Using Satellite Data to Quantify Cropland Burning and Related Emissions in the Contiguous United States: Lessons Learned

Jessica L. McCarty
Michigan Tech Research Institute, Ann Arbor, MI 48105
jmccarty@mtu.edu

George Pouliot
Atmospheric Modeling and Analysis Division, National Exposure Research Laboratory, Environmental Protection Agency, Research Triangle Park, NC 27711
Pouliot.George@epa.gov

Sean M. Raffuse
Sonoma Technology, Inc., Petaluma, CA 94954
sraffuse@sonomatech.com

Mark Ruminski
NOAA/NESDIS, Camp Springs, MD 20746
Mark.Ruminski@noaa.gov

James J. Szykman
Environmental Sciences Division, National Exposure Research Laboratory, Environmental Protection Agency, c/o NASA Langley Research Center, Hampton, VA 23681
james.j.szykman@nasa.gov

Amber J. Soja
Institute of Aerospace (NIA), NASA Langley Research Center, Hampton, VA 23681
amber.j.soja@nasa.gov

ABSTRACT

Prescribed fires in agricultural landscapes generally produce smaller burned areas than wildland fires but are important contributors to emissions impacting air quality and human health. Currently, there are a variety of available satellite-based estimates of crop residue burning, including the NOAA/NESDIS Hazard Mapping System (HMS), the Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation (SMARTFIRE), the Moderate Resolution Imaging Spectroradiometer (MODIS) Official Burned Area Product (MCD45A1), the MODIS Active Fire Product (MOD/MYD14), a regionally-tuned 8-day cropland differenced Normalized Burn Ratio product for the contiguous U.S., and the 2008 National Emissions Inventory. Detailed comparisons of burned area and emission estimates from these datasets will be presented, with a focus on years 2003 through 2008, as well as methodological differences. For example, many of the operational remote sensing datasets derived from MODIS lack adequate training and validation data to accurately map prescribed fires from crop residue burning. Quantifying burned area in cropland landscapes from the 4 km Geostationary Operational Environmental Satellite (GOES) Wildfire Automated Biomass Burning Algorithm (WF-ABBA) or 1 km MODIS MOD/MYD14A1 active fire detections require in-situ knowledge of field size and/or fire management practices.

INTRODUCTION

Crop residue burning is a common agricultural practice used globally[1-5]. In the contiguous United States (CONUS), crop residue burning is used by farmers as an inexpensive and effective method to remove excess residue to facilitate planting, control pests and weeds, and/or provide fast-acting ash fertilization prior to planting or re-seeding[6-8]. Previous research has shown that crop residue burning is a seasonal practice for the CONUS, occurring mainly in the spring (April to June) and fall (October to December), with some summer (July to September) and winter (January to March) burning associated with the specific crop types of Kentucky bluegrass and sugarcane, respectively[9]. Prescribed fires in agricultural landscapes generally produce smaller burned areas than wildland fires but are important contributors to emissions impacting air quality and human health[10].

The purpose of this analysis is to present a detailed comparison of burned area and $PM_{2.5}$ emission estimates from four current datasets, with a focus on years 2003 through 2008, to illustrate both the current state of the science in calculating agricultural and/or cropland burning emissions for air quality monitoring as well as the range of the resulting methodologies. Data and methodological differences in how agricultural and/or cropland burned area is determined as well as approaches to emission calculations are also described. This paper will focus on satellite-based estimates of crop residue burning from the NOAA/NESDIS Hazard Mapping System (HMS)[11], the Satellite Mapping Automated Reanalysis Tool for Fire Incident Reconciliation (SmartFire Version 2)[12,13], a regionally-tuned 8-day cropland differenced Normalized Burn Ratio product for the CONUS[14, 9], and the 2008 National Emissions Inventory. Additionally, emission estimates derived from combining official MODIS fire products from NASA - the Moderate Resolution Imaging Spectroradiometer (MODIS) Official Burned Area Product (MCD45A1)[15,16] and the MODIS Active Fire Product (MOD/MYD14)[17,18] - for the CONUS are also included for year 2006. Burned area and $PM_{2.5}$ emission estimates from the Fire INventory from NCAR (FINN)[19] and the Global Fire Emissions Database (GFED)[20] were not included in this analysis. Therefore, this is not a complete comparison of all existing fire emission inventory datasets for agricultural and/or cropland burning sources for the CONUS.

BODY

Burned Area and Emission Calculations: Fire Data and Emission Variables

<u>Cropland-specific burned area product from MODIS data</u>

A regionally adapted hybrid method of mapping burned area in crop-dominated landscapes was developed by combining changes in surface reflectance due to burning of crop residues with locations of burning from active fire detections. Two Collection 5 MODIS products were utilized in this approach: the 500 m MODIS 8-day Surface Reflectance Product (MOD09A1)[21] [Terra satellite only] and the 1 km MODIS Active Fire Product (MOD14/MYD14) [both Terra and Aqua satellites][17,18]. 8-day differencing of Normalized Burn Ratio (dNBR) burned area maps were derived for each MODIS tile in the CONUS and combined with MODIS active fire counts calibrated into area. Areas undetected by the dNBR approach were mapped by calibrating the 1 km MODIS active fire product into area using coincidental high resolution (15 m) Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data and the 1 km MODIS active fire points were found to approximate the average field size in each agricultural region. A detailed description of this cropland burned area methodology, validation methodology and results, and crop residue burned area estimates for the CONUS is further explained in McCarty et al.[9]

For this comparison analysis, $PM_{2.5}$ emission estimates were estimated utilizing the methodology described in McCarty[10]. In general, crop type maps for the CONUS were created to assign specific crop type values to each active fire point or burned area pixel. This allowed for crop type-specific emission calculations. For this comparison, the resulting agricultural burning emission calculations are reported for years 2005, 2006, and 2007 and are referred to as McCarty Cropland.

NOAA Hazard Mapping System

The Hazard Mapping System (HMS) was developed in 2001[22] as an interactive tool to identify fires and smoke over North America in an operational environment. It was devised as a result of the massive transport of smoke into the Gulf Coast states and beyond due to seasonal burning in Central America in 1998. The HMS uses two geostationary and five polar orbiting environmental satellites. The polar satellite instruments (NASA's MODIS and NOAA's AVHRR) are superior to the Geostationary Operational Environmental Satellite (GOES) geostationary platform in detecting smaller, cooler burning fires and in estimating fire size due to their higher spatial resolution (1 km vs 4 km at nadir). However, the frequent update cycle of GOES imagery (routine 15 minute with the possibility of 5 minute refresh) allows for the detection of shorter duration fires or those obscured by clouds at the time of polar satellite overpass. Automated fire detection algorithms are employed for each sensor. Each algorithm utilizes multi-spectral imagery and applies a form of temperature threshold and horizontal spatial characterization to evaluate each hotspot.

The HMS analysis domain includes all of North America, although the analysis over central and northern Canada and Alaska is only performed during the burning season from May to November. Analysts view the satellite imagery and apply quality control procedures for the automated fire detections to eliminate hot spots that are deemed to be false detections and to add hot spots that the algorithms have not detected. The addition and deletion of fire locations are based on analyst experience in satellite image interpretation, consistency of a fire signal across image times and platforms, various layers of ancillary data (including the locations of known, recurring false detections), confirmation via the presence of smoke emissions, etc. The daily analysis is available at: http://www.firedetect.noaa.gov/viewer.htm

In addition to analyzing fire locations, the HMS analysts also identify those fires producing smoke that can be detected in visible satellite imagery. These fires are a subset of all fire hot spots. The number of input points representing a fire is considered to be proportional to an approximation of the areal extent of the fire. An estimate of the initial time and duration of smoke emissions for each fire is also noted. This information is used as input for a smoke forecast run daily by the National Weather Service (http://airquality.weather.gov/). Analysts also draw outlines of the smoke plumes that are observed and assign an estimate of the smoke concentration (density). The analyzed smoke plumes include those that are associated with actively burning fires as well as remnant smoke from previous day's fires that have drifted away (sometimes thousands of kilometers) from the source fire.

The HMS uses imagery from seven NOAA and NASA satellites to quantify all potential wildland and prescribed fires in the CONUS, as well as much of southern Canada[22]. Geostationary data are obtained via GOES-11 and GOES-12 and offer high temporal resolution (approximately every 15 minutes) but a nominal spatial resolution of 4 km. Polar orbiting data is obtained from MODIS on-board Terra and Aqua as well as the Advanced Very High Resolution Radiometer (AVHRR) on NOAA-15/17/18. Low- and mid-latitudes are scanned twice per day by the MODIS and AVHRR sensors while higher latitudes receive more frequent coverage (as much as 6 daily overpasses in Alaska and northern Canada). The MODIS Terra and NOAA-17 spacecraft have similar overpass times of ~ 1030 AM/PM local time while MODIS Aqua and NOAA-18 have overpass times of ~130 AM/PM local standard time. NOAA-15 provides coverage of ~ 600 AM/PM local standard time. For much of the western half of the U.S., the geostationary GOES-11 and GOES-12 satellites experience an overlap that provides for nearly 200 images per day[23].

The HMS system utilizes separate automated algorithms for each of the sensors, including the MODIS active fire algorithm, the WildFire-Automated Biomass Burning Algorithm (WF-ABBA) for GOES[24], and the Fire Identification, Mapping and Monitoring Algorithm (FIMMA) for AVHRR[25] were developed by Dr. Ivan Csiszar (NOAA/NESDIS) and subsequently updated for use with NOAA-15/17/18 [23]. Finally, an HMS analyst reviews these automated detections to remove any false detects not associated with vegetative biomass burning – such as power plants, manufacturing, and previously identified false detects. HMS data can be viewed and downloaded here: http://www.osdpd.noaa.gov/ml/land/hms.html.

Dr. George Pouliot, Physical Scientist in the Emissions and Model Evaluation Branch of the Atmospheric Modeling and Analysis Division/NERL/ORD of the U.S. Environmental Protection Agency, utilized the HMS data to produce an estimate of both burned area and $PM_{2.5}$ emissions for year 2006 for the CONUS. Dr. Jessica McCarty of Michigan Tech Research Institute collaborated with Dr. Pouliot on these cropland burning emission estimates, specifically assisting in crop type mapping and field size determination. The HMS satellite detects and a year specific crop type map from McCarty[10] were used to identify the satellite detections as crop residue burning and the type of crop. If the satellite detection was within 2 km and at the same time as a GOES detection, the detection was deemed to be a duplicate and was removed. This process only removed a small number of detections over the year - less than 0.1% of all detections. The crop type maps were seasonal in that a different spring crop type map (before July 1 of any given year) and a fall crop type map (after July 1) were used to assign crop types to the GOES fire pixels. After identifying the satellite detection as crop residue burning, we used state specific field size information[10] to estimate the acres burned. Combined with emission factors for the criteria pollutants, we obtained daily emission estimates of crop residue burning for the CONUS.

SmartFire 2

The national default data for the 2008 NEI (Version 2) was developed using SmartFire 2 (SF2)[13] and the BlueSky smoke modeling framework (BlueSky)[27]. The SF2-BlueSky methodology estimates emissions for wildfires (including forest and rangeland) and prescribed burns. It does not, however, provide emissions estimates for agricultural burning. One of the fire activity data sources in SF2 is the NOAA HMS, which consists of satellite detected hot spots from both polar-orbiting and geostationary platforms as previously described and includes agricultural burns. For wildland fire emissions processing, the agricultural fires were segregated from the analysis by intersecting fire locations with the USGS National Land Cover Dataset (NLCD) and tagging as agricultural all fires within the land cover types 81-Pasture Hay or 82-Cultivated Crops. For the analysis in this paper, we assumed a nominal per fire size of 40 acres to calculate state totals. PM2.5 emission estimates for year 2008 were calculated by utilizing average cropland emission factors, fuel loadings, and combustion completeness values (corresponding with the "other/fallow/lentils" values) as those utilized in cropland-specific burned area products for years 2005 through 2007 [9,10,14].

MODIS Official Burned Area Product (MCD45A1)

The MODIS Burned Area product is a 500 m daily standard MODIS product derived from both Terra and Aqua detections[16]. The MODIS Burned Area algorithm utilizes changes in spectral, temporal, and vegetation structural characteristics to identify and map burned areas[16]. 'Burned' pixels are identified through statistically significant drops in 500 m MODIS daily surface reflectance data. Estimated day of burn (i.e., "start date") is determined by identifying the first date that a decrease in surface reflectance was detected. Statistical temporal constraints within the algorithm are also employed to identify persistent burned areas and to omit potential false detections caused by shadow, clouds, water, and dark soils[15]. Finally, as a daily product, emission estimates can be produced at various time steps versus the approximate weekly (specifically 8-day) time step limitation of the cropland-specific burned area product.

MODIS Active Fire Product (MOD/MYD14)

Active fire detections from the MODIS sensors, onboard the sun-synchronous polar-orbiting satellites Terra and Aqua, are acquired four times daily for nearly the entire Earth at 1030 and 2230 (Terra) and 0130 and 1330 (Aqua), equatorial local time. The MODIS Level 2 fire product is collected daily at 1 km resolution and includes, among other information, the latitude, longitude, fire radiative power, and confidence of the fire detection[17,18]. While an assumption of the entire 1 km pixel being burned can be made when using the active fire product, this analysis assumed the same regional average field size areas as those used in the cropland-specific burned area product.

For this paper, the burned area estimates from MCD45A1 and MOD/MYD14 active fire detections calibrated into area were combined into one product (referred to as the Official MODIS Combined) and $PM_{2.5}$ emission estimates for year 2006 were calculated by utilizing average cropland emission factors, fuel loadings, and combustion completeness values (corresponding with the "other/fallow/lentils" values) as those utilized in cropland-specific burned area product for years 2005 through 2007[9,10,14]. The calibrated area of the active fire detections was based on regional average field size, the same approach utilized in the cropland-specific burned area product[14].

Emission Calculation Variables

Four remote sensing-based emission calculations were compared for this analysis. In all cases, the same emission factors, fuel loadings, and combustion completeness values as those utilized in cropland-specific burned area product[9,10,14]. Table 1 shows the cropland-specific burned area analysis (referred to as McCarty Cropland) and the HMS-based analysis (referred to as the Pouliot HMS Cropland). These two approaches were able to use crop-type specific emission variables due to the implementation of crop type maps into their approaches. Average values for combustion completeness, fuel loadings, and $PM_{2.5}$ emission factors were used in the SmartFire2 and the MCD45A1 product combined with MOD/MYD14 product (referred to as Official MODIS Combined). These average values are shown in Table 2 and correspond directly to the "other/fallow/lentils" values from the crop type-specific analyses.

Table 1. Crop type-specific emission calculation variables used for the MODIS cropland-specific burned area analysis (referred to as McCarty Cropland) and the HMS-based analysis (referred to as the Pouliot HMS Cropland).

Crop Type	Fuel Loading (tons/acre)	Combustion Completeness	$PM_{2.5}$ (lbs/ton)
Kentucky bluegrass	2.91	0.85	23.23
Corn	4.19	0.75	9.94
Cotton	1.70	0.65	12.38
Rice	2.99	0.75	4.72
Soybean	2.50	0.75	12.38
Sugarcane	4.46	0.65	8.69
Wheat	1.92	0.85	8.07
Other/fallow/lentils	2.95	0.75	12.31

Table 2. General "cropland" emission calculation variables used for the SmartFire2 and the MCD45A1 product combined with MOD/MYD14 product (referred to as Official MODIS Combined) emission calculations.

Crop Type	Fuel Loading (tons/acre)	Combustion Completeness	$PM_{2.5}$ (lbs/ton)
Average Ag Class	2.95	0.75	12.31

Emissions were calculated using the following equation:

$$e = a * ef * ce * f \qquad (1)$$

where e = emissions
a = burned area
ef = emission factor
ce = combustion completeness
f = fuel load

Results: Comparisons of the burned area and $PM_{2.5}$ emission estimates

As the scale of this analysis was the CONUS, much of the resulting detailed tables and figures have been broken down into the corresponding EPA regions (Figure 1) minus Alaska, Hawaii, Puerto Rico, Guam, Trust Territories, American Samoa, and Northern Mariana Islands. In addition to the four satellite-based approaches, $PM_{2.5}$ emission estimates from agricultural burning from the 2008 NEI Version 2 were also included (http://www.epa.gov/ttnchie1/net/2008inventory.html). Burned area is reported in acres and $PM_{2.5}$ emissions are reported in short tons.

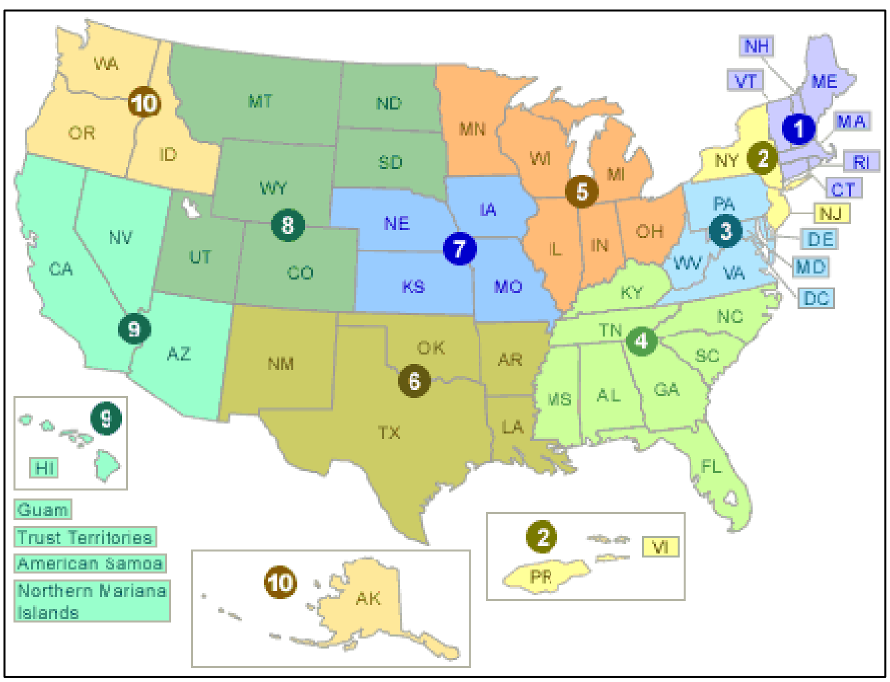

Figure 1. Map of EPA regions (image taken from http://www.epa.gov/oust/regions/regmap.htm).

Table 3 lists the agricultural burned area detected by the four satellite-based approaches for each state and divided by EPA Region. In general, the Official MODIS Combined product of the burned area and active fire data reported the smallest amounts of agricultural burning, especially in the eastern U.S. The Pouliot HMS approach also generally detected higher agricultural burned areas than the other approaches. Figure 2 graphically depicts this difference in agricultural burned area estimates across the EPA Regions. Similarly, Table 4 lists the $PM_{2.5}$ emission estimates from these four satellite-based approaches plus the 2008 NEI Version 2 (v2) for the CONUS with Figure 3 showing the emission variation across the regions.

Table 3. Agricultural burning burned area as detected by each of the satellite-based approaches; area reported in acres.

State	Pouliot HMS (2006)	McCarty Cropland (2005)	McCarty Cropland (2006)	McCarty Cropland (2007)	SmartFire2 (2008)	Official MODIS Combined (2006)
Region 1						
CT	0	0	0	0	80	0
ME	240	0	0	0	40	0
MA	40	228	689	470	80	0
NH	160	0	0	0	0	0
RI	0	0	152	40	0	0
VT	240	192	305	2,576	120	0
Region 2						
NJ	2,960	1,688	3,041	4,578	800	53
NY	2,440	3,959	5,938	6,010	1,120	623
Region 3						
DE	1,360	2,063	1,960	2,643	840	0
MD	4,800	4,066	3,804	4,577	2,560	0
PA	4,640	7,316	6,004	9,679	2,120	0
VA	10,720	3,010	5,484	4,812	14,800	40
WV	1,400	783	1,851	778	1,440	0
Region 4						
AL	106,920	7,904	21,103	22,296	39,800	1,853
FL	549,060	203,516	912,895	273,882	99,880	8,047
GA	321,520	8,517	16,479	20,282	108,520	220,612
KY	24,360	2,883	9,759	6,530	20,440	1,210
MS	94,560	35,280	39,831	38,775	97,640	10,423
NC	60,720	18,321	11,744	15,994	52,440	7,902
SC	68,200	6,582	8,068	8,988	23,440	1,558
TN	42,560	12,499	13,329	15,883	29,160	1,186
Region 5						
IL	66,600	27,910	26,318	28,766	31,720	56,561
IN	18,660	20,752	26,025	18,211	14,440	11,074
MI	6,280	37,000	38,432	20,295	2,040	2,599
MN	120,900	36,739	40,463	35,469	46,520	311,055
OH	8,960	28,021	29,337	19,588	6,360	3,499

WI	17,560	26,581	26,496	24,464	8,200	3,912
Region 6						
AR	227,960	234,514	242,916	208,193	229,200	43,885
LA	205,000	99,021	63,333	110,778	131,600	23,380
NM	3,120	12,868	12,140	7,932	1,640	212
OK	233,440	86,051	89,824	123,668	110,480	14,116
TX	762,080	159,005	201,254	187,644	126,240	81,295
Region 7						
IA	109,620	42,821	47,117	45,346	33,280	97,680
KS	594,720	144,045	117,411	135,584	247,440	99,778
MO	224,340	81,143	55,157	95,994	143,080	35,316
NE	111,060	28,000	41,271	42,145	28,960	34,803
Region 8						
CO	29,040	93,927	67,009	88,840	8,520	6,037
MT	385,200	49,754	83,930	88,061	14,280	50,934
ND	389,640	97,011	82,281	112,678	66,720	227,440
SD	53,460	101,738	61,973	102,404	13,880	23,859
UT	13,960	26,699	51,245	42,366	880	1,156
WY	23,600	11,872	27,060	18,949	1,280	3,505
Region 9						
AZ	8,560	38,342	44,512	37,685	4,120	5,795
CA	279,720	218,493	142,599	164,039	57,040	144,002
NV	2,120	3,423	8,299	7,256	600	877
Region 10						
ID	241,560	216,547	263,948	155,106	11,480	263,948
OR	115,320	67,997	79,685	103,421	14,520	138,975
WA	316,560	147,758	119,539	246,658	18,920	127,881
CONUS Total						
CONUS	5,865,940	2,456,842	3,152,011	2,710,335	1,868,760	2,238,375

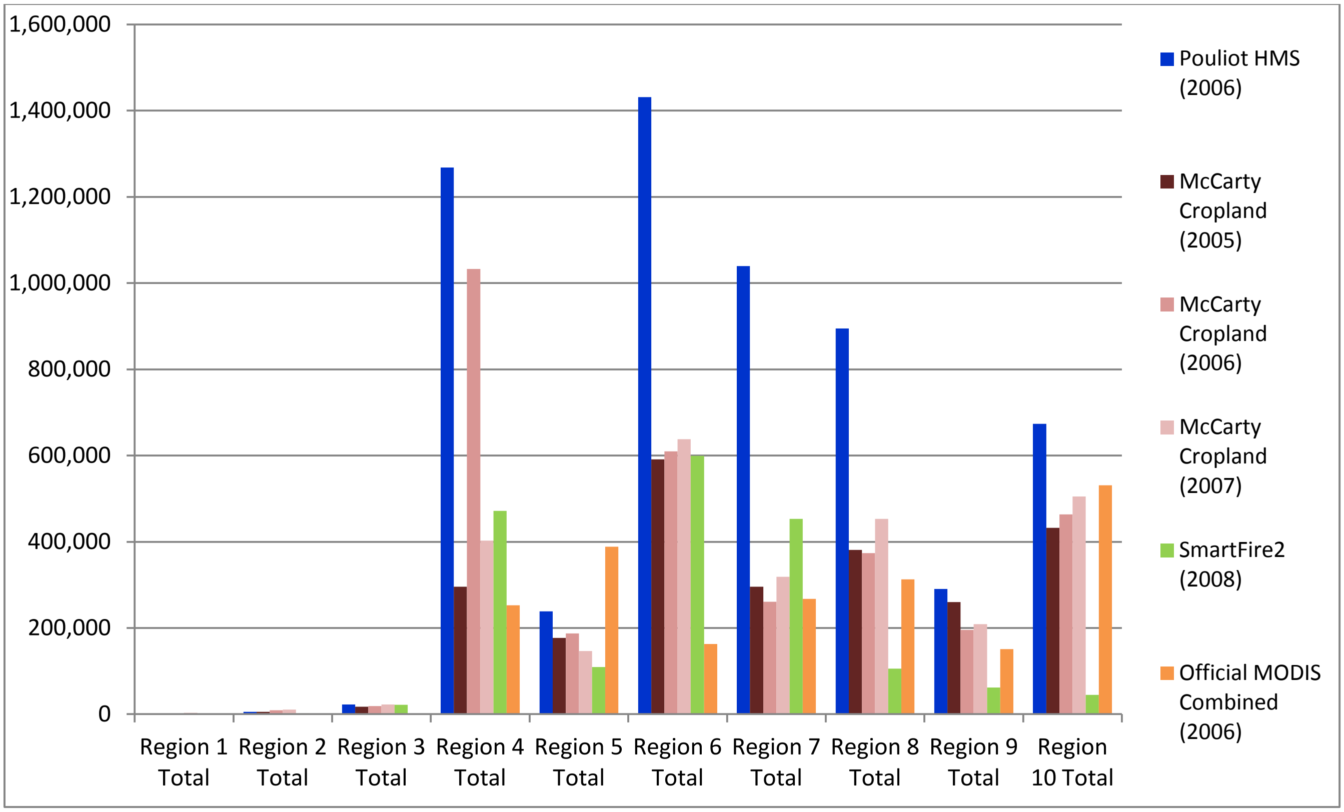

Figure 2. Total cropland burned area by EPA region as calculated by the Pouliot HMS, McCarty Cropland, SmartFire 2, and Official MODIS combined products approaches.

Table 4. Agricultural burning $PM_{2.5}$ emissions as detected by each of the satellite-based approaches and reported in the 2008 NEI v2; emissions reported in short tons.

State	Pouliot HMS (2006)	McCarty Cropland (2005)	McCarty Cropland (2006)	McCarty Cropland (2007)	SmartFire2 (2008)	Official MODIS Combined (2006)	NEI (2008)
Region 1							
CT	0	0	0	0	1	0	0
ME	3	0	0	0	1	0	0
MA	1	3	7	6	1	0	0
NH	2	0	0	0	0	0	0
RI	0	0	2	0	0	0	0
VT	3	2	3	38	2	0	0
Region 2							
NJ	44	22	37	67	11	1	209
NY	33	51	76	87	15	8	7
Region 3							
DE	18	27	15	31	11	0	12
MD	62	53	42	61	35	0	59
PA	61	79	75	132	29	0	20

VA	135	34	66	68	202	1	115
WV	17	10	23	11	20	0	0
Region 4							
AL	1,024	84	181	233	542	20	432
FL	6,297	2,498	11,481	3,153	1,361	79	3,371
GA	2,991	86	140	182	1,478	1,702	3,757
KY	326	28	97	278	189	15	518
MS	753	353	401	339	1,330	124	3,270
NC	613	184	102	154	714	96	1,015
SC	670	66	77	76	319	19	406
TN	323	127	144	173	397	12	690
Region 5							
IL	1,013	279	255	387	432	862	1,472
IN	286	236	297	222	197	166	671
MI	78	450	441	275	28	40	49
MN	844	267	528	488	634	2,252	1,850
OH	135	298	347	249	87	54	234
WI	238	289	312	325	112	52	230
Region 6							
AR	1,625	2,055	2,395	2,435	3,112	496	7,309
LA	2,000	1,015	704	1,061	1,793	285	8,278
NM	24	97	114	57	22	2	25
OK	1,622	713	608	839	1,505	118	1,753
TX	6,632	1,352	1,993	1,658	1,720	874	1,540
Region 7							
IA	1,113	556	626	573	453	756	1,562
KS	5,789	1,026	860	1,129	3,371	1,050	6,195
MO	2,797	847	636	979	1,949	434	3,680
NE	734	345	550	594	395	295	1,300
Region 8							
CO	210	906	504	994	116	41	268
MT	2,773	475	601	828	195	362	113
ND	2,566	669	684	1,105	909	1,507	1,704
SD	354	1,386	693	800	189	167	328
UT	118	306	509	507	12	9	1,274
WY	178	116	210	203	17	23	17
Region 9							
AZ	53	339	311	380	56	57	59
CA	2,263	2,345	1,322	1,799	777	1,569	8,093
NV	14	41	81	98	8	6	10
Region 10							
ID	2,593	2,231	2,633	1,337	156	2,633	872

OR	996	997	881	1,118	198	958	235
WA	2,265	1,149	984	1,682	258	893	1,177
CONUS Total							
CONUS	52,689	24,493	33,047	26,965	17,259	20,172	64,179

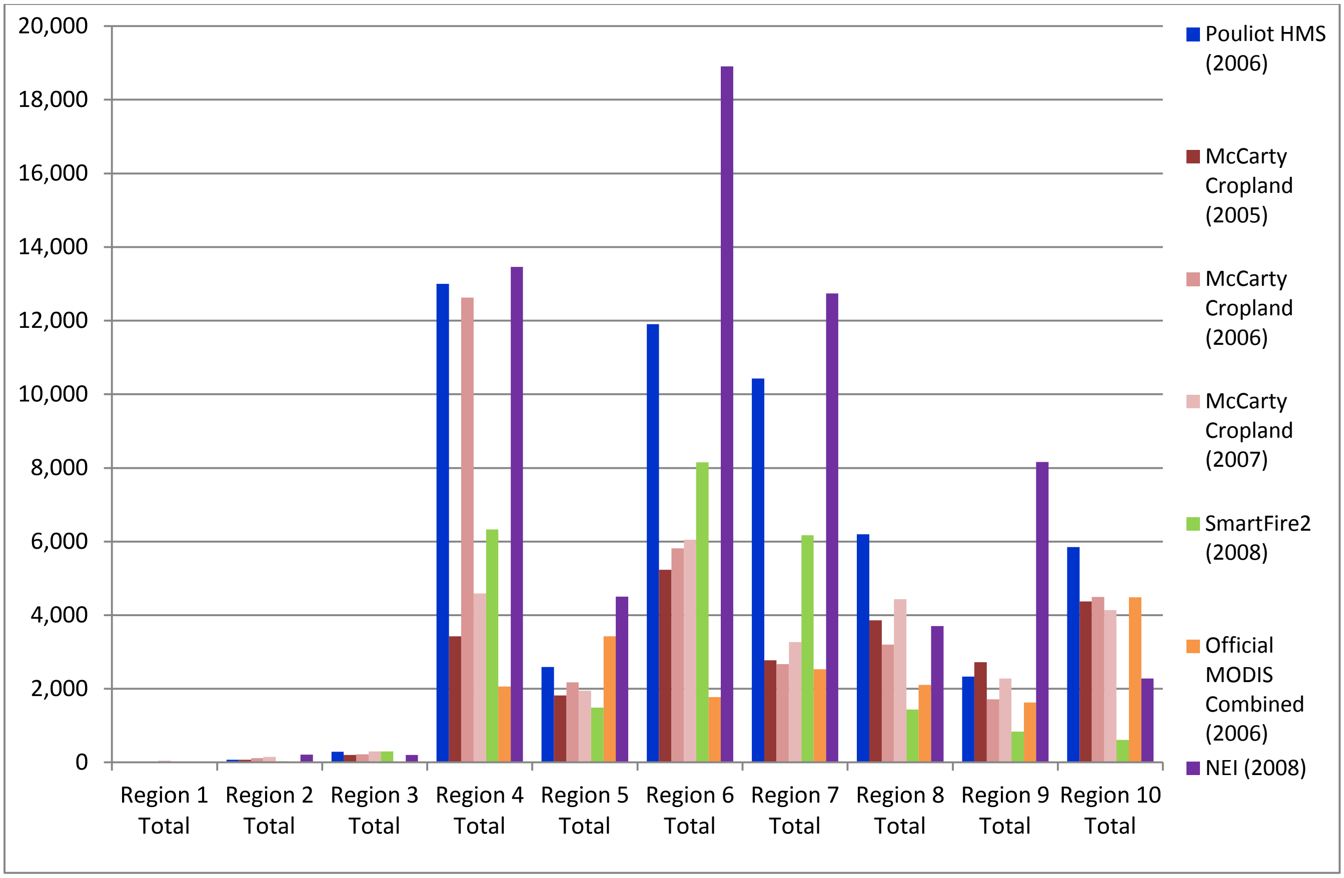

Figure 3. Total $PM_{2.5}$ emissions from cropland burning by EPA region from the Pouliot HMS, McCarty Cropland, SmartFire 2, Official MODIS combined products, and 2008 NEI Version 2 data sources.

In general, there is a moderate level of variability in the burned area and $PM_{2.5}$ emissions reported from the satellite-based products and the NEI. A comparison across all years reported, 2005 through 2008, results in a mean annual agricultural burned area for the entire CONUS of 3,048,711 acres, with a minimum of approximately 1,868,760 acres (reported by SmartFire2), a maximum of approximately 5,865,940 acres (Pouliot HMS), and a standard deviation of approximately 1,446,457 acres. The $PM_{2.5}$ emission estimates (Table 4) from these four approaches plus the 2008 NEI v2 for the CONUS results in a mean annual $PM_{2.5}$ emission of approximately 34,145 short tons, a maximum of 64,179 short tons (NEI 2008 v2), a minimum of 17,259 short tons (SmartFire2), and a standard deviation of approximately 17,665 short tons. The MODIS-based burned area products from McCarty and the Official MODIS Combined estimates had less variability for years 2005 through 2007, with a mean agricultural burned area of approximately 2,639,391 acres, a minimum of approximately 2,238,375 acres (Official MODIS Combined), a maximum of approximately 3,152,011 acres (McCarty Cropland 2006), and a standard deviation of approximately 392,407 acres. The $PM_{2.5}$ emission estimates for the MODIS-only approaches produce a mean annual $PM_{2.5}$ emission of approximately 26,169 short tons, a maximum of 33,047 short tons (McCarty Cropland 2006), a minimum of 20,172 short tons (Official MODIS Combined), and a standard deviation of approximately 5,376 short tons. Comparing the MODIS-based burned estimates for 2006 only from the McCarty and the Official MODIS Combined products results in a range of 913,636 acres - a nearly 1 million acre difference in agricultural burned estimates for the CONUS. The $PM_{2.5}$ emission estimates for these two MODIS-based approaches produced a difference (range) of 12,875 short tons for year 2006. Based on this comparison, it is clear that current satellite-based approaches result in varied estimates of burned area and emissions, as much as 1+ million acres and 17,000 + short tons of $PM_{2.5}$ emissions.

This variability can be seen at the state-level as well (Figure 4 and 5). In EPA Regions 3 through 10, which experience the most agricultural burning, a small number of states experienced a general agreement in terms of $PM_{2.5}$ emission estimates from the four satellite-based approaches and the 2008 NEI, including Arizona, Kentucky, Nevada, New Mexico, Tennessee, and Wyoming. For California and Mississippi, the satellite-based approaches produced very similar emission estimates but the numbers reported in the 2008 NEI v2 were much higher. Additionally, states like Florida, Idaho, Minnesota, Montana, North Dakota, and Washington showed very little agreement across any of the approaches.

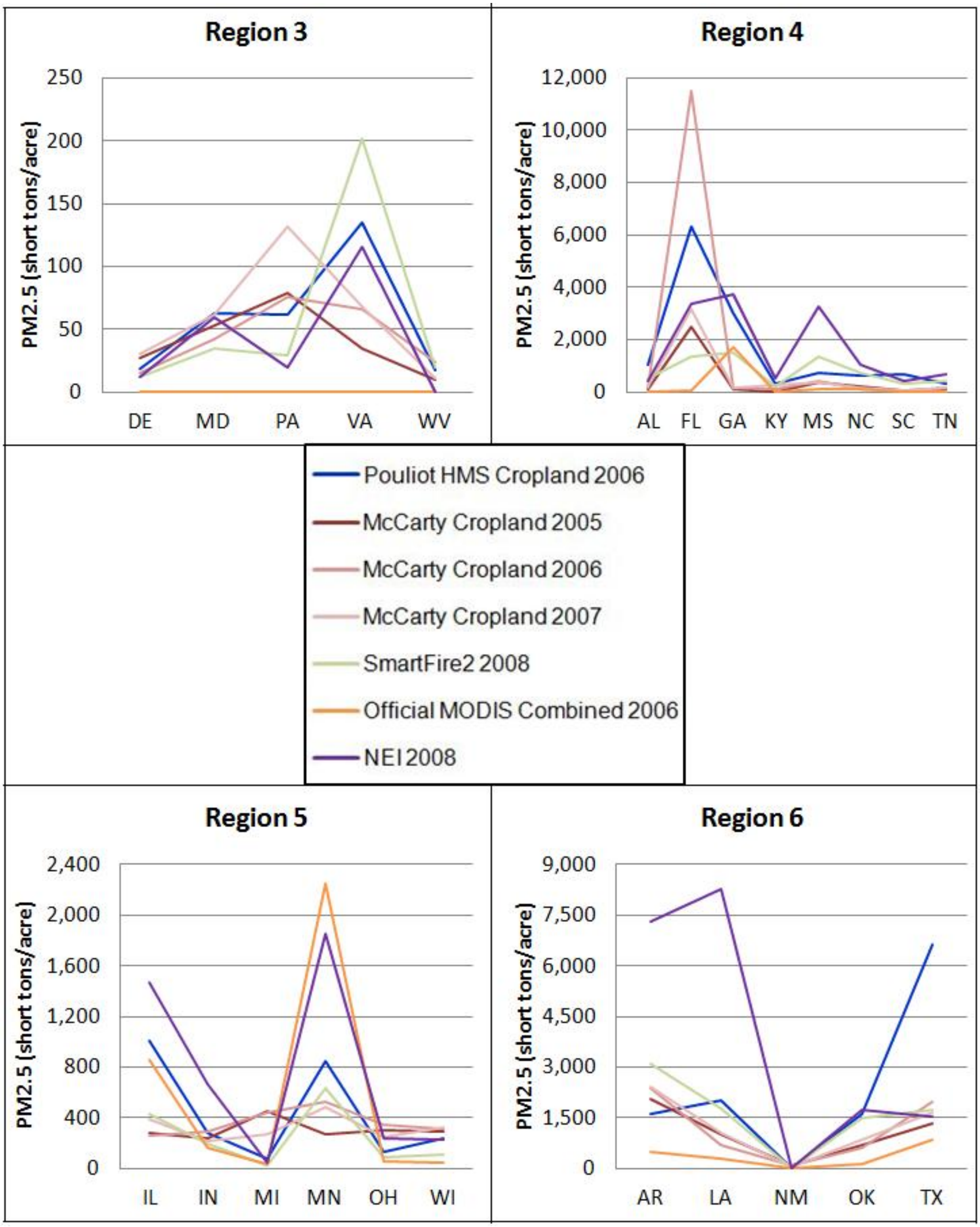

Figure 4. Total $PM_{2.5}$ emissions from cropland burning by state divided by EPA Region from the Pouliot HMS, McCarty Cropland, SmartFire 2, Official MODIS combined products, and 2008 NEI Version 2 data sources; focus on EPA Regions 3 through 6.

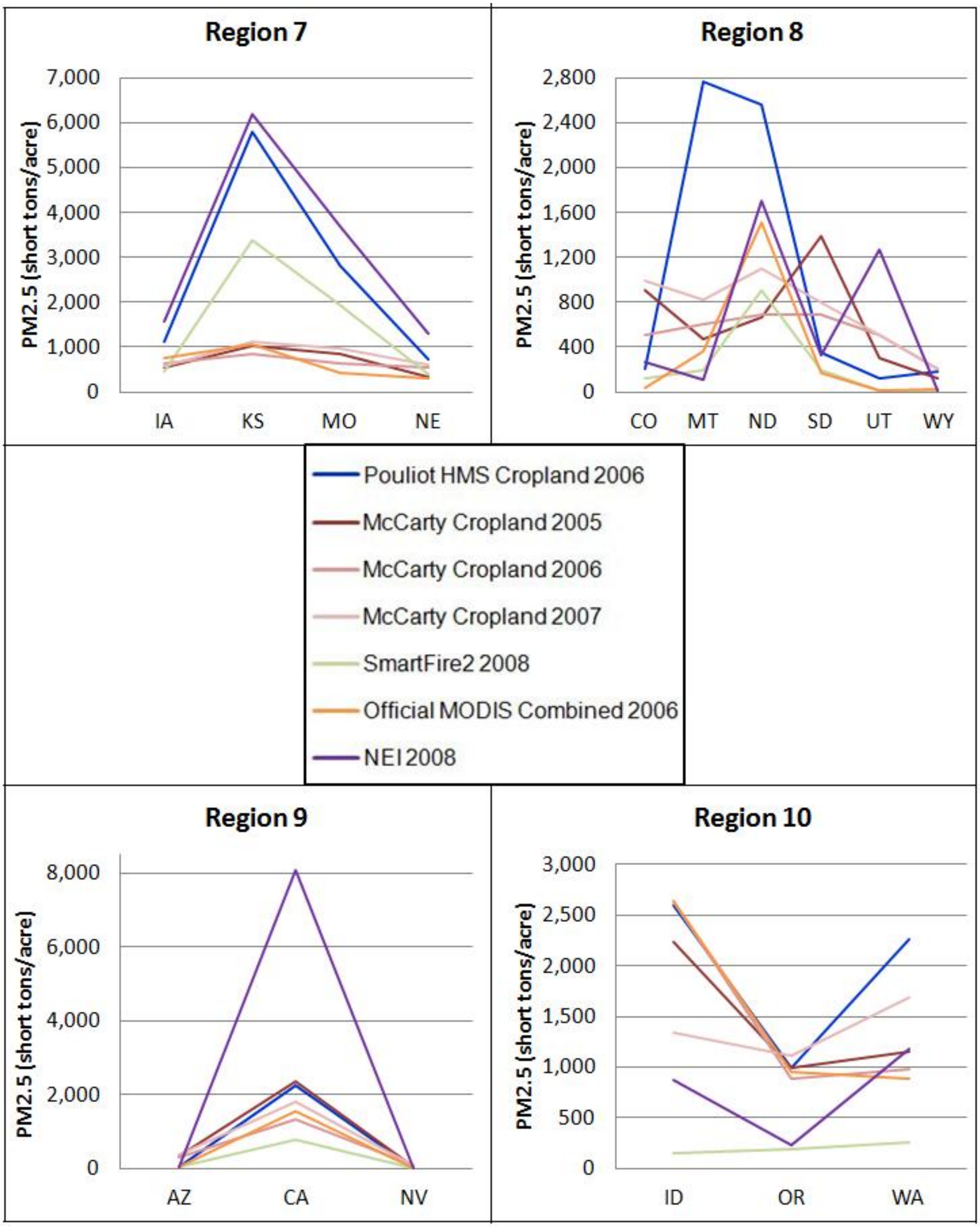

Figure 5. Total $PM_{2.5}$ emissions from cropland burning by state divided by EPA Region from the Pouliot HMS, McCarty Cropland, SmartFire 2, Official MODIS combined products, and 2008 NEI Version 2 data sources; focus on EPA Regions 7 through 10.

Discussion: A path forward

The difference in the fire activity data (in this case the satellite inputs), the definition of croplands, and the emission calculation variables were most likely the main factors influencing the disparate results in the satellite-based approaches. In terms of the satellite fire data, the spatial resolution (i.e., detection area) of the satellite burned area used (MODIS, Landsat) vary from 64 to 0.22 acres, the assumption of average area to assign individual active fire detections (from GOES or MODIS) varied from 40 to 120 acres, and the temporal resolution of the data (i.e., timing of detection) varied from 15 minute to daily to 8-day. This spatial, areal, and temporal difference is difficult to reconcile but first steps have been made to understand this phenomena. Additionally, two different definitions of croplands were used in this comparison of agricultural burning emissions in the CONUS: the crop type maps supplied by the USDA NASS Cropland Data Layer product and the NLCD General Cultivated Crop and Pasture classes. Finally, where possible the same emission factors, fuel loadings, and combustion completeness were used or were at the very least from the same source. However, depending on the product, these emission calculation variables were crop type-specific or derived from a general agriculture class, and therefore not the same.

In order to more accurately estimate agricultural burning emissions in the CONUS, a consensus on cropland extent definition must be made. Given its 30 m resolution (0.22 acres) and high accuracy, the freely available USDA NASS Cropland Data Layer[27] is an ideal candidate for this consensus agricultural land cover product. Additionally, given that it is available for the CONUS from 2008 to present (current year is 2012), it is also an ideal product for future uses by the EPA and further emission inventory needs.

Currently, there is a paucity of ground truth data related to prescribe burning and/or the sharing of existing data from state and local sources. To improve current agricultural burning emission estimates, a data sharing plan and gateway is likely needed. Additionally, to be able to better assess the accuracy of a given satellite product, a standard validation practice applied to all fire products is needed. Currently, the Global Observations of Forest and Land Cover Dynamics (GOFC-GOLD; http://www.fao.org/gtos/gofc-gold/) recommends a moderate resolution-based validation protocol (i.e., Landsat-like or 30 m spatial resolution) for application to current scientific (MODIS) and operational (Suomi Visible Infrared Imaging Radiometer Suite or VIIRS) platforms. This protocol may be a useful standard to apply to all satellite-based fire data included in future emission inventories.

Finally, current emission calculation variables, like fuel loadings and emission factors need to be improved. The FCCS (Fuel Characteristic Classification System; http://www.fs.fed.us/pnw/fera/fccs/) has been developed by the US Forest Service to provide a comprehensive description of fuel layers. FCCS fuelbeds represent fuels across the US and Mexico. They were compiled from scientific literature, fuels photo series, fuels inventories, and expert opinion. Allometric equations in the FCCS calculator produce fuel loadings, other plot-level metrics, and fire-hazard potential. This geospatial dataset is currently being updated through the efforts of Michigan Tech Research Institute (PI: Dr. Nancy H.F. French), the U.S. Forest Service, and the USDA NASS to include crop type-specific fuel loadings for the entire CONUS by incorporating the Cropland Data Layer and crop type-specific fuel calculations into the FCCS. Agricultural burning emission factors for the CONUS for the National Ambient Air Quality Standards (NAAQS) species, not including volatile organic compounds (VOCs) and hazardous air pollutants (HAPs), range from crop type-specific to a generic cropland class and lack seasonality, e.g., spring vs. fall, and a sufficient geographical representation across the CONUS[10]. Further research must be done improve the seasonality and sample distribution of NAAQS, VOCs, and HAPS emission factors for major crop types in the CONUS.

CONCLUSIONS

In general, there is a moderate level of variability in the four satellite-based approaches compared in this analysis, with a difference in the burned area estimates as large as 1+ million acres and a difference of 17,000 + short tons for the $PM_{2.5}$ emissions. This variability can be seen at the state-level as well when the $PM_{2.5}$ emission estimates from the four satellite-based approaches and the 2008 NEI are compared, with states like Florida, Idaho, Minnesota, Montana, North Dakota, and Washington showing very little agreement across any of the approaches. Future improvements in quantifying agricultural burning emissions should include adopting a standard validation protocol for all satellite-based fire products and a standard cropland (and crop type) map as well as improving the fuel loadings and emission factors used in the emission calculations.

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KEY WORDS

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Area Sources

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Remote Sensing