Monitoring agricultural cropping patterns across the Laurentian Great Lakes Basin using MODIS-NDVI data

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ABSTRACT

The Moderate Resolution Imaging Spectrometer (MODIS) Normalized Difference Vegetation Index (NDVI) 16-day composite data product (MOD12Q) was used to develop annual cropland and crop-specific map products (corn, soybeans, and wheat) for the Laurentian Great Lakes Basin (GLB). The crop area distributions and changes in crop rotations were characterized by comparing annual crop map products for 2005, 2006, and 2007. The total acreages for corn and soybeans were relatively balanced for calendar years 2005 (31,462 km^2 and 31,283 km^2, respectively) and 2006 (30,766 km^2 and 30,972 km^2, respectively). Conversely, corn acreage increased approximately 21% from 2006 to 2007, while soybean and wheat acreage decreased approximately 9% and 21%, respectively. Two-year crop rotational change analyses were conducted for the 2005–2006 and 2006–2007 time periods. The large increase in corn acreages for 2007 introduced crop rotation changes across the GLB. Compared to 2005–2006, crop rotation patterns for 2006–2007 resulted in increased corn–corn, soybean–corn, and wheat–corn rotations. The increased corn acreages could have potential negative impacts on nutrient loadings, pesticide exposures, and sediment-mediated habitat degradation. Increased in US corn acreages in 2007 were related to new biofuel mandates, while Canadian increases were attributed to higher world-wide corn prices. Additional study is needed to determine the potential impacts of increases in corn-based ethanol agricultural production on watershed ecosystems and receiving waters.

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1. Introduction

Ethanol production, especially corn ethanol, increased rapidly across the mid-western USA from 2005 to 2007 (RFA, 2007). Recently, the environmental implications associated with corn based ethanol production has received increasing attention (Pimentel, 2003; Pimentel and Patzek, 2005; Zah et al., 2007; Scharlemann and Laurence, 2008). The research of Zah et al. (2007) suggested that corn ethanol may have greater overall environmental cost than using fossil fuels. Water quality, soil erosion, air pollution, biodiversity and the loss of natural habitats are concerns at both local and regional scales (Hodge, 2002; Huston and Marland, 2003; Pimentel and Patzek, 2005; Searchinger et al., 2008).

Environmental assessments often need site-specific information about crop distributions (e.g., SWAT, 2007). Researchers are not only interested in the total area of ethanol crop production, but also require data documenting geographic distributions and changes over time to support distributed modeling efforts. Such information is particularly useful for identifying watersheds subject to potential environmental damages or ecological degradations. Due to the limited availability of National Agricultural Statistics Service (NASS) Crop Data Layer (CDL) products, researches often rely on agricultural statistics estimates (i.e., state or county-level), developed by the United States Department of Agriculture (USDA) NASS program (Sheehan et al., 2004). The spatial details of the crop location, extent and distribution, and the pattern of crop change are generally unavailable from the estimated agricultural statistics. Researchers are thus forced to use unrealistic assumptions of crop distributions and crop rotation patterns, which may lead to high uncertainties in modeling predictions of potential environmental impacts.

The mapping of crops using remote sensor data has shown good potential for characterizing the extent, distribution and condition of croplands (Moran et al., 1997; Frolking et al., 1999; Doraiswamy et al., 2005; Thenkabail et al., 2009). The Moderate Resolution Imaging Spectroradiometer (MODIS) data, which combine moderate spatial resolution (250 m) and a high temporal resolution (1–2

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day repeat cycle), were found to be particularly useful to differentiate general cropland versus non-cropland and to categorize individual crop types (Lobell and Asner, 2004; Chang et al., 2007; Wardlow et al., 2007; Wardlow and Egbert, 2008). The phenology-based categorization (or time-series analysis) of MODIS-NDVI (Normalized Difference Vegetation Index) is one of the most used approaches (DeFries and Townshend, 1994; Shao et al., 2010; Hansen et al., 2003). Most previous MODIS-NDVI crop-mapping applications have focused on single year crop mapping efforts. MODIS-NDVI datasets have rarely been used to study the crop changes or rotations over multiple years. The potential of multi-year MODIS-NDVI crop mapping has not yet been fully exploited.

The principle objective of this research was to examine the cropland changes across the Great Lakes Basin (GLB) using map products derived from MODIS-NDVI data. The GLB is a region thought to have undergone significant changes in cropping patterns, because the US government implemented substantial subsidies to encourage corn ethanol production during the study period (2005–2007). Research questions of interest included the following: (1) how did crop acreage distributions (i.e., corn, soybean, and wheat) change through the GLB? (2) Was there a change in crop rotational patterns due to increased corn ethanol demand? (3) If yes, were there any geographic differences associated with variations in crop rotation patterns across the GLB (i.e., US versus Canadian)? The answers to these questions are particularly important for identifying areas or regions with a high potential for environmental degradation. Two specific research objectives of this paper were to map annual crop distributions across the GLB for 2005, 2006, and 2007, and compare the two-year crop change or rotation patterns for 2005–2006 and 2006–2007.

2. Study area

The GLB region includes all or part of eight states of US and a portion of the Province of Ontario, Canada (Fig. 1). While the basin is among the most industrialized regions in the world, the southern portions of the GLB are prime areas for corn, soybean and other types of agricultural crop production (USEPA, 2008). GLB agricultural production represents 7% and 25% of the total US production and Canadian production, respectively (USEPA, 2008). The total agricultural land in the US portion of GLB has decreased slightly from 1970 to 2001 (Erickson, 1995; Wolter et al., 2006). The loss of agricultural land mostly occurred near urban edge areas. For example, southeast Michigan alone lost 13% of agricultural land area from 1990 to 2000; mainly due to the urban expansion (SEMCOG, 2003). A majority of Ontario's prime agricultural lands are located in the southern part of the province; which have also been subject to extensive urban expansion. Approximately 18% of the prime agricultural land in Ontario has been converted to urban from 1976 to 1996 (Statistics Canada, 1998). However, crop yields associated with major crop types have increased dramatically over the past decades due to technology improvement (Matson et al., 1997). Urbanization and intensive agricultural production are believed to cause a number of environmental problems including: (a) sedimentation and excessive nutrient loading (Crosbie and Chow-Fraser, 1999); (b) hydrological modifications (Environment Canada and EPA, 2003); and (c) the loss of natural habitats and diminished biodiversity (Detenbeck et al., 1999).

3. Methods

3.1. Data

The MODIS-NDVI data were pre-processed using the method developed by Lunetta et al. (2006). MODIS-NDVI data preprocessing was conducted to provide a filtered (anomalous data removed) and cleaned (excluded data values estimated) uninterrupted data stream to support time-series analysis. MODIS-NDVI 16-day composite grid data (MOD13Q1, version 5.0) in HDF format

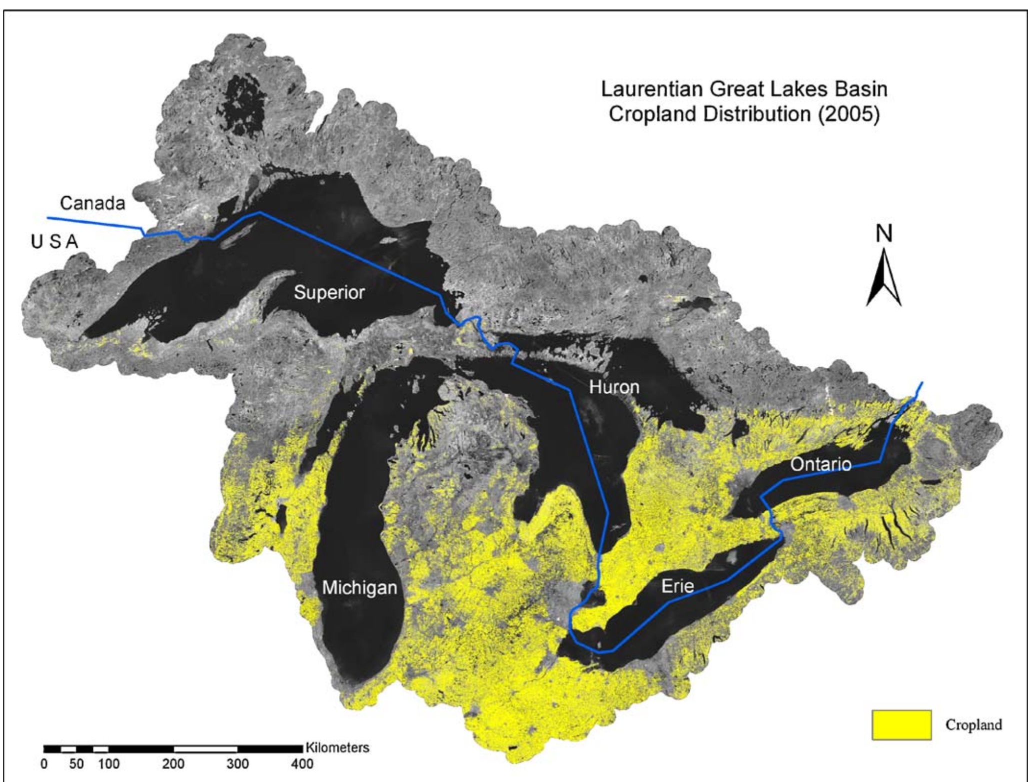

Fig. 1. MODIS-NDVI derived cropland extent and distribution across the GLB in 2005.

were acquired between February 2000 and December 2007 from the NASA Earth Observing System (EOS) data gateway. Details documenting the MODIS NDVI compositing process and Quality Assessment Science Data Sets (QASDS) can be found at NASA's MODIS web site (MODIS, 1999). NDVI data were subset to the GLB study boundary (10 km buffer), re-projected from a sinusoidal to an Albers Equal-Area Conic projection, using a nearest-neighbor resampling routine, and entered into a 250 m × 250 m grid cell multilayer image stack. Separate data stacks were developed for both the original NDVI data and QASDS.

The NDVI data stack was first filtered to eliminate anomalous high (hikes) and low (drops) values and then filtered for a second time using the QASDS ratings to remove poor quality data values from the NDVI data stack. Hikes and drops were effectively eliminated by removing data values that suddenly decreased or increased and then immediately returned to near the previous NDVI value. The threshold for the removal of pseudo hikes and drops was set at ±0.15% to achieve the best setting (determined qualitatively) to eliminate most all anomalous points, while not inadvertently removing good data points, resulting in a smoother temporal profile. The MODIS QASDS data quality ratings were then applied to retain only those pixels rated as "acceptable" or higher. The filtered data were then transformed into frequency domain using a discrete Fourier transformation and the signal and noise spectrum separated (Roberts et al., 1987; Azzali and Menenti, 2000; Roerink and Menenti, 2000). The removed (corrupted) NDVI data points were estimated from the frequency domain signal spectrum using a nonlinear deconvolution approach described by Roberts et al. (1987) to estimate complete "filtered and cleaned" NDVI temporal profiles for each pixel within the GLB.

The filtered and cleaned NDVI temporal profiles provided a "high quality" dataset that was used to support both the general cropland and crop-specific (e.g., corn, soybean, wheat) mapping. For the cropland versus non-cropland mapping, the 2001 National Land Cover Dataset (NLCD-2001) was obtained to provide training data. We also collected most available Landsat Enhanced Thematic Mapper Plus (ETM+) images covering the time interval 2000–2002 to construct a seamless image mosaic for the GLB. The Landsat seamless mosaic provided sufficient spatial resolution for a visual interpretation of general cropland and non-cropland classes. This was useful for a validation of cropland mapping results, especially for the Canadian portion of the GLB.

For crop type specific classifications (e.g., corn, soybean, wheat), we obtained all available cropland data layers (CDLs) for 2007 across the US portion of the GLB. The CDL data was primarily developed from AWiFS (Advanced Wide Field Sensor) imagery and had a high classification accuracy (>90%) for most major crop types (NASS, 2007). A problem related to the CDL was its limited spatial coverage—primarily focused on the intensive agricultural regions in the Midwestern US. Across the GLB region, only limited spatial coverage of CDLs was available, mainly for the states of Michigan and Ohio. Additionally, we obtained the state and provincial level agricultural statistics from the NASS and Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA).

3.2. General cropland mapping

The categorization of general cropland and non-cropland cover types was conducted prior to the crop-specific identifications using training samples derived from the NLCD-2001 (reference data). Specifically, we built a geographic linkage between the NLCD-2001 and the MODIS-NDVI dataset. For each center position of MODIS pixels, we calculated cover proportions for different cover types from the NLCD-2001. Instead of calculating the cover type proportions within the 250 m MODIS-NDVI pixel, we employed a 300 m pixel resolution to reduce the impacts of registration errors. The primary cover type classes considered included water, urban, barren land, forest, shrub/scrub, hay/pasture, cultivated crops, and wetland. Pure MODIS-pixels were identified when the 300 m resolution pixel was dominated by one cover type (i.e., >85% homogeneous). A random sample selection was then conducted to collect MODIS training pixels corresponding to each cover type. The training pixels were further grouped into two general classes of cropland and non-cropland. The total numbers of training pixels were 5170 and 4349 for cropland and non-cropland, respectively. It should be noted that the hay/pasture class was included in the cropland group for this study. We did not use the NLCD-2001 to generate a cropland mask, because it only included the US portion of the GLB. It was important to build a general MODIS-NDVI classifier for the entire GLB study area to maintain the categorization consistency across both the US and Canada.

We used a three-layer MLP (multilayer perceptron) neural network classifier for the categorization of the cropland and non-cropland (Richards and Jia, 1999; Shao et al., 2010). The input layer in the MLP consisted of 13 nodes corresponding to 13 MODIS-NDVI values from Julian days 97–289. The MODIS-NDVI values for the remaining dates were discarded due to low information contents (i.e., snow cover in winter). A total number of 15 nodes were used in the hidden layers. The output layers consisted of two nodes indicating two classes of cropland and non-cropland. The MLP classifier was trained using a three fold stratified cross-validation approach to improve the performance (Duda et al., 2001). The trained network was then employed to classify the MODIS-NDVI image of the entire GLB study area. We assessed the initial cropland map using the Landsat seamless mosaic as reference. Obvious categorization errors were identified and additional training data points were added iteratively to improve the categorization results. The cropland categorization procedures were conducted for annual MODIS-NDVI datasets corresponding to years 2005, 2006, and 2007.

For the 2005 cropland map, an accuracy assessment was conducted using the Landsat ETM+ seamless mosaic as the primary reference data source. We randomly selected 300 pixels for cropland and non-cropland, respectively. The pixels were visually interpreted from the ETM+ mosaic to assess the accuracy of cropland maps. It should be noted that there was a three-year time difference between the 2002 ETM+ mosaic and the 2005 MODIS-NDVI cropland map; however, it was the only independent dataset available for the selected study area and time-period.

3.3. Crop-specific mapping

The identifications of individual crop types were conducted within the cropland mask for each calendar year. Three major crop types were considered including corn, soybean, and wheat. The identification of hay was considered initially, but discarded because of its high phenological variability (i.e., different harvesting time). Hay and the remaining crop types (e.g., sugar beet, potato, etc.) were grouped as a mixed class of the "other" crop type. The training pixels were primarily identified using visual interpretation of MODIS-NDVI temporal profiles (Wardlow et al., 2007; Wardlow and Egbert, 2008). For example, the NDVI values for wheat peaked around late-May or early-June, while NDVI values for corn peaked around late-July or early-August. The unique crop phenology provided the basis for differentiating these main crop types using MODIS-NDVI data. One major challenge associated with the NDVI-based categorization approach was the within-class variability of crop phenology across the large geographic study area. The phenology of a specific crop type (e.g., corn) in northern Michigan may be different from those from Ohio. We employed an ecoregion-stratified categorization approach to improve the categorization performance (Homer et al., 2004). Specifically, we divided the study area into 12 ecoregions (Omernik, 1987) and conducted independent crop-specific categorizations within each ecoregion. The climate and soil conditions are relatively homogenous within each ecoregion, thus we assumed that crop phenology within each ecoregion was also similar for each of the individual crop types.

The crop-specific categorization was also performed using MLP classifier. The results for the 2007 MODIS-NDVI categorization were assessed using the CDL derived from 2007 AWiFS imagery data (56 m) as reference data. We used the same approach described above for the general crop type mapping to assess the performance of the MODIS-NDVI categorization results. The percentages of individual crop types within each 300 m resolution pixel were calculated. Similarly, "pure" pixels were identified if one dominant crop type consisted of >85% homogeneous. All "pure" pixels were used as the reference dataset for the accuracy assessment of MODIS-NDVI crop-specific classification. Overall accuracy and Kappa coefficient were calculated and reported. For classification results corresponding to years 2005 and 2006, there was no reference map available to perform a pixel-wise accuracy assessment. We assumed that categorization accuracies would be similar across study years.

3.4. Crop statistics and crop rotation analysis

The total crop acreages of the GLB were calculated from the crop map products of 2005, 2006 and 2007. The estimated crop acreages from MODIS-NDVI were compared to the state or province-level agricultural statistics obtained from the NASS and OMAFRA. The comparison was conducted for the State of Michigan and the Province of Ontario only, because they are located entirely within the geographic boundaries of the GLB. We did not conduct a county-level comparison, because these data were considered less reliable than state-level values (OMAFRA). More importantly, the county-level agricultural statistics were not complete for all counties or time-periods.

The area distributions of three crop types were analyzed at both the GLB and the sub-regional scales. For the sub-regional scale, we simply divided the GLB into US and Canadian sub-regions. The crop distributions in these two sub-regions were compared over the three-year period. For each of the study years, we also calculated the percentages of corn and soybean areas using 5 km × 5 km window. The changes of crop intensity or proportional crop areas from t_1 to t_2 (e.g., 2005–2006), were calculated using the following equation:

$$\Delta P_i = P_{i_2} - P_{i_1} \quad (1)$$

where ΔP_i indicates the percent change of crop area in the *i*th window (5 km × 5 km). P_{i_1} and P_{i_2} are the percentage individual crop type area at t_1 and t_2.

At the individual pixel level, the crop rotations were analyzed by stacking two-year crop maps and conducting a post-categorization comparison. This generated two-year crop rotation patterns of consecutive years for 2005–2006 and 2006–2007. The frequency of crop rotation patterns (i.e., corn–soybean, soybean–wheat) were calculated within the GLB. This allowed us to identify the most common crop rotation patterns and associated temporal variations.

4. Results

4.1. General cropland

The overall accuracy for 2005 cropland map was 89% and Kappa coefficient was 0.78. No formal accuracy assessments were conducted for the 2006 and 2007 cropland map products, but we expected similar accuracy levels because the same methods of training data selection and categorization training were employed. The total cropland areas in the GLB were 115,590 km^2, 117,973 km^2, and 117,352 km^2 for year 2005, 2006, and 2007, respectively. The numbers were relatively stable over the three-year time-period. Fig. 1 shows the cropland map from year 2005. The total cropland consisted of approximately 20% of the total land area in the GLB. Over 97% of the croplands were located in the southern half of the GLB, especially in the states of Michigan, Ohio, and Wisconsin in the US and the southern portions of Ontario. Large tracks of land in the northern portion of the GLB remained as forest. Climate and soil quality limit large scale agriculture in the northern GLB region.

An overlay analysis of three cropland maps indicated that about 106,342 km^2 or 92% of cropland pixels remained stable as cropland over the three-year period; the remaining cropland pixels were labeled as non-cropland for at least one years between 2005 and 2007. One possible explanation was that fallow or marginal lands (e.g., conservation reserve program) were involved in conversions between cropland and non-cropland during different calendar years. For example, farmers may leave the land fallow in a certain year. We visually interpreted these "inconsistent" cropland pixels using the ETM+ seamless mosaic and CDL 2007 as reference data. We determined that the majority were spatially scattered, and most were located at the edges of the agricultural land patches, especially at the edges of hay/pasture fields. Therefore, these "inconsistent" croplands might also be associated with classification uncertainties from mixed pixels (Lobell and Asner, 2004). Without available ground truth or reference images across multiple years, it was not possible to provide a more detailed quantitative assessment for these "inconsistent" cropland pixels.

4.2. Crop-specific mapping

The crop-specific categorization results of 2007 were assessed using CDL 2007 as a reference data source. The CDL 2007 itself was a remote sensing-based crop map product. The accuracies of the CDL was relatively high, especially for major crop types such as corn, soybean, and wheat (>92% in Michigan). For the 2007 crop-specific categorization, the overall accuracy was 84% (Kappa = 0.73). The user's accuracies for corn, soybean, and wheat were 87%, 82%, and 81%, respectively. The producer's accuracies for corn, soybean, and wheat were 85%, 81%, and 83%, respectively. The site-specific accuracy assessment was conducted for year 2007 only, because there were no reference datasets available for years 2005 and 2006.

Table 1 shows the comparisons of crop area estimations between the MODIS-NDVI categorizations and statistical estimated obtained from the NASS and OMAFRA. Comparisons were performed to conform with state (Michigan) and province (Ontario) boundaries. Other states were not entirely located within the GLB boundary, thus state-level comparison was not possible. The MODIS-NDVI categorization slightly over-estimated corn acreages for Michigan, with the largest difference being observed in 2005 (5.4%). Conversely, the MODIS-NDVI classification underestimated soybean acreages (−1.8 to −13.8%) for both Michigan and Ontario. The estimate discrepancies for corn and soybean were largely due to the confusion between corn and soybean phonological patterns or NDVI profiles (Chang et al., 2007). The mis-categorization of soybean as corn, or vise versa, was the likely source of confusion. The MODIS-NDVI categorization also under-estimated wheat acreages, but the differences between the MODIS estimations and the numbers from the NASS-OMAFRA were generally <10.0%. It should be noted that there were double cropped fields (wheat harvest in spring and soy harvest in fall). The winter wheat and soybean in NASS-OMAFRA statistics may share

Table 1
Comparisons of MODIS-NDVI estimated crop areas with the NASS (United States) and OMAFRA (Canadian) agricultural statistics for 2005–2007. All area units are in km^2.

	2005			2006			2007		
	MODIS	NASS/OMAFRA	Difference (%)	MODIS	NASS/OMAFRA	Difference (%)	MODIS	NASS/OMAFRA	Difference (%)
Michigan									
Corn	9,600	9,105	5.4	8,964	8,903	1.0	10,943	10,724	2.0
Soybean	7,198	8,094	−11.1	7,949	8,094	−1.8	6,280	7,284	−13.8
Wheat	2,245	2,428	−7.5	2,374	2,671	−11.1	2,140	2,226	−3.9
Ontario									
Corn	6,007	6,475	−7.2	6,467	6,385	1.3	8,342	8,498	−1.8
Soybean	8,629	9,409	−8.3	7,831	8,725	−10.2	8,061	9,065	−11.1
Wheat	3,057	3,359	−9.0	3,896	4,162	−6.4	2,243	2,408	−6.9

Table 2
Crop areas and distributions for corn, soybean, and wheat based on MODIS-NDVI classifications across the GLB for 2005, 2006, and 2007. All area units are in km^2.

	2005		2006		2007	
	Crop areas	Distribution (%)	Crop areas	Distribution (%)	Crop areas	Distribution (%)
Corn	31,462	44.1%	30,766	42.8%	37,318	50.7%
Soybean	31,283	43.8%	30,972	43.1%	28,207	38.3%
Wheat	8,623	12.1%	10,163	14.1%	8,062	11.0%
Total	71,368	100.0%	71,900	100.0%	73,587	100.0%

the same agricultural field, while the MODIS-NDVI classification produced mutually exclusive classes. This may have resulted in discrepancies in crop area estimations.

4.3. Crop statistics

Table 2 shows the crop area distributions for the entire GLB study area over the three-year period. The total areas of the three crop types were 71,368, 71,900, and 73,586 km^2 for 2005, 2006, and 2007, respectively. These numbers were quite stable over the three-year study period and corresponded to approximately 62.0% of total croplands in the GLB. The corn acreage decreased by 2.2% from year 2005 to 2006, and then increased approximately 21.3% from 2006 to 2007. The soy acreage decreased only slightly (1.0%) from 2005 to 2006, and then further decreased approximately 9.0% from 2006 to 2007. Conversely, wheat acreage increased about 17.9% from 2005 to 2006 and decreased 20.7% from 2006 to 2007.

The change in individual crop acreages altered the general crop area distributions in the GLB (Table 2). For example, the area distributions of corn and soybean were almost equal in 2005 (44.1% and 43.8%) and 2006 (42.8% and 43.1%). However, in 2007, the area distribution of corn increased to 50.7%, while soybeans decreased to 38.3%. For wheat, the area distribution increased from approximately 12.1% in 2005 to 14.1% in 2006, and then dropped to 11.0% in 2007. We further calculated the crop distributions at the sub-regional level to examine whether there were large spatial variations. Fig. 2a and b depicts the area distributions of three crop types for the US portion and the Canadian portion of the GLB. For the US, large increases in corn acreage (19.1%) from 2006 to 2007 resulted in crop acreage decreases for both soybean (−13.1%) and

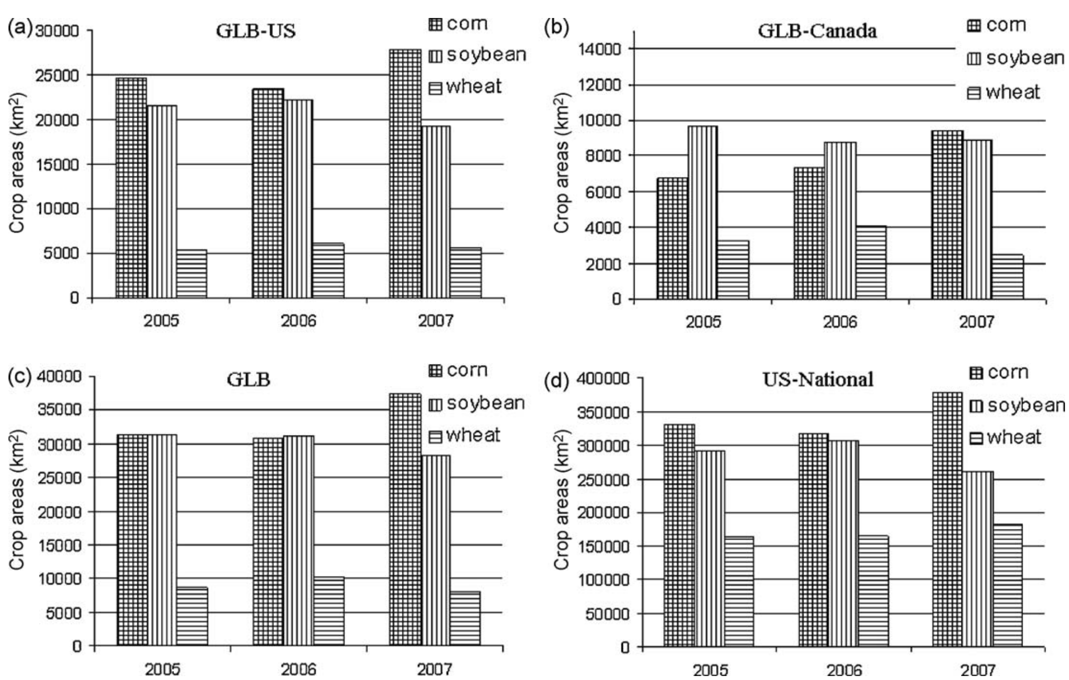

Fig. 2. The total area plantings of corn, soybean, and wheat for the US-GLB (a), Canadian-GLB (b), entire GLB(c), and entire US from national statistics (d).

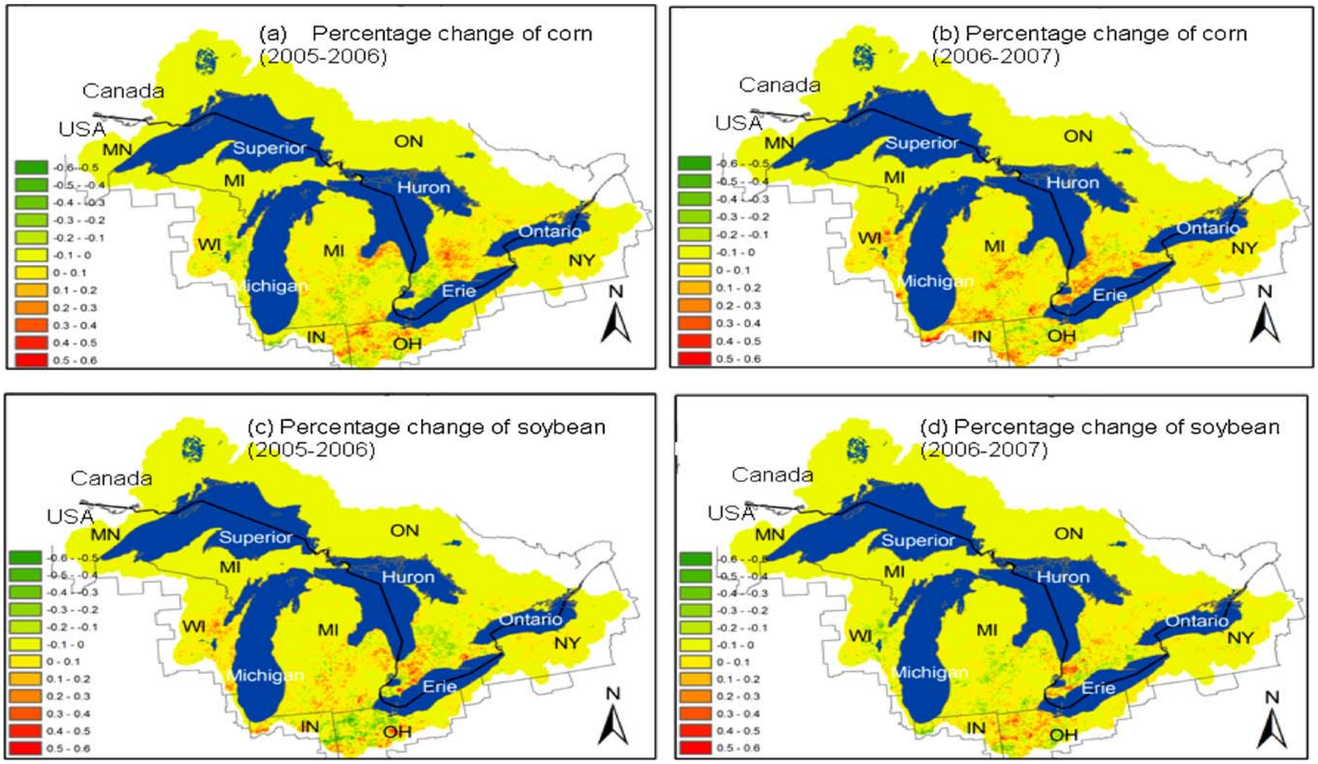

Fig. 3. The percentage crop changes for corn and soybean. Change of corn percentage from 2005 to 2006 (a), change of corn percentage from 2006 to 2007 (b), changes of soybean percentage from 2005 to 2006 (c), and change of soybean percentage from 2006 to 2007 (d).

wheat (−7.8%). For the Canadian portion of the GLB (Ontario), there was a 28.2% increase in corn acreage from 2006 to 2007. This coincided with a large decrease in wheat acreage (approximately 40.8%). Fig. 2c and d shows the area distribution of three crop types for the GLB and the entire US from national statistics (NASS), respectively. The comparison of Fig. 2a and d suggested similar cropping change patterns across the US portion of the GLB compared to the US national level statistics. The large increases in corn acreage from 2006 to 2007, mainly resulted in crop acreage decreases for soybean.

Crop intensities were calculated for both corn and soybean using 5 km × 5 km moving window. Fig. 3a–d shows the changes in crop intensity (percentage) from 2005 to 2006 and 2006 to 2007. From 2005 to 2006, the highest increases of proportional corn areas occurred in the ''thumb'' area of Michigan, northern Ohio, and south-western Ontario. The proportion of corn subsequently decreased in these areas from 2006 to 2007. It was also evident that corn proportions had increased for most of the other GLB regions from 2006 to 2007. Visual interpretation suggested an inverse relationship between the changes of corn and soybean percentages.

We further developed cross-plots to compare the changes of cropping intensity for corn and soybeans (Fig. 4a and b). Generally, the changes in corn percentages were negatively correlated with the changes in soybeans for both 2005–2006 ($R^2 = 0.50$) and 2006–2007 ($R^2 = 0.53$). These results were expected because the

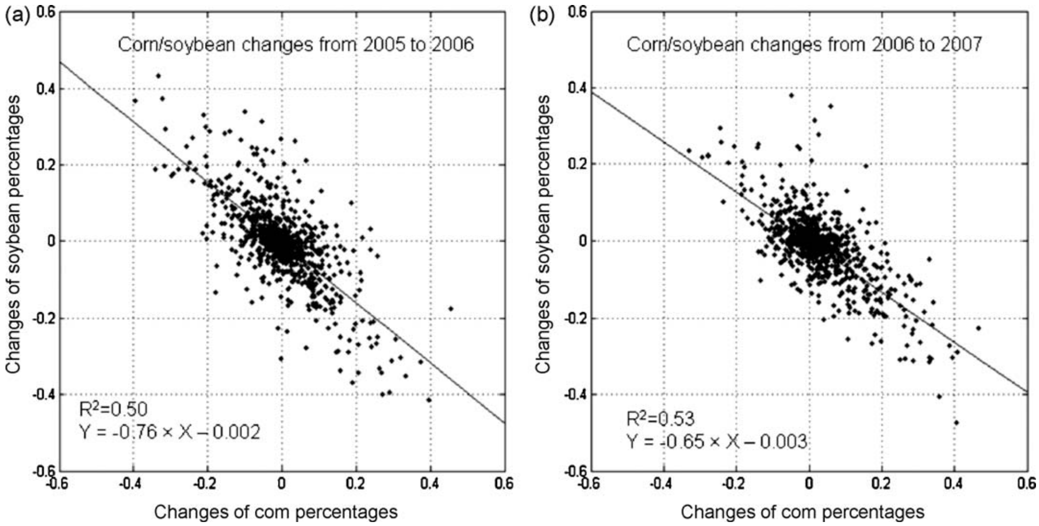

Fig. 4. The relationship between corn and soybean changes from 2005 to 2006 (a) and 2006 to 2007 (b). There were negative correlations between the corn and soybean crop changes. Individual points represent the proportional changes in corn/soybean per 5.0 km window.

Table 3
Percent crop rotations from 2005 to 2006 (a) and 2006 to 2007 (b).

	2006				
	Corn	Soybean	Wheat	Other	Total
(a) 2005					
Corn	24.7%	41.8%	5.6%	27.8%	100%
Soybean	40.9%	22.9%	13.8%	22.4%	100%
Wheat	25.3%	30.4%	15.9%	28.4%	100%
Other	29.3%	29.4%	9.9%	31.4%	100%
	2007				
	Corn	Soybean	Wheat	Other	Total
(b) 2006					
Corn	32.6%	35.7%	5.4%	26.4%	100%
Soybean	47.9%	24.0%	9.2%	18.8%	100%
Wheat	32.9%	27.4%	9.2%	30.5%	100%
Other	33.9%	26.1%	9.8%	30.1%	100%

corn–soybean rotation was a common agricultural practice in both the US and Canada. The slope values from a linear regression analysis were −0.76 and −0.65 for 2005–2006 and 2006–2007, respectively. The lower steep slope for the 2006–2007 suggests that the increases in corn percentages may have also resulted from other crop changes (i.e., other crop to corn) in addition to the typical soybean–corn rotations.

4.4. Crop rotation analysis

We aggregated pixels into sixteen categories based on the "from-to" crop rotation or change classes. Table 3a and b summarized the crop rotation patterns of the GLB for 2005–2006 and 2006–2007, respectively. For 2005–2006, approximately 41.8% of corn fields were converted to soybean fields in 2006 and 24.7% of corn fields in 2005 remained corn fields in 2006. Also 27.8% of corn fields were converted to other crops. For soybean fields in 2005, 40.9% were converted to corn fields. These changes in crop rotation patterns were anticipated because corn–soybean rotation was the most often used crop rotation (Meese et al., 1991). Approximately 22.9% of soybean fields remained as soybean fields in 2006. This percentage was higher than expected because farmers typically did not plant soybean in consecutive years. Categorization confusion (errors) between corn and soybean might be the reason. A post-categorization change detection analysis will generate errors propagating from both individual crop maps (Singh, 1989). An additional source of error could be attributed to mixed pixels containing partial corn and soybean fields. A hard label categorization approach may not be suitable for these mixed pixels (Richards and Jia, 1999). Most wheat fields in 2005 were either converted to soybeans (30.4%) or remained in wheat (28.4%) fields in 2006. For the "other" mixed class type, about 31.4% remained in the same category, while approximately 29.3% were converted to corn and soybean, respectively. The "other" crop type class was a mixed class, thus it was not possible to identify which specific crop type was involved in the crop rotation.

For 2006–2007 crop rotations, smaller percentages (35.7%) of corn fields were converted to soybean fields compared to 2005–2006 (41.8%). Additionally, 32.6% (2006–2007) versus 24.7% (2005–2006) of corn fields remained in continuous corn production. The percentage of soybean–corn rotation increased to 47.9%, while the percentage of soybean–wheat rotation decreased to 9.2%. The crop rotations of wheat–corn increased to 32.9% as compared to 25.3% for 2005–2006. These results suggested that the large increase in corn acreages in 2007 was responsible for substantial modifications in crop rotation patterns across the GLB from 2006 to 2007.

4.5. Discussion

The objectives of this research were to characterize the crop distributions and changes in crop rotations from 2005 to 2007 across the GLB. The MODIS-NDVI 16-day composite product was sufficient to support the development of both general cropland and crop-specific map products at a moderate spatial resolution of 250 m. The spatially explicit crop information was particularly useful for study locations without detailed crop map products (e.g., CDL). For the GLB, the state and provincial-level annual agricultural statistics did not provide spatially explicit data at an adequate temporal frequency to support field level crop inventory or time trajectory analysis. The MODIS-NDVI crop mapping and analysis provided a cost-effective and timely approach for the regional to sub-regional scale crop change analysis.

The total corn acreages from 2005 and 2006 were quite stable. The numbers were also similar to the total soybean acreages. The corn acreages increased by 21.3% from 2006 to 2007. The increase of corn acreages were directly related to the decrease of soybean acreages (13.1%) in the US portion of the GLB and the decrease of wheat acreages (approximately 40.8%) in the Canadian portion of the GLB. The levels of crop changes greatly exceeded the potential errors attributable to categorization uncertainties. Errors associated with corn and wheat categorizations were generally <10.0% (Table 1). The observed crop changes were attributed to cropland changes occurring in the GLB. There were also changes in crop rotation patterns (i.e., increased corn–corn and decreased corn–soybean rotations) for 2006–2007, compared to the 2005–2006 results. With current trends of an expanding ethanol industry and high export demand, it is important to monitor crop distributions and crop rotations using timely site-specific approaches, because changes in cropping patterns may potentially increase non-point pollution to the water, soil erosion, and other environmental costs (Pimentel, 2003). Due to the advantages of the moderate spatial and high temporal resolutions, the MODIS-NDVI based crop map products are well-suited for environmental assessment applications at watershed or other ecological meaningful units.

It should be noted that the crop changes were only analyzed using a two-year crop change or rotation period. Although this study identified the most common two-year crop rotations such as corn–soybean, wheat–soybean, and corn–wheat, it would be difficult to characterize the crop rotational changes that involve three or more sequential years. The greatest challenge would be the cumulative classification errors or error prorogation uncertainty associated with post-categorization comparisons (Singh, 1989). For example, a correct identification of three year crop rotation would require that three individual pixels (three separate image dates) be accurately labeled. The image mis-registration and categorization uncertainty may seriously affect the crop rotation results associated with additional dates ($n > 2$) (Townshend et al., 1992).

5. Conclusions

MODIS-NDVI datasets were used to develop annual cropland and crop-specific map products for the GLB for growing seasons corresponding to 2005, 2006, and 2007. The crop area distributions and crop rotational changes were characterized by comparing crop map products using two time-steps (2005–2006 and 2006–2007). The area distributions of corn and soybean were almost equal in 2005 and 2006, but there were large increases (21.3%) in corn acreages from 2006 to 2007. Alternatively, soybean and wheat areas decreased approximately 9.0% and 20.7% from 2006 to 2007, respectively. The crop rotation change analyses suggested that the large increase of corn acreages in 2007 introduced changes in crop rotation practices throughout the GLB. These changes resulted in substantial increases of corn–corn, soybean–corn, and wheat–corn crop rotations throughout the GLB. Increases in corn acreages for 2007 were greater in Ontario (28.2%) compared to the US (19.1%). The increases in corn acreages associated with biofuel mandates could have potential negative impacts on nutrient loadings, pesticide exposures, and sediment-mediated habitat degradation in the US. The increased US corn acreages in 2007 were attributed to the higher per bushel corn prices world-wide.

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