Evaluation of revised emissions factors for emissions prediction and smoke management

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Summary

Revised emissions factors based on the latest research have important implications for estimation of wildland fire emissions and downwind smoke concentrations. A new synthesis of emission factor information for North America is being incorporated into Consume and the First Order Fire Effects Model (FOFEM) and smoke prediction tools used in national emissions inventories. Emissions factor tables support 8 pollutant species categories including CO, CO_2, CH_4, $PM_{2.5}$, NH_3, NO_x, N_2O and SO_2 and report fire-average, flaming and smoldering emissions factors for major vegetation types of the US and Canada. Long-term smoldering emissions factors are also available for coarse wood (stumps and logs) and organic soils in temperate and boreal forests. To evaluate potential differences in emissions prediction between current and new emissions factors, we used data collected for past fuel consumption studies in southeastern pine forests and western pine forests. For each dataset, we compared predictions of pollutant emissions using emissions factors within the 2001 Smoke Management Guide and revised emissions factors. Although some pollutant emissions estimates, such as $PM_{2.5}$, are notably higher in the revised emission factors tables, pre-burn fuel loading and fuel consumption are by far the most important drivers of pollutant emissions. By using emissions factors specific to flaming, smoldering, and residual smoldering phases of combustion, wildland fire managers can better inform emissions reduction techniques and identify burn prescriptions that limit sources of long-term smoldering emissions.

Table 1: Revised emissions factors by major vegetation type in the United States. Fire average values (F/S) are presented for all pollutants and represent short-term flaming and smoldering. Flaming (F) and Smoldering (S) values are provided for $PM_{2.5}$, CO_2, CO, CH_4 and NH_3 and partitioned by published MCE (≥ 0.9 = Flaming).

	$PM_{2.5}$ (g/kg)					Carbon Dioxide (CO_2, g/kg)					Carbon Monoxide (CO, g/kg)					Methane (CH_4, g/kg)					NH_3 (Ammonia, g/kg)				
	Avg	Min	Max	SD	n	Avg	SD	Min	Max	n	Avg	SD	Min	Max	n	Avg	Min	Max	SD	n	Avg	Min	Max	SD	n
ALASKA/CANADA																									
Boreal forest - F/S						1606	88	1436	1847	18	117.1	41.9	44.8	175.0	19	5.25	0.80	9.18	2.82	17	2.07	0.59	8.69	2.95	7
Boreal forest - F						1690	87	1588	1847	6	73.5	19.1	44.8	96.5	7	2.19	0.80	3.31	0.90	6					
Boreal forest - S						1570	17	1537	1594	8	153.6	9.8	139.1	172.2	8	7.90	7.26	9.18	0.68	8					
SOUTHEASTERN US																									
Grass - F/S	12.08	3.73	20.00	5.24	10	1700	87	1522	1859	18	70.2	26.2	34.7	119.0	18	2.67	0.60	5.40	1.41	12	1.20	0.40	1.90	0.56	6
Grass - F						1710	79	1522	1859	17						2.42	0.60	4.12	1.17	11					
Grass - S						1538				1						5.40				1					
Hardwood - F/S	14.32	14.09	14.48	14.09	3	1688	103	1580	1891	9	78.9	24.3	51.9	129.5	11	2.42	1.35	5.90	1.47	8	1.79	0.35	3.70	1.63	4
Hardwood - F						1702	101	1583	1891	8	68.6	14.1	51.9	90.2	8	1.92	1.35	2.70	0.47	7					
Hardwood - S						1580		1580	1580	1	129.5				1	5.90				1					
Pine - F/S	29.43	0.66	191.00	27.88	73	1606	177	950	1793	48	94.6	55.7	17.8	302.0	53	3.74	1.20	24.10	4.35	42	0.70	0.02	5.30	1.16	31
Pine - F	17.56	6.49	66.20	11.26	31	1677	57	1437	1793	36	72.4	21.1	17.8	116.0	36	2.38	1.20	6.66	1.17	33	0.48	0.02	3.60	0.90	18
Pine - S	58.04	2.07	191.00	54.71	10	1394	240	950	1710	12	156.2	57.6	113.0	302.0	11	8.72	2.20	24.10	7.48	9	1.01	0.05	5.30	1.43	13
Pine - RS											254.0	42.3	222.0	302.0	3										
Shrub - F/S	12.03	6.91	16.74	4.25	5	1703	198	1096	1903	14	74.3	15.7	54.7	116.5	16	2.44	1.65	4.80	0.89	11	2.21	0.47	6.60	2.50	5
Shrub - F						1743	99	1622	1903	12	72.4	12.5	54.7	95.7	12	2.24	1.65	2.90	0.45	9					
Shrub - S						1461	515	1096	1825	2	93.8	32.2	71.0	116.5	2	3.30	1.80	4.80	2.12	2					
WESTERN US																									
Mixed conifer - F/S	12.60	1.20	46.50	6.94	91	1564	155	667	1933	206	128.2	63.3	11.2	359.0	212	5.78	0.70	19.40	2.88	182	1.07	0.20	2.10	0.72	15
Mixed conifer - F	10.36	1.20	20.87	5.82	42	1664	138	667	1933	78	76.8	30.5	11.2	162.2	79	3.31	0.70	6.32	1.46	68					
Mixed conifer - S	14.58	7.00	46.50	7.30	47	1570	56	1311	1656	82	146.2	33.5	73.0	263.0	92	7.24	1.80	19.40	2.37	85					
Mixed conifer - RS											235.4	54.5	156.0	359.0	27										
Grass - F/S	9.89	3.62	18.78	6.90	4	1531	238	1032	1750	10	55.8	29.5	11.7	115.3	10	1.98	1.07	4.20	1.08	8	0.30	0.21	0.37	0.08	3
Grass - F						1638	78	1554	1750	8	45.0	19.4	11.7	75.6	8	1.67	1.07	2.68	0.65	7					
Grass - S						1102	99	1032	1172	2	98.9	23.2	82.5	115.3	2	4.20				1					
Hardwood - F/S	10.77	1.10	33.70	6.04	25	1577	141	1098	1786	30	109.3	65.9	29.0	326.0	30	5.79	0.66	18.50	4.32	30	0.58	0.27	0.95	0.28	4
Hardwood - F	6.36	1.10	10.12	3.25	8	1711	34	1668	1786	12	55.3	33.3	29.0	155.0	13	1.89	0.66	3.23	0.89	12					
Hardwood - S	12.84	8.80	33.70	5.98	17	1489	114	1098	1627	17	150.6	53.5	71.0	326.0	17	7.92	3.30	18.50	3.20	17					
Shrub - F/S	7.99	4.86	12.25	2.12	19	1570	147	1174	1876	76	107.2	55.4	22.6	278.7	93	2.51	0.20	6.31	1.56	36	1.48	0.09	4.24	1.16	31
Shrub - F	6.97	4.86	8.66	1.25	11	1696	78	1538	1876	24	66.4	18.4	22.6	109.0	37	2.02	0.20	6.31	1.25	26	1.45	0.41	4.24	1.10	26
Shrub - S	9.39	5.35	12.25	2.33	8	1549	55	1471	1600	4	101.6	23.3	55.5	131.5	8	4.44	2.05	6.20	1.31	7	2.12	0.35	4.00	1.83	3

	NH_3 (Ammonia, g/kg)					SO_2 (g/kg)					NO_x (g/kg)					NO (g/kg)					NO2 (g/kg)					N_2O (g/kg)	
	Avg	Min	Max	SD	n	Avg	Min	Max	SD	n	Avg	Min	Max	SD	n	Avg	Min	Max	SD	n	Avg	Min	Max	SD	n	Avg	n
ALASKA/CANADA																											
Boreal forest F/S	2.07	0.59	8.69	2.95	7	0.15	0.10	0.20	0.07	2	2.33	1.05	3.50	1.08	5	2.76	1.61	3.90	1.62	2	3.20				1	0.24	3
SOUTHEASTERN US																											
Grass F/S	1.20	0.40	1.90	0.56	6	0.97	0.50	1.44	0.36	6	3.26	2.65	3.90	0.49	5	4.26	1.98	8.10	2.34	6	1.13	1.03	1.23	0.14	2		
Hardwood F/S	1.79	0.35	3.70	1.63	4	0.63	0.44	0.87	0.20	4	2.43	1.77	3.10	0.66	3	4.78	1.37	9.60	3.91	4	0.75	0.62	0.89	0.19	2		
Pine F/S	0.70	0.02	5.30	1.16	31	0.79	0.43	1.55	0.46	5	1.96	0.23	4.80	1.13	23	1.67	0.23	7.01	1.86	22	1.32	0.06	3.30	0.98	19		
Shrub F/S	2.21	0.47	6.60	2.50	5	0.87	0.30	1.70	0.57	5	4.23	2.03	6.79	1.84	7	6.53	1.15	11.29	3.35	9	0.81	0.34	1.35	0.36	6		
WESTERN US																											
Mixed conifer F/S	1.07	0.20	2.10	0.72	15	0.88	0.30	2.25	0.62	10	3.22	0.81	11.01	2.51	20	1.63	0.28	4.90	1.23	24	1.15	0.30	2.85	0.82	17	0.27	1
Grass F/S	0.30	0.21	0.37	0.08	3											3.11	1.41	4.80	1.58	6	7.17	4.80	10.20	2.76	3		
Hardwood F/S	0.58	0.27	0.95	0.28	4	0.52	0.00	1.00	0.24	26	3.25	3.16	3.42	0.15	3	2.17	0.87	2.83	1.13	3	1.85	0.50	4.48	2.28	3		1
Shrub F/S	1.48	0.09	4.24	1.16	31	0.53	0.10	0.90	0.22	16	3.57	1.29	8.90	1.75	25	2.45	0.41	6.60	1.59	22	0.92	0.20	2.86	0.78	22	0.29	2

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Introduction

Scientists, land managers, regulators and policy makers require improved emission estimates to assist in local to regional assessments including prescribed burn programs, emissions inventories and carbon accounting. Wildland fires, including prescribed fire and wildfires, are a significant source of fine particulate matter ($PM_{2.5}$), carbon monoxide, and nitrogen oxides, which are criteria air pollutants regulated by the US EPA. Wildland fires also produce greenhouse gases including carbon dioxide and methane, which play an important role in the global climate system. Emission factors are used in fire effects and emission models to estimate pollutant emissions from total fuel consumption. This analysis was based on a synthesis of emission factors (Lincoln et al., 2014) from hundreds of publications funded by the Department of Defense Strategic Environmental Research and Development Program (SERDP) and augmented with publications since 2011 (see References). To date, it represents the most comprehensive analysis of emissions factors for North America.

The objective of this project was to develop emissions factors that support emission reduction techniques and are employable in modeling tools such as CONSUME, FOFEM and the BlueSky Smoke Modeling Framework. Trace gas species and particulates were summarized by vegetation category and combustion phase (flaming, smoldering, and residual smoldering). One of the key advancements in recent emissions studies is the inclusion of Modified Combustion Efficiency for characterization of flaming versus smoldering combustion (Urbanski 2014). Selecting the most appropriate emission factors to represent emissions from biomass burning must consider the combustion of smoldering fuels (e.g., large down dead wood and duff) and can assist fire managers in identifying burn prescriptions and emissions reduction techniques to potentially mitigate pollutant emissions and long-term smoke impacts.

Methods

To evaluate potential differences in emissions prediction between old and new emission factors, we used data collected for past fuel consumption studies in southeastern and western pine forests. Consumption data were partitioned into fuel categories that consumed in flaming, smoldering and residual phases of combustion. Based on measured fuel consumption by flaming and smoldering, we calculated wildland fire emissions using emissions factors currently in CONSUME from Hardy (2001) ("Old Consume"), fire-average emissions factors that estimate an average flaming-smoldering emissions ("Fire Average"), and emissions factors specific to flaming, smoldering and residual-smoldering combustion ("Component"). We used PM2.5 predictions to evaluate trends in pre-burn fuel loading and consumption relative to PM 2.5 emissions (Figure 1). We also compared the three emissions prediction approaches for CO, CO_2 and $PM_{2.5}$.

Summary of Findings

This study presents revised emissions factors for pollutant and greenhouse gases by major vegetation type and combustion phase (**Table 1**). For residual smoldering emissions factors, we recommend using Urbanski (2014). Using measured fuel consumption from 60 pine-dominated sites in the southeastern US and 60 pine-dominated sites in the western US, we evaluated the influence of fuel composition and loading on $PM_{2.5}$ emissions.

- **Figures 1 and 2** demonstrate a strong relationship between pre-burn loading and fuel consumption and emissions and suggest that variability in pollutant emissions is primarily influenced by fuel loading and consumption. Reducing errors in pre-burn fuel loading and fuel consumption estimates will provide the greatest refinements to estimating pollutant emissions.

We also evaluated three different techniques in estimating pollutant emissions across the SE and western pine sites using 2001 Smoke Management Guide emissions factors, fire average emissions factors, and component emissions factors by flaming, smoldering and residual combustion.

- Using revised emissions factors, $PM_{2.5}$ and CO emissions factors are higher than the original estimates within the 2001 Smoke Management Guide (**Figures 2a,b**). Revising CONSUME and FOFEM to include these values will increase estimated $PM_{2.5}$ and CO, particularly on sites with fuel categories that contributed to long-term residual smoldering combustion (e.g., coarse wood and duff).
- Using component EFs by flaming, smoldering and residual smoldering produced lower $PM_{2.5}$ emissions than using fire-average EFs and suggests that component EFs will be useful in informing smoke reduction techniques.
- In contrast, carbon dioxide (CO_2) emissions estimates do not vary much between approaches..

Finally, our synthesis of available emissions factors highlights the need for increased observations to offer emissions factors for other vegetation types and by combustion phase for a wider range of pollutant categories than is supported to date.

- These revised emissions factors will be published in a peer-reviewed manuscript.
- Plans are also underway to create an online emissions factor database that provides a clearinghouse for pollutant emissions measurements, source references, modified combustion efficiency values, and emissions factors summarized by region and major vegetation type.

Figure 1 : Pre-burn biomass by fuel category, fuel consumption and $PM_{2.5}$ emissions by combustion phase for western pine sites (A) and southeastern pine sites (B). Sites are ordered by total fuel consumption.

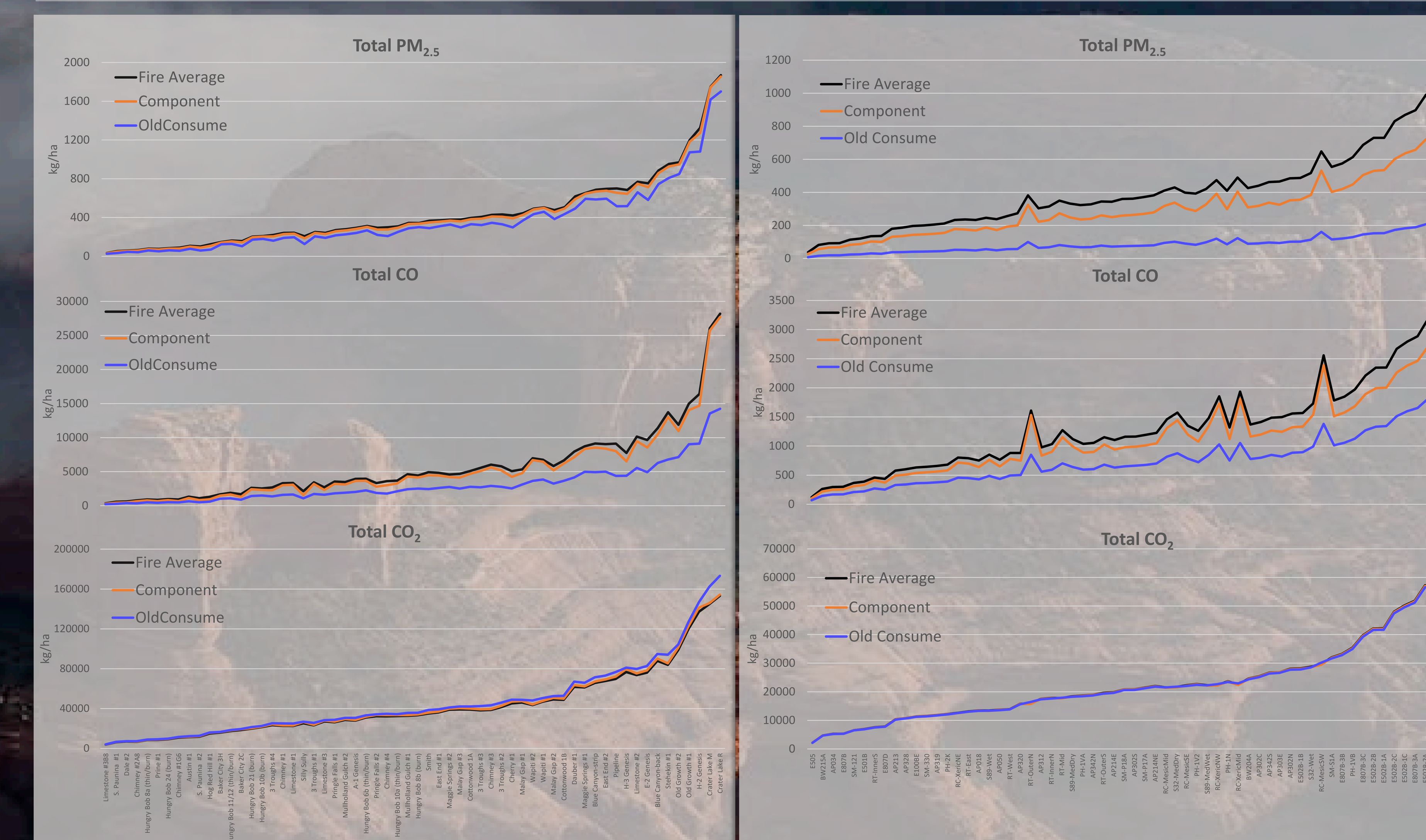

Figure 2: Comparison of estimated PM2.5 emissions across western pine sites (A) and southern pine sites (B) using fire average emissions factors, component emissions factors by flaming, smoldering and residual smoldering phases, and original emissions factors within CONSUME.