Air Sciences Inc.
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TECHNICAL MEMORANDUM

REVIEW OF AGRICULTURAL CROP RESIDUE LOADING, EMISSION FACTORS, AND REMOTE FIRE DETECION

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Summary

Quantification of fire emissions from agricultural crop residue burning is essential to the accounting of anthropogenic fire emissions in the United States, as well as globally. This technical memorandum reviews the current WRAP-based methodology to estimate air emissions from agricultural burning, and reviews the development of alternative methods and improvements reported in the scientific literature and regulatory documents. The procedures to estimate fuel loading and emission factors by crop type have changed relatively little. However, significant progress has been made in the detection of fire activity through remote sensing, as well as in the development of GIS-based agricultural land use and crop layers. Preliminary research is underway to extent the Fuel Characteristic Classification System (FCCS) to agricultural fuels, which would allow integration into CONSUME3 for use in the Fire Emissions Tracking System (FETS).

Current Methodology

Fuel Loading

The first set of fuel loading and smoke emission factors for the WRAP were developed in support of a wildfire and prescribed fire emissions inventory (EI) for the year 1996 (Air Sciences, 2002). The methodology for this EI was extended to include emissions from agricultural crop residue burning, as part of an EI for the year 2002 (Air Sciences 2005a), and an extension thereof to projected emissions in the year 2018 (Air Sciences. 2005b). In this methodology activity data on agricultural crop residue burning was collected from regulatory sources and through surveys (Air Sciences, 2005a). Due to limited data availability this process required significant gap-fill procedures and assumptions regarding location and day of individual burns. Fuel loading and emission factors were based on work by ERG (2002a, 2002b). This data consisted of a set of default fuel loading and pollutant specific emission factors by crop type. The main sources of these default values (ERG, 2002a, 2002b) were a set of wind tunnel experiments performed at UC Davis, California (Jenkins et al., 1996a and 1996b), and the AP-42 documentation developed by the US Environmental Protection Agency (EPA, 1992). The AP-42 document has not been updated since 1992, and draws from agricultural burning information dating to the mid 1970's (EPA, 1992). Thus, the current default fuel loading and emission factor data are limited due to their age, regional character (mostly based on crops in California and Hawaii), and representativeness (emission factors obtained through wind tunnel experiments are not necessarily representative of "typical" field burning conditions). Nevertheless, this default dataset is still the best reference data currently available, and is still used by the California Air Resources Board (CARB, 2000 and 2005). Air Sciences developed a refined EI for the state of Wyoming (Air Sciences, 2007), utilizing the same set of fuel loading and emission factor data as used for the WRAP region. However, in this effort (Air Sciences, 2007) the agricultural burning activity data was refined through an agricultural land burn survey for the state of Wyoming and county-specific crop production statistics from the National Agricultural Statistics Service (NASS). The default set of crop residue loading and emission factors is provided in Table 1 of this technical memorandum.

Agricultural Emissions Calculations In The FETS

Currently, agricultural burning in the FETS is not delineated by crop type: a single classification code, "Agricultural Land," is used to describe all burns. Thus, the same fuel loading and emission factors are used for all agricultural burns, derived by averaging all values from Table 1. Fuel loading information submitted to the FETS along with activity data is used preferentially, but even in this case information regarding crop type is not stored. Because there are currently no fuel beds for agricultural land for use with CONSUME3, emissions from agricultural burns are calculated by multiplying acres, an emissions factor, and a fuel loading.

Review of Current Research

Fuel Loading

A review of the scientific literature and regulatory documentation did not yield major potential updates or improvements of fuel loading estimates compared to the current default values used in FETS (WRAP, 2010). NASS (2010c) has not produced new research in this area as their primary focus is on agricultural production and economics data. Extensive additional field research has been performed for two western crop types, wheat stubble (representative of "cereal grains") and Kentucky Bluegrass (representative of "turf grasses"). Research efforts in Eastern Washington and Northern Idaho resulted in improved fuel loading estimates for these crop types (Air Sciences, 2003; Dhammapalla et al., 2006 and 2007a; Johnston and Golob, 2004). These updates have been included in scientific studies (for example, Jain et al., 2007), the Idaho State 2009 " Open Burning of Crop Residue State Implementation Plan (SIP) Revision" (ID DEQ, 2009), as well as the ClearSky model (Jain et al., 2007; Vaughan, 2010). However, even with the same crop, there might be significant variation in crop residue loading due to differences between regions, yield, and fuel management practices prior to a burn (Air Sciences, 2003; Johnston and Golob, 2004).

Emission Factors

Similar to fuel loading, relatively little new data regarding emission factors has been reported over the last decade. Several studies report emission factors for major crops in Asia (Dalphi et al, 2006; Sahai et al, 2007; Yang et al., 2008; Zhang et al, 2008; Gadde et al., 2009), but these may not be representative for crops in the (western) United States. Additional studies in the United States are limited to those conducted in the northwest for wheat and Kentucky Bluegrass (Air Sciences, 2003; Dhammapalla et al., 2006 and 2007a; Johnston and Golob, 2004). These updates have been included in the Idaho State 2009 "Open Burning of Crop Residue State Implementation Plan (SIP) Revision" (ID DEQ, 2009), and the in ClearSky model (Jain et al., 2007; Vaughan, 2010). ClearSky provides the agricultural modeling portion of the BlueSky smoke model, a modeling framework to simulate cumulative smoke impacts from wildland fire, and prescribed and agricultural burning (Larkin et al., 2007).

Finally, although the current WRAP-FETS frame work applies a set of default emission factor for each crop type, emission factors have been reported to vary considerably as a function of factors such as fuel moisture, burn type and the layout of the fuelbed (Carroll et al, 1977; Air Sciences, 2003). This variation primarily acts through changes in the combustion efficiency (Air Sciences, 2003; Dhammapalla et al., 2006 and 2007a; Johnston and Golob, 2004), with higher the combustion efficiencies leading to higher CO_2 emissions, but lower CO and particulate emissions.

Fire Activity Detection through Remote Sensing

One of the main potential improvements from the initial WRAP EIs for agricultural burning is the characterization of fire activity. The early EIs were based on a combination of spotty data obtained from regulatory agencies, and gap-filling procedures through a series of assumptions regarding amount of crop land in production, percentage area burned, and the burn date (e.g., Air Sciences, 2005a). These were the best available methods at the time. EPA applied a similar methodology in a recent greenhouse gas inventory for the United States (EPA, 2009). A recent development that will improve the assignment of fuel type is a GIS-based crop layer produced by NASS (2010a and 2010b), in cooperation with Dr. Jessica McCarty (University of Louisville). These layers can be applied to identify crop type based on geographical coordinates originating from agency reported burns or satellite detected burns.

Detection of fire activity through remote sensing has improved considerably over the last decade, and is currently embedded in FETS (WRAP, 2010). Given the importance of emissions from agricultural burning as a source of greenhouse gasses, many research studies have focused on improving remote sensing fire detection, worldwide (Korontzi et al., 2006), in Asia (Duan et al., 2004; Yan et al., 2006), Australia (Smith et al., 2007) and in the United States. Recent progress in the United States consists of estimating the spatial and temporal extent of agricultural burning through MODIS in the southeast (McCarty et al., 2007), the Mississippi Delta (McCarty et al., 2008) and most recently the contiguous United States (McCarty et al., 2009). A major strength of this methodology is that fire activity can be detected real-time, without relying on subsequent reporting systems (with associated time delays). The remote sensing techniques have improved over time through increased resolution of the MODIS data, as well as improved hybrid post-processing techniques (McCarty et al., 2008 and 2009). A limitation of the remote sensing methodology is that smaller fires may not be detected. Hawbaker et al (2008) reported that a 260-acre fire in the United States had a 50 percent chance of detection with MODIS. Detection rates in China (Yan et al., 2006) and Australia (Smith et al., 2007) were less than 1 and 13 percent, respectively. The especially low detection rate in China was attributed to the small scale of individual burns (Yan et al., 2006). Cloud cover, and the short duration and low- intensity of many agricultural burns also contribute to low detection rates through remote sensing (Hawbaker et al., 2008). However, much higher detection rates have been reported for the application for hybrid MODIS techniques in the United States, with detection rates of 80 to 90 percent in the southeast (McCarty et al., 2008 and 2009), where the typical crop residue burn is about 40 acres in size (McCarty et al., 2008).

Finally, an important promising development in this area is the extension of the FCCS framework (Ottmar et al., 2007) to agricultural crops, through a joint project between Drs. Soja (NASA), French (Michigan Technological University) and McCarty (University of Louisville). While only in a preliminary stage, this project aims to develop FCCS type fuel beds for agricultural crops and residues (French, 2010). Detected or reported fire activity in a fuel bed would be run through the CONSUME 3 model (Ottmar and Prichard, 2008; Ottmar, 2009), in a similar manner as currently implemented in FETS for wildland and prescribed fires (WRAP, 2010). This would greatly improve emission estimates, as these would be based on individual burns accounting for the effects of fuel moisture on fuel consumption and emission factors.

Improvements to Emissions Calculations in the FETS

Review of the recent developments in fuel loading and emission factor methodology did not yield any recent improvements to estimate emissions from agricultural burning. There are, however, three distinct sources of data missing from the FETS that are currently available for use:

- Crop-specific fuel loadings and emission factors, listed in Table 2, used in previous emission inventories (Air Sciences, 2005a and 2007);
- Emission factor improvements for wheat and Kentucky Bluegrass in the Pacific Northwest region (Air Sciences, 2003; Johnston and Golob, 2004; Dhammapalla et al., 2006 and 2007a);
- 30-meter RASTER crop layers developed by National Agricultural Statistics Service (NASS). For many States, multiple years (2007-2009) are available. A 2009 crop layer is available for every State.

Table 1 shows a hierarchy of preferred sources of information for calculating emissions for Agricultural burning. For future emission inventory work, the hierarchy will act as a decision tree for creating the best-available inventory for a reasonable level of effort. “Availability” refers to the earliest the data source will be included in the FETS system. Inclusion of “2002 WRAP EI Methods” represents an absolute worst-case scenario for agricultural data, as it relies on crop yield by State rather than actual burn activity data. In all likelihood, given the availability of other gap-filling techniques such as satellite detection, this method will not be necessary.

Table 1. Hierarchy of Data Sources for Calculating Agricultural Burning Emissions

Data Source	Location	Date/Time	Acres	Crop Type	Fuel Loading	Emission Factors	Availability in FETS
FCCS Crop-Specific Fuel beds					1	1	Unknown (in early development)
Published Fuel loadings/EFs (Table 2)					2	2	Summer 2010
Agency Reports	1	1	1	1	3	3	Crop Type available Summer 2010
Satellite Detection (gap-filling)	2	2	2				2011
NASS Crop Layer (current year)				2			Varies by State; earliest Fall 2010
NASS Crop Layer (latest available year)				3			Fall 2010
2002 WRAP EI Methods (obsolete)	3	3	3	4			Likely not necessary

Note: “1” indicates the most preferred alternative.

Development of the FCCS concept to agricultural fuel beds, while only in a preliminary phase, may be readily incorporated into the FETS for use with CONSUME3 and will bring greater consistency of emissions calculations across all fire types. Until it is available, however, the use of fuel loadings and emission factors in Table 2 will be adequate to calculate consistent, crop-specific emissions from Agricultural burning. Data from Table 2 are preferred over user-supplied data in the Table 1 hierarchy because unlike Prescribed burning, where region-specific fuel loadings are well documented and burners have considerable knowledge of local fuel beds, research and documentation on crop residue loadings—especially by region—is sparse. Therefore, since user-supplied estimates are likely derived from, if not identical to, Table 2, using a singe set of values leaves unperturbed the comparability of emissions estimates across regions.

Table 2: WRAP-Based Fuel Loading and Emission Factors for Agricultural Crop Residues (Air Sciences, 2005a).

Crop Type	Residue Loading (ton/acre)	Emission Factors by Pollutant (lbs pollutant/ton residue)											
		PM	PM_{10}	$PM_{2.5}$	EC	OC	VOC	CH_4	NH_3	NO_x	CO	SO_2	PM_C
almonds	1	8.72	8.60	8.20	2.15	3.70	8.90	2.34	1.28	7.24	63.86	0.12	0.40
apples	2.3	8.55	8.39	7.96	2.10	3.61	4.95	3.73	1.81	11.18	90.32	0.22	0.43
apricots	1.8	9.07	8.90	8.45	2.22	3.83	6.94	5.24	1.48	7.84	73.91	0.15	0.45
asparagus	1.5	32.94	32.40	30.90	8.10	13.93	14.99	11.32	2.72	5.02	135.88	0.67	1.50
avocado	1.5	29.69	29.14	27.44	7.28	12.53	26.17	19.76	3.28	7.36	164.07	0.14	1.70
barley	1.7	15.52	15.36	14.86	2.46	6.14	23.34	4.94	3.95	5.44	197.34	0.08	0.50
beans; all dry edible	2.5	15.72	15.46	14.67	3.87	6.65	16.03	12.10	3.34	5.87	167.04	0.11	0.79
blueberries	1.7	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
bushberry	1.7	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
canola	1.3	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
cherries	1	12.62	12.38	11.60	3.10	5.32	9.40	7.10	1.38	8.15	68.97	0.16	0.78
citrus	1	8.50	8.35	7.92	2.09	3.59	9.62	7.26	2.29	7.36	114.57	0.14	0.42
coffee	1	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
corn; for grain*	4.2	12.62	12.42	11.96	1.86	4.35	9.12	3.50	1.55	3.64	77.56	0.40	0.46
corn; for silage	0	12.62	12.42	11.96	1.86	4.35	9.12	3.50	1.55	3.64	77.56	0.40	0.46
cotton; amer. pima	1	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
cotton; upland	1	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
CRP	2.6	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
dates	1.7	11.52	11.30	10.73	2.83	4.86	4.38	3.31	1.29	6.00	64.59	0.12	0.58
ditches and ditch banks	3.2	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
ditches and fenceline	1.6	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
figs	0.75	10.06	9.87	9.30	2.47	4.24	8.58	6.48	1.63	7.44	81.55	0.14	0.57
filberts*	1.7	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
flaxseed*	1.7	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
fruits and vegetables; other	2	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
grapes	1.47	7.29	7.15	6.72	1.79	3.08	5.55	4.19	1.49	7.59	74.45	0.15	0.44
hay; alfalfa	2.5	32.34	31.81	30.36	7.95	13.68	24.22	18.29	2.66	5.02	132.81	0.67	1.45
hay; all	0.8	32.34	31.81	30.36	7.95	13.68	24.22	18.29	2.66	5.02	132.81	0.67	1.45
hay; all other	0.8	32.34	31.81	30.36	7.95	13.68	24.22	18.29	2.66	5.02	132.81	0.67	1.45
hops	0.8	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
kiwi	1.9	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
lentils	1.7	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
macadamia nuts	2.5	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
mint	1.7	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
nectarines	0.5	5.84	5.74	5.44	1.43	2.47	3.38	2.55	0.97	7.65	48.53	0.15	0.29
oats	1.7	23.28	22.90	21.79	5.72	9.85	11.39	8.60	3.01	4.98	150.44	0.66	1.11
olives	1.6	18.08	17.74	16.69	4.44	7.63	15.49	11.69	3.43	7.82	171.43	0.15	1.05
onion seeds	1.7	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
orchard pruning; unspecified	1.7	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
orchard removal	15	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
peaches	2.5	7.13	7.00	6.64	1.75	3.01	3.56	2.69	1.00	6.17	49.82	0.12	0.36
Peanuts	1.2	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
Pears	2.6	13.65	13.39	12.63	3.35	5.76	7.76	5.86	1.74	7.91	86.76	0.15	0.76
peas; dry edible	2.5	15.72	15.46	14.67	3.87	6.65	16.03	12.10	3.34	5.87	167.04	0.11	0.79
Pecans	1.7	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
Persimmons	1.7	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
Pistachio	1.7	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
plums and prunes	1.2	3.96	3.88	3.75	0.97	1.67	6.16	4.65	1.26	6.96	62.92	0.13	0.13
pomegranates*	1.7	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
Potatoes	1.2	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
proso millet	1.9	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
quinces*	1.7	11.16	10.96	10.25	2.74	4.71	8.85	6.68	1.85	7.30	92.70	0.14	0.70
rice; all	3	6.98	6.92	6.44	1.25	1.38	6.74	1.44	1.26	5.68	62.78	1.24	0.48
rye	1.9	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78

*These crops do not have unique emission factors but are associated with emission factors for other crops.

Table 2: WRAP-Based Fuel Loading and Emission Factors for Agricultural Crop Residues (Air Sciences, 2005a), Cont'd.

	Residue Loading (ton/acre)	Emission Factors by Pollutant (lbs pollutant/ton residue)											
Crop Type		PM	PM_{10}	$PM_{2.5}$	EC	OC	VOC	CH_4	NH_3	NO_x	CO	SO_2	PM_C
safflower	1.3	20.95	20.61	19.67	5.15	8.86	17.23	13.01	3.35	5.24	167.64	0.70	0.93
seeds; alfalfa*	0.8	32.34	31.81	30.36	7.95	13.68	24.22	18.29	2.66	5.02	132.81	0.67	1.45
seeds; KBG	2	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
seeds; other	2	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
seeds; unspecified*	2	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
sorghum*	2.9	21.74	21.38	20.41	5.34	9.19	6.16	4.65	1.86	5.43	93.00	0.72	0.97
soybeans*	1	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
sudan*	2	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
sugarbeets*	1	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
sugarcane	14	11.22	10.86	9.98	1.63	4.02	3.68	0.82	1.02	2.80	50.96	1.24	0.88
sunflower	1	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
various weeds and ditch banks*	1	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
walnuts*	1.2	6.44	6.30	5.92	1.83	2.96	9.30	3.28	2.00	6.78	100.08	0.28	0.38
wheat; all	1.9	11.64	11.48	10.88	1.61	4.36	10.84	3.64	2.67	4.66	133.38	0.94	0.60
wheat; durum	1.9	11.64	11.48	10.88	1.61	4.36	10.84	3.64	2.67	4.66	133.38	0.94	0.60
wheat; other spring	1.9	11.64	11.48	10.88	1.61	4.36	10.84	3.64	2.67	4.66	133.38	0.94	0.60
wheat; other spring (irrigated)	4	11.64	11.48	10.88	1.61	4.36	10.84	3.64	2.67	4.66	133.38	0.94	0.60
wheat; unspecified*	1.9	11.64	11.48	10.88	1.61	4.36	10.84	3.64	2.67	4.66	133.38	0.94	0.60
wheat; winter all*	1.9	11.64	11.48	10.88	1.61	4.36	10.84	3.64	2.67	4.66	133.38	0.94	0.60
unspecified	--	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CARB average field crop	2.6	9.01	8.86	8.47	2.22	3.81	5.96	4.50	1.27	2.51	63.55	0.33	0.39
other ag burning*	2.6	9.01	8.86	8.47	2.22	3.81	5.96	4.50	1.27	2.51	63.55	0.33	0.39
CO average field crop*	4.2	12.62	12.42	11.96	1.86	4.35	9.12	3.50	1.55	3.64	77.56	0.40	0.46
Idaho Crop N/A*	2	18.02	17.73	16.95	4.43	7.62	11.93	9.01	2.54	5.02	127.09	0.67	0.78
berries; other*	1.3	20.95	20.61	19.67	5.15	8.86	17.23	13.01	3.35	5.24	167.64	0.70	0.93

*These crops do not have unique emission factors but are associated with emission factors for other crops.

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