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Particulate emissions from wheat and Kentucky bluegrass stubble burning in eastern Washington and northern Idaho

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Abstract

The $PM_{2.5}$ emission factors (EF) in smoke from post-harvest wheat and Kentucky bluegrass (KBG) stubble burning were quantified in the United States Environmental Protection Agency test burn facility. The $PM_{2.5}$ EFs from high and low combustion efficiency (CE) wheat burns were 0.8 ± 0.4 and $4.7 \pm 0.4\,g\,kg^{-1}$, respectively, and decreased with increasing CE. While these EFs are generally in agreement with literature, it is difficult to compare the $PM_{2.5}$ EFs from KBG burns ($12.1 \pm 1.4\,g\,kg^{-1}$) due to the scarcity of published data. Wheat burns conducted with randomly piled stubble resulted in $PM_{2.5}$ EFs different to those where the stubble was oriented as found in the field post harvest. Two separate methods for estimating EFs were employed and found to be in good agreement. The carbon in the biomass was almost quantitatively accounted for by measuring CO_2, CO, total hydrocarbons (THC) and $PM_{2.5}$ emissions. The $PM_{2.5}$/CO emission ratios for wheat (0.05 ± 0.01) agree with literature data, while the same ratio for KBG (0.23 ± 0.02) was slightly higher than data reported. These ratios exhibit low dependence on CE and can be used to predict the level of one pollutant in a plume, when the concentration of the other is known. Wheat and KBG fields in 18 counties of eastern Washington and northern Idaho are burned on less than a tenth of the days of the year. Yet the fires were estimated to have produced between 0.04% and 34.5% of the total $PM_{2.5}$ and CO emissions within the respective counties, during 2002.
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1. Introduction

Southeastern Washington (WA) and north central Idaho (ID) are among the most productive wheat growing regions in the world (Scheinost et al., 2001). In addition 65% of the Kentucky bluegrass (*Poa pratensis* L., KBG) produced in the USA was also produced in this region (Mazzola et al., 1997). KBG is still produced in northern ID and on a smaller scale in eastern WA. Post-harvest field burning is commonly practiced for clearing agricultural residues. Growers resort to burning rather than its alternatives (baling, composting, land filling, crop rotation, compression into briquettes and use as a raw material in processes such as chipboard manufacture) for the purposes of pest

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and disease control, increased yield, tillage reduction (lower potential for soil erosion), reduction of agrochemical usage, convenience and cost effectiveness (US EPA, 2001a, b; ASI, 2003; WA DOE, 2003; Roberts and Corkill, 1998; Johnston et al., 1996).

Pollutants emitted from agricultural fires include, among others, CO_2, CO, hydrocarbons, and particulate matter nominally smaller than 2.5 μm in aerodynamic diameter ($PM_{2.5}$). $PM_{2.5}$ is a known trigger of respiratory health complications (Roberts and Corkill, 1998; Mar et al., 2004a, b; Slaughter et al., 2003). Knowledge of emission factors (EF)—defined as the mass of pollutants emitted per unit mass of dry stubble burned—is needed as input to dispersion models that serve as management tools. EFs are also needed in emission inventories and to evaluate the effectiveness of pollution control strategies.

EFs are influenced by factors that affect the combustion efficiency (CE) of the fire (Ward et al., 1992; Ward and Hardy, 1991). These include the amount of available oxygen, combustion temperature, stubble moisture content, residence time of ventilation air, prevalent meteorological conditions, rate of flame spread, fire management techniques and turbulence. EFs are also affected by the stubble characteristics including fuel type and chemical makeup, residue mass per unit area (loading), stubble orientation and extent of compaction in the field (Ward et al., 1992; Radke et al., 1988; ASI, 2003; Darley et al., 1974).

Few studies list EFs of pollutants from KBG stubble burning (Boubel et al., 1969; ASI, 2004). Region specific EFs for wheat are scarce (ASI, 2003). The United States Environmental Protection Agency (US EPA) AP-42 (US EPA, 1995) provides EFs of total suspended particulate matter, CO and hydrocarbons from burning wheat and grasses. Both wheat and grass EFs are based on a single study (Darley et al., 1974; Boubel et al., 1969, respectively) in which stubble orientation in the field has not been reconstructed during laboratory experiments. The Darley et al. study evaluates EFs according to the EF (carbon) method (see section on alternative method for calculation of EFs), but neglects the contribution of CO, total hydrocarbons (THC) and $PM_{2.5}$ to the carbon mass balance (~10% error). The Boubel et al. study involves only 4 KBG burns at 5% and 23% stubble moisture. The data therein show a decrease in particulate, CO and hydrocarbon EFs with increasing fuel moisture, whereas the opposite trend is expected (ASI, 2003; Carroll et al., 1977; Darley et al., 1974).

The objectives of the research reported here are to quantify $PM_{2.5}$ emission factors from the combustion of wheat and KBG stubble collected in eastern WA and northern ID, and validate one of the methods used to calculate EFs (see section on Alternative method for calculation of EFs). Since field experiments are not easily conducted or replicated, we simulated the field burns with laboratory-scale, controlled burn experiments. Field scenarios were mimicked during the laboratory burns, by reproducing the field orientation and loading of the stubble.

2. Materials and methods

The wheat stubble tested was irrigated winter wheat straw (*Triticum aestivum* L., variety Madsen). The stubble moisture content in wheat and KBG was measured immediately after obtaining the stubble from the field (see Table 1), and had not changed by more than 2% by the time burns were conducted.

Burn experiments were conducted at the US EPA open burn test chamber in Research Triangle Park, NC, in May 2001, August 2001 and August 2003. The burn chamber is described in detail by Lemieux

Table 1
Summary of experiments conducted and samples collected

Parameter measured	Wheat stubble		Grass
	May 2001	August 2001	August 2003
% H_2O at burn time (w/w wet basis)	8.9	8.8	9.0
No. of burns/valid $PM_{2.5}$ samples on teflon filters/ dataRAM $PM_{2.5}$	30/28/27	31/31/23	30/85/30
Valid O_2, CO_2, CO and THC data, temperature and stubble mass	THC for 25 burns, rest 30	Data for 31 burns	Data for 30 burns

et al. (2000). Between August 2001 and August 2003, the chamber was re-built in another location, though the same air supply fans and ducts were used in the new chamber. The internal volumes of both chambers were approximately 20 m^3. The chambers were operated in a flow-through manner and assumed to be well mixed.

In the middle of the burn chamber was a weighing platform, on which 725–800 g stubble was mounted to correspond to the orientation and loading in the field post harvest. Stubble was ignited manually with a propane torch and the chamber door was closed immediately. The flaming phase typically lasted 1–2 min, followed by about 15 min of smoldering. As the instantaneous O_2 concentrations were always $\geqslant 18.5\%$ (v/v), the O_2 supply was deemed sufficient for combustion. The ash remaining accounted for $3.6 \pm 0.1\%$ ($n = 91$) of the mass of dry stubble exposed to the fire.

Five burns involving randomly piled wheat stubble were conducted in May 2001, to assess the effect of stubble orientation on EFs. A lower volumetric flowrate of chamber air was employed in August 2001, which raised the incremental chamber temperatures (ΔT: average temperature during sampling period minus pre-burn chamber temperature) due to lowered dilution rates. CEs and stubble consumption rates were also lower during August 2001, compared to May 2001.

2.1. Sampling and analysis

$PM_{2.5}$ mass measurements were made with the use of integrated low-volume (lo-vol) (5 L min^{-1}) air samplers (Airmetrics Inc.), fitted with a $PM_{2.5}$ size selective inlet. Teflon filters were loaded on to lo-vol samplers for capturing particles for later gravimetric analysis. Quartz filters were used in some lo-vol samplers for total carbon (TC) analyses (not reported in detail here). Prior to and after sampling, Teflon filters were equilibrated in a controlled chamber (RH 45–55%, T 22–26 °C) for 24 h and weighed with a Cahn C-34 microbalance (Cahn Instruments, CA, USA). The reproducibility of replicate $PM_{2.5}$ measurements was 3.9% (based on $n = 39$ during August 2003 experiments).

Continuous $PM_{2.5}$ monitoring was conducted using a DataRAM 2000 (MIE, Inc.) nephelometer, which was calibrated against the lo-vol samplers. Gaseous pollutants measured continuously included CO [Horiba VIA 510, dual beam Non-Dispersive Infra Red (NDIR)], CO_2 (Rosemount 880A, NDIR), O_2 (Rosemount 755, paramagnetic susceptibility) and THC (TECO THC 51, Flame Ionization Detector. These detectors respond poorly to oxygenated non-methane hydrocarbons, but this uncertainty affects the calculations by $<5\%$). The continuous gas analyzers were operated in accordance with the procedures outlined in 40 CFR Part 60, Appendix A, Method 6C. Pollutant samplers were placed close to the stack exit. Stubble mass loss and chamber temperature were also monitored continuously. Sampling was carried out for about 20 min, from the time of ignition.

Burn-specific background concentrations of CO_2, CO, THC and $PM_{2.5}$ (i.e. pre-ignition concentrations recorded by the continuous monitors) were assumed to remain constant over the sampling period. Pertinent experimental details are summarized in Table 1.

2.2. Calculation of emission factors

If a steady-state flow-through chamber is well mixed, uniform conditions and concentrations are expected throughout the chamber and will equal those in the exit stream (Cooper and Alley, 1994). The EFs were thus determined as follows:

$$\mathrm{EF}_x\ (\mathrm{g\ kg^{-1}}) = (\Delta C_x \times Q_{\mathrm{chamber}} \times t_{\mathrm{run}}) / (1000\ \mathrm{mg\ g^{-1}} \times m_{\mathrm{burned}}), \quad (1)$$

where EF_x is the emission factor in g of pollutant $X\,\mathrm{kg^{-1}}$ dry stubble burned, ΔC_x the exit concentration of pollutant X in excess of the background, $\mathrm{mg\,m^{-3}}$, Q_{chamber} the flow rate of dilution air into the burn chamber, $\mathrm{m^3\,min^{-1}}$, t_{run} the sampling time, min, and m_{burned} the mass of dry stubble consumed during the burn, kg.

This method of calculating EFs is referred to as EF (direct) henceforth.

The degree of mixing in the chamber was assessed to justify the application of the well-mixed flow through model. Additional $PM_{2.5}$ samples obtained in an opposite corner of the chamber during the KBG burns, differed from the main sample by an average of 4.1% ($n = 11$), although the difference is not significant ($t_{0.05,10} = 1.19$, $P = 0.26$ for a paired t test). Neither is this difference significantly affected by the chamber air flowrate ($t_{0.05,4} = 0.71$, $P = 0.52$).

Further, four thermocouples were placed around the chamber to assess if temperature was uniformly distributed. Two factor ANOVA was performed

with a SAS program (SAS Institute Inc., Cary, NC, USA) and it was found that the temperatures did not vary significantly from one area of the chamber to another ($F_{3,115} = 0.33$, $P = 0.806$). Neither did the air flowrate into the chamber have a significant effect on the temperature distribution throughout the chamber ($F_{1,115} = 1.85$, $P = 0.176$). It was concluded that conditions throughout the chamber were uniform, and that the well-mixed flow through model reasonably described the burn chamber.

2.3. Measurement of chamber air flowrate

The flowrate of chamber air (Q_{chamber}) was initially measured by multiplying the linear velocity of air in the air supply duct to the chamber, by the duct cross sectional area. Velocity measurements were made upstream of the air supply fan using a pitot tube. However, since air leaks at the flanges of the fan were observed, a pair of SF_6 tracer experiments was conducted in July 2004 to better evaluate Q_{chamber}. Chamber air flowrates used during each of the previous campaigns were re-created by adjusting the fan speed, so as to obtain the previous linear velocities of air through the duct. SF_6 was introduced into the duct, downstream of the fan and the air leaks at the flanges were assumed to remain at a constant fraction of the flow for all experiments. No air leaks were present downstream of the SF_6 release point.

At each fan speed setting, grab samples of air were drawn into 30 mL plastic syringes, at the chamber exit stack. Samples were analyzed for SF_6 on a gas chromatograph fitted with an electron capture detector (GC-ECD). SF_6 losses during transport and handling were negligible.

Chamber air flowrates were calculated to be $9.6\,\text{m}^3\,\text{min}^{-1}$ (May 2001 and first 11 burns of August 2003) and $14.0\,\text{m}^3\,\text{min}^{-1}$ for the last 19 burns of August 2003. For August 2001, Q_{chamber} was estimated to be $7.2\,\text{m}^3\,\text{min}^{-1}$, based on pitot tube data and the average leak rates determined from the SF_6 experiments. The relative standard deviation (RSD) of calculated flow rates did not exceed 2% but an error of 15% (twice the largest RSD of the pitot tube measurements) is assigned to the value of Q_{chamber} to account for uncertainties with the estimation of leaks during the past burn experiments.

The tracer experiment was also used to determine if the exhaust from the chamber could be recirculated through the air intake, thereby biasing the background signal. During the burns, integrated SF_6 samples were drawn at the chamber air intake. Since SF_6 concentrations in these samples were below detection limits, it was concluded that no pollutants were recirculated.

2.4. Combustion efficiency

The CE is defined as the fraction of the total carbon released in the form of CO_2 during combustion. The total carbon (C) released is calculated by the sum of the C concentrations in CO_2, CO, THC and $PM_{2.5}$ (Turn et al., 1997; Ward et al., 1992).

$$\text{CE, \%} = \frac{\Delta CO_2 - C}{(\Delta CO_2 - C) + (\Delta CO - C) + (\Delta THC - C) + (\Delta PM_{2.5} - C)} \times 100, \tag{2}$$

where $\Delta CO_2 - C$ ($\text{mg}\,\text{m}^{-3}$) is the [mass fraction of C (w/w) in CO_2 (i.e. 12/44)] × [background−corrected average CO_2 concentration in burn chamber ($\text{mg}\,\text{m}^{-3}$)], $\Delta CO-C$ ($\text{mg}\,\text{m}^{-3}$) the 12/28 × [background−corrected CO concentration ($\text{mg}\,\text{m}^{-3}$)], $\Delta THC-C$ ($\text{mg}\,\text{m}^{-3}$) the [background−corrected THC concentration ($\text{mg}\,\text{m}^{-3}$)]. CH_4 was used as the calibrant and the analyzer reports ppm C. [However THC EFs were calculated assuming the average composition of C_3H_8 (Nelson, 1982)].

$\Delta PM_{2.5} - C$ ($\text{mg}\,\text{m}^{-3}$) = C content of $PM_{2.5}$ × [background−corrected $PM_{2.5}$ concentration ($\text{mg}\,\text{m}^{-3}$)]. TC analyses, when corrected for adsorption artifacts (Turpin et al., 1994), show that the C content of $PM_{2.5}$ is 62.5% for wheat and 63% for KBG. This is similar to results reported by Crutzen and Andreae (1990) (66%), Ward et al. (1992) (62.5%) and Cachier et al. (1995) (73%), although it is unclear whether those authors accounted for the above-mentioned artifact.

2.5. Alternative method for calculation of EFs

This method, hereafter referred to as EF (carbon), is based on the conservation of C in the biomass, and does not require pre- and post-burn weighing of biomass (ASI, 2003; Andreae and Merlet, 2001). The EF (carbon) method is used for

evaluating EFs during field experiments (Hurst et al., 1994; Ward et al., 1992; ASI, 2003; Andreae and Merlet, 2001) and is used here for validation purposes and comparing against the EF (direct) method.

$$\mathrm{EF}_x\,(\mathrm{g\,kg^{-1}}) = \frac{\Delta C_x \times (1000\ \mathrm{g\,kg^{-1}}) \times \mathrm{C_{fraction}}}{(\Delta \mathrm{CO_2-C} + \Delta \mathrm{CO-C} + \Delta \mathrm{THC-C} + \Delta \mathrm{PM_{2.5}-C})}, \tag{3}$$

where $\mathrm{C_{fraction}}$ is the mass fraction of C in dry stubble. In May and August 2001 the $\mathrm{C_{fraction}}$ of wheat was 0.434 and 0.442, respectively (calculated from data in Gullett and Touati, 2003). The $\mathrm{C_{fraction}}$ of KBG in August 2003 was measured (CNS2000 total carbon analyzer, LECO Corporation, St. Joseph, MI) as 0.451 ± 0.003 ($n = 4$, ~0.3 g sample per analysis). These data agree with Jenkins et al. (1996) ($\mathrm{C_{fraction}}$ 0.443) and Ortiz de Zarate et al. (2000) ($\mathrm{C_{fraction}}$ 0.44 ± 0.016).

The assumptions made in the EF (carbon) method are:

1. Physico-chemical processes between emission and sampling are considered to have negligible effect on the pollutant concentrations. This constraint is reasonably well satisfied since samplers were placed a few meters away from the source. All pollutants are present in a unit volume of air sampled, in the same proportion in which they were produced by the fire (Nelson, 1982; Radke et al., 1988).
2. The C release rate is proportional to the mass loss rate of the fuel (Susott et al., 1991).
3. Stubble and ash have similar $\mathrm{C_{fractions}}$ (Nelson, 1982; ASI, 2003). We found the $\mathrm{C_{fraction}}$ in KBG ash to be 0.453 ± 0.011 ($n = 4$), which is very close to that of unburned stubble. Moreover these $\mathrm{C_{fractions}}$ are assumed to be representative of the whole field.
4. All C in the biomass consumed by the fire is released into the atmosphere during combustion, and can be accounted for by measuring concentrations of CO_2, CO, THC and $PM_{2.5}$ in the plume (Radke et al., 1988; Andreae and Merlet, 2001). Time-averaged concentrations of these pollutants are considered to be representative of the entire plume over the whole sampling period (Nelson, 1982), if the sampling period extends over the total burning time. A carbon mass balance closure is used (Eq. (4)) to validate this assumption.

$$\text{Biomass C accounted for, } \% = \frac{(\Delta \mathrm{CO_2-C} + \Delta \mathrm{CO-C} + \Delta \mathrm{THC-C} + \Delta \mathrm{PM_{2.5}-C})}{m_{\mathrm{burned}} \times \mathrm{C_{fraction}} \times 0.01} \times Q_{\mathrm{chamber}} \times t_{\mathrm{run}}. \tag{4}$$

In May 2001, August 2001 and August 2003, $106.5 \pm 4.6\%$, $111.2 \pm 4.4\%$ and $93.1 \pm 6.8\%$ of biomass C, respectively, was accounted for by measuring these 4 species. The few reported carbon mass balances [Nelson (1982): 91.8–114.3%; Hurst et al. (1994): $95 \pm 4.3\%$; Boubel et al. (1969): $99 \pm 10\%$] are in agreement. Therefore assumption #4 was deemed reasonable.

Unless otherwise stated, all EFs reported here are calculated with the EF (direct) method. All data were checked for normal distribution and uncertainties associated with results follow the format "mean $\pm$ 95% confidence interval". Based on propagation of error analysis, the EF (direct) and EF (carbon) have uncertainties of $\pm 20\%$.

3. Results and discussion

As seen in Figs. 1–3, EFs of $PM_{2.5}$, CO and THC show inverse relationships with CE. The EFs of $PM_{2.5}$ (Fig. 1) and THC (Fig. 3) from KBG burns are higher than in wheat burns, although the CO EFs are comparable (Fig. 2). The lower CE KBG burns are also characterized by slower stubble consumption rates and significantly lower ΔT's than wheat burns ($t_{0.05,35} = 5.2$, $P < 0.001$, comparing burns with the same m_{burned} and Q_{chamber}).

CE variations explain 60% or more of the $PM_{2.5}$, CO and THC fluctuations (Fig. 2). The bulk of C is emitted as CO_2: 94.5% and 90.4% on average for wheat and grass stubble, respectively. Table 2 shows

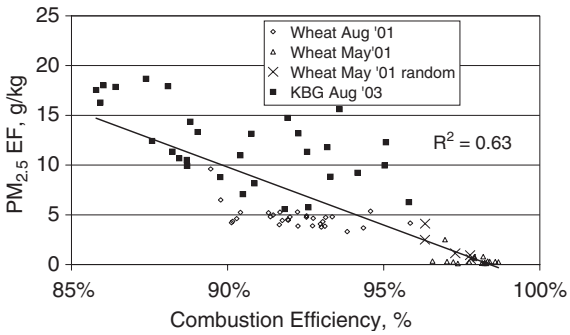

Fig. 1. Plot of $PM_{2.5}$ emission factors vs. combustion efficiency.

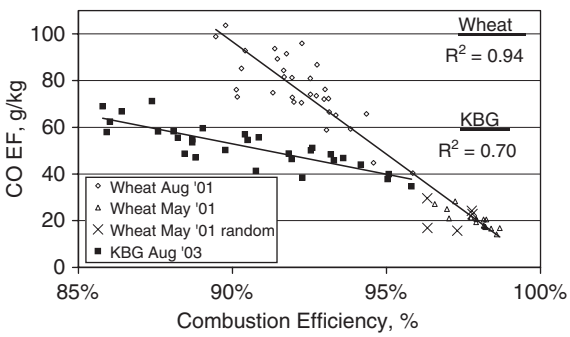

Fig. 2. Plot of CO emission factors vs. combustion efficiency.

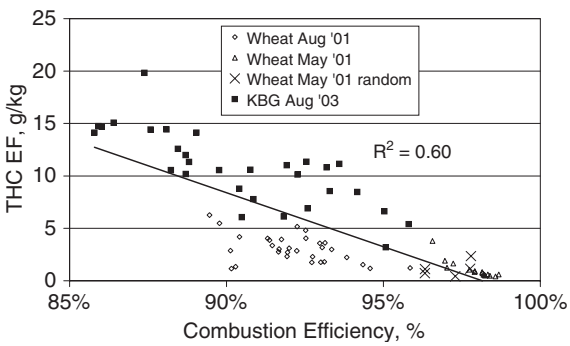

Fig. 3. Plot of THC emission factors vs. combustion efficiency.

how emission factors measured in this study compare with those found in literature. The May 2001 wheat burns may have been operated at CEs slightly higher than those typically seen in the field. Nevertheless, overall averages of EFs from wheat straw burning are in reasonable agreement with published values, including those involving some other stubble types.

EFs from KBG are difficult to compare against those reported by Boubel et al. (1969), due to the few data points ($n = 4$) and unexpected stubble moisture–EF relationship in that study. Though $PM_{2.5}$ and CO EFs are lower than those in ASI (2004), the ASI (2004) field study was characterized by (i) CEs lower than those we encountered, partly due to higher stubble moisture content (ii) high RSD of $PM_{2.5}$ EFs and (iii) a weak $PM_{2.5}$ EF–CE correlation ($R^2 = 0.22$).

The average combustion efficiencies of the burns performed in May 2001 on randomly piled wheat stubble were 1% lower than the corresponding CE's of the oriented burns. $PM_{2.5}$ EFs of oriented burns (range 0.1–2.5, average 0.5) were lower than randomly piled burns (range 0.6–4.1, average 1.9). A larger burn-to-burn variation is associated with the random stubble orientation. While more tests at CEs typical of field burns are required in this regard, the data available here suggest that fuel orientation does affect the EFs.

The magnitude of the differences between EF (direct) and EF (carbon) are the same for CO_2, CO, THC and $PM_{2.5}$ emitted during a particular burn. EF (carbon) expressed as a % of EF (direct) was $94.4 \pm 4.2\%$ (May 2001), $91.1 \pm 3.9\%$ (August 2001) and $110.7 \pm 7.2\%$ (August 2003). Since the differences are within experimental error, the two methods for estimating EFs compare well. If all C in the stubble was converted to CO_2 (i.e. CE 100%) the CO_2 EF is given by $(C_{fraction} \times 1000 \times 44/12)\,g\,kg^{-1}$. Table 3 shows that the CO_2 EFs are consistent with these upper limits when the confidence intervals are considered.

Emission ratios (ER) can be computed for pollutants that are emitted during the same phase of combustion, and exhibit low dependence on CE (Andreae and Merlet, 2001; Ortiz de Zarate et al., 2000; Hurst et al., 1994; Ward et al., 1992). ERs can help predict the level of one pollutant in a plume, when the concentration of the other is known. The average $PM_{2.5}$/CO ER for wheat is in agreement with data in literature (Table 2), while bluegrass fires have higher $PM_{2.5}$/CO ratios than wheat. The KBG ER is slightly higher than those by ASI (2004) and Boubel et al. (1969).

3.1. Annual emissions from wheat and KBG stubble burning

In WA, cereal stubble burning (90% wheat) occurs in 10 counties east of the Cascades. Typically no KBG is burned in WA. Turf grasses (90% KBG) are produced in 8 north central and northern ID

Table 2
Emission factors ($g\,kg^{-1}$) and emission ratios from biomass burning, based on burns for which all pollutants were available

	KBG (CE 90.4±1.0%, $n=30$)	Wheat stubble			Literature
		May 2001 (CE 97.7±0.3%, $n=23$)	August 2001 (CE 92.2±0.5%, $n=31$)	Overall average (CE 94.5±0.8%, $n=54$)	
$PM_{2.5}$	12.1±1.4	0.8±0.4	4.7±0.4	3.0±0.6	4.2[a], 3.6±0.7[b], 3[c], 6.2[d], 5.6[e], 29.6±10.4[f], 8[g], 8.5[h]
CO	51.8±3.3	21.1±1.9	76.5±5.1	52.9±8.0	38.2[a], 44.1±7.4[b], 86[d], 190±38[f], 61[g], 59[h], 80[i], 35[j]
THC	10.7±1.3	1.1±0.4	3.0±0.5	2.2±0.4	2.9[a], 8.7[g] (as C_3H_8), 7[i],
$PM_{2.5}$/CO ER	0.23±0.02	0.03±0.01	0.06±0.01	0.05±0.01	0.08±0.01[b], 0.06[d], 0.17±0.05[f], 0.14[g], 0.07[j]

[a]Dennis et al. (2002); wheat fires.
[b]ASI (2003); wheat (CE 95.6±0.8%).
[c]USFS CONSUME Model, forest fires.
[d]Ward et al. (1992), forest fires.
[e]From data in Turn et al. (1997), wheat.
[f]ASI (2004), KBG (CE 84.5±3.1%).
[g]Boubel et al. (1969), KBG (CE 90%).
[h]EPA AP-42 (1995), avg. head + back fires, wheat.
[i]Hurst et al. (1994), savannah fires.
[j]Ortiz de Zarate et al. (2000), wheat.

Table 3
CO_2 EF consistency check, based on burns for which all pollutants were available

	Upper limit, based on C in biomass, $g\,kg^{-1}$	Measured EF, $g\,kg^{-1}$
May 2001	1596	1658±72
August 2001	1620	1664±68
August 2003	1654	1403±117

counties, which include two Native American reservations. These 18 WA and ID counties are located in common or adjacent airsheds. For 2002, the total $PM_{2.5}$ and CO emissions from wheat and KBG burning in this area were evaluated as: Area burned (m^2) × Residue loading in field ($kg\,m^{-2}$) × Dry Matter Content of Residue (%) × Burning Efficiency (i.e. % dry biomass consumed by fire) × Pollutant EF ($g\,kg^{-1}$).

We estimate the emissions from wheat burning in the airshed(s) to be 0.7 Gg $PM_{2.5}$ and 12.3 Gg CO. Similarly KBG burning released 0.6 Gg $PM_{2.5}$ and 2.5 Gg CO, during 2002. Data sources are: acreage burned and loading—WA DOE (2004) and ISDA (2003); wheat and KBG fractions among cereals and turf grasses grown—USDA (2002); loadings and burning efficiencies—ASI (2003, 2004); dry matter content—Table 1; EFs: Table 2.

Total $PM_{2.5}$ and CO emissions from wheat and KBG burning in 2002 were compared against $PM_{2.5}$ and CO emissions from mobile, stationary, point and area sources, inventoried in these counties (WA DOE, 2004; IDEQ, 2005). Wheat burning in the 10 WA counties accounted for 3.7% of annual $PM_{2.5}$ emissions (range 0.04–18.5%) while CO emissions made up 7.7% (range 0.1–34.5%). CO inventories from 4 ID counties were available for comparison. KBG and wheat burning therein accounted for 2.2% (range 1.1–4.3%) of annual CO emissions. Though these appear to be relatively small fractions, it must be borne in mind that agricultural burning only occurs during a few weeks each year (33 and 23 days in 2002, in WA and ID respectively). Thus short-term contributions from agricultural burning to the local emissions can be substantial.

4. Conclusions

EFs are smoke management tools; dispersion models employed within forecast systems (such as the ClearSky project—http://www.clearsky.wsu.edu) could utilize region-specific EFs and assist authorities determine the advisability of agricultural burning. Knowledge of KBG EFs is scarce and would benefit the smoke managers in areas where KBG stubble is burned. On average, the EFs of

$PM_{2.5}$, CO and THC were 3.0 ± 0.6, 52.9 ± 8.0 and $2.2 \pm 0.4\,g\,kg^{-1}$, respectively for wheat stubble, and 12.1 ± 1.4, 51.8 ± 3.3 and $10.7 \pm 1.3\,g\,kg^{-1}$, respectively for KBG. Since EFs of these pollutants are inversely correlated with CE, identifying methods of increasing the CEs of burns would help reduce the emissions from agricultural field burning.

The assumptions made in the EF (carbon) method are reasonable, and it is a viable tool for use during field experiments. An example of the application of ERs would be the estimation of $PM_{2.5}$ concentrations in a plume, by measuring CO. Sampling $PM_{2.5}$ on board an aircraft requires a specially designed isokinetic sampling inlet. But CO could be measured more easily and multiplied by a previously determined ER, to estimate the $PM_{2.5}$ level.

Randomly piled stubble could represent varying degrees of stubble compaction, which appears to influence $PM_{2.5}$ EFs. The compactness of KBG straw implies less contact with ambient air compared to the more spaced out, hollow, wheat straw. Compared to wheat, a larger KBG stubble mass fraction was consumed during the slow propagating, low CE smoldering phase, which also dissipates less heat than flaming combustion. These factors could partly explain the observed differences between CEs, ΔTs and burn rates of wheat and KBG fires.

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