MEASURING SMOKE EMISSIONS FROM PRESCRIBED RANGELAND BURNING IN THE FLINT HILLS REGION USING UNMANNED AIRCRAFT SYSTEMS

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HIGHLIGHTS

- Smoke samples collected with UAS during rangeland prescribed burns were used to develop representative smoke emission factors for rangeland fires.
- The head fire emission factors of $PM_{2.5}$ and NO_x were consistent with the low end of the range of flaming emission factors in the literature.
- The combination of high air temperatures and high absolute humidity resulted in higher levels of $PM_{2.5}$ and O_3 in smoke.

ABSTRACT. *Prescribed burning is an ecological process critical to maintaining and improving rangeland ecosystems. Smoke impacts related to prescribed burning have been the subject of intense discussion and public debate. The objectives of this study were to collect accurate smoke emissions data using unmanned aircraft systems (UAS) and use the data to develop smoke emission factors representative of prescribed rangeland fires in the tallgrass prairie Flint Hills region of Kansas and Oklahoma. The emission factors will be used to improve the input parameters used in smoke modeling tools. Four prescribed burns on unique burn units were sampled for this study. Smoke emission factors were determined using the carbon mass balance method. Average emission factors for head fires were: $PM_{2.5}$, 11.3±10.8g/kg fuel; NO_x as NO, 1.4±0.9 g/kg fuel; CO_2, 1569±28 g/kg fuel; CH_4, 6.8±4.3 g/kg fuel; NMHC as propane, 3.3±2.5 g/kg fuel; and VOC as propane, 4.5±3.5 g/kg fuel. Compared with head fires, back fires tended to produce lower emissions of $PM_{2.5}$ but higher emissions of NO_x and VOC. Green, high-moisture vegetation present during the growing season fires in September resulted in a larger head fire $PM_{2.5}$ emission factor compared to April fires. Generally, the combination of high air temperature and high absolute humidity resulted in high $PM_{2.5}$ and O_3 in smoke. Conducting prescribed fires under conditions of cool air temperature and low absolute humidity can reduce the generation of $PM_{2.5}$ and O_3 in smoke, as long as these conditions fall within the prescribed range for the burn.*

Keywords. *Carbon mass balance, Drone, Fire, Grass, Ozone, Pasture, Prescribed burning, Rangeland management, Rangelands, Smoke emission factor, Tallgrass prairie, Unmanned aircraft system.*

Prescribed burning is critical to maintaining rangeland ecosystem services and functions. The Flint Hills region of eastern Kansas and Oklahoma encompasses the largest remaining extent of old-growth tallgrass prairie in North America and is extensively burned to promote desirable native vegetation, eliminate undesirable weeds and woody species, and enhance forage nutritional value for grazing. Approximately one third of Flint Hills rangelands are burned each year, mostly in April, immediately prior to green-up. From 2000-2022, on average, more than 2.1 million acres in the region burned annually. In 2019, a total of 2.6 million acres in the Flint Hills were burned with more than 3000 prescribed fires.

While ecologically beneficial, prescribed burning impacts air quality. Smoke from Flint Hills prescribed fires has contributed to daily ozone (O_3) and fine inhalable particulate matter ($PM_{2.5}$) exceedances of the National Ambient Air Quality Standards (NAAQS) in Kansas, Oklahoma, and surrounding states. While the benefits of prescribed burning are undisputed, the impact of smoke from the fires has been the subject of intense discussion and public debate.

Smoke from fires is a complex mixture of airborne solid and liquid particulate matter (PM), vapors, and gases, which can contain thousands of individual compounds with a huge

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range of chemicals such as volatile and semi-volatile organic compounds (VOC and SVOC), inorganic gases (including O_3 and nitrogen oxides [NO_x]), and water vapor (Reid et al., 2005). Despite some commonalities, fires vary drastically in terms of pollutant characteristics. Fine particulates ($PM_{2.5}$) and O_3 precursors such as NO_x and VOC are often the smoke constituents of concern in wildland fires. The one parameter often used to characterize emissions from fires is the emission factor, which is defined as the amount of a smoke component generated per unit mass of fuel burned. The PM emission factor, also referred to as smoke yield, ranges from fractions of a percent to about 20% of the fuel mass (Butler and Mulholland, 2004). Emission factors from different studies are highly variable due to variability in fuel and combustion conditions. Inventory estimates of emissions of smoke components from open fires are traditionally calculated from empirical emission factors, ecosystem-based estimates of fuel loading per area, burned area, and combustion completeness (Langmann et al., 2009). Quantifying the contribution of prescribed fires to air pollution may provide an opportunity to develop effective mitigation strategies. Developing an accurate emission inventory can assist state air quality scientists to more accurately assess the contribution from prescribed fires during air quality exceedances and provide the opportunity to request an EPA exceptional events designation. Emissions data from prescribed burns can also be used to determine major factors that influence the emissions and represent the emissions quantitatively in atmospheric chemistry and transport models.

Emission factors are impacted by ignition techniques, fuel conditions, and the temperature of combustion. Biomass type and fuel moisture substantially influence emissions from prescribed burns. Different moisture levels play an important role in the carbon (C) and nitrogen (N) species emission factor (Chen et al., 2010). Fuel moisture reduces combustion efficiency and increases $PM_{2.5}$ because it absorbs energy that would otherwise be available for combustion, and emitted water vapor dilutes volatized gases and reduces the rate of oxidation reactions (Ward, 1990). More emissions factor uncertainty can arise from fire behavior, reflecting fuel, weather, and topography, as well as the direction of fire spread relative to the wind (Robertson et al., 2014). As head fire intensity (rate of heat release per length of fire line) increases, $PM_{2.5}$ emissions have been observed to initially decrease and then increase due to changing levels of oxygen deficiency (Ward et al., 1980, 1983; Ward and Hardy, 1991). In North America, prescribed fire and wildfire forest emissions in the western and southeastern US have been extensively studied (Starns et al., 2020). In the southeastern US, grass and grass-shrub wildlands emissions have been measured (Aurell et al., 2015; Holder et al., 2016) and modeled (Hu et al., 2008), but few of the results are relevant to Great Plains tallgrass prairie prescribed burns.

Laboratory measurements have been used to generate emission data from biomass burning, but emissions data from field measurements under typical environmental conditions and scales are more representative (Christian et al., 2003; Burling et al., 2011). Results from laboratory measurements require verification with field studies (Yokelson et al., 2013). However, field measurement of smoke emissions from prescribed fires is difficult due to the dynamic systems and rapid changes in concentration profiles in space and time, and measurement of smoke using traditional airborne platforms with heavy instruments is expensive. Recent technologies in unmanned aircraft systems (UAS) and lightweight sensors make UASs a practical option for direct measurement of smoke.

The objectives of this study were to test the applicability of UASs to collect accurate smoke emissions data and to generate accurate $PM_{2.5}$ and O_3 input parameters for smoke modeling tools, such as the web-based model developed by the Kansas Department of Health and Environment and Sonoma Technology, Inc. (Petaluma, CA), which operates during March and April each year (http://ksfire.sonomatechdata.com/view/summary/).

METHODS

SAMPLING SITES

Four Kansas Flint Hills prescribed burns on different sites (ranging from 8 to 80 ha) were sampled for this study (table 1). All sites were healthy native rangelands grazed by either cattle or bison the year of (or prior to) the study at moderate to light stocking rates and without any woody species present (herbaceous vegetation only).

SMOKE SAMPLING USING UAS

Two UAS drones equipped with air monitoring equipment were used to sample each prescribed burn. The drones sampled the same smoke using different instrumentation to verify the accuracy of instantaneous sampling with more traditional lab analysis (table 2 and fig. 1). The UAS 1 carried $PM_{2.5}$ and O_3 instantaneous sensors to continuously sample smoke plumes by first flying to altitude and then repeatedly flying a horizontal path through the plume back and forth at relatively short time intervals and at increasing heights (fig. 2). The location within the plume was determined by observation from the ground. The UAS 2 (integrated sampling) carried a small pump and sampling bags that collected gas samples within the plume for lab analysis of NO_x, CO_2,

Table 1. Sampling sites and the four sampling events.

Date	Sampling Time	Location	Ambient Air Temperature	Ambient Relative Humidity (RH)	Fire Type	Number of UAS Flights: Continuous Sampling	Number of UAS Flights: Integrated Sampling
16 April, 2018	2:54 p.m. - 7:21 p.m.	Chase County	10.5 - 13.3ºC	25.6% - 27.1%	Back fire	3	3
					Head fire	5	3
26 September, 2018	11:53 a.m. - 4:00 p.m.	Chase County	14.3 - 18.6ºC	31.8% - 54.7%	Back fire	5	-
					Head fire	8	-
1 April, 2019	1:20 p.m. - 3:00 p.m.	Elk County	9.2 - 9.3ºC	25.4% - 30.9%	Head fire	6	5
26 April, 2022	9:30 a.m. - 1:07 p.m.	Chase County	15.5 - 16.2ºC	19.2% - 26.5%	Head fire	5	10

Table 2. Specifics of sampling packages on the UAS and on the ground, Spring 2018.

UAS 1, continuous measurements	• Personal ozone monitor (2B Technologies) for Ozone (Accuracy: Greater of 1.5 ppb or 2% of reading) • Aerosol monitor (Thermo Fisher Scientific pDR-1500) for $PM_{2.5}$ (Accuracy: ±5% of reading; Aerodynamic Particle Cut-Point Range: 1.0 to 10 μm) • Personal air monitor (2B Technologies) for CO, CO_2, $PM_{1/2.5/10}$ • Weather probe (InterMet iMet-XQ2) for temperature, relative humidity (RH), pressure, altitude, position (GPS) • Radio (Campbell Scientific RF407) • Datalogger (Campbell Scientific CR300-RF407) • Total package is 2.3 kg
UAS 2, integrated sampling	• Integrated gas samples are taken using 1-liter sampling Tedlar bag for about 1min. The sampling bags will be immediately analyzed for NO_x, CO_2, CO, CH_4, NMHC and VOC when return to ground. • Sampling pump (SKC Grab air) • Personal air monitor (2B Technologies) for CO, CO_2, $PM_{1/2.5/10}$ • Weather probe (InterMet iMet-XQ2) for temperature, RH, pressure, altitude, position (GPS) • Radio (Campbell Scientific RF407) • Datalogger (Campbell Scientific CR300-RF407) • Total package is 1.9 kg
UAS 3, black carbon	• MA200 black carbon monitor: 420g
UAS 4, Thermal image and RGB sensor	• Thermal imaging data will be transmitted at 8.5 MHz. • Hover over the fire itself, not in the smoke plume (46 m above the fire)
Ground station	• Laptop computer, real-time data in text and graphical, remote operation of integrated sampling. • Personal air monitor (2B Technologies) for CO, CO_2, $PM_{1/2.5/10}$

CO, CH_4, non-methyl hydrocarbon (NMHC), and VOC. Lab analysis was performed by Atmospheric Analysis & Consulting Inc. in Ventura, CA, USA. Total NMHC (C_2-C_{12}) was analyzed by GC/MS/FID (Gas chromatography / mass spectrometry / flame ionization detector), and VOC was analyzed by EPA Method TO-15 (EPA, 1999). Integrated sampling was accomplished by first flying to altitude and then hovering for about 3 min within the plume to collect a sample. Samples were also collected outside the plume to ascertain background concentrations of pollutants before and after the prescribed fires using both ground and UAS measurements at an upwind location. The altitude of the UAS sampling flights ranged from 8 to 98 m.

Figure 1. Photos of UAS 1 for continuous measurements (left) and UAS 2 for integrated sampling (right).

During the first prescribed burn, additional UASs were used to capture unique data only from that burn. The UAS 3 carried a black C sensor as part of a collaborative effort with the National Aeronautics and Space Administration (NASA) to verify satellite detection accuracy, which required synchronizing the fire with satellite overflight. The results were used to estimate the percentage contribution of black C in total C in smoke. The UAS 4 collected visible light camera footage and was used to better understand UAS performance within the smoke plume. The first sampling event was

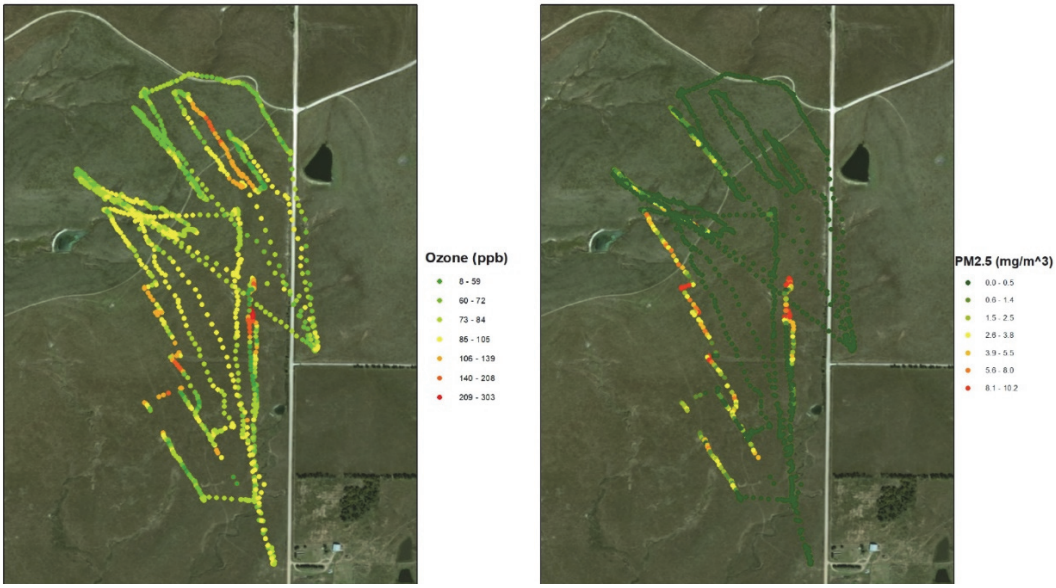

Figure 2. Example of UAS 1 flight trajectory on April 16, 2018, with continuous O_3 and $PM_{2.5}$ readings.

uniquely experimental, with the purpose of testing all equipment for robustness in the fire environment. After this initial event, only UAS 1 (continuous measurement) and UAS 2 (integrated sampling) were used as described above.

Biomass Fuel Sampling

Four warm-season grass species contribute most of the biomass in Flint Hills rangelands: big bluestem (*Andropogon gerardii* Vitman), little bluestem (*Schizachyrium scoparium* Michx.Nash), switchgrass (*Panicum virgatum* L.), and Indian grass (*Sorghastrum nutans* (L.) Nash). The prescribed burning fuel load includes standing vegetation, litter on the soil surface, and cattle manure pats. Forage, litter, and cow manure pats were sampled by clipping, hand pulling, and pat collection, respectively, and analyzed for C and N content at Kansas State University using a LECO TruSpec CN combustion analyzer (LECO Corp., St. Joseph, MI). The biomass fuel loads ranged from 229 to 473 g/m^2. Three sampling events were in early spring, when vegetation was still largely dormant and fuels consisted of cured vegetation. One sampling event was during the growing season with green vegetation fuel.

The Carbon Mass Balance Method for Calculating Emission Factors

The C mass balance method is widely used for the quantification of smoke emission factors under both laboratory and field conditions (Nelson, 1982; Ward and Hardy, 1991; Akagi et al., 2011; Liu et al., 2016; Strand et al., 2016; Holder et al., 2017). In this method, the emission factor of a species is calculated from the ratio of the mass concentration of those species to the total C concentration emitted in the plume, assuming that all C in the fuel is emitted into measurable portions of C in various forms, including CO_2, CO, CH_4, VOC, and particulate C in smoke particles.

$$EF_x = F_C \times \Delta C_X / \Delta C_T = F_C \times \Delta C_X / \left(\Delta C_{CO2} + \Delta C_{CO} + \Delta C_{CH4} + \Delta C_{VOC} + \Delta C_{PM2.5}\right) \quad (1)$$

where

EF_x = emission factor for species x (g/kg fuel)

F_C = C content in the dry sample of biomass fuel , (gC/kg fuel)

ΔC_x = concentration of species x in smoke with background concentration subtracted (g/m^3)

ΔC_T = total concentration of C in all C-containing species in smoke with background concentration being subtracted (gC/m^3)

ΔC_{CO2}, ΔC_{CO}, ΔC_{CH4}, ΔC_{VOC}, and $\Delta C_{PM2.5}$ = concentrations of C in CO_2, CO, CH_4, VOC, and $PM_{2.5}$, respectively, with background concentration being subtracted (gC/m^3).

The emission factors of CO_2, CO, and CH_4 were then converted to the unit of g/kg fuel based on the ratio of their molecular weight over that of C. The emission factors of NMHC and VOC were calculated as equivalent gram of propane per kg fuel. The emission factor of NO_x was calculated as the equivalent gram of NO per kg fuel.

Results

Carbon and Nitrogen Content of Biomass

The biomass fuel C and N analysis results are presented in table 3.

Carbon Distribution in Smoke

The C emissions in smoke can be in the forms of CO_2, CO, CH_4, VOC (including NMHC), and black C. While the CO concentrations were mostly not detectable (<5.35ppm), CO_2 concentrations ranged from 476 to 1794 ppm, and accounted for 92.5% to 99.4% of the total C emissions in the smoke, indicating high levels of complete combustion. CH_4 accounted for 0.3% to 3.5%, and VOC accounted for 0.1% to 0.6% of the total C emissions. The black C concentrations in smoke were related to $PM_{2.5}$ concentrations, and they accounted for around 2% of the $PM_{2.5}$ concentrations based on a single sampling event (fig. 3).

As a comparison, Whitehill et al. (2019) estimated the average product distribution of gaseous C from the smoke plumes for tallgrass fires as follows: 89.56% CO_2, 8.96% CO, 0.62% CH_4, and 0.86% speciated VOC, in which the near-ground measurements of emissions were influenced by smoldering combustion. In our study, combustion was more complete, thus more CO_2 and less CO and VOC were emitted.

Emission Factors

Emission factors for $PM_{2.5}$, NO_x, CO_2, CH_4, NMHC, and VOC (including NMHC) from four sampling events are presented in table 4. In the two sampling events where head fires and back fires were sampled separately, head fires produced higher $PM_{2.5}$ and lower NO_x, NMHC, and VOC emissions factors as compared to back fires. The September growing season fire had a much higher head fire $PM_{2.5}$ emission factor when compared to all the April dormant season fires. The difference in $PM_{2.5}$ emissions was attributed to the green vegetation and an ambient RH of 31%-54% in the growing season fire as compared to a RH of 19%-30% in the dormant season fires.

Table 3. Testing results of carbon and nitrogen content of biomass.

Fuel Type	Number of Samples	Carbon Content (%)	Nitrogen Content (%)
Forage (grass)	7	44.4±1.7	0.83±0.51
Cow manure patties	4	25.3±5.7	1.52±0.37
Overall[a]		44.3	0.83

[a] Overall C and N biomass content was calculated based on an estimate that 0.5% of the fuel load consisted of cow patties.

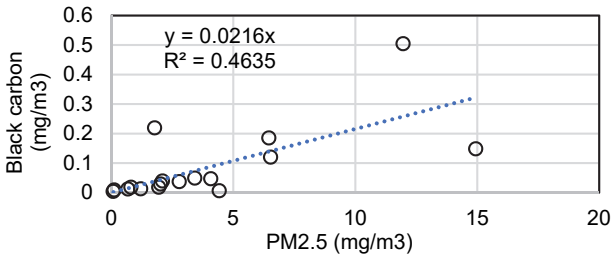

Figure 3. Relationship between black carbon and $PM_{2.5}$ (single sampling event).

Table 4. Emission factors calculated from the four sampling events.[a]

Sampling Date	Fire Type	Emission Factors (g/kg fuel)						Number of Flights	
		$PM_{2.5}$	Nox as NO	CO_2	CH_4	NMHC as Propane	VOC as Propane	Continuous Sampling	Integrated Sampling
16 April, 2018	Back fire	6.6±8.5	1.8±2.1	1568±52	-	1.1±0.0	1.8±0.3	3	3
	Head fire	11.5±7.1	0.7±0.2	1545±34	-	0.6±0.1	0.9±0.3	5	3
26 September, 2018	Back fire	1.7±1.9	-	-	-	-	-	5	-
	Head fire	17.3±14.1	-	-	-	-	-	8	-
1 April, 2019	Head fire	7.0±10.3	-	1559±8	-	1.5±1.2	1.9±1.3	6	5
26 April, 2022	Head fire	6.9±3.6	1.7±0.9	1583±23	6.8±4.3	5.0±1.9	7.0±2.9	5	10
Average	Back fire	3.5±5.4	1.8±2.1	1568±52	-	1.1±0.0	1.8±0.3	8	3
	Head fire	11.3±10.8	1.4±0.9	1569±28	6.8±4.3	3.3±2.5	4.5±3.5	24	18

[a] Data in the table is presented in the form of "average value ± standard deviation".

Because of the fairly low combustion temperatures in vegetation fires, atmospheric N_2 is not converted to fixed N to a significant extent, and the N species emissions are based only on fuel N (Andreae and Merlet, 2001). Based on the emission factors and the measured N content of the biomass fuel, on average, about 6% of the N in the biomass fuel was emitted as NO_x in smoke.

Concentrations of $PM_{2.5}$ and O_3 in Smoke

The continuous $PM_{2.5}$ and O_3 equipment sampled the smoke plume at two second intervals, with an average flight time of 10 min. Average $PM_{2.5}$ and O_3 concentrations for each flight ranged from 0.06 to 14.94 mg/m^3 and from 23.6 to 224.1 ppb, respectively. In figures 4 to 8, the average $PM_{2.5}$ and O_3 concentrations in smoke, and the average temperatures or humidity levels during the same time periods were plotted against each other, to demonstrate how the $PM_{2.5}$ and O_3 concentrations were affected by temperature and humidity level. The O_3 measurements in this study were comparable with the range of O_3 (8.3 ppb to 330 ppb) measured for Kansas prescribed burns by Long et al. (2021). As shown in figure 4, the $PM_{2.5}$ and O_3 concentrations in smoke were positively correlated, and the O_3 concentrations were also significantly affected by temperature and humidity level in the smoke. Higher O_3 concentrations were observed for higher air temperature and lower RH. Since RH is not an independent variable and is affected by air temperature, absolute humidity was calculated to investigate the role of moisture on the generation of $PM_{2.5}$ and O_3. At similar levels of absolute humidity, both $PM_{2.5}$ and O_3 concentrations tracked together with increased air temperature, with increased sensitivity to temperature as humidity increased. Higher $PM_{2.5}$ and O_3 concentrations were associated with higher air temperatures and higher levels of absolute humidity. When the air temperature was lower, both $PM_{2.5}$ and O_3 concentrations were lower, no matter the absolute humidity (figs. 5-8).

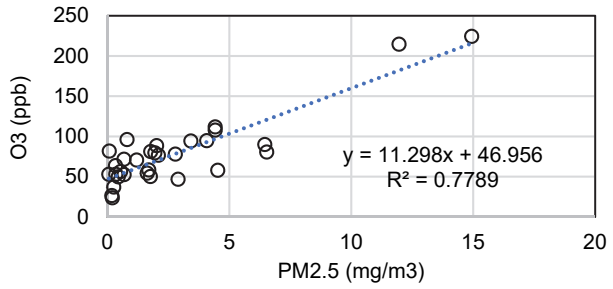

Figure 4. Relationship between O_3 and $PM_{2.5}$ concentrations.

Discussions

Comparing the Carbon and Nitrogen Content of Biomass in the Literature

Both the C and N content of the grass in this study were on the low end of the range of values reported in the literature (table 5). This may be one of the reasons that grass emission factors were lower than those of other biomass fuels reported in the literature, which may have included leaves and stems. The C content of manure from grazing cattle was much lower than that of grass or manure from straw or woodchip bedded cattle.

Comparing the Emission Factors in the Literature

Comparisons of smoldering and flaming fires generally reported that emission factors of $PM_{2.5}$ and NMHC are about 50% larger in smoldering fires, while CO_2 emission factors are smaller, indicating lower combustion completeness (table 6). The head fire emission factors of $PM_{2.5}$ and NO_x in this study were consistent with the low end of the

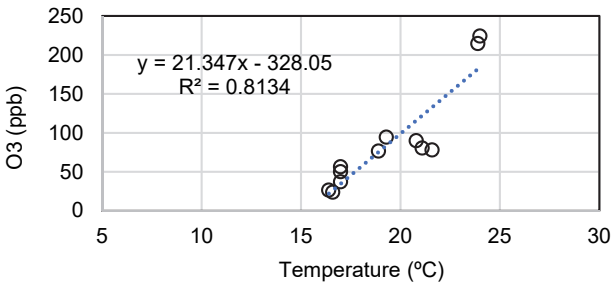

Figure 5. O_3 vs. temperature when absolute humidity >4 g/m^3.

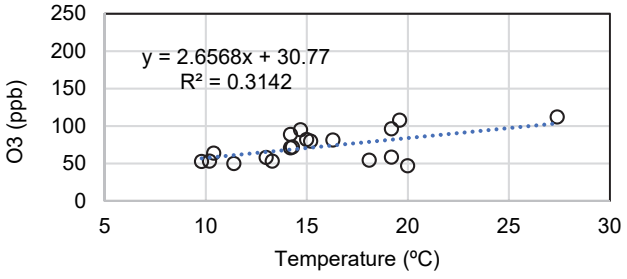

Figure 6. O_3 vs. temperature when absolute humidity <4 g/m^3.

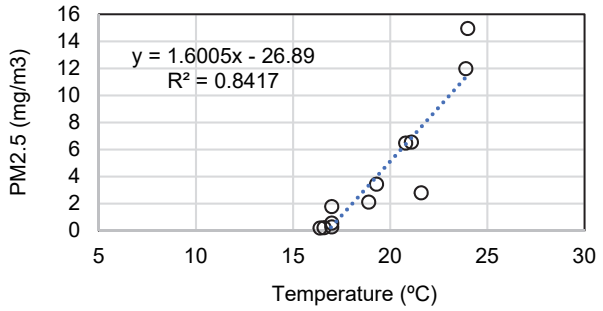

Figure 7. $PM_{2.5}$ vs. temperature when absolute humidity >4 g/m^3.

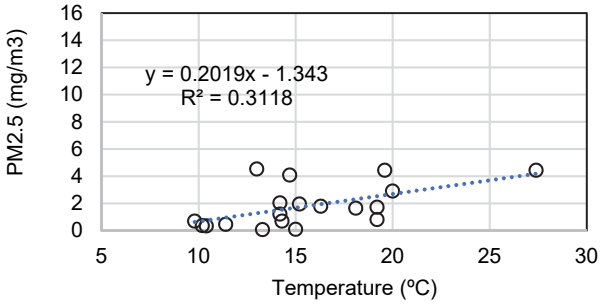

Figure 8. $PM_{2.5}$ vs. temperature when absolute humidity <4 g/m^3.

range of flaming emission factors reported in the literature, possibly due to the relatively lower C and N content of biomass fuel. The CO_2, CH_4, and NMHC emission factors agreed with the flaming emission factors in the literature. In contrast, the VOC emission factors in this study were much smaller than those reported by Whitehill et al. (2019), in which the tallgrass smoldering VOC emission factor was estimated from ground-based equipment rather than sampling in the plume.

Reducing the Generation of $PM_{2.5}$ and O_3 in Smoke

Smoldering conditions usually result in higher $PM_{2.5}$ and VOC emissions, and could potentially be reduced by shortening the amount and duration of smoldering conditions during a prescribed fire. The effects of head fire vs. back fire on emissions are complex. Head fires may result in lower VOC emissions but higher $PM_{2.5}$ emissions.

Both air temperature and absolute humidity play an important role in the generation of $PM_{2.5}$ and O_3 in smoke. The effect of RH on emissions is often confounded by the effect of air temperature. The common observations of higher emissions associated with lower RH are mainly due to the effect of higher temperature and not lower absolute humidity. Typically, when RH is lower and the air temperature remains the same, the emission will be lower due to lower absolute humidity. The September 26, 2018 head fire under higher RH and green vegetation conditions generated the highest $PM_{2.5}$ emission factor observed, confirming the effect of moisture on emissions. At high levels of absolute humidity, both $PM_{2.5}$ and O_3 concentrations very substantially increased with increasing air temperature. In summary, the combination of high air temperature and high absolute humidity results in high $PM_{2.5}$ and O_3 generation. Therefore, the generation of $PM_{2.5}$ and O_3 in smoke can be reduced by burning at either a lower air temperature or a lower absolute humidity.

Conclusion

Smoke emission factors for prescribed burning in the Flint Hills region were determined using the C mass balance method based on the results of field sampling of smoke using UAS. The average emission factors for head fires were: $PM_{2.5}$, 11.3±10.8g/kg fuel; NO_x as NO, 1.4±0.9 g/kg fuel;

Table 5. Carbon and nitrogen content of the vegetation biomass and cattle manure in the literature.

	References	Type	Carbon Content (%)	Nitrogen Content (%)
Vegetation	Andreae and Merlet, 2001		45	
	Penman et al., 2003	Grassland biomass (default)	50	
	Keene et al., 2006	Grass	43.22±1.01	0.59±0.20
	Matamala et al., 2008	Grass at Drummer soil	44.5±0.5	0.49±0.07
		Grass at Wauconda soil	43.7±0.2	0.44±0.03
	Burling et al., 2010	Oak savanna	49	1
	Chen et al., 2010	Litter	50	
		Duff	32	
		Bitterbrush leaves	52	
		Bitterbrush stem	48	
		Manzanita leaves	49	
		Manzanita stem	48	
	Vassilev et al., 2010	Prairie grass	43.71±0.22	1.45±0.21
		Switch grass	43.66±1.22	1.95±0.74
	Strand et al., 2016	Grass, understory grass field	49.6	<5
	Holder et al., 2017	Kentucky bluegrass	44	
	Range in the literature		43.2~50	0.44~1.95
	This study		44.4±1.7	0.83±0.51
Cattle manure	Helgason et al., 2005	Wood chip-bedded	46.2	1.8
		Straw-bedded	36.1	2.1
	Hao et al., 2004	Straw-bedded	33.05	1.99
		Chip-bedded	44.72	1.24
	Keene et al., 2006	Cow dung	32.6	1.67
	Range in the literature		32.6~46.2	1.24~2.1
	This study		25.3±5.7	1.52±0.37

Table 6. Emission factors in the literature.

References	Fuel Type	Conditions	Emissions Factors (g/kg fuel) $PM_{2.5}$	CO	CO_2	CH_4	NMHC as Propane	VOC as Propane	NOx as NO
Andreae and Merlet, 2001	Grass		5±2						
Penman et al., 2003	Default	Flaming	7.33	22.38	1678.40	2.09	3.24		-
		Smoldering	12.7	62.48	1144.21	7.78	7.53		-
Reid et al., 2005	Savanna		8±2						
	Grass		7±2						
Chen et al., 2007	Sage grass (Lab)	Flaming	5.4±0.6	22.6±4.1	1692.2±7.3				1.6±0.5
		Smoldering	8.2±2.2	131.5±17.9	1506.4±35.1				6.6±0.5
	Dambo grass (Lab)	Flaming	2.1±1.0	16.8±1.0	1612.5±5.0				1.7±0.1
		Smoldering	3.0±6.2	121.7±18.9	1447.3±41.3				0.4±0.5
	Montana grass (Lab)	Flaming	4.5±1.6	11.7±1.8	1553.8±11.6				4.3±1.1
Janhäll et al., 2010	Savanna		6±3						
	Grass		7±4						
Chen et al., 2010	Litter (Composite)	Flaming	8.1±0.9	126.2±12.7					5.9±0.3
	Duff	Flaming	18.3±10.2	140.6±27.3					4.9±0.9
	Bitterbrush-leaves	Flaming	27.1±5.8	112.6±30.3					9.1±2.8
	Bitterbrush-stem	Flaming	13.0±3.9	127.4±8.8					9.1±1.0
	Manzanita-leaves	Flaming	47.5±14.1	113.2±43.5					7.1±3.0
	Manzanita-stem	Flaming	8.7±0.4	128.4±6.7					8.7±0.4
Akagi et al., 2011	Pasture maintenance	Flaming	14.8	135	1548	8.71			0.75
	Dung burning	Smoldering		105	859	11.0			0.5
Robertson et al., 2014	Grass (Jan-Jun) -Open	Flaming	14.7±2.5						
		Smoldering	66.2±52.8						
	Grass (Apr-Jul) -Open	Flaming	22.9±2.6						
		Smoldering	96.9±89.7						
	Grass (Jan-Jun) 3-4 years-Open	Flaming	23.6±4.1						
		Smoldering	85.5±104						
	Grass (Apr-Jul) 3-4 years-Open	Flaming	27.9±3.0						
		Smoldering	191±108						
Strand et al., 2016	Understory grass	Ground	20	55.0±5.4	1743±8	1.57±0.48			
		Aerostat	15	108.4±21.4	1651±37	4.32±1.58			
Holder et al., 2017	Kentucky bluegrass (Field study)	Aerostat	14±7.0	44.0	1600	1.0	1.7		
		Ground	14±7.0	59	1500	1.8	2.3		
Andreae, 2019	Dung	Smoldering		89±42	1050±230	8.9±4.9			
	Savanna and grassland		6.7±3.3	69±20	1660±90	2.7±2.2			2.5±1.3
Whitehill et al., 2019	Tallgrass prairie	Smoldering		102.6	1611.5	4.07		15.5	
Prichard et al., 2020	Grasslands	SE USA	12.08±5.24	68.17±27.16	1685.82±81.19	2.53±1.51			3.53±0.4
	Grasslands	SW USA		56.26±38.89	1421±208.48	2.90±1.86			
	Northern grassland		9.89±6.90	64.44±16.18	1697.38±39.83	2.04±0.99			2.27
All in literature		Flaming	5~47.5	22~141	1421~1697	1~11	1.7~3.24	-	0.75~9.1
This study		Head fire	11.3±10.8	-	1569±28	6.8±4.3	3.3±2.5	4.5±3.5	1.4±0.9

CO_2, 1569±28 g/kg fuel; CH_4, 6.8±4.3 g/kg fuel; NMHC as propane, 3.3±2.5 g/kg fuel; and VOC as propane, 4.5±3.5 g/kg fuel. Compared with head fires, back fires may result in lower emissions of $PM_{2.5}$, but higher emissions of NO_x and VOC. Also, due to the higher moisture level, the green vegetation fire in September generated the highest $PM_{2.5}$ head fire emission factor.

The combination of high air temperatures and high absolute humidity resulted in high $PM_{2.5}$ and O_3 levels in smoke. Conducting prescribed fires under conditions of cool air temperature and low absolute humidity can reduce the generation of $PM_{2.5}$ and O_3 in smoke, as long as these conditions fall within the prescribed range for the burn.

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