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A Hybrid Remote Sensing Approach to Quantifying Crop Residue Burning in the United States

J. L. McCarty, T. Loboda, S. Trigg

Abstract. *Crop residue burning is an important land use activity in the United States. Currently, satellite-based burned area methodologies specifically calibrated for crop residue burning are limited. This article describes a satellite observations-based hybrid approach to estimate the amount of burned crop residues that combines Moderate Resolution Imaging Spectroradiometer (MODIS) 8-day differencing of Normalized Burn Ratio (dNBR) burned area mapping with MODIS active fire counts calibrated into area. The dNBR approach utilizes the spectral response of the 2.1-μm shortwave infrared MODIS band to detect burned pixels. A time series of 8-day MODIS composites produces burned area estimates during harvest on a near-weekly scale. This approach was tested on the study area of MODIS tile h10v05, which encompasses much of the Mississippi River Delta and the southern Great Plains, for the years 2003 through 2006. Within this area, an average of 12,700 and 10,835 km*^{2} *burned in the spring and fall harvests, respectively. Results from the hybrid approach are validated through comparison with high-resolution Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data and field data. Validation of the hybrid approach shows strong correspondence with both the ASTER (mean* $R^2 = 0.92$*) and* in-situ *data (mean accuracy 85.5%). At the state level, the estimated burn rates from this analysis compare well with reported Arkansas burn rates. Results suggest potential for using the approach to monitor and quantify fire activity in cropland areas of the United States.*

Keywords. *Remote sensing, fire, crop residues, burned area, MODIS.*

Crop residue burning is a land use activity that is practiced globally (Yevich and Logan, 2003; Chen et al., 2005; Korontzi et al., 2006). Its impacts are observed at the local and regional scales in both the developing and the developed world (He et al., 2007; Witham and Manning, 2007). As an important source of gaseous and particulate emissions, crop residue burning affects air quality and contributes to global warming (Jenkins et al., 1992; Dennis et al., 2002; Wiedinmyer et al., 2006). Andreae and Merlet (2001) estimate that agricultural residue burning accounts for approximately 9.5% of total global biomass burning activities as well as roughly 9% of total CO_2 released from global biomass burning. In 2005, burning agricultural residues emitted approximately 1% of the total N_2O emissions released from energy consumption through transportation, residential, industrial, commercial, and electric power production in the United States (DOE/EIA, 2006). The wide-ranging impacts of crop residue burning have intensified the need to quantify their extent at all scales.

Previous attempts to quantify crop residue burning have used indirect approaches; that is, methods based on indirect measurements, using non-spatial data, which necessitated the use of large simplifying assumptions. For example, Andreae (1991) estimated global agricultural waste burning based on 1986 United Nations Food and Agricultural Organization (FAO) crop production statistics by relying on two fundamental assumptions: (1) that the amount of agricultural residue able to be burned was equal to the total crop production, and (2) that 80% of residues were burned in the developing world and 50% of residues were burned in the developed world for any given year. Similarly, Hao and Liu (1994) estimated tropical crop residue burning by combining FAO crop production and biofuel consumption statistics and assumed that 23% of crop residues were used for fuels and 17% of residues were burned in the field. Yevich and Logan (2003) used a combination of national statistics, World Bank energy assessments, international and national technical reports, and expert knowledge to estimate agricultural waste burning in the developing world. Studies using indirect methods to quantify amount of crop residue burning have large discrepancies in the assumptions of area burned, and there is no reliable reason to consider one assumption as more accurate than another. In addition, crop residue burning rates vary by crop type and region. In the United States alone, residue burning estimates range from less than 1% for corn residues to 70% for sugarcane fields (WRAP, 2002).

Satellite observations provide a reliable approach for quantifying crop residue burning consistently over large areas (Korontzi et al., 2006), but existing remotely sensed burned area data within croplands publicly available for the United States is unsuitable for a multi-year analysis fine-tuned to the specifics of fire occurrence in agricultural areas. Heritage burned area mapping initiatives such as the GBA 2000 (Tansey et al., 2004) and GLOBSCAR projects (Simon et al., 2004) delivered the first global burned area maps from Systeme Pour l'Observation de la Terre (SPOT) VEGETA-

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TION and ATSR-2 Along Track Sounding Radiometer (ATSR-2) data, respectively; however, these products are limited to a spatial resolution of 1 km and are available only for the year 2000. The global burned area product derived from data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) presents a considerable improvement in burned area mapping because it is produced yearly at a higher (500 m) resolution. This product (MCD45A1), however, has shown commission errors associated with labeling plowed fields as burned areas (Roy et al., 2005) and is currently only available provisionally.

Another remotely sensed data driven approach to estimating burned area relies on the use of active fire detections as a proxy for burned area and assumes that either a fraction or the entire pixel has burned (Kasischke et al., 2003; van der Werf et al., 2004; Wiedinmyer et al., 2006). The advantage of this approach is its ability to detect burning of smaller areas compared to burned area algorithms, though an inaccurate fraction assumption would lead to either over- or underestimating burned area. Cropland burns present a mosaic of relatively small (field-size) non-contiguous patches. As elaborated by Robinson (1991), burned areas are sensed at a scale close to pixel resolution; therefore areas of crop residue burning smaller than the pixel size are likely to be missed. In comparison, active fires, when sensed in the short wave infrared (SWIR) spectrum, constitute a signal that is highly amplified over that of the background (Robinson, 1991) allowing for detection of fires at a scale considerably smaller than pixel resolution. For example, under favorable conditions, the MODIS 1-km Active Fire Product (MOD14/MYD14 for Terra and Aqua satellites, respectively) can detect fires as small as 100 m^2 (Giglio et al., 2003). Little is known about the relationship between active fire detections and the extent of cropland burned area except that the fraction of area burned per active fire pixel depends on the regional and ecosystem specifics of fire occurrence (Giglio et al., 2006).

The inapplicability of the existing burned area products to multi-year analyses of cropland residue burning requires the development of new methodologies. This study addresses two major objectives related to mapping crop residue burning: (1) to establish requirements for mapping burned area from satellite data in croplands of the continental United States; and (2) to present a hybrid (burned area plus active fire counts calibrated into area) remotely sensed data based approach to map crop residue burning over 1.23 million km^2 of the United States. The presented algorithm is built on standard publicly available remotely-sensed data sources including the MODIS surface reflectance (Vermote et al., 2002) and active fire products (Giglio et al., 2003). The inputs are analyzed within a semi-automated image processing/GIS environment to produce spatially explicit estimates of burned area in intensive croplands of the United States. A similar approach of integrating MODIS burned area mapping with MODIS active fires has been found effective in mapping slash and burn agricultural burning in Borneo (Miettinen et al., 2007), but has not been tested in cropland landscapes present in our study area. Intensive croplands, established agricultural areas that are often multi-cropped in a single calendar year, represent a unique fire management system different from slash and burn agricultural practices. Within intensive croplands, crop residue burning occurs consistently over several years, fields can be burned multiple times in one year, and the burned area is limited to field boundaries and not always contiguous. The accuracy of the burned area estimates, developed from our algorithm, was assessed using high resolution satellite images, field data, and Arkansas state-level statistical information on crop residue burning. We further used the algorithm to quantify crop residue burning during the 2003-2006 harvest seasons. The results of this study show that this hybrid approach provides a repeatable, consistent, and realistic assessment of burned area in intensive croplands of the United States.

Study Area

The study area was chosen to encompass an intensive cropland landscape known to experience widespread residue burning in the United States (Jenkins et al., 1992; Dennis et al., 2002; Brye et al., 2006; McCarty et al., 2007). We selected MODIS tile h10v05 (fig. 1), which covers an area of over 1,244,400 km^2 and is centered on 90° W and 35° N, as a test area for the algorithm developments and application. Croplands make up approximately 145,370 km^2 or 12% of the tile. The study area represents a complex agricultural system that ranges from a double cropped system of soy, rice, winter wheat, and cotton in the southeastern United States to a monoculture grains production in the southern Great Plains. The complexity of the crop systems makes the selected area a suitable site to test the flexibility of this hybrid approach to crop residue mapping in various agricultural systems.

Methodology

Development of a successful algorithm for mapping burned areas in croplands requires understanding the specifics and patterns of fire occurrence in these unique managed ecosystems. Because of the variability of agricultural practices involving the use of fire worldwide, input data and algorithm parameterization requirements will differ across geographic regions and political entities. This article focuses on cropland residue burning in the United States; therefore the algorithm and findings of this project may not be applicable to agricultural areas outside the United States.

Considerations in Algorithm Design

The extent of crop residue burning can be assessed through direct monitoring of on-going burning activity (active fire detection) or through observations of post-fire impacts on the surface (burn scar mapping). Due to the specifics of fire occurrence in agricultural landscapes within the United States, each of these strategies presents a distinct set of requirements when developing satellite data driven methodologies.

Crop rotation practiced in the study area generally requires several burning events within the same fields within a year. Therefore, the first requirement for burned area estimates addresses the need for mapping burned area per burning period rather than once a year. The burning period is defined here as a time-frame during which fields may be burned as a result of various agricultural practices. For the study area, two burning periods were identified as 1 May to 4 July and 30 September to 27 December. These two burning periods roughly correspond to the harvesting seasons in the southeastern and central United States, where fire is a common management tool for crop residue management,

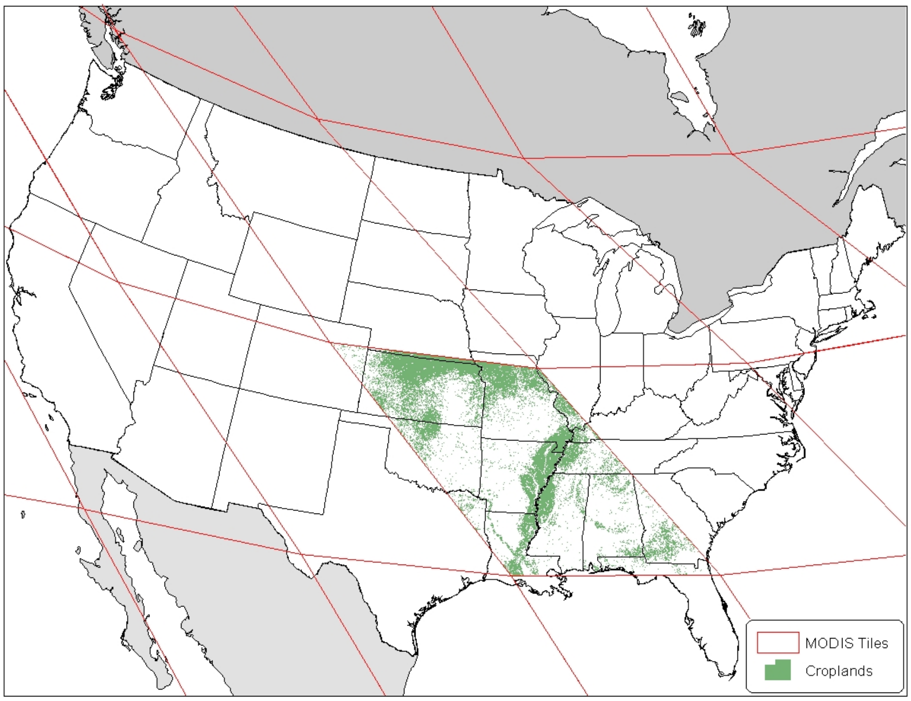

Figure 1. Study area of MODIS tile h10v05 with cropland mask. The MODIS tile boundaries, defined in MODIS sinusoidal projection, appear skewed when displayed in the projection used for this figure.

especially along the Mississippi River (Brye et al., 2006; McCarty et al., 2007).

Cropland management fires rarely follow seasonal and diurnal fire dynamics of wildland fire occurrence. The timing and periodicity of cropland fires depend on residue management techniques and crop rotation practices (UF, 1998; LSU Ag Center, 2000; Brye et al., 2006). Fires are often ignited during optimal weather conditions and generally the burning is completed within 2 h. Crop residue burning during night-time is extremely rare (LSU Ag Center, 2000), thus daytime observations of fire activity are particularly important. These characteristics necessitate high frequency of observations of on-going burning activity in croplands during the harvesting periods.

High frequency of observations is also important for mapping burn scars during harvest seasons due to the limited longevity of post-burn conditions on the ground. The post-burning effects are present on the surface for a short period of time before the burned fields are plowed over or re-seeded to facilitate the crop rotation mechanisms. This condition leaves a narrow time-window during which the burned areas can be mapped.

The last major requirement to the input datasets is driven by the field size of cropland areas. In the United States, average field sizes range from 0.16 km^2 in the southeastern United States (McCarty et al., 2007) to 0.48 km^2 in the western United States (Personal communication with Dr. Steve Van Vleet, Agriculture Extension Agent for Whitman County, Washington State University, Colfax, Wash., 23 April 2007). Often several fields are burned at the same time allowing for the use of coarser resolution imagery than the exact 0.16-km^2 field size of the study area; however, there is a need to account for contribution from smaller single-burned fields to the total burned area in croplands.

Data

The MODIS instrument on board of two polar orbiting satellites (Terra and Aqua) provides daily global observations at the 250-, 500-, and 1000-m resolutions. Table 1 shows the spectral and spatial attributes of all 36 MODIS bands (NASA, 2008). Although 250-m resolution provides a more detailed view of the surface and therefore is more likely to detect burning in single 0.16-km^2 field, only two MODIS bands (red and near infrared [NIR]) are collected at this resolution. The MODIS 500-m observations are available for a broader range of electro-magnetic spectrum including SWIR bands. The red-NIR bi-spectral space and the conventional vegetation indices have been shown to provide a poorer discrimination of burned areas than the NIR-SWIR bi-spectral space (Trigg and Flasse, 2001). The Normalized Burn Ratio index, based on post-fire surface reflectance in the NIR and 2.1-μm SWIR range, was developed specifically for burn mapping (Lopez Garcia and Caselles, 1991). Loboda et al. (2007) have demonstrated that delta NBR (dNBR), calculated as the difference between pre- and post-burn imagery, has the largest amplitude of post-fire response and therefore has the greatest sensitivity to fire-induced change in surface reflectance compared to other NIR/SWIR-based vegetation indices commonly used for burn detection. This sensitivity is particularly important for differentiating between burned and plowed fields in agricultural landscapes. MODIS is currently the only instrument collecting daily observations in the ~2.1-μm range. Additionally, a dNBR based algorithm has been successfully applied, using MODIS surface reflectance composites, to map burned areas in herbaceous cover dominated ecosystems including sagebrush steppes of the United States (Loboda et al., 2007). Therefore, this study considers the spectral resolution of the

500 m MODIS land observations of higher importance than the spatial resolution of the 250-m data.

Additionally, we expect that the spatial resolution of the MODIS 500-m data (0.25-km^2 pixel area) is sufficient to map burned fields as small as 0.16 km^2 due to the practice of burning several neighboring fields during harvest in the United States (Canode and Law, 1979; Brye et al., 2006). Publicly available standard MODIS land surface products provide atmospherically corrected data. More importantly, the standard MODIS 8-day surface reflectance composites within MOD09A1 product (Vermote et al., 2002), which include MODIS bands 1 through 7 at 500-m resolution, minimize obscuration of the surface by clouds while retaining a sufficient frequency of surface observations for burned area mapping in croplands.

The information on crop residue burning in smaller fields can be acquired using the fractional assessment of burned area inferred from actively burning pixels. The MODIS active fire product provides daily observations of burning with a nominal resolution of 1 km. Currently, no higher spatial resolution global daily active fire detection products are available. The overlap of data acquisition swaths in the latitudes of the study area allows for multiple daily daytime observations of fire activity (up to two times from each Terra and Aqua satellites). However, even with four daily overpasses the MODIS active fire product provides only episodic observations of on-going burning and is likely to omit a considerable portion of agricultural burning if used as the only method for crop burned area assessment. Despite the limitation imposed by the frequency of data acquisition, the MODIS active fire product is expected to provide additional information on the extent and amount of crop residue burning missed by the burned area algorithm.

Table 1. Spectral and spatial characteristics of MODIS.

Band	Bandwidth (μm)	Spatial Resolution (m)
1	0.620 - 0.670	250
2	0.841 - 0.876	250
3	0.459 - 0.479	500
4	0.545 - 0.565	500
5	1.230 - 1.250	500
6	1.628 - 1.652	500
7	2.105 - 2.155	500
8	0.405 - 0.420	1000
9	0.438 - 0.448	1000
10	0.483 - 0.493	1000
11	0.526 - 0.536	1000
12	0.546 - 0.556	1000
13	0.662 - 0.672	1000
14	0.673 - 0.683	1000
15	0.743 - 0.753	1000
16	0.862 - 0.877	1000
17	0.890 - 0.920	1000
18	0.931 - 0.941	1000
19	0.915 - 0.965	1000
20	3.660 - 3.840	1000
21	3.929 - 3.989	1000
22	3.929 - 3.989	1000
23	4.020 - 4.080	1000
24	4.433 - 4.498	1000
25	4.482 - 4.549	1000
26	1.360 - 1.390	1000
27	6.535 - 6.895	1000
28	7.175 - 7.475	1000
29	8.400 - 8.700	1000
30	9.580 - 9.880	1000
31	10.780 - 11.280	1000
32	11.770 - 12.270	1000
33	13.185 - 13.485	1000
34	13.485 - 13.785	1000
35	13.785 - 14.085	1000
36	14.085 - 14.385	1000

Description of the Algorithm

The burned area retrieval algorithm follows the scheme presented in figure 2. It detects areas affected by crop residue burning by combining burned area and active fire information in a hybrid approach. The algorithm was developed and tested using MODIS data collected over the 2003-2006 period. Additional data sources, used in the algorithm development, include high resolution satellite imagery from the 30-m Landsat Thematic Mapper (acquired in 2004) and 15-m ASTER (acquired in 2003, 2004, and 2006) and *in-situ* GPS locations of burned fields (collected during the 2004 and 2006 field campaigns). Methods and data used to derive burned area and active fire estimates are now described in turn.

Processing Direct Burned Area: 500-m Burned Area Estimation from MOD09A1 MODIS 500-m 8-day Surface Reflectance Data

The MODIS 500-m 8-day surface reflectance composites were preprocessed to exclude low quality observations using the standard quality assessment bits provided within the MOD09A1 product. Table 2 provides a summary of quality values which were applied to the original composites. The pre-processed composites were then used to calculate NBR as the basis for detecting burned areas using MODIS Surface Reflectance product bands 2 (0.841-0.876 μm) and 7 (2.105-2.155 μm):

$$NBR = \frac{band2 - band7}{band2 + band7} \quad (1)$$

The NBR was calculated from each pre-processed composite, then burned areas were identified through differencing of the NBR (dNBR) between pre- and post-burn images. The dNBR was calculated on the rolling 8-day differencing principle. Missing NBR values for composite date n, resulting from removal of low quality input data at the pre-processing stage, were filled with acceptable quality values from the NBR image of composite date n-8. This reduced the omission of burned areas due to low quality observations in two subsequent 8-day composites. The gap-filled NBR composite was then considered to be the pre-burn NBR image n. The dNBR was calculated by subtracting the NBR image from day n+8 from the composited pre-burn NBR image n. The resultant 8-day dNBR images were thresholded at the value of 0.375 to identify burned areas.

The 0.375 threshold was found to detect burned areas while minimizing commission error from plowed fields. To set the thresholds, GPS points were collected in 29 plowed fields during two field campaigns in Arkansas in 2004 and 2006. From these points, corresponding polygons of plowed fields were digitized from 2004 Landsat Thematic Mapper

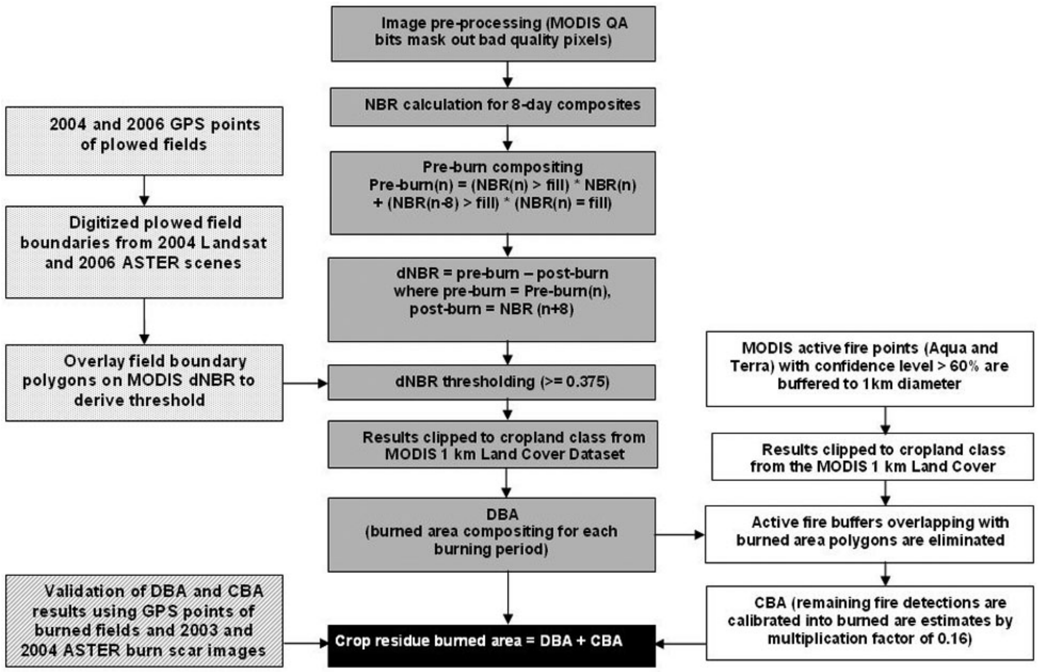

Figure 2. Description of data processing and burned area algorithm for croplands; n = composite date, NBR = Normalized Burn Ratio, and dNBR = differencing of the Normalized Burn Ratio. Different background colors show the data flow for different components of the hybrid approach: grey – dNBR based burned area mapping (DBA), white – calibrated active fire estimates (CBA), black – the combined estimates, grey dotted background – thresholding of dNBR values from *in-situ* data, grey diagonals – validation of DBA and CBA .

(30 m) and 2006 ASTER (15 m) images. These 29 observations had an average dNBR value of 0.276 with values ranging from 0.180 to 0.374. In order to eliminate errors of commission from plowed fields in the dNBR product to the fullest extent, the threshold was set at 0.375. It is important to note that dNBR thresholds are affected by the vegetation type and vegetative cover density (Loboda et al., 2007). Therefore, the developed threshold of 0.375 dNBR is not broadly applicable to mapping cropland burning across various geographic regions and crop types.

The thresholded dNBR images were subsequently merged into a single 'end-of-burning period' mask that retained the date of first observation as an attribute. Finally, the 'end-of-burning period' dNBR masks were clipped to a cropland mask. This cropland mask was derived from the 'Cropland' and 'Cropland/Natural Mosaic Vegetation' classes within the MODIS 1-km Land Cover dataset (MOD12Q1) (Friedl et al., 2002). The resulting 500-m product is hereafter referred to as Direct Burned Area (DBA).

Processing Calibrated Burned Area: Burned Area Estimation from MOD14/MYD14 MODIS 1-km Active Fire Product

To capture the contribution from smaller "single-field" burning, active fire detections at 1-km resolution were included in the algorithm. In this study, we used the MODIS Active Fire Product provided by the University of Maryland Fire Information for Resource Management System (FIRMS) (NASA/UMD, 2002). The FIRMS system delivers point shapefiles identifying the centers of actively burning 1-km MODIS pixels. Assuming the entire pixel burned would be a potential overestimation of burned area as the average agricultural field size in the MODIS tile h10v05 region is 0.16 km^2 (McCarty et al., 2007) or 16% of the total 1-km pixel. An assessment of burned area as a fraction of active fire detection pixel presents the basis for inferring the burned area amount from active fire detections.

To relate MODIS active fire detections to burned cropland, 10 ASTER scenes were used to assess the areas burned by fires detected by the MODIS active fire product. Both MODIS and ASTER instruments are flown on board the Terra satellite and are set to acquire temporally coincidental imagery close to the nadir viewing angle, thus providing a unique opportunity to analyze features at sub-pixel resolution within the MODIS 1-km imagery (Morisette et al., 2005). The 15-m ASTER scenes, used for the algorithm development, cover part of the Mississippi River in southeastern Missouri and eastern Arkansas and were acquired at exactly the same time as the MODIS active fire detections. Two dates were selected, the first from the spring harvest of 2003 (22 June 2003) and the second from the fall harvest of 2004 (5 October 2004) as these dates contained high numbers of active detections. For each ASTER scene, both the visible flame/burn scar areas and the estimated field boundaries of each given fire were digitized in this synoptic comparison of Collection 4 MODIS active fire product (Giglio et al., 2003)

Table 2. Accepted MODIS surface reflectance QA science data set bit values (Loboda et al., 2007).

Quality Bit Parameters	Cloud State	Cloud Shadow	Land/Water Flag	Aerosol Quality	Cirrus Detected	PGE11 Internal Cloud Mask	Snow/Ice Flag	PGE11 Internal Snow Mask
Value accepted	0	0	1	1-2	0-2	0	0	0

to high resolution 15-m ASTER data. To make the burned area estimates from the active fire detections more representative of actual conditions, this analysis assumed the entire field burned rather than the fraction of field associated with the visible flame burned. This allowed two parameters to be estimated: area burned per MODIS active fire pixel area and number of false active fire detections.

The MODIS active fire product was assessed to determine the range of product confidence values that relate to flames and burned areas visually interpreted from the ASTER data. Initially, fire detections of all confidence values were included in the analysis. 42 active fire points were detected over the spatial coverage of the 2003 and 2004 ASTER images. The ASTER images from 22 June 2003 and 5 October 2004 contain 8 and 34 fire detections, respectively. Visual analysis of the ASTER data showed that 8 of the 42 total fires were false detections, whereby an active fire detection was recorded in a pixel where no fire was present. In this analysis we did not find any actively burning fires visible in the ASTER imagery omitted by the MODIS active fire detections. Approximately 81% of active fire detections corresponded to burned areas observed from the ASTER data. Closer inspection of the active fire metadata revealed the eight false detections to have a product-specific confidence level less than 60%. Therefore, only MODIS active fires with a confidence level greater than or equal to 60% were included in the calculations. A coefficient for calibrating active fires into burned area was developed by analyzing the 34 active fire points that corresponded with the visually interpreted active fires and burn scars in the 2003 and 2004 ASTER images. Based on the ASTER analysis, the average burned area for the active fire points in cropland areas was 0.16 km^2, which is consistent with the average field size in the southeastern United States. This study assumed that the presence of an active fire in the field means that the entire field ultimately burned, thus this method compensates for the omission of small burned areas by assuming that all active fire points with a confidence flag greater than or equal to 60% in cropland areas represent a burned area equal to 0.16 km^2. These active fire detection points were buffered to a 1-km diameter to simulate the MODIS 1-km pixels. We assumed that no field was burned twice during the same harvesting period. Subsequently, all active fire buffers overlapping with DBA polygons were eliminated from further analysis as the DBA pixels had accurately mapped the burned area of the active fires detected within a 1-km diameter. The final active fire burned area estimates were produced by multiplying the count of remaining non-overlapping MODIS active fire points by the correction coefficient 0.16 km^2. The resulting product is hereafter referred to as the Calibrated Burned Area (CBA).

Results

The results section provides an accuracy assessment of the DBA estimates and a brief overview of crop residue burning during 2003-2006. The calibration of the MODIS active fire detections into amount of burned area (CBA) is based on the observed relationships between the MODIS pixels flagged as "fire" and the high resolution ASTER estimates of burned area, and thus does not require an additional accuracy assessment. However, the DBA product maps burned area independently of the input of high spatial resolution data. Therefore, an assessment of the mapping accuracy of the DBA product is crucial for understanding the overall accuracy of the burned area estimates provided by the hybrid approach.

We further demonstrate the results from the hybrid DBA plus CBA burned area mapping approach for the state of Arkansas and our total study area within the MODIS tile h10v05. The results for Arkansas are compared with reported burned acreages and burn rates, estimated from the state-level statistics, to evaluate the algorithm performance during 2003-2006. Subsequently the analysis was expanded to assess the variability of cropland residue burning in the intensive agricultural landscapes of the United States within the study area of the project during the 2003-2006 period.

Cropland Burned Area Accuracy Assessment

The accuracy of the DBA component of the final cropland burned area product was assessed using reference data developed from high resolution ASTER burned area and field reference data. Burned areas in ASTER images from 22 June 2003 and 5 October 2004 (described in section 3.3.2) were compared to the DBA polygons. These five scenes cover an area of approximately 26,000 km^2 or 2% of total area of MODIS tile h10v05. Field reference data was collected in burned fields during field campaigns in November 2004 and June 2006. This reference data covers more than eight counties in northeastern and eastern Arkansas. While these approaches provide a limited assessment of the commission error for the resultant burned area estimates, they do allow for a direct comparison of the algorithm-based burned area to *in-situ* observations.

To compare DBA estimates to burned area estimates from ASTER, we followed MODIS validation protocols (Hansen et al., 2002) and used pixel averaging techniques to aggregate 15-m ASTER pixels to 500 m, comparable to the resolution of the DBA product. The DBA showed a slight overestimation of burned area for both 2003 (slope = 1.03, R^2 = 0.92, n = 58) and 2004 (slope = 1.06, R^2 = 0.93, n = 43) seasons (fig. 3). The clustering apparent in both years is related to the aggregation of the 15-m ASTER data to 500 m, where the averaged ASTER pixels produced similarly sized burned areas - a well-defined artifact of averaging aggregation techniques (Bian and Butler, 1999). There is a considerable amount of spatial disagreement between aggregated ASTER pixels and DBA mapped pixels (with Kappa values 0.28 for 2003 scenes and 0.24 for 2004 scenes); however, this is expected as a result of aggregating ASTER data to a coarser resolution.

DBA also showed strong agreement with the *in-situ* observations of burned fields collected over two field campaigns in Arkansas. For 2004, the DBA correctly classified 81% of the known burned fields (n = 21 with Kappa of 0.79) (table 3). DBA showed greater agreement with the field data collected in 2006 with 90% of burned fields being correctly classified (n = 48 with a Kappa of 0.89) (table 4).

Localized Results: Arkansas

The hybrid DBA-CBA approach estimated the average burned area for croplands in Arkansas at approximately 1,746 km^2 for the spring harvest and 1,649 km^2 for the fall harvest (table 5). Figures 4 and 5 show the burned area

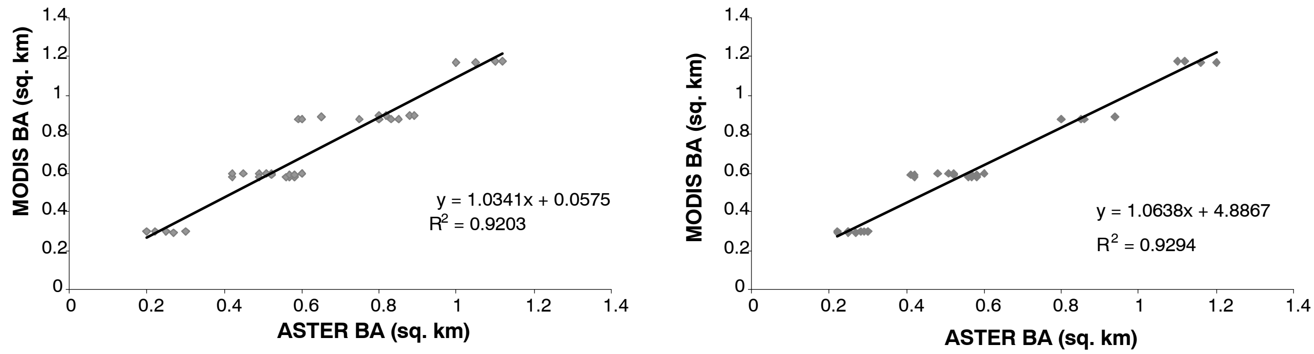

Figure 3. Accuracy assessment for MODIS DBA compared to ASTER burn scars aggregated to 500 m for years 2003 and 2004 (DBA = Direct Burned Area product).

Table 3. Error matrix comparing 2004 ground truth burned area data with DBA (Direct Burned Area product).

		DBA Pixels					
		15 Oct	23 Oct	31 Oct	8 Nov	Totals	User's Accuracy
Field data GPS Counts	15 Oct	3	1	0	0	4	0.75
	23 Oct	0	7	1	1	9	0.78
	31 Oct	0	1	4	0	5	0.80
	8 Nov	0	0	0	3	3	1.00
	Totals	3	9	5	4	21	
	Producer's accuracy	1.00	0.78	0.80	0.75		
	Percent correctly classified	80.95%					
	Kappa	0.79					

Table 4. Error matrix comparing 2006 ground truth burned area data with DBA (Direct Burned Area product).

		MODIS dNBR Pixels							
		9 May	17 May	25 May	2 Jun	10 Jun	18 Jun	Totals	User's Accuracy
Field data GPS counts	9 May	3	0	0	0	0	0	3	1.00
	17 May	0	15	1	0	0	0	16	0.94
	25 May	0	0	2	0	0	0	2	1.00
	2 Jun	0	0	1	11	1	0	13	0.85
	10 Jun	0	0	0	0	6	1	7	0.86
	18 Jun	0	0	0	0	1	6	7	0.86
	Totals	3	15	4	11	8	7	48	
	Producer's accuracy	1.00	1.00	0.50	1.00	0.75	0.86		
	Percent correctly classified	89.58%							
	Kappa	0.89							

Table 5. Burned area for croplands in Arkansas during the spring and fall harvest season with burn rate comparison of crops known to burn in Arkansas; crop area corresponds to wheat and rice acreages in the spring and rice and soy acreages in the fall.

Year	DBA[a] (km^2)	CBA[b] (km^2)	Total (km^2)	Crop Area (km^2)	Area Burned (%)	Harvest Season: Likely Crop Residues
2003	2,524.03	33.92	2,557.95	7,640.00	33%	Spring: Wheat/Rice
2004	863.40	19.84	883.24	7,640.00	12%	Spring: Wheat/Rice
2005	1,095.58	20.00	1,115.58	6,240.00	18%	Spring: Wheat/Rice
2006	2,395.93	32.96	2,428.89	7,332.00	33%	Spring: Wheat/Rice
Average	1,719.74	26.68	1,746.42	7,213.00	24%	Spring: Wheat/Rice
2003	1,698.13	152.48	1,850.61	5,800.00	32%	Fall: Rice/Soy
2004	1,056.24	48.48	1,104.72	18,200.00	6%	Fall: Rice/Soy
2005	1,686.14	202.88	1,889.02	18,132.00	10%	Fall: Rice/Soy
2006	1,683.84	66.72	1,750.56	17,820.00	10%	Fall: Rice/Soy
Average	1,531.09	117.64	1,648.73	14,988.00	14.5%	Fall: Rice/Soy

[a] DBA = Direct Burned Area product.
[b] CBA = Calibrated Burned Area product.

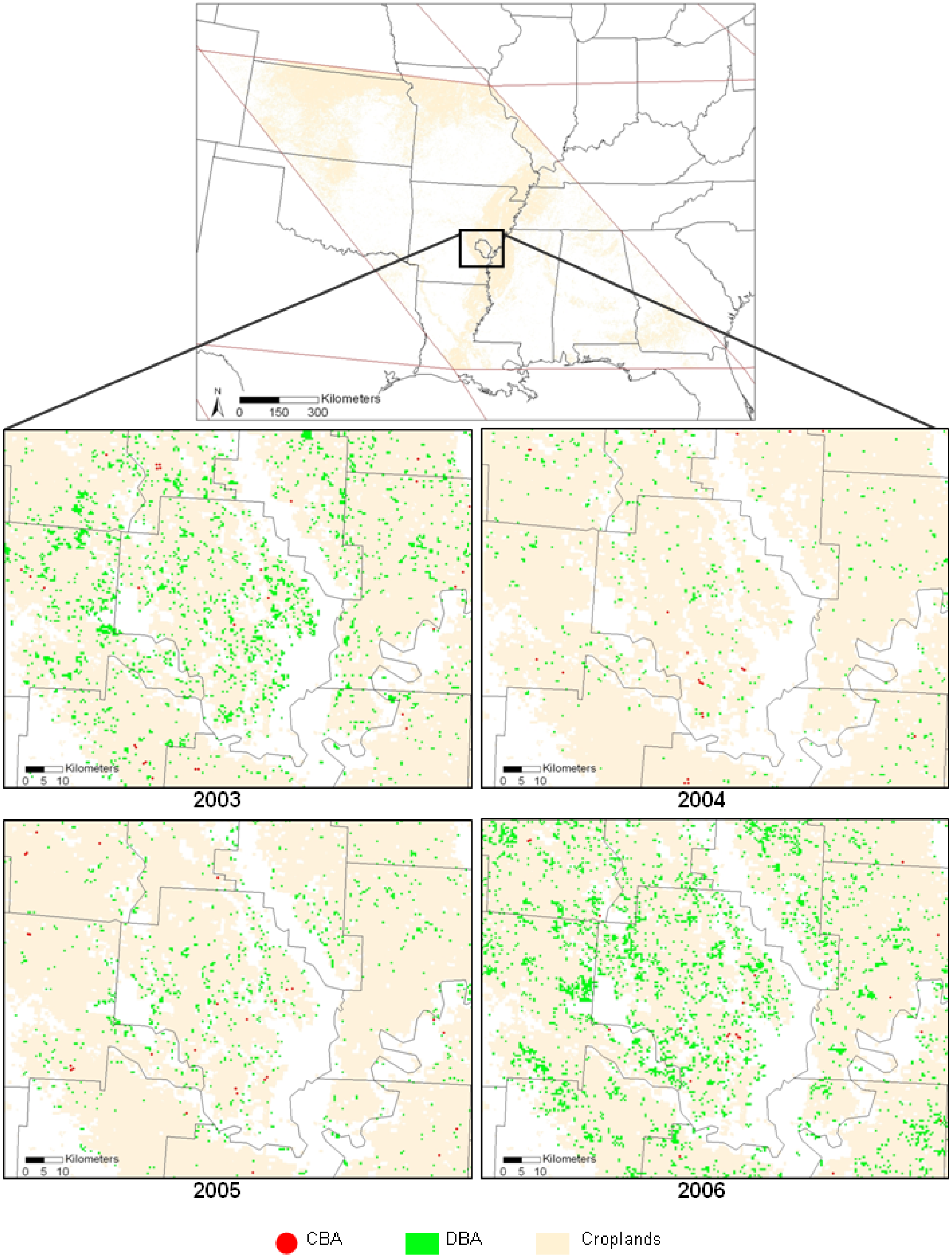

Figure 4. Crop residue burning results for 2003, 2004, 2005, and 2006 spring harvest for Arkansas County, Arkansas and surrounding areas (DBA = Direct Burned Area product; CBA = Calibrated Burned Area product).; CBA not shown to true scale.

maps from the hybrid approach for Arkansas County, Arkansas and surrounding areas for both the spring and fall harvests of 2003 through 2006. Our results show that the amount of crop residue burning changes considerably between 2003 and 2006 while the reported crop acreages remain fairly stable (USDA NASS, 2003, 2004, 2005, 2006). These crop acreages are based on USDA statistics which are produced annually through a combination of state-submitted agricultural acreage estimates to the Agricultural Statistics Board and an annual, nationwide ground-based survey of 11,000 parcels of land and 89,000 farm operators within the first two weeks of June (USDA NASS, 2003). Experts estimate that ~40% of total winter wheat acreages are burned in Arkansas (Personal communication with Dr. Jason Kelley, Arkansas State Wheat Specialist, Little Rock, Arkansas, 15 June 2006). Reid et al. (2004) used telephone and mail

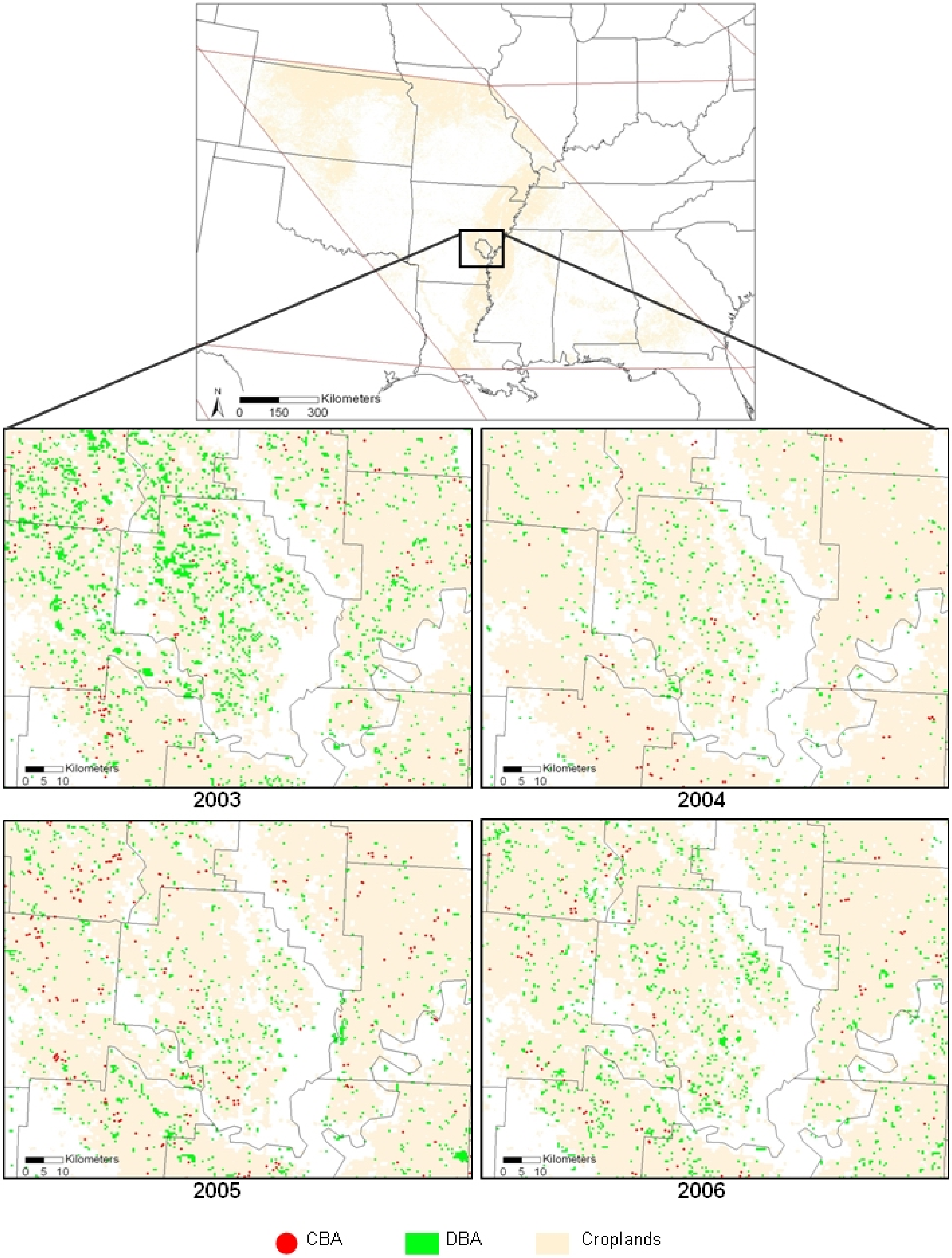

Figure 5. Crop residue burning results for 2003, 2004, 2005, and 2006 fall harvest for Arkansas County, Arkansas and surrounding areas (DBA = Direct Burned Area product; CBA = Calibrated Burned Area product); CBA not shown to true scale.

surveys of Agriculture Extension Service Agents to produce best estimates of acreages burned within the Central States Regional Air Planning Association. Approximately 2,651 km^2 of winter wheat burned in Arkansas in 2002, which is the same order of magnitude as the expert assessment. However, according to our results, only 2003 and 2006 spring harvest crop residue burning matches these estimates.

Based on a comparison with *in-situ* data, the DBA estimates for the 2004 fall harvest and the 2006 spring harvest had accuracy rates of 81% and 90%, respectively (see section 4.1); yet, the results for 2004 showed significantly less burned area for the spring harvest season and fall harvest seasons than the other three years. This decrease in burning might be explained by increased precipitation in 2004. During the fall harvest, precipitation in Arkansas was more than 17 cm above normal (NWS-SRH, 2004) deterring the harvesting of soy, rice, and cotton and the planting of winter wheat (Crockett, 2004). Following the anomalously wet conditions of the harvest season in 2004, winter wheat acreages in Arkansas declined by 63% in spring 2005 (Robinson, 2005), consequently reducing the wheat residue burning during the 2005 spring harvest. Our estimates show a nearly 45% reduction in the amount of burned area in croplands during the 2005 spring harvest compared to the same time period during 2003 and 2006.

The results demonstrate more consistency in the total amount of area burned in fall crop residue burning. Although there is a large difference in the reported crop acreage between 2003 and other years (<40% from the multi-year average), the total amount of burned area is the second largest during the 2003-2006 period. The burn rate for fall 2003 was three times higher than 2004, 2005, and 2006. This may be explained by the record-breaking rice crop in fall 2003 (Johnson, 2003) whereby Arkansas farmers also faced record-setting residue levels in the fields.

Multi-Year Assessment of Crop Residue Burning in Intensive Croplands of the Study Area

Similar to the findings of the Arkansas analysis, our results for the full study area show a considerable inter-annual variability in the amount of crop residue burning during 2003-2006 (table 6). For 2003 the hybrid method detected approximately 19,850 km^2 of crop residue burning in harvest period 1 (spring) and 9,900 km^2 in harvest period 2 (fall); this equates to approximately 14% and 7% of the total cropland area, respectively. Year 2003 showed more burned area for the first harvest season (related to winter wheat harvest and clearing of stubble from rice and soy fields for planting) than the other three years but less burning in the second harvest season (associated with the rice harvest and clearing stubble from soy fields for planting). The area of crop residue burning for both harvest seasons for the years 2004, 2005, and 2006 was as much as 7% less than 2003. Crop residue burning for harvest seasons in years 2004, 2005, and 2006 accounted for 13%, 16%, and 15% of total cropland area, respectively. Table 5 lists the combined burned area estimates of the DBA and CBA for croplands in the study area for both harvest seasons. On average, 12,719 and 10,836 km^2 burned in the spring and fall harvests, respectively.

Table 6. Burned area for croplands in MODIS tile h10v05 during the spring and fall harvest seasons.

Year	DBA[a] (km^2)	CBA[b] (km^2)	Total (km^2)	Harvest
2003	19,761.57	84.48	19,846.05	Spring
2004	7,550.12	85.12	7,635.24	Spring
2005	11,669.01	69.60	11,738.61	Spring
2006	11,577.25	79.52	11,656.77	Spring
Average	12,639.49	79.68	12,719.17	Spring
2003	9,559.28	313.92	9,873.20	Fall
2004	11,732.59	109.60	11,842.19	Fall
2005	10,966.90	416.00	11,382.90	Fall
2006	10,061.75	183.68	10,245.43	Fall
Average	10,580.13	255.80	10,835.93	Fall

[a] DBA = Direct Burned Area product.
[b] CBA = Calibrated Burned Area product.

The CBA estimates added between 0.5% and 4% area to the DBA estimates (table 6). Although the CBA component did not change the total amounts of burned area considerably, it did improve the spatial aspects of mapping burned fields. On average during 2003-2006, 70% of active fire detections did not overlap with burned area. These detections represented small, single field fires that were missed by the direct dNBR-based assessment of burning and may be the result of several conditions. In contrast, fire management of large tracts of continuous fields, mapped by the DBA algorithm, is unlikely to occur during sub-optimal burning conditions. Due to comparatively low crop residue biomass, the active fire product may miss cool agricultural fires and map only "special" cases. These cases may include either ideal conditions for active fire detection (e.g. low cloud cover, low aerosol emissions, close to nadir look angle) or fields with enough biomass accumulation to cause more intense burning. An increase in the number of fire detections not overlapping with the DBA within the agricultural areas was found during the fall season (mean of 1400 detections in the fall compared to a mean of 500 detections in spring); this may be attributed to clearer atmospheric conditions.

Discussion

The specifics of crop residue burning in the intensive agricultural areas of the United States present a unique set of requirements for satellite monitoring of agricultural burning. Hourly observations of on-going burning activity at ≤1-km resolution in combination with daily observations of post-fire impacts in NIR and ~2.1-μm SWIR spectrum at ≤250-m resolution (based on the mean 0.16-km^2 field size of the intensive croplands in the United States) would be ideal in providing a close-to-comprehensive view of crop residue burning in the United States. However, no current satellite systems are exceptionally well-suited for mapping or monitoring crop residue burning.

Our results show that inferring the amount of crop residue burning from active fire detections acquired by polar orbiting satellites (e.g. MODIS) provide a largely limited view of fire activity in agricultural landscapes. Fire detections calibrated into burned area contributed <4% of the total burned area estimated by our algorithm. However, despite the small overall contribution to the total amount of burned area, active fire detections add important information on the spatial distribution of agricultural burning omitted by the DBA-based burn maps. Nearly 70% of active fires were detected in areas non-overlapping with DBA maps, representing a large group of small sources of potential emissions and pollutants not accounted for within the estimates from multi-field burning practices. Consequently, if burned area mapping is undertaken in part for spatially explicit air quality assessment purposes, the inclusion of the CBA component is highly important as burning of crop residues affect nearby rural and urban populations (Dhammapala et al., 2006).

The DBA approach provides better estimates of the amount of crop residue burning than the CBA. However, the current resolution of the input data, particularly for the 500-m MODIS ~2.1-μm band, limits its capabilities to fully map burned fields. Mapping phenomena that occur at finer scale than pixel resolution lowers the algorithm's ability to map a similar object (e.g. burned field) consistently. The position of a burned field of 0.16 km^2 within the MODIS 500-m pixel (0.25 km^2) influences the magnitude of dNBR change; the dNBR will be higher if the 500-m pixel is centered on the entire field compared to a position of the field in the corner of the MODIS pixel or on the boundary of two neighboring 500-m pixels. The spatial resolution of 250 m (~0.0625 km^2) is smaller than the average field size and is more likely to capture the change due to burning within a single field and thus improve the total burned area estimates.

The presented hybrid approach focuses on mapping harvest related crop residue burning. Although management fires occur in croplands during seasons other than harvest, our assessment shows that the amount of area burned during non-harvest related management fires (e.g. pest and weed management) is close to negligible. The analysis of active fire detections shows that ~94% of cumulative yearly active fires are found within the two time windows identified in this analysis as harvest periods (see section 3.1.). In terms of air quality, this cropland burning occurring before and after the harvest periods is unlikely to be a significant contributor, as these fires are more than likely the burning of fallow fields (Personal communication with Dr. Steve Van Vleet, Agriculture Extension Agent for Whitman County, Washington State University, 7 April 2008).

The large inter-annual variability of burned area estimates shown by our results emphasizes the importance of developing direct monitoring approaches for crop residue burning assessment. The analysis of crop residue burning in Arkansas demonstrates that indirect assessment methods (e.g. burned area as a fractional assessment of crop acreage) can over- or underestimate the actual amount of burned area during a single year by a large margin. In addition, the direct observations allow for developing spatially explicit and temporally dynamic models of emissions and air quality estimates.

Conclusion

Crop residue burning is a widespread agricultural practice in the established intensive agricultural landscapes of the United States. The emissions from these fires have local and regional impacts on atmospheric composition and air quality. Indirect methods of emission estimates rely on large, simplifying assumptions and often lead to estimates of unknown accuracy. Satellite observations provide an opportunity for development of direct observations of crop residue burning and strengthen our understanding of the contribution from these fires to the biogeochemical cycles. Although the current satellite systems do not meet the exact requirements posed by the specifics of agricultural burning, the combination of multiple daytime observations of on-going fire activity at 1-km resolution and daily observations of surface reflectance in the NIR and ~2.1-μm SWIR range at 500-m resolution presents MODIS as the most appropriate instrument for mapping burned areas in croplands of the United States.

The hybrid approach of combining the dNBR-based approach with calibrated active fire detections has strong potential for cropland burned area mapping applications. The hybrid approach shows high agreement with known burned areas from both ground reference data and high resolution ASTER images. Both the DBA and the CBA products within the hybrid algorithm can be readily replicated by various users as they are based on operational MODIS products. While the DBA accounts for more than 96% of total crop residue burned area estimated by the hybrid approach, the CBA enhances the burned area mapping capabilities by providing additional information about the volume and geographic distribution of total crop residue burns. For the purposes of air quality monitoring, the small improvement in areal estimates and spatial precision of crop residue burning from the CBA is important for improving the information distributed to policy makers, agriculture officials, and farmers. Therefore, the hybrid approach presents a more comprehensive assessment of crop residue burning at the regional and national scales.

The intra- and inter-annual dynamics of crop residue burning, demonstrated in this study, promote the need for development of better systems aimed at monitoring crop residue fires in the United States. Such systems or constellations of systems should include enhanced capabilities for hourly observations of ongoing burning activity at ≤1-km resolution and daily mapping of burned area at ≤250-m resolution in the NIR and ~2.1-μm SWIR spectral space. In the absence of systems specifically adapted for fire monitoring in croplands, the hybrid MODIS burned area mapping approach provides a reliable and accurate method to quantify burned area. A threshold, set for this study at 0.375, successfully eliminated plowed fields in the selected study area. However, a different threshold may be needed for cropland areas with lighter or darker soil. Due to its high accuracy, readily available data, and relatively short processing time from satellite retrieval to end product, the presented approach could be used to monitor and quantify local, state, and regional crop residue burning - a burgeoning concern and initiative for a growing number of users in the agricultural community (FL DOF, 2007; ISDA, 2007; WA DOE, 2007). This approach is suitable as an input for empirical modeling, such as predicting carbon release from burned crop residues, and is being used in a related study to estimate burned area for a remote sensing-based calculation of greenhouse gas and air quality emissions from crop residue burning for the contiguous United States.

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