIGH_2	Maximum	5.6	1.1	.	6.4	27.7	6.2	3139	369.2	33.6	34.8	0.86
WO_HIGH_2	Mean	3.8	0.9	.	4.4	20.9	5.1	3139	369.2	33.6	34.8	0.86
WO_HIGH_2	Std. Error	0.5	0.1	.	0.7	4.2	0.4	.	.	.	.	
WO_LOW_3	N of cases	7	3	4	0	0	4	2	2	1	2	2
WO_LOW_3	Minimum	0.7	1.3	3.9	.	.	4.2	3373	186.8	9.2	19.1	0.92
WO_LOW_3	Maximum	3.4	1.5	22.2	.	.	5.2	3411	187.4	9.2	48.6	0.93
WO_LOW_3	Mean	1.8	1.4	10.8	.	.	4.5	3392	187.1	9.2	33.8	0.93
WO_LOW_3	Std. Error	0.4	0.1	4.1	.	.	0.2	19	0.3	.	14.8	0.01
WO_HIGH_3	N of cases	8	4	0	4	4	4	2	2	1	2	2
WO_HIGH_3	Minimum	3.7	0.5	.	3.7	14.5	5.1	3272	238.0	19.4	23.5	0.89
WO_HIGH_3	Maximum	6.0	0.9	.	4.3	30.2	7.1	3327	341.0	19.4	24.5	0.91
WO_HIGH_3	Mean	4.7	0.7	.	4.0	21.7	6.0	3299	289.5	19.4	24.0	0.90
WO_HIGH_3	Std. Error	0.3	0.1	.	0.1	3.3	0.4	28	51.5	.	0.5	0.01

APPENDIX 2:SUMMARY OF PHYSICAL SITE DATA, BY BURN UNIT (CONTINUED)

Summary Physical Site Data, By UNIT 6/2/2003 **0=NO DATA**

Site_Load_Unit	Parameter	tons/acre Pre_Load	tons/acre Post_Load	% H2O_tot	% H2O_up	% H2O_low	% H2O_soil	lbs/ton CO2	lbs/ton CO	lbs/ton CH4	lbs/ton PM2.5	% CE
RA_LOW_1	N of cases	7	3	4	0	0	4	1	1.0	1.0	1.0	1.00
RA_LOW_1	Minimum	1.1	0.2	12.0	.	.	6.0	3069	341.8	23.2	88.4	0.84
RA_LOW_1	Maximum	2.2	1.0	40.1	.	.	8.7	3069	341.8	23.2	88.4	0.84
RA_LOW_1	Mean	1.8	0.5	20.9	.	.	7.2	3069	341.8	23.2	88.4	0.84
RA_LOW_1	Std. Error	0.2	0.3	6.5	.	.	0.6	.	.	.	.	.
RA_HIGH_1	N of cases	6	4	0	2	2	4	2	2	2	2	2
RA_HIGH_1	Minimum	1.9	0.2	.	8.4	21.2	6.3	3110	293.6	21.0	35.8	0.85
RA_HIGH_1	Maximum	5.9	0.3	.	8.7	34.1	9.2	3246	391.6	32.6	39.3	0.88
RA_HIGH_1	Mean	3.8	0.3	.	8.6	27.6	7.5	3178	342.6	26.8	37.6	0.87
RA_HIGH_1	Std. Error	0.6	0.0	.	0.1	6.4	0.7	68	49.0	5.8	1.8	0.02
RA_LOW_2	N of cases	7	3	4	0	0	4	1	1	1	1	1
RA_LOW_2	Minimum	1.6	0.3	9.3	.	.	4.9	3022	424.2	31.8	61.2	0.82
RA_LOW_2	Maximum	2.2	0.6	52.1	.	.	10.4	3022	424.2	31.8	61.2	0.82
RA_LOW_2	Mean	1.9	0.5	28.7	.	.	7.7	3022	424.2	31.8	61.2	0.82
RA_LOW_2	Std. Error	0.1	0.1	11.1	.	.	1.1	.	.	.	.	.
RA_HIGH_2	N of cases	8	4	0	4	4	4	2	2	0	2	2
RA_HIGH_2	Minimum	2.5	0.3	.	3.9	12.4	8.0	3081	521.4	.	26.8	0.84
RA_HIGH_2	Maximum	4.6	0.6	.	13.1	21.0	11.2	3085	522.6	.	29.2	0.84
RA_HIGH_2	Mean	3.3	0.4	.	6.3	16.5	9.5	3083	522.0	.	28.0	0.84
RA_HIGH_2	Std. Error	0.2	0.1	.	2.2	1.8	0.8	2	0.6	.	1.2	0.00
RA_LOW_3	N of cases	7	3	4	0	0	4	2	2	2	2	2
RA_LOW_3	Minimum	1.5	0.3	7.5	.	.	4.7	3113	307.4	21.2	43.6	0.85
RA_LOW_3	Maximum	2.8	0.4	25.5	.	.	9.0	3209	374.8	27.4	50.0	0.87
RA_LOW_3	Mean	1.9	0.3	15.2	.	.	7.2	3161	341.1	24.3	46.8	0.86
RA_LOW_3	Std. Error	0.2	0.0	3.8	.	.	0.9	48	33.7	3.1	3.2	0.01
RA_HIGH_3	N of cases	8	4	0	4	4	4	2	2	2	2	2
RA_HIGH_3	Minimum	2.0	0.1	.	3.6	12.8	7.0	3212	91.6	14.2	25.7	0.88
RA_HIGH_3	Maximum	4.3	0.5	.	6.1	28.3	13.2	3458	334.8	28.4	38.7	0.94
RA_HIGH_3	Mean	2.9	0.3	.	4.5	21.1	8.9	3335	213.2	21.3	32.2	0.91
RA_HIGH_3	Std. Error	0.2	0.1	.	0.6	3.4	1.5	123	121.6	7.1	6.5	0.03

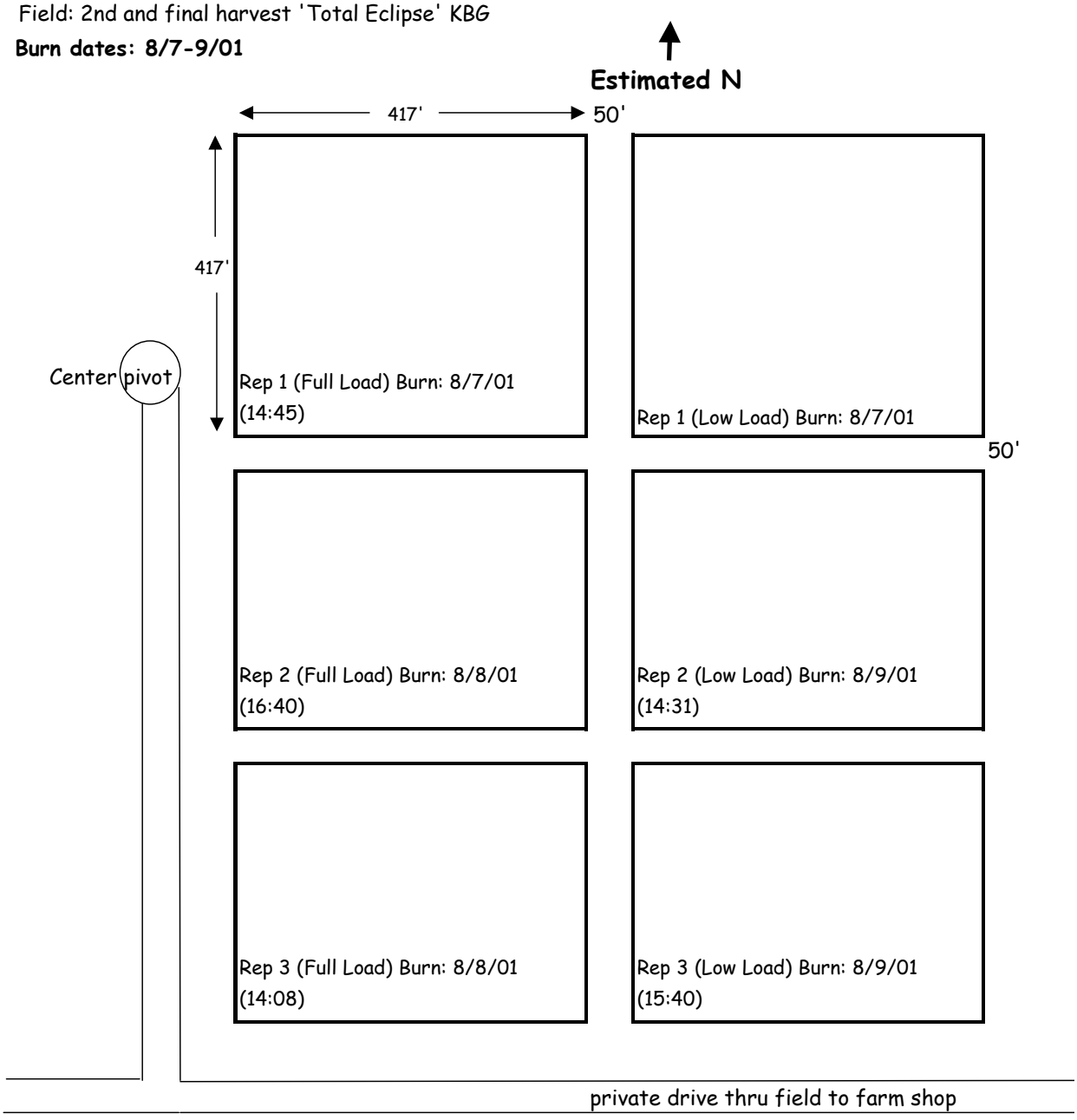
APPENDIX 3: EMISSION FACTOR COMPARISON WITH OTHER STUDIES

Summary of Emission Factors for CO_2, CO, CH_4, and $PM_{2.5}$ From Other Reports in the Literature

Source	Residue Type	Emission Factor, lbs ton^{-1} of residue consumed			
		CO_2	CO	CH_4	$PM_{2.5}$
Air Sciences Inc., 2003	Wheat Residue				
	Spring (95% C.I.)	3527 - 3561 (mean 3546)	57 - 77 (mean 67)	1.3 – 2.0 (mean 1.6)	4.0 – 6.9 (mean 5.3)
	Fall (95% C.I.)	3396 – 3495 (mean 3447)	93 - 141 (mean 117)	2.6 – 4.5 (mean 3.6)	7.3 – 12.4 (mean 9.8)
Jenkins and 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				
	Flaming				mean ~6.6
	Smoldering				mean ~12.2
Ward and Hardy, 1991	Wildfires, U.S.A.				
	CE > 90 %				2 - 12
	CE 74 to 90 %				12 – 40
Ward et al., 1992a	Wildfires, U.S.A.				
	Flaming	3424 – 3518	72 – 116	2.8 – 5.8	4.0 – 12.8
	Smoldering	2472 – 2580	490 – 526	34.8 – 42.8	44.4 – 65.2
Ward et al., 1992b	Cerrado Forest, Brazil				
	Flaming	3380 – 3498	92 – 140	2.0 – 3.2	1.0 – 2.4
	Smoldering	3062 - 3304	182 – 304	8.6 – 18.0	4.8 – 9.8

APPENDIX 4.0: COLUMBIA BASIN - PLOT PLANS AND FIELD NOTES

Kentucky bluegrass emissions on an irrigated site in the Columbia Basin
Location: Connell, WA
Field: 2nd and final harvest 'Total Eclipse' KBG
Burn dates: 8/7-9/01



APPENDIX 4.0: COLUMBIA BASIN - PLOT PLANS AND FIELD NOTES (CONTINUED)

Kentucky bluegrass emissions on an irrigated site in the Columbia Basin
Location: Connell, WA
Field: 2nd and final harvest 'Total Eclipse' KBG
Burn date: 8/7/01

Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Columbia Basin (irrigated)	1	Low					

Pre-burn residue load 8-1 ft2 samples/plot

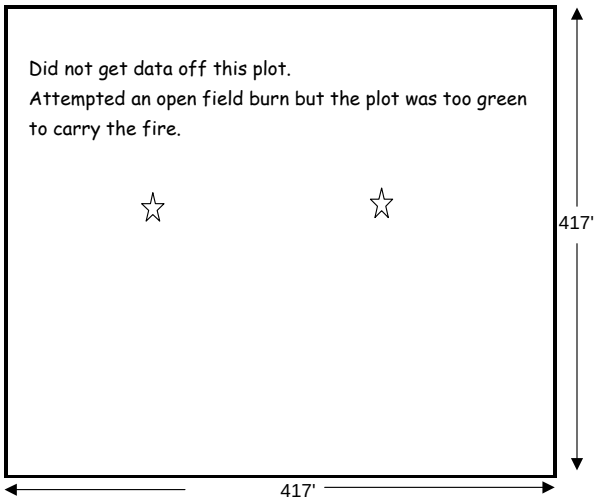
Pre-burn residue moisture 4-1 ft2 samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
min. flame
min. smolder



COMMENTS:
Combine harvest 7/31/01 with residue scattered onto field.
Raked and baled 8/1/01.
Lit plot with a propane torch mounted on an four wheel ATV. Plot too green did not carry a fire.
Stubble height approximately 2". (Mean of 3 measurements)

Kentucky bluegrass emissions on an irrigated site in the Columbia Basin
Location: Connell, WA
Field: 2nd and final harvest 'Total Eclipse' KBG
Burn date: 8/7/01

Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Columbia Basin (irrigated)	1	Full	14:45				15:15

Pre-burn residue load 8-1 ft2 samples/plot

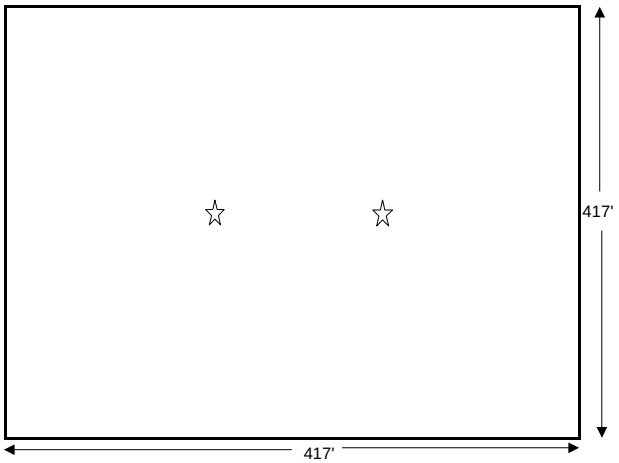
Pre-burn residue moisture 4-1 ft2 upper samples/plot and 4 lower stubble samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
min. flame
min. smolder



COMMENTS:
Combine harvest 7/31/01 with residue scattered onto field.
Lit fire with propane torch mounted on a four wheel ATV.
Stubble height approximately 2". (Mean of 3 measurements)

APPENDIX 4.0: COLUMBIA BASIN - PLOT PLANS AND FIELD NOTES (CONTINUED)

Kentucky bluegrass emissions on an irrigated site in the Columbia Basin

Location: Connell, WA

Field: 2nd and final harvest 'Total Eclipse' KBG

Burn date: 8/9/01 Site	Rep	Residue Load	Propane Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Columbia Basin (irrigated)	2	Low	NW	14:30			15:07

Pre-burn residue load 8-1 ft2 samples/plot

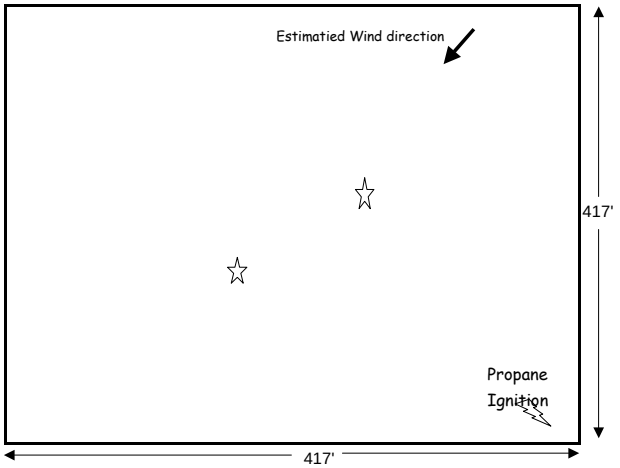
Pre-burn residue moisture 4-1 ft2 samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
min. flame
min. smolder



COMMENTS:

Combine harvest 7/31/01 with residue scattered onto field.
Raked and baled 8/1/01.
Lit fire with an 18' wide propane flamer pulled with a tractor.
9 loops (18 passes) with propane burner (time to complete propane burn 25 min).
Stubble height approximately 2". (Mean of 3 measurements)

Kentucky bluegrass emissions on an irrigated site in the Columbia Basin

Location: Connell, WA

Field: 2nd and final harvest 'Total Eclipse' KBG

Burn date: 8/8/01 Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Columbia Basin (irrigated)	2	Full	16:40				17:10

Pre-burn residue load 8-1 ft2 samples/plot

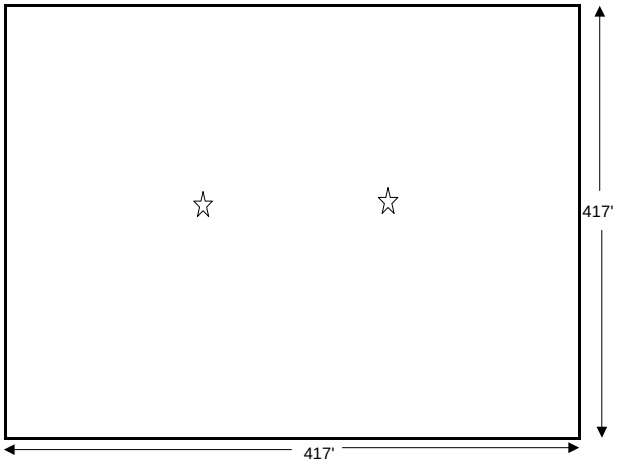
Pre-burn residue moisture 4-1 ft2 upper samples/plot and 4 lower stubble samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
min. flame
min. smolder



COMMENTS:

Combine harvest 7/31/01 with residue scattered onto field.
Lit fire with burning residue and a pitchfork.
Stubble height approximately 2". (Mean of 3 measurements)

APPENDIX 4.0: COLUMBIA BASIN - PLOT PLANS AND FIELD NOTES (CONTINUED)

Kentucky bluegrass emissions on an irrigated site in the Columbia Basin

Location: Connell, WA

Field: 2nd and final harvest 'Total Eclipse' KBG

Burn date: 8/9/01 Site	Rep	Residue Load	Propane Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Columbia Basin (irrigated)	3	Low	15:40				16:20

Pre-burn residue load 8-1 ft2 samples/plot

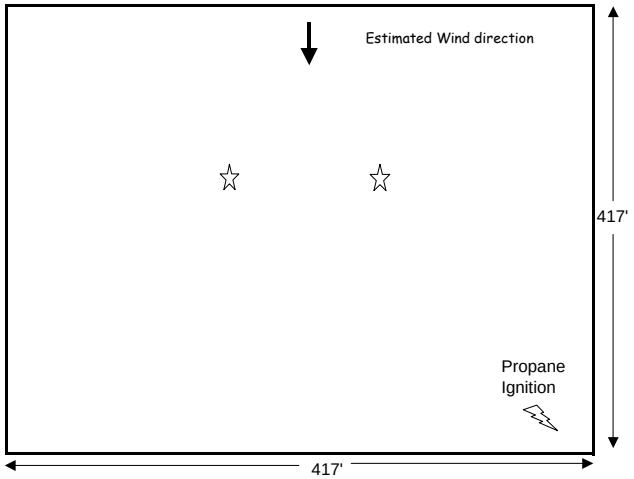
Pre-burn residue moisture 4-1 ft2 samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
min. flame
min. smolder



COMMENTS:

Combine harvest 7/31/01 with residue scattered onto field.
Raked and baled 8/1/01.
Lit fire with an 18' wide propane flamer pulled with a tractor. Only 2 of the three burner booms worked. Therefore, only 12' swath burned behind flamer.
6 loops (12 passes) with propane burner (time to complete propane burn 20-25 min).
Stubble height approximately 2". (Mean of 3 measurements)

Location: Connell, WA (Columbia Basin)

Field: 2nd and final harvest 'Total Eclipse' KBG

Burn date: 8/8/01 Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Columbia Basin (irrigated)	3	Full	14:08				14:31

Pre-burn residue load 8-1 ft2 samples/plot

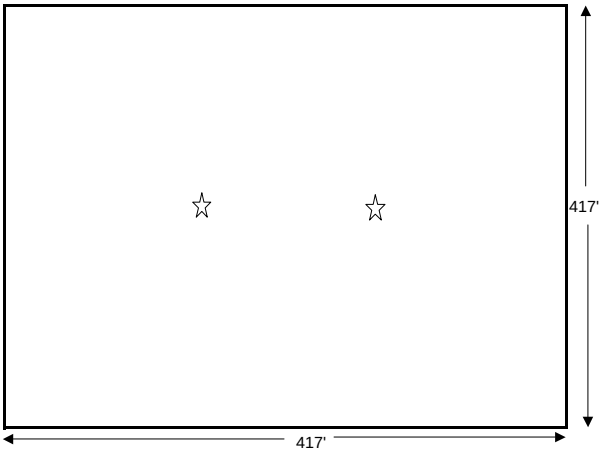
Pre-burn residue moisture 4-1 ft2 upper samples/plot and 4 lower stubble samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
min. flame
min. smolder

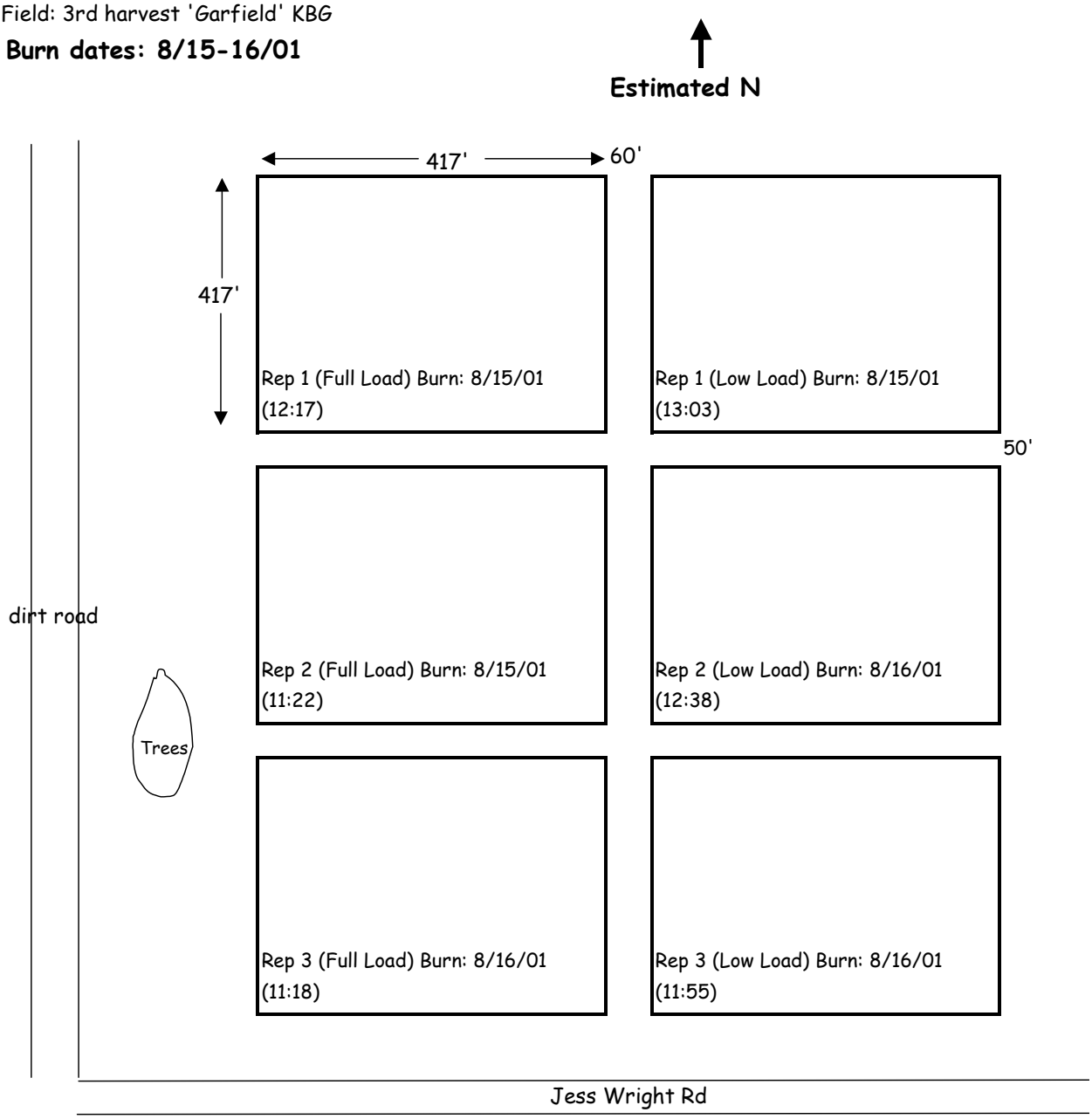


COMMENTS:

Combine harvest 7/31/01 with residue scattered onto field.
Lit fire with burning residue and a pitchfork.
Stubble height approximately 2". (Mean of 3 measurements)

APPENDIX 4.1: WORLEY - PLOT PLANS AND FIELD NOTES

Kentucky bluegrass emissions on a nonirrigated site in Northern Idaho
Location: Worley, ID
Field: 3rd harvest 'Garfield' KBG
Burn dates: 8/15-16/01



APPENDIX 4.1: WORLEY - PLOT PLANS AND FIELD NOTES (CONTINUED)

Kentucky bluegrass emissions on a dryland site in Northern Idaho

Location: Worley, ID

Field: 3rd harvest 'Garfield' KBG

Burn date: 8/15/01 Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Worley (dryland)	1	Low	13:03	13:13		13:16	13:23

Pre-burn residue load 4-1 ft2 samples/plot

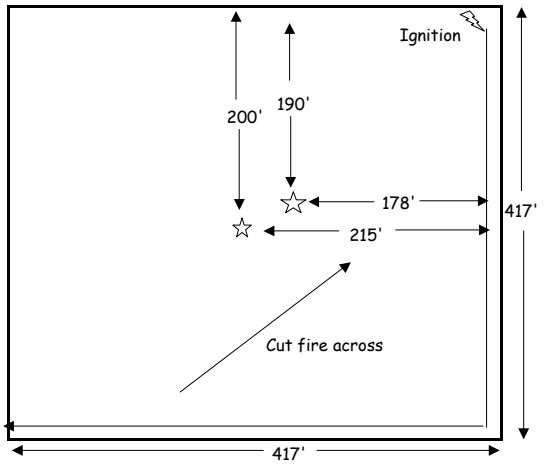
Pre-burn residue moisture 4-1 ft2 samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:

Combine harvest 8/3/01 with residue scattered onto field.
Low residue reswathed and raked 8/5/01.
Low residue baled 8/6/01.
Lit fire with a propane torch mounted on an ATV.
Area burned in front of towers: 2.2 Acres

Kentucky bluegrass emissions on a dryland site in Northern Idaho

Location: Worley, ID

Field: 3rd harvest 'Garfield' KBG

Burn date: 8/15/01 Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Worley (dryland)	1	Full	12:17	12:25		12:34	12:45

Pre-burn residue load 4-1 ft2 samples/plot

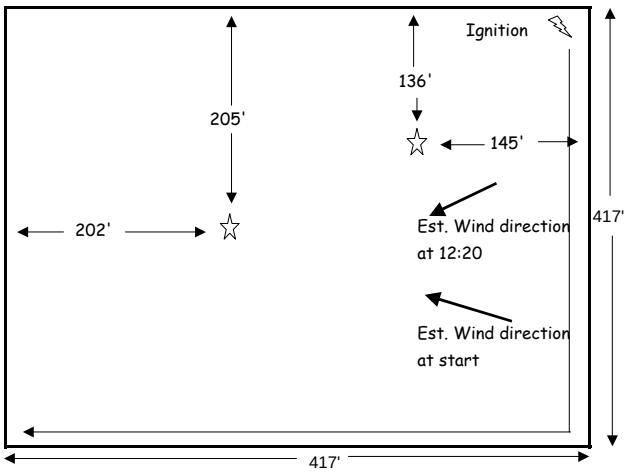
Pre-burn residue moisture 4-1 ft2 upper samples/plot and 4 lower stubble samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:

Combine harvest 8/3/01 with residue scattered onto field.
Lit fire with a propane torch mounted on an ATV.
Wind direction at ignition NNE and wind shifted to NNW at 12:20.

APPENDIX 4.1: WORLEY - PLOT PLANS AND FIELD NOTES (CONTINUED)

Kentucky bluegrass emissions on a dryland site in Northern Idaho

Location: Worley, ID

Field: 3rd harvest 'Garfield' KBG

Burn date: 8/16/01

Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Worley (dryland)	2	Low	12:38	12:41	12:43	12:52	12:53

Pre-burn residue load 4-1 ft2 samples/plot

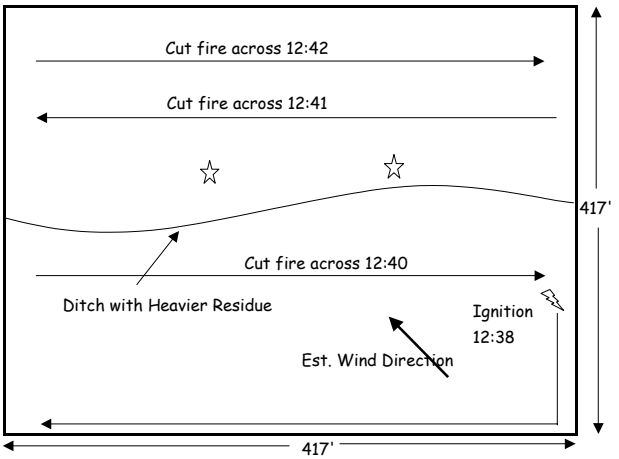
Pre-burn residue moisture 4-1 ft2 samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:

Combine harvest 8/3/01 with residue scattered onto field.
Low residue reswathed and raked 8/5/01.
Low residue baled 8/6/01.
Lit fire with a propane torch mounted on an ATV.
Candice Claiborn samplers placed on top of hill east of this burn unit.

Kentucky bluegrass emissions on a dryland site in Northern Idaho

Location: Worley, ID

Field: 3rd harvest 'Garfield' KBG

Burn date: 8/15/01

Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Worley (dryland)	2	Full	11:22			11:29	11:38

Pre-burn residue load 4-1 ft2 samples/plot

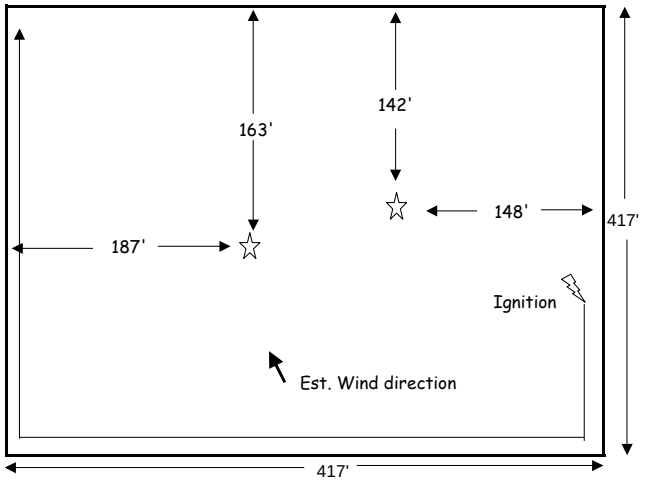
Pre-burn residue moisture 4-1 ft2 upper samples/plot and 4 lower stubble samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:

Combine harvest 8/3/01 with residue scattered onto field.
Lit fire with a propane torch mounted on an ATV.

APPENDIX 4.1: WORLEY - PLOT PLANS AND FIELD NOTES (CONTINUED)

Kentucky bluegrass emissions on a dryland site in Northern Idaho

Location: Worley, ID

Field: 3rd harvest 'Garfield' KBG

Burn date: 8/16/01 Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Worley (dryland)	3	Low	11:55	11:58		12:17	12:22

Pre-burn residue load 4-1 ft2 samples/plot

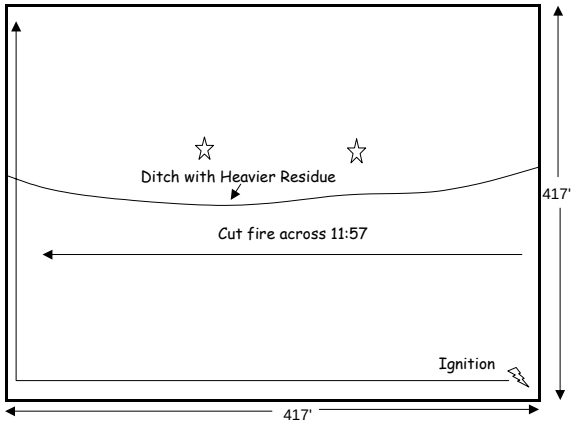
Pre-burn residue moisture 4-1 ft2 samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:

Combine harvest 8/3/01 with residue scattered onto field.
Low residue reswathed and raked 8/5/01.
Low residue baled 8/6/01.
Lit fire with a propane torch mounted on an ATV.
Left tower got a lot of late smolder from ditch.

Stubble Height (in)	
slope	draw
4.25	4.75
4.25	2.75
2.50	2.00
Avg 3.94	Avg 3.06

Kentucky bluegrass emissions on a dryland site in Northern Idaho

Location: Worley, ID

Field: 3rd harvest 'Garfield' KBG

Burn date: 8/16/01 Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Worley (dryland)	3	Full	11:18	11:20		11:44	12:00

Pre-burn residue load 4-1 ft2 samples/plot

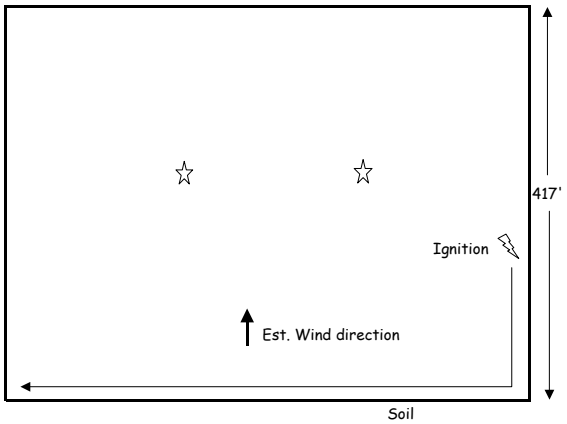
Pre-burn residue moisture 4-1 ft2 upper samples/plot and 4 lower stubble samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:

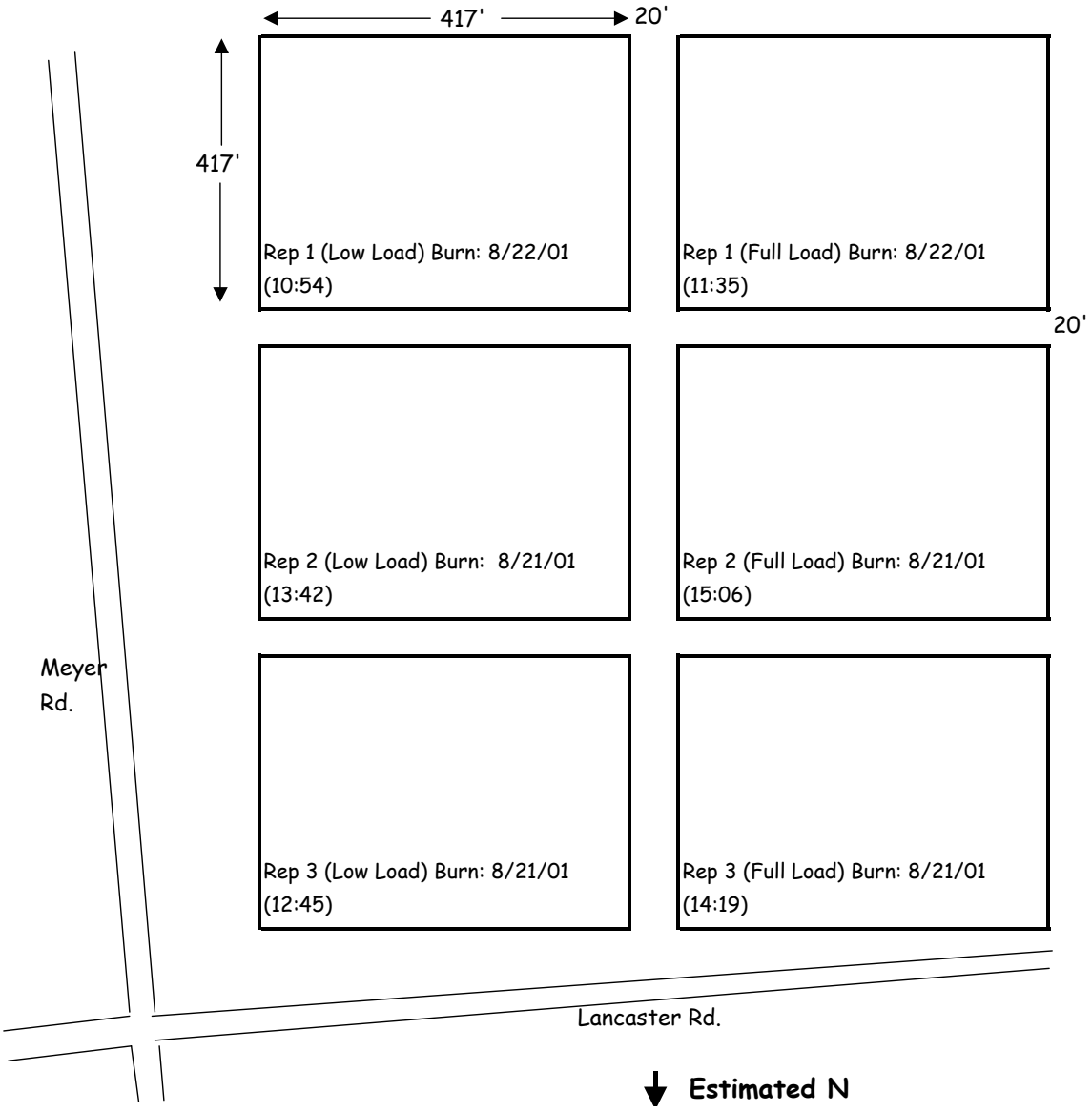
Combine harvest 8/3/01 with residue scattered onto field.
Lit fire with a propane torch mounted on an ATV.

Residue architecture:

Top of Residue	Thickness of Top Residue	Soil Surface to bottom of Residue	Stubble Height (in)	
8.00	3.50	4.50	7.00	11.25
7.75	4.50	3.25	9.25	12.00
5.75	3.25	2.50	7.75	7.25
2.75	2.75	0.00	9.25	10.50
Avg 6.06	Avg 3.50	Avg 2.56	Avg 8.31	10.25

APPENDIX 4.2: RATHDRUM - PLOT PLANS AND FIELD NOTES

Kentucky bluegrass emissions on an irrigated site on the Rathdrum Prairie
Location: Rathdrum, ID
Field: 3rd harvest 'Alene' KBG
Burn dates: 8/21-22/01



APPENDIX 4.2: RATHDRUM - PLOT PLANS AND FIELD NOTES (CONTINUED)

Kentucky bluegrass emissions on an irrigated site on the Rathdrum Prairie

Location: Rathdrum, ID

Field: 3rd harvest 'Alene' KBG

Burn date: 8/22/01

Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Rathdrum Prairie (irrigated)	1	Low	10:54	11:06	11:10	11:17	11:25

Pre-burn residue load 4-1 ft2 samples/plot

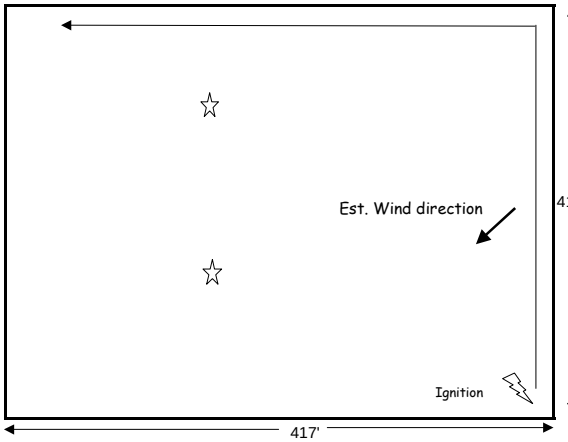
Pre-burn residue moisture 4-1 ft2 samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ **FASS Tower**

FASS setting:
3 min. flame
20 min. smolder



Stubble Ht (in)
7.25
9.50
11.25
10.75
Avg 9.69

COMMENTS:

Swathed 7/4/01.
Combine harvest 7/23/01 with residue scattered onto field.
Raked and baled 8/6/01.
Lit fire with with a propane torch while driving pickup around burn unit.

Kentucky bluegrass emissions on an irrigated site on the Rathdrum Prairie

Location: Rathdrum, ID

Field: 3rd harvest 'Alene' KBG

Burn date: 8/22/01

Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Rathdrum Prairie (irrigated)	1	Full	11:35	11:44	11:46	12:00	12:15

Pre-burn residue load 4-1 ft2 samples/plot

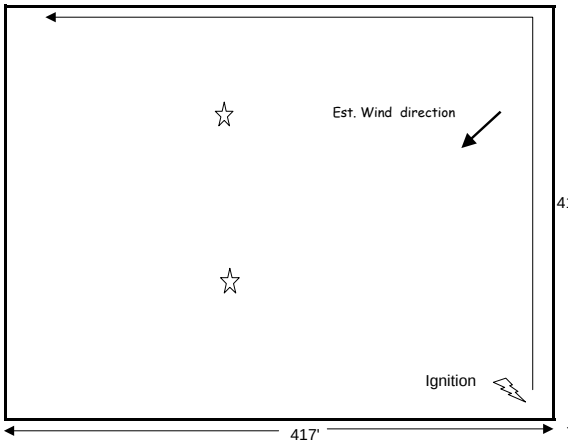
Pre-burn residue moisture 4-1 ft2 upper samples/plot and 4 lower stubble samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:

Swathed 7/4/01.
Combine harvest 7/23/01 with residue scattered onto field.
Lit fire with with a propane torch while driving pickup around burn unit.

Top of Residue (in)	Thickness of Top Residue layer (in)	Surface to bottom of Residue layer (in)
8.00	3.00	5.00
5.50	4.00	1.50
10.00	4.00	6.00
Avg 7.83	Avg 3.67	Avg 4.17

APPENDIX 4.2: RATHDRUM - PLOT PLANS AND FIELD NOTES (CONTINUED)

Kentucky bluegrass emissions on an irrigated site on the Rathdrum Prairie

Location: Rathdrum, ID
Field: 3rd harvest 'Alene' KBG
Burn date: 8/21/01

Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Rathdrum Prairie (irrigated)	2	Low	13:42			13:55	

Pre-burn residue load 4-1 ft2 samples/plot

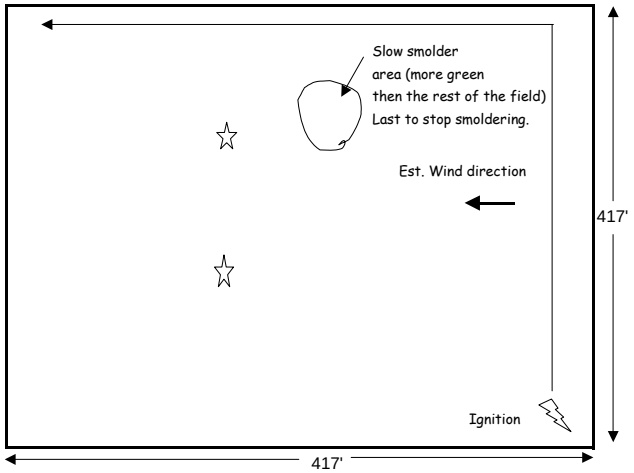
Pre-burn residue moisture 4-1 ft2 samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ **FASS Tower**

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:
Swathed 7/4/01.
Combine harvest 7/23/01 with residue scattered onto field.
Raked and baled 8/6/01.
Lit fire with with a propane torch while driving pickup around burn unit.

Location: Rathdrum, ID
Field: 3rd harvest 'Alene' KBG
Burn date: 8/21/01

Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Rathdrum Prairie (irrigated)	2	Full	15:06			15:17	

Pre-burn residue load 4-1 ft2 samples/plot

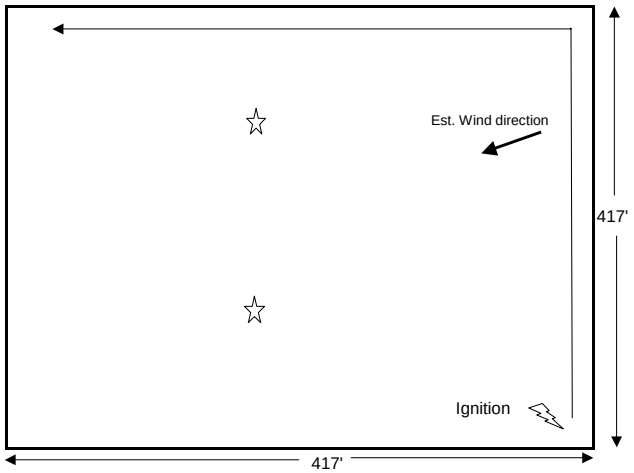
Pre-burn residue moisture 4-1 ft2 upper samples/plot and 4 lower stubble samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ **FASS Tower**

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:
Swathed 7/4/01.
Combine harvest 7/23/01 with residue scattered onto field.
Lit fire with with a propane torch while driving pickup around burn unit.

APPENDIX 4.2: RATHDRUM - PLOT PLANS AND FIELD NOTES (CONTINUED)

Kentucky bluegrass emissions on an irrigated site on the Rathdrum Prairie

Location: Rathdrum, ID

Field: 3rd harvest 'Alene' KBG

Burn date: 8/21/01

Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Rathdrum Prairie (irrigated)	3	Low	12:45			13:03	

Pre-burn residue load 4-1 ft2 samples/plot

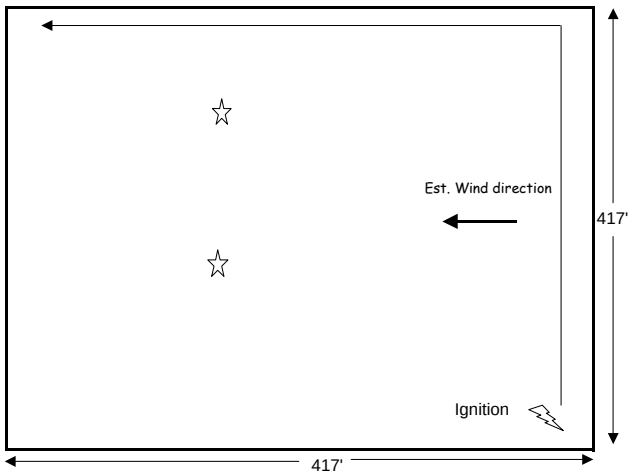
Pre-burn residue moisture 4-1 ft2 samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:

Swathed 7/4/01.

Combine harvest 7/23/01 with residue scattered onto field.

Raked and baled 8/6/01.

Lit fire with with a propane torch while driving pickup around burn unit.

Kentucky bluegrass emissions on an irrigated site on the Rathdrum Prairie

Location: Rathdrum, ID

Field: 3rd harvest 'Alene' KBG

Burn date: 8/21/01

Site	Rep	Residue Load	Ignition Time	Flames to Towers	Smolder Only to Tower	Smolder Past Tower	Plot Out
Rathdrum Prairie (irrigated)	3	Full	14:19			14:37	

Pre-burn residue load 4-1 ft2 samples/plot

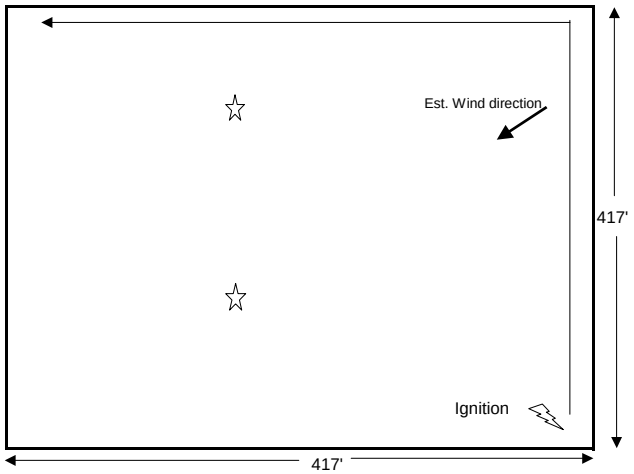
Pre-burn residue moisture 4-1 ft2 upper samples/plot and 4 lower stubble samples/plot

Post-burn residue 4-1 ft2 sample/plot

Soil moisture 4 samples/plot

☆ FASS Tower

FASS setting:
3 min. flame
20 min. smolder



COMMENTS:

Swathed 7/4/01.

Combine harvest 7/23/01 with residue scattered onto field.

Lit fire with with a propane torch while driving pickup around burn unit.

APPENDIX 5. Percentage of $PM_{2.5}$ emissions in flaming and smoldering combustion phases.

Study Site and Residue Loading	Flaming (%)	Smoldering (%)
Connell WA, irrigated		
High loading	93.0 (n=4)	7.0 (n=4)
Low loading	71.0 (n=2)	29.0 (n=2)
Rathdrum ID, irrigated		
High loading *	99.3 (n=4)	0.7 (n=4)
Low loading **	100.0 (n=3)	0.0 (n=4)
Worley ID, dryland		
High loading	95.8 (n=4)	4.2 (n=4)
Low loading ***	98.8 (n=5)	1.2 (n=5)

* Exclude 2 outliers; ** Excluded 1 outlier; *** Excluded 1 outlier

Appendix 6. **QUALITY ASSURANCE PROJECT PLAN FOR THE WASHINGTON STATE UNIVERSITY FIELD RESEARCH ON QUANTIFYING POST-HARVEST EMISSIONS FROM GRASS FIELD BURNING**

Prepared by Dan Redline, Idaho Department of Environmental Quality
Prepared for:

Washington State University
Department of Crop and Soil Sciences
Pullman, Washington 99164-6420

6.1. QUALITY ASSURANCE PROJECT PLAN IDENTIFICATION

Title: Quality Assurance Project Plan for Washington State University Field Research on Quantifying Post-harvest Emissions from Grass Field Burning

*This QAPP became a requirement after the field work for the project was already complete, therefore, the approval page has been modified to show the various project managers and grant coordinators associated with this study.

Project Manager -- William. J. Johnston, Professor/Agronomist, Department of Crop and Soil Sciences, WSU, Pullman, WA

Assistant Project Manager -- Mark. D. Schaaf, Associate Atmospheric Scientist, Air Sciences Inc., Portland, OR.

Assistant Project Manager – Ron Babbitt, Electrical Engineer, USFS Missoula Fire Science Lab, Missoula, MT.

USEPA Grant Manager – Robert Kotchenruther, Ph.D. Environmental Scientist, EPA Region 10 Seattle, WA.

Idaho Department of Environmental Quality Project Coordinator – Dan Redline, Air Quality Analyst, Coeur d'Alene Regional Office, ID.

Washington Department of Ecology Project Coordinator – Karen Wood, Agricultural Burn Team Leader, Spokane Regional Office, WA.

Coeur d'Alene Indian Tribe Coordinator – Marvin Sonder**, Agricultural Burn Team, Plummer, ID.
**As of April 2003, Mr. Sonder is no longer a member of the Coeur d'Alene Tribe Agricultural burn team.

6.2. TABLE OF CONTENTS

DISTRIBUTION LIST

William Johnston	Washington State University
Mark Schaaf	Air Sciences Inc.
Ron Babbitt	USFS Missoula Fire Science Laboratory
Robert Kotchenruther	EPA Region 10
Karen Wood	Washington Department of Ecology
Les Higgins	Coeur d'Alene Indian Tribe
Linda Clovis	North Idaho Farmers' Association
Art Schultheis	Washington Turfgrass Seed Commission
Dan Redline	Idaho DEQ

6.4. PROJECT ORGANIZATION

6.4.1 Principal Investigators:

W. J. Johnston, Professor/Agronomist, Department of Crop and Soil Sciences, WSU, Pullman, WA.

M. D. Schaaf, Associate Atmospheric Scientist, Air Sciences Inc., Portland, OR.

6.4.2 Cooperators:

Missoula Fire Sciences Laboratory, USDA Forest Service, Missoula, MT. Will provide instrumentation and staff for emissions collection at the burn sites.

DataChem Laboratories*, Salt Lake City, UT. Will perform chemical analysis.
*Southwest Research Institute, San Antonio, TX, was subcontracted by MFSL. Southwest Research Institute was the same subcontractor utilized by MFSL in the eastern Washington cereal emissions study.

C. Claiborn, Assoc. Professor, CEE, WSU. Will participate in emissions monitoring as able.

Washington Turfgrass Seed Commission, Pasco, WA. Growers will provide research sites and provide field assistance as necessary.

North Idaho Farmers' Association, Coeur d'Alene, ID. Growers will provide research sites and provide field assistance as necessary.

6.4.3 Potential Data Users:

WA DOE and IDEQ -- Will use emission estimates for evaluating the impacts of agricultural burning to the environment.

Idaho State Department of Agriculture (ISDA) and WA DOE -- Will use data to assist with policy decisions regarding agricultural smoke management programs.

Growers and Grower Organizations. Use data to improve their understanding of air quality impacts and better manage KBG residue burning.

6.5. PROBLEM DEFINITION AND BACKGROUND

6.5.1. Objective

Quantify, under field conditions at dryland and irrigated sites, with and without residue removal, amount of selected emissions generated by Kentucky bluegrass seed production post-harvest residue field burning.

6.5.2. Description of Problem

The amount of residue loading is one of the factors used to estimate emissions from burning residue in KBG fields. It has been hypothesized that reducing the residue loading should reduce the amount of emissions produced by open-field burning. Others have speculated that reducing the residue loading will lower the combustion efficiency of the burn and actually increase emissions from the same field. Growers have experimented with residue reduction followed by open-field burning over the past few years with anecdotal observations of the smoke plumes. To date, the research community has not conducted scientific measurements of the emissions from KBG fields with residue treatments combined with open-field burning.

This study was designed to quantify emissions from burning full-straw load fields versus the emissions from burning fields treated by residue removal. This study will measure the emissions for the following list of pollutants/compounds; $PM_{2.5}$, PM_{10}, carbon monoxide, benzo(a)pyrene (BaP) [a PAH], and six additional BaP-equivalent carcinogens listed in WAC 173-460-050(4)(c), including benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, and indenol(1,2,3-cd)pyrene.

This study will evaluate emissions generated from grass seed production fields with fuel reductions in comparison to those burned without fuel reductions in an effort to reduce emissions. The information obtained from this study will help establish appropriate burning practices needed to significantly reduce emissions, contribute to the scientific database on agricultural burning emissions, as well as provided data to direct future research. This study will provide the public with additional information about the chemical make-up of smoke from burning KBG fields following harvest. This has been an on-going concern related to the public health impacts often associated with this agricultural practice.

A similar study was conducted on cereal grain residue in Washington in 2000. A final report entitled, "Cereal-Grain Residue Open-field Burning Emissions Study" is available through the Washington State Department of Ecology.

6.5.3. Background

Fire has long been used as a management tool in grass seed production (Burton, 1944; Conklin, 1976; Chilcote et al., 1978; Hardison, 1980; Johnston et al., 1996; Kamm and Montgomery, 1990; Mazzola et al., 1997; Schirman, 1997). However, increasing concerns over the health impact of emissions from open-field burning have pointed to the need for information on grass fire emissions. Although some data are currently available that identify and quantify the various chemical components of grassfire emissions in the Pacific Northwest (Adams, 1976; Boubel et al., 1969; Jenkins, et al., 1996), and biomass burning (Crutzen and Andreae, 1990; Kuhlbusch et al., 1991), little research has been performed with residue reduction-flaming (bale and burn) systems. Because mechanical residue removal is an option growers can use to reduce the fuel load on grass fields, emissions from fields where residue has been removed and fields with typical post-harvest

residue fuel loads will be studied. Although past WSU research, in a never completed project, indicated increased emissions with residue removal and open-field burning (Adams, 1976), current WSU research with residue reduction (baling) followed by diesel or propane flaming indicates the possibility of reduced emissions and reduced smoldering while maintaining good seed yield (Felgenhauer, personal communication, 1999; Johnston, 1997). Characterization of particulate emissions from the 'bale and flame/burn' system are needed since a cooler burn, compared to open-field burning, is possible. Ultimately, smoke reduction and management should be based on emissions rather than number of acres burned. However, insufficient research on grassy fuels has been conducted to characterize emissions to the degree necessary for the development of BMPs.

6.6. PROJECT/TASK DESCRIPTION

The study design and work plans for this project evolved from previous efforts to complete this work with other partners. The project managers reworked the tasks and work teams to meet the financial limitations and time constraints this project faced. The project tasks and work assignments are described below.

Task 1: Experimental Plan. Washington State University (WSU) will prepare the proposal and a comprehensive experimental monitoring plan (Task list).

Task 2: Unit Identification and Treatments. WSU will identify three, 20- to 50-acre minimum (depending on size of burn units) study sites in eastern Washington (Site 1, Columbia Basin) and northern Idaho (Site 2, dryland site in north Idaho and Site 3, irrigated site in north Idaho) during late spring and early summer, 2001. Two alternative residue treatments will be evaluated at each site: no residue treatment ("full load"), and pre-burn baling ("reduced load"). Each treatment will consist of three separate 2- to 8-acre burn units (replications). A total of 18 burns will be conducted (3 sites, 2 residue loads, and 3 replications).

Task 3: Unit Layout. WSU will stake the corners of each burn unit with wooden stakes. A firebreak will be constructed around each burn unit of a type and size adequate to stop the forward progress of fire under the most extreme conditions that are likely to occur at each site. The host grower will be responsible for constructing and maintain the firebreak, for igniting the fire under the conditions prescribed by the principle investigators, and for providing fire suppression equipment and personnel during the burn in order to respond in the event of an escaped fire.

Task 4: Pre-burn Residue Loading. The pre-burn surface fuel loading within each burn unit will be characterized. The residue loading will be determined by destructive sampling at random locations within the burn units. Air Sciences Inc. will provide one technician with past residue sampling experience at the initial burn site (Site 1, Columbia Basin) to assist in performing pre-burn fuel sampling (on site labor 6 hours). WSU will provide 3 technicians to assist at initial site (Site 1) and will be responsible for performing the pre-burn fuel sampling at Sites 2 and 3. Following sampling, WSU will be responsible for handling the samples, laboratory analysis, and transmitting the pre-burn residue dry weight data electronically to Air Sciences Inc.

Task 5: Pre-burn Moisture Sampling. Immediately prior to the burn, the moisture content of the grass residue and the upper layer of soil will be characterized. Air Sciences Inc. will provide one technician with past residue and moisture sampling experience at the initial burn site (Site 1) to assist in performing sampling. WSU will provide 3 technicians to assist Air Sciences at Site 1 and will be responsible for performing the pre-burn moisture characterization at additional sites. Following sampling, Washington State University will be responsible for handling the samples, laboratory analysis, and transmitting the pre-burn residue moisture and soil moisture data electronically to Air Sciences Inc.

Task 6: Emissions Monitoring. Missoula Fire Science Laboratory (MFSL) will perform the emissions monitoring using the Missoula Fire Science Laboratory's Fire-Atmosphere Sampling System (FASS). FASS is a tower-based system that measures real-time emissions (Susott et al., 1991b; Ward et al., 1992a). The computer control system, battery, pumps and flow meter, manifolds, particulate matter filters (Teflon and glass), real time analyzers, and the three-part gas collection system (one part for each phase of the burn, i.e., flaming, transitional, and smoldering;

note: in study only two phases were recorded, flaming and smoldering) are buried near the instrumentation towers. Two guyed instrument towers (two sub-samples per plot) holding the FASS equipment will be erected on each plot. Air Sciences Inc. will also provide one experienced field technician for directing the emissions sampling, given the assistance of at least two experienced field technicians provided under a contract with the Missoula Fire Sciences Laboratory.

Air Sciences will provide a portable meteorological station for use in monitoring and recording the meteorological events during each of the burns at each of the sites.

Task 6 also includes post-burn residue sampling of each of the 18 burn units. WSU will provide 3 technicians to assist Air Sciences in performing the post-burn residue sampling at Site 1. WSU will perform the post-burn residue sampling at Sites 2 and 3. Following sampling, WSU will be responsible for handling the samples, laboratory analysis, and transmitting the post-burn residue dry weight data electronically to Air Sciences Inc.

Task 7: Sample Analyses. The Missoula Fire Sciences Laboratory will be responsible for Task 7. Following the burn, MFSL will analyze the filter and gas samples for the following constituents: PM_{10}, $PM_{2.5}$, CO, benzo(a)pyrene (BaP) [a PAH], and six additional BaP-equivalent carcinogens listed in WAC 173-460-050(4)(c), including benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, and indenol(1,2,3-cd)pyrene. PAHs need not be measured directly in the field; they will be determined from laboratory analysis of the filter samples. The $PM_{2.5}$ samples collected on glass-fiber filters for total mass and speciated PAH mass will be analyzed at DataChem Laboratories (DCL) at Salt Lake City, UT. The DCL facility in Salt Lake City is the National Institute for Occupational Safety and Health contract laboratory for analytical chemistry services. The Missoula Fire Sciences Laboratory will be responsible for all gas and filter sample analysis and for providing the data to Air Sciences Inc.

Task 8: Burn Characteristics. WSU and Air Sciences will share the responsibility of documenting the characteristics of each experimental burn. Burn characteristics will include: date and time of burning, type of fire and ignition pattern, air temperature, relative humidity, and mid-flame wind speed. Flame length, flame depth, flame angle, flame height, fire line depth, and rate of fire spread will be estimated and recorded on each burn if the conditions permit. In addition, each burn may be videotaped in order to more fully document the evolution and characteristics of each burn. Air Sciences and WSU will perform these tasks in conjunction with those listed under Task 6, Emissions Monitoring.

Task 9: Calculations, Data Analysis, and Interpretation. Air Science will compute the residue consumption, pollutant-specific emission factors, and total pollutant-specific emissions according to standard calculating procedures:

Equation 1. Pre- and Post-burn loading – Standard units conversion.

Equation 2. Residue Moisture Content – Calculated (Air Sciences Inc., 2002).

Equation 3. Bulk density, layer – Defined as dry weight (mass) per volume (Turgeon, 2002).

Equation 4. Bulk density, entire – Standard calculation by addition.

Equations 5 and 6. Residue consumption, absolute and relative – Calculated (Air Sciences Inc., 2002).

Equation 7. Emissions factors – Calculated (Ward et al., 1992b).

Equation 8. Emission factor for PAH – (Ward et al., 1992b).

Equations 9 and 10. Total $PM_{2.5}$ emissions – Standard calculation, units canceling.

Air Sciences will be responsible for interpretation of emissions data.

Task 10: Report. The results will be documented in a technical report (e.g., Air Sciences Inc., Experimental design: cereal grain crop open-field burning emissions study [draft], Project 152-01, Sect. 6.6, January 2000). WSU and Air Sciences Inc. will share the responsibility for completing this task. Air Sciences will provide technical assistance in developing the report (maximum of 32 hours). WSU will assume primary responsibility for oral reports and presentations to grower groups, environmental agencies, and other stakeholders as warranted and residual project funding permits.

Plot Layout in Test Fields: Plot size = 4 acres per treatment (experimental unit)

Full residue Load	Full residue Load	Full residue Load
Residue Reduced	Residue Reduced	Residue Reduced

Test Field Locations:

Connel, WA – irrigated field in Franklin County; cultivar 'Total Eclipse'

Rathdrum, ID – irrigated field (Rathdrum Prairie) Kootenai County; cultivar 'Alene'

Worley, ID – dryland field (Coeur d'Alene Tribe Reservation) in Kootenai County; cultivar 'Garfield'

6.7 DATA QUALITY OBJECTIVES

This project will collect field and laboratory data to determine the following parameters for each field type (dryland or irrigated) and residue treatment (full-load or baled) burned under the test conditions described earlier.

Pre-burn Residue Loading (dry mass) = tons/acre
Post-burn Residue Loading (dry mass) = tons/acre
Residue Moisture Content = percent moisture on dry weight basis
Residue Consumption = pre-burn minus post-burn residue loading (tons/acre)
Residue Thickness = inches
Combustion Efficiency = percent
PM_{10} emission factor = lb/ton residue consumed
$PM_{2.5}$ emission factor = lb/ton residue consumed
CO emission factor = lb/ton residue consumed
Emission factors for PAH's; benzo(a)pyrene , benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, and indenol(1,2,3-cd)pyrene = tons/acre

For this project, the emission measurements are collected with the intent to quantify the effect of residue management on open-field burning of KBG fields. The information obtained from this study will help establish appropriate burning practices needed to significantly reduce emissions, contribute to the scientific database on agricultural burning emissions, as well as provide data to direct future research.

For certain parameters, such as residue loading, the data is based on well-established techniques that have been used countless other agricultural studies. Because there has been little or no quantitative field measurements in past of emissions from Kentucky bluegrass seed fields or other grassy fuels, the emissions portion of this project is more research oriented which entails the use of trial and error techniques to establish proven methods for future studies. The emission measurement techniques were originally developed for forest fuel types and the equipment was modified for grassy fuels in this study. The modified technique was field tested for the cereal grain emission study conducted in the spring and fall of 2000 (Air Sciences Inc., 2003).

6.7.1 Data Quality Indicators

This project will rely on experienced field and laboratory personnel to collect data that will meet accepted data quality indicators. Data quality indicators are listed below.

- ***Precision*** - "Precision is a measure of agreement between two replicate measurements of the same property, under prescribed similar conditions. This agreement is calculated as either the range or as the standard deviation." (US EPA QA/G-5, Appendix D). This is the random component of error.

- ***Bias*** - "Bias is the systematic or persistent distortion of a measurement process that causes errors in one direction." (US EPA QA/G-5, Appendix D) Bias is determined by estimating the positive and negative deviation from the true value as a percentage of the true value.

- ***Comparability*** - "Comparability is the qualitative term that expresses the confidence that two data sets can contribute to a common analysis and interpolation. Comparability must be carefully evaluated to establish whether two data sets can be considered equivalent in regard

to the measurement of a specific variable or groups of variables." (US EPA QA/G-5, Appendix D).

- **Representativeness** - "Representativeness is a measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point or for a process condition or environmental condition. Representativeness is a qualitative term that should be evaluated to determine whether in situ or other measurements are made and physical samples collected in such a manner that the resulting data appropriately reflect the media and phenomenon measured or studied." (US EPA QA/G-5, Appendix D).

- ***Completeness*** – "Completeness is a metric quantifying the amount of valid data obtained from a measurement system compared to the amount that was expected to be obtained under correct, normal conditions. Completeness can be expressed as a ratio or a percentage." Data completeness requirements are included in the reference methods (40 CFR Part 50).

6.7.2 General Data Quality Objectives

All data shall be of a known and documented quality. The level of quality required for each specific monitoring project shall be established during the initial planning stages of the project and will depend upon the data's intended use. Two major measurements used to define quality are precision and bias. Refer to Section 6.7.1 for definitions of the metrics precision and bias.

All data shall be comparable. This means all data shall be produced in a similar and scientific manner. The use of the standard methodologies for sampling, calibration, audition, etc. found in the QAPP should achieve this goal.

All data shall be representative of the parameters being measured with respect to time, location, and the conditions from which the data are obtained. The use of the standard methodologies contained in the QAPP should ensure that the data generated are representative.

Ideally, a 95% confidence of both precision and bias should be maintained with a ±15% difference or better between the actual amount of an introduced parameter (to a measurement system) and the indicated response of the measurement system.

6.8 TRAINING REQUIREMENTS

No special training for the field staff or the laboratory staff was required prior to completion of this project. Because this project involved the cooperation of growers and the use of their fields for the test burns, the project managers and technical staff will discuss specific tasks and needs with the growers to best coordinate the research work with the farm operations. Field technicians were advised of fire safety concerns during the test burns to insure personnel safety and to protect equipment and property.

6.9 DOCUMENTS AND RECORDS

6.9.1 Notebooks

Each field and laboratory technician will be responsible for obtaining appropriate field notebooks. These notebooks will be uniquely numbered and associated with the individual and/or a specific program. The notebooks will be used to record information about the field sampling and laboratory operations, as well as document routine operations.

Field Notebooks - Notebooks will be used for each sampling site, specific program, or individual. Each notebook should be hardbound and paginated. Appropriate data entry forms may be used instead of notebooks; however, these forms are not required for routine operations, inspection and maintenance operations, or SOP activities as long as the information is contained in a notebook.

Lab Notebooks – An electronic database typically exists in which the laboratory retains all records pertaining to equipment calibrations and materials tracking, preparation, storage, and disposal, as well as general comments and notations and other pertinent information required for support of the analytical activities completed by the laboratory.

6.9.2 Electronic Data Collection

Certain instruments can provide an automated means for collecting information that would otherwise be recorded on data entry forms. In order to reduce the potential for data entry errors, automated systems will be utilized where appropriate and will record the same information that would be recorded on data entry forms. In order to provide a backup, a hard copy of automated data collection information will be stored for the appropriate time frame in project files.

6.10 DATA GENERATION AND ACQUISITION

The following sections describe the experimental design for this research project with major tasks organized together and a discussion of the quality control measures employed for each section where appropriate. The experimental design was used as the basis for grant work plans and contractual agreements to complete various tasks or subtasks.

6.10.1 Experimental Design

Task 1: Experimental Plan.
Washington State University (WSU) will prepare the proposal and a comprehensive experimental monitoring plan (Task list). Air Sciences Inc. will review the experimental plan (Air Sciences labor 4 hour).

Task 2: Unit Identification and Treatments.
Washington State University will identify three, 20- to 50-acre minimum (depending on size of burn units) study sites in eastern Washington (Site 1, Columbia Basin) and northern Idaho (Site 2, dryland site in north Idaho and Site 3, irrigated site in north Idaho) during late spring and early summer, 2001. Two alternative residue treatments will be evaluated at each site: no residue treatment ("full load"), and pre-burn baling ("reduced load"). Each treatment will consist of three separate 2- to 8-acre burn units (replications). A total of 18 burns will be conducted (3 sites, 2 residue loads, and 3 replications). WSU will select the burn units in consultation with Air Sciences Inc. (Air Sciences may, but will not be required to, make site visits for unit identification and can lend expertise via phone, email, etc.). WSU will be responsible for contacting the prospective host growers to obtain their consent.

Task 3: Unit Layout.
WSU will be responsible for Task 3. WSU will stake the corners of each burn unit with wooden stakes. A firebreak will be constructed around each burn unit of a type and size adequate to stop the forward progress of fire under the most extreme conditions that are likely to occur at each site. The host grower will be responsible for constructing and maintain the firebreak, for igniting the fire under the conditions prescribed by the principle investigators, and for providing fire suppression equipment and personnel during the burn in order to respond in the event of an escaped fire. The grower(s) will be responsible for any and all costs related to establishing the firebreak around each burn unit and any costs incurred in the event of an escaped fire.

Task 4: Pre-burn Residue Loading.
The pre-burn surface residue loading within each burn unit will be characterized. The residue loading will be determined by collecting all above ground residue at random locations within the burn units. Air Sciences will provide 3 cordless rechargeable grass clippers to aid in the pre-burn sampling. WSU will supply additional materials required to obtain pre-burn residue samples (Air Sciences and WSU will consult, via phone, etc., as to sampling technique and materials required). Following sampling, WSU will be responsible for handling the samples, laboratory analysis, and transmitting the pre-burn residue dry weight data electronically to Air Sciences Inc.

Surface residue loading will be taken at 4 random locations (subsamples) within each treatment at the Worley and Rathdrum sites and at 8 random locations at the Columbia Basin site.

- A 1-foot square constructed of PVC pipe will be used to determine the area to sample.
- Battery powered clippers will be used to cut vertically down through the residue around the perimeter of the PVC square and to cut the standing stubble as close to the ground as possible. Extra care will be taken to make sure that noncombustible material (i.e. soil, rocks,

etc.) will not be included in any sample. All residue within the one square foot area, which includes standing and loose straw, will be taken for surface residue loading.

- The clipped residue will be put into paper bags (labeled by site, treatment, replication and subsample), stapled shut, transported to WSU, dried in a forced air oven at 50°C for 5 to 7 days, and weighed to determine amount of pre-burn surface fuel. Samples will be weighed on a Mettler balance to two decimals. Any samples with outlying values will be examined to determine if they contain noncombustible material. If so, that material will be removed and the samples will be redried and reweighed. Residue will be expressed on a dry weight basis per unit area.
- Data will be emailed to Air Sciences Inc. in an Excel spreadsheet.

Pre-burn Fuel Load Architecture

- Stubble height will be measured with a ruler at 3 to 4 random locations (subsamples) within each burn unit.
- In the full residue treatment where residue layering is anticipated, the residue will be partitioned and measured to top of residue, thickness of residue, and soil surface to bottom of the residue layer. This will be done by carefully exposing a profile of the residue (cross-section) prior to measurement.
- Thickness of the residue layer is determined by subtraction.

Task 5: Pre-burn Moisture Sampling.

Immediately prior to the burn, the moisture content of the grass residue and the upper layer of soil will be characterized. Following sampling, WSUwill be responsible for handling the samples, laboratory analysis, and transmitting the pre-burn residue moisture and soil moisture data electronically to Air Sciences Inc. If possible, these tasks will be performed in conjunction with those listed under Task 4, Pre-burn Residue Loading.

Residue Samples:

- Pre-burn residue moisture will be taken at 4 random locations (sub-samples), each one square foot in area, within each treatment (burn unit) at each of the three sites.
- Residue from the full residue load burn units will be divided and bagged separately into upper (loose grass straw) and lower (standing grass stubble) samples. Sample procedures will be the same as mentioned in Task 4.
- Residue will be put into pre-dried, pre-weighed, and pre-numbered 'Ziploc' plastic bags immediately after being sampled.
- The samples will be kept in an ice chest, transported to WSU, weighed to determine fresh weight, dried at 50°C for 5 to 7 days, and weighed. Residue moisture will be determined by subtracting dry weight from fresh weight divided by dry weight. Residue will be expressed on a dry weight basis.
- Data will be emailed to Air Sciences Inc. in an Excel spreadsheet.

Soil Samples:

- A soil probe will be used to take several soil samples 4 inches deep for a composite pre-burn soil moisture sample at each of 4 random locations in each of the treatments (burn units) at the Columbia Basin and the Worley sites. Soil moisture samples from the Rathdrum site will be taken using a shovel because the soil is very rocky.
- Each composite soil sample will be placed in a pre-numbered plastic 'Ziploc' bag, transported to WSU, in the laboratory approximately 100 g of soil will be transferred from the 'Ziploc' bag to a pre-weighed soil moisture drying can, weighed for fresh weight, dried at 105°C for 24 hours, and weighed.

- Soil moisture will be determined by subtracting dry weight from fresh weight divided by dry weight. Soil moisture will be expressed on a dry weight basis.
- Pre-burn soil moisture data will be emailed to Air Sciences Inc. in an Excel spreadsheet.

Task 6a: Emissions Monitoring.

Missoula Fire Science Laboratory will perform the emissions monitoring using the Missoula Fire Science Laboratory's Fire-Atmosphere Sampling System (FASS). FASS is a tower-based system that measures real-time emissions (Susott et al., 1991b; Ward et al., 1992a). The computer control system, battery, pumps and flow meter, manifolds, particulate matter filters (Teflon and glass), real time analyzers, and the three-part gas collection system (one part for each phase of the burn, i.e., flaming, transitional, and smoldering) are buried near the instrumentation towers. Two guyed instrument towers (two sub-samples per plot) holding the FASS equipment will be erected on each plot.

Air Sciences will provide a portable meteorological station for use in monitoring and recording the meteorological events during each of the burns at each of the sites.

Task 6 also includes post-burn residue sampling of each of the 18 burn units. WSU and ASI will jointly conduct the post-burn residue sampling at Site 1. WSU will perform the post-burn residue sampling at Sites 2 and 3. Following sampling, WSU will be responsible for handling the samples, laboratory analysis, and transmitting the post-burn residue dry weight data electronically to Air Sciences Inc.

Task 6b. Post-burn Residue Samples

- Post-burn residue will be taken at 4 random locations within each of the burn units. Sampling procedures will be the same as mentioned in Task 4.
- A technician will collect the ash plus all bluegrass residue not combusted in the fire within the square foot area for the post-burn residue sample. Extra care will be taken to make sure that noncombustible materials (i.e., soil, rocks, etc.) will not be included in any sample.
- Residue will be put into pre-labeled paper bags, stapled shut, transported to WSU, dried in a forced air oven at 50^{o}C for 5 to 7 days, and weighed to determine post-burn residue remaining. Residue will be expressed on a dry weight basis per unit area.
- Post-burn residue data will be emailed to Air Sciences Inc. in an Excel spreadsheet.

Task 7: Sample Analyses.

The Missoula Fire Sciences Laboratory will be responsible for Task 7. Following the burn, analyze the filter and gas samples for the following constituents: PM_{10}, $PM_{2.5}$, CO, benzo(a)pyrene (BaP) [a PAH], and six additional BaP-equivalent carcinogens listed in WAC 173-460-050(4)(c), including benzo(a)anthracene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, and indenol(1,2,3-cd)pyrene. PAHs need not be measured directly in the field; they will be determined from laboratory analysis of the filter samples. The $PM_{2.5}$ samples collected on glass-fiber filters for total mass and speciated PAH mass will be analyzed at DataChem Laboratories (DCL) at Salt Lake City, UT. The DCL facility in Salt Lake City is the National Institute for Occupational Safety and Health contract laboratory for analytical chemistry services. The Missoula Fire Sciences Laboratory will be responsible for all gas and filter sample analysis and for providing the data to Air Sciences Inc.

Task 8: Burn Characteristics.

WSU and Air Sciences Inc. will share the responsibility of documenting the characteristics of each experimental burn. Burn characteristics will include: date and time of burning, type of fire and

ignition pattern, air temperature, relative humidity, and mid-flame wind speed. Flame length, flame depth, flame angle, flame height, fire line depth, and rate of fire spread will be estimated and recorded on each burn if the conditions permit. In addition, each burn may be videotaped in order to more fully document the evolution and characteristics of each burn. Videotaping may be omitted if deemed not warranted by WSU. If burns are videotaped, WSU will provided needed equipment. Air Sciences Inc. will be responsible for documenting the burn characteristics listed herein for Sites 1 and 2. WSU will be responsible for documenting the burn characteristics at Site 3. Air Sciences and WSU will perform these tasks in conjunction with those listed under Task 6, Emissions Monitoring.

Task 9: Calculations, Data Analysis, and Interpretation.
Air Science will compute the residue consumption, pollutant-specific emission factors, and total pollutant-specific emissions according to standard calculating procedures **:**

Equation 1. Pre- and Post-burn loading – Standard units conversion.

Equation 2. Residue Moisture Content – Calculated (Air Sciences Inc., 2002).

Equation 3. Bulk density, layer – Defined as dry weight (mass) per volume (Turgeon, 2002).

Equation 4. Bulk density, entire – Standard calculation by addition.

Equations 5 and 6. Residue consumption, absolute and relative – Calculated (Air Sciences Inc., 2002).

Equation 7. Emissions factors – Calculated (Ward et al., 1992b).

Equation 8. Emission factor for PAH – (Ward et al., 1992b).

Equations 9 and 10. Total $PM_{2.5}$ emissions – Standard calculation, units canceling.

Air Sciences will be responsible for interpretation of emissions data. Air Sciences will not exceed 100 labor hours on this task, nor will Air Sciences be responsible for costs related to shipping or sharing of data.

Task 10: Report.
The results will be documented in a technical report (e.g., Air Sciences Inc., Experimental design: cereal grain crop open-field burning emissions study [draft], Project 152-01, Sect. 6.6, January 2000.

6.10.2 Description of Quality Control Measures Implemented

This section provides a brief description of the quality control (QC) measures that were taken by Air Sciences Inc. (ASI), Washington State University (WSU), and Intermountain Fire Sciences Laboratory at Missoula, MT (MFSL) 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, measurements and description of residue architecture, weather conditions at time of burning, recording of moisture fresh weights, data handling including chain of custody, screening criteria used by MFSL 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.

Task 2 Site and Burn Unit Selection

All the study fields and units within the fields were selected based on the uniformity of pre-burn residue loading, site physiographic conditions, and the availability of grower cooperators (cooperators were required to provide personnel and equipment, e.g., swathers, baling equipment, ignition equipment, water trucks, etc.). All cooperators had been growing Kentucky bluegrass for seed for many years (10+ years). Fields with uniform site conditions (irrigated sites at Connell [Circle P Farms, T14 R31 E1/2, Sect. 22, NW1/4; cultivar 'Total Eclipse'] and Rathdrum Prairie SW of the intersection of Meyer and Lancaster Roads; cultivar 'Alene') or typical of dryland Kentucky bluegrass dryland production fields (Worley [Coeur d'Alene Tribe land at the west end and the north side of Jess Wright Road, cultivar 'Garfield']) were chosen by WSU personnel. Later, WSU selected the locations of individual 4-acre burn units within the fields. The location of individual burn units was as close together as possible to ensure similar site conditions within all three replications of a treatment.

Task 4a Pre-burn Residue Load

Pre- and post-burn residue loading was sampled in order to accurately assess the total residue consumption following each test burn. To determine pre-burn residue load, within each 4-acre burn unit, 8 to 12 (12 at Connell, and 8 at Worley and Rathdrum Prairie) sampling locations were randomly chosen. At each sampling location, the residue within a 0.09-m^2 constructed of 1-inch PVC pipe was clipped to the soil surface with electronic clippers. Considerable care was taken to keep soil aggregates and/or rocks out of the sample bags. Two of the WSU personnel taking samples have been utilizing this methodology for approximately 10 years and are quite skilled in the technique (Johnston and Golob, 1992).

Paper sample bags were clearly labeled with the field and unit name, date, treatment description, and type of sample (e.g., pre-burn residue), folded, and sealed using staples. All the residue sample bags from each field were assembled in cloth bags, labeled with the field name, and transported by WSU personnel to Pullman, WA. There the samples were dried (5 days at 140^{o}F) and weighed to determine oven-dried weight (1/100th gram resolution). A tare weight for the paper bags was obtained by averaging the oven-dry weights of four paper bags identical to those used for sampling. The oven-dried bag tare weight was subtracted from the total dry weight (residue sample + bag) to obtain the Kentucky bluegrass residue dry weight.

Task 4b Pre-burn Fuel Load Architecture

The fuel load architecture of the pre-burn residue was determined by WSU personnel for all sites. At the Connell site, 18 measurements (3 per burn unit) of stubble height were taken at random.

Standing stubble height was measured with a ruler from the soil surface to the estimated mean stubble height. Due to the short swathing height, to maximize hay yield by the grower, there was no suspended residue in any of the low residue load burn units following raking and baling. Residue had filtered through the standing stubble to the soil surface. At the Worley and Rathdrum Prairie sites, one replication of a low residue load burn unit was chosen at random in which stubble height was measured at four randomly chosen locations. In addition, due to topographic variability in the burn unit at Worley, stubble height was measured in two locations, i.e., slope and draw. Within one randomly chosen high residue load burn unit at each of the Worley and Rathdrum sitess additional characterization of the residue load architecture was determined. At 4 randomly selected locations within the high residue load burn unit the height from the soil surface to the top of the residue and the height from the soil surface to the bottom of the suspended residue was measured. Thickness of the top (suspended) residue layer was then determined by subtraction.

Task 5a Pre-burn Residue Moisture

Residue moisture was sampled at four randomly selected locations in a burn unit by WSU personnel. Oven-dried weight of each sample bag (plastic 'Ziploc' bags) was determined for tare weight prior to collection, weighed to 1/100th gram resolution. All moisture samples were collected within a 30-minute period immediately preceding the ignition time. Four samples at randomly selected locations within each burn unit were taken. Each sample was taken from 1 square foot (0.09-m^2) area using the same sampling techniques as described for pre-burn residue and immediately sealed and place on ice in a cooler. All sample bags were clearly labeled as discussed above. Samples were transported to WSU in Pullman, where they were weighed for fresh weight, the 'Ziploc' bags were then opened and a 2-inch-long section of 3-inch diameter pipe was inserted in the bags to keep them open while drying. Samples were dried (5 days at 140^{o}F), and weighed to determine oven-dried weight (1/100th g resolution). WSU calculated percent moisture on a dry weight basis following the procedure outlined by Anderson and Grant (1993). Data were transmitted electronically to ASI ASI calculated percent moisture on a dry weight basis to determine pre-burn residue moisture of each sample. In addition, residue dry weight from each of the residue moisture samples was incorporate to determine average residue load for that burn unit.

Task 5b Pre-burn Soil Moisture

Soil moisture was sampled at 4 randomly selected locations within each burn unit prior to ignition by WSU personnel. At each location, six to seven 2-inch deep soil samples were taken with a soil probe (except at the Rathdrum Prairie site where a shovel was used due to the gravelly soil at that site), placed in plastic 'Ziploc' bags, and sealed. The samples were immediately placed on ice in an ice chest and transported to Pullman, WA. Prior to analysis all samples were thoroughly mixed with an approximate 100 g sub-sample removed and placed in pre-weighed metal soil moisture cans and weighed to determine wet weight of sample. Soil samples were dried at 105^{o}C for 24 hours and weighed. Percent soil moisture was determined by subtracting the oven dried weight from the wet weight divided by the oven dry weight.

Task 6a Ignition of Test Plots

At all sites, burns were done on days and under environmental conditions that burning was permitted (Washington DOE for the Connell site and Idaho DEQ for the Worley and Rathdrum sites). All burns, at all sites, were ignited between late morning and early afternoon and ignited

upwind (open-field head fires or strip head fires) from the MFSL's Fire Atmospheric Sampling System (FASS) apparatus. There were two FASS sampling towers per burn unit. Ignition techniques were essentially those used as current practices by growers. Growers utilized their own equipment at the Worley and Rathdrum sites to perform ignition of the burn units. At the Worley site, each burn unit was ignited using a propane torch and a 4-wheel ATV. At the Rathdrum site, ignition was performed by lighting the edge of a burn unit using a propane torch from the cab of a pick-up truck. At the Connell site, ignition of the burn units was performed by WSU personnel. In the high residue load units, residue was ignited with a small propane torch and three people moving ignited residue with pitchforks rapidly moved the fire along the burn front. Two low residue load burn units were ignited with an 18-foot propane burner (12-foot burn in one replication as one 6-foot section of the burner malfunctioned) making multiple passes across the burn unit upwind (strip head fires) from the FASS towers. An attempt to burn one low residue load burn unit as an open-field head fire failed and was deleted from the study.

Task 6b Emissions Collection

MFSL collected emissions samples using two FASS towers per burn unit utilizing procedures outlined by ASI (2003) for the Cereal-Grain Residue Open-Field Burning Emissions Study conducted in eastern Washington during April and October 2000.

Task 6c Meteorology

Variations in weather conditions were minimized between burns by burning between treatments as soon as possible on a given day and burning on consecutive days (2-day period at Worley and Rathdrum Prairie, 3-day period at Connell). Meteorological parameters, i.e., wind speed and direction, temperature, and relative humidity were monitored with a 2-meter meteorological tower by ASI before, during, and after each burn.

Task 6d Post-burn Residue Load

The post-burn sampling was conducted immediately following each burn (within 10 minutes following the end of the set sampling time of the FASS towers) by WSU and ASI personnel. Post-burn residue was collected using the same technique as described for pre-burn residue sampling. Care was taken to avoid possible disturbance of the post-burn sample area. In the few incidences, where it appeared that wind could disturb the burned residue, the post-burn sample area was shielded during sample collection. Samples were take at 4 randomly selected locations within each burn unit.

Task 7 Emissions Analysis

The MFSL and their subcontractor, Southwest Research Institute, 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. MFSL provided the following description of methodology.

<u>Canister Analysis:</u>

Canister samples were analyzed by gas chromatography (Hewlett Packard model 5890 Series II) for CO_2, CO, CH_4, and hydrocarbons. The canisters were pressurized with sample to

approximately 20 pounds per square inch absolute (pisa). Two columns and chromatography systems are used, one for CO_2 and CO, and another for CH_4, and C_2 and C_3 gases.

The CO_2 and CO analysis setup has a 1-ml sample loop that is filled directly from the canister. The column for this analysis is a 1/8 in x 6 ft. Carbosphere (Alltech) carbon molecular sieve, with He carrier gas, 16 ml/min., subsequently passing through a methanizer, and FID at 300°C. CO and CO_2 are analyzed for in separate isothermal runs, CO at 30°C, and CO_2 at 100°C.

CH_4, C_2, and C_3 analysis is performed with a 0.53 mm x 35 m GS-Q (J&W Scientific) megabore column with a 0.53 mm x 6ft HP-1 pre-column. The sample is directly injected from the canister into a 0.25-ml sample loop. The carrier gas is He, 4 ml/min., with an FID at 200°C, and He makeup gas. The temperature program is 30°C for 6 min, then increasing at 10°C/min to a final temperature of 90°C.

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

Filter Analysis:

Teflon filters for $PM_{2.5}$ determination were conditioned and weighed in controlled environment room at 68°F, and 50% RH. Prior to weighing the filters are conditioned for at least 24 hours to stabilize the particulate weight and reduce the effects of static electricity on the weighing process. The filters are weighed three times on a Mettler M4 microbalance to 1 microgram precision. The balance is linked to a software program that collects the weight and room condition data. Filters whose weight is not reproducible to within 5 micrograms are kept for further analysis and not used if this reproducibility is not reached. Before each sample was weighed the balance tare was zeroed. A control calibration weight is weighed every five filter weights to verify balance accuracy and calibration. Each filter is pre-weighed prior to sample collection using this procedure, and then again after particulate collection. Control filters follow the same protocol and are used to correct for environmental and handling variability on filter weight.

The $PM_{2.5}$ concentration is calculated by the software based on the final particulate weight (post-weight minus pre-weight) and the volume of air that was collected through the filter during emission sampling.

Data were screened for internal consistency (ASI personal communication with MFSL, R. Susott). The consistency checks including the following procedures. First, FASS data and canister data for CO_2 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. 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 (ASI personal communication with MFSL, 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 residue 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 (ASI personal communication with MFSL, R. Susott).

Task 9 Data Analysis and Statistics

A complete set of data on residue loading and residue moisture content was provided to ASI by WSU. ASI processed the meteorological data. The MFSL provided ASI with the screened atmospheric concentration data, and the calculated emission factors of all atmospheric species in MS Excel. Data for all the units were summarized at the sub-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 that were then eliminated from the data set. Summaries by unit for both the complete and the screened database are summarized in Appendix 2. PAH emission factor calculations were checked by both the MFSL (Steve Baker) and Air Sciences (Maarten Schreuder), to ensure that both the input data and the calculations were correct.

ASI performed statistical analyses 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.

6.11 ASSESSMENTS AND OVERSIGHT

6.11.1 Assessments

An assessment is the process used to measure the performance or effectiveness of the quality system for the project. Due to limited scope and duration of this research project, assessments were conducted internally utilizing replicate sampling of the field data. For this research project, the data analysis process, including all the statistical computations, that will become part of the final report provide for the assessment of the quality assurance components. The final report will identify the field variables that significantly influence the computation of the different emissions evaluated in this project and from that, identify the field parameters and data collection techniques that critical to completing high quality, reliable research. Because this is a research-based project, standard methodologies are still evolving. At the completion of this Kentucky bluegrass emission study, researchers will have completed two recent studies on evaluating combustion emissions from burning agricultural fields utilizing similar sampling techniques.

6.11.2 Oversight

The research group organized for this project completed this work fairly independent of any external oversight. The collaborative nature of this project, as described in Section 4, identifies an informal network of individuals and organizations that followed this project closely. Annual progress reports were prepared and presented to the Grass Seed Cropping System for Sustainable Agriculture (GSCSSA) organization. The annual reports are reviewed by the GSCSSA's Industry Advisory Committee and Technical Advisory Committee. The committees make recommendations to the Agricultural Experiment Station Directors for Washington, Oregon, and Idaho. These directors have the ability to allocate USDA research funds in the tri-state region. This project was the recipient of a USDA research grant through the GSCSSA process.

6.12 DATA VALIDATION AND USABILITY

Data validation was performed by the various research cooperators for each of the data parameters identified in Section 7. For example, in Section 10.2, the filter analysis section describes how the Missoula Fire Science Lab and Air Science staff reviewed the PM2.5 mass derived from the filter analysis process and compared that data to the carbon monoxide concentrations. Discrepancies lead to a further review of the field sampling data and laboratory data. If large discrepancies could not be resolved, the data were removed from the data set. Outliers were identified in other data sets such as residue loading and then were examined for possible sources of error. Emission factors were compared to literature values and against results obtained from recent emission studies on cereal grain burning.

The database used for statistical analysis was carefully checked against the original data sets to verify the accuracy of the data. The research team independently checked each other's data sets for completeness and accuracy. The project coordinators, especially those that provided funding to the project, will review the draft reports and datasets to verify completeness and conformance with contractual obligations.

Eventually, the final results and report may go through the peer review process prior to publishing in a relevant professional journal. This last step would ensure the usability of the results drawn from this research project.