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Quantifying the area and spatial distribution of double- and triple-cropping croplands in India with multi-temporal MODIS imagery in 2005

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Cropping intensity, defined as the numbers of crops (single, double and triple cropping) per year in a unit cropland area, is one of the major factors in crop production and agriculture intensification. Changes in cropping intensity are driven by a number of socio-economic and climate factors. Agricultural census statistics of India contain much information on the distribution of crop types and total cropland area but contain no detailed spatially explicit information on the spatial distribution of double and triple cropping fields. In this study, we used multi-temporal images from the Moderate Resolution Imaging Spectroradiometer (MODIS) in 2005 to identify and map double-and triple-cropping land in India. The phenology algorithm we developed is based on the temporal profile analysis of three vegetation indices: Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI) and Land Surface Water Index (LSWI). The MODIS-based phenology algorithm estimates that India has a total area of 57.8 million ha of multiple-(including both double and triple-) cropping fields in 2005, which is about 6.4%higher than the estimate (54.3 million ha) from the agriculture census data in 2004/ 2005. The resultant MODIS-derived map of multiple-cropping croplands at 500-m spatial resolution in 2005 was compared with the state and district levels using the agricultural census data. We also evaluated the MODIS-derived map using in situ observation data collected in India. The results of this study demonstrate the potential of the phenology algorithm in delineating double-and triple-cropping practice in India. The resultant geospatial dataset of multiple-cropping croplands in India is useful for the study of irrigation, food security and climate.

1. Introduction

India had rapid increases of human population, from 553 million in 1970, 838 million in 1990, 1004 million in 2000 and 1129 million in 2007; and it is now the home to one-sixth of the world's population. Meeting the rising demand of food due to increasing population and changes in diet structure has been a challenging task in India. Agriculture in India has been a prominent sector in its economy. Agriculture, together with associated sectors, accounted for 18.6% of the gross domestic production (GDP) in 2005 and employed 60% of the country's population. In 2000, India accounted for 11% of the total cropland area in the world, and ranked second in the world in terms of agricultural production. Agricultural expansion, mostly through land conversion (e.g. conversion of forests, grassland and wetlands to croplands), was the dominant factor for the increase of

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agricultural production; and during the period of 1970–1990 the cultivated area rose by 2% per year. Agricultural intensification (e.g. multiple cropping in a unit area over a year, irrigation, fertilizer application) also contributed significantly to the increase of agricultural production (Frolking *et al.* 2006). Cropping intensity (number of crops per year in a unit area) increased substantially over the period of 1970–1990 (~130% in 1990). As human population continues to rise and the total arable land area in India is not expected to increase significantly, future increase of agricultural production will depend more upon agricultural intensification. Cropping intensity was projected to increase from 126.7% in 1993 to 140.9% by 2015, which might result in the gross sown area to rise from 178.5 to 204.6 million ha (Mohanthy *et al.* 1998).

Irrigation and multiple-cropping agriculture in India has been a key component of economic development and poverty alleviation. Most of the multiple-cropped areas are irrigated and generally receive higher amounts of chemical fertilizers than single cropped and rainfed crop fields. Cropping intensity may have significant impact on irrigation water use (Frolking *et al.* 2006), biogeochemical cycles (Li *et al.* 2003) and climate. It is important to note that cropping intensity varies substantially year by year, mostly driven by weather and climate, regional and global markets of crop production, and individual famers' decisions on crop cultivation; therefore, there is a need to have accurate and updated estimates of multiple-cropping croplands for a country.

Traditionally, there have been two approaches to obtain estimates of cropland area and cropping intensity in a country: agricultural census statistics and land survey (Qiu *et al.* 2003, Frolking *et al.* 2006). In India, the grassroots (village)-level revenue department officials (*Village Patwari*) report cropland statistics as a part of agricultural censuses. The village-level agricultural statistics have been aggregated to different administrative levels such as block, taluka, district, state and national levels. This is often a time-consuming and resources-intensive process carried out by governmental agencies. Moreover, these statistics are not readily available to the public in the same calendar year.

Space-borne remote sensing technology provides an alternative and independent approach for mapping cropland area and cropping intensity in a country (Xiao et al. 2003, Galford et al. 2008, Wardlow and Egbert 2008). Over the last few decades, satellite remote sensing has been widely used to map croplands at local, national and global scales (Frolking et al. 1999, Loveland et al. 2000, Lobell and Asner 2004, Thenkabail et al. 2005, Dash et al. 2007). The earlier global land cover mapping effort used time series data (1992-1993) of Normalized Difference Vegetation Index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) sensors onboard National Oceanic and Atmospheric Administration (NOAA) weather satellites and produced a global land cover map at 1-km spatial resolution, including croplands. The VEGETATION (VGT) sensor onboard the SPOT-4 satellite, which is the first moderate resolution sensor designed specifically for the study of vegetation and the land surface, was launched in 1998 and offered unprecedented image data to map land cover. The Global Land Cover 2000 (GLC2000) project, carried out by a consortium of international scientific institutions, used VGT images from 1 December 1999 to 31 December 2000 to generate a global land cover map at 1-km spatial resolution, including croplands (Bartholome and Belward 2005). As part of the NASA Earth Observing System (EOS) program, the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra satellite has acquired daily images of the globe since February 2000. The MODIS Land Science Team produced the standard global land cover product at 1-km spatial resolution, including croplands (Friedl et al. 2002). Recently several studies have used MODIS data to map land cover at river basins in India, for example, the Ganges and Indus river basin (Thenkabail *et al.* 2005) and the Krishna river basin (Biggs *et al.* 2006). All of these global and regional land cover data products include the area and distribution of croplands, but they provide no information on cropping intensity.

The objective of this study is to assess the potential of MODIS images for identifying multiple cropping fields. India was selected as the case study area for MODISbased large-scale mapping of cropping intensity because it has a large area of multiple cropping fields and ground-based survey data are available for the evaluation of MODIS-based maps. If successful, the MODIS-based algorithm could be applied to other countries in Asia to generate an updated continental-scale database of cropping intensity; and the resultant data product at moderate spatial resolution (500 m) could be used for various analyses that address food security, water use and management, the biogeochemical cycle and the climate in Asia.

2. Brief description of the study area

India borders Pakistan to the west, China, Nepal and Bhutan to the north-east, and Bangladesh and Burma to the east (figure 1). The vast territory (approximately 297



Figure 1. The administrative boundary map of India and the distribution of ground-truth field sites (731) collected in 2005. Brown symbol – single crop; green symbol – double crop; blue symbol – triple crop.

million ha land area) of India has very diverse geography, including the Himalayas in the north and the Thar Desert in the north-west. The landscape and agriculture pattern varies in different parts of the country from tropical south to temperate north.

The weather and climate of India vary substantially across a large geographical scale and diverse topography. Based on the Köppen climate classification system, India has six climatic zones: Alpine (Jammu and Kashmir), humid subtropical (Bihar and Jharkhand, and Uttar Pradesh), tropical wet and dry (Andhra Pradesh, Orrisa, Maharashtra and West Bengal), tropical wet (Kerala), semi-arid (Karnataka) and arid (Rajasthan). India has four seasons: winter (January and February), summer (March–May), a monsoon (rainy) season (June–September) and a post-monsoon period (October–December). The average annual rainfall in India is estimated at ~1170 mm, but varies significantly over space, ranging from a low of 150 mm per year in the north-west desert of Rajasthan to over 2500 mm in the north-eastern region of the country.

The cropping pattern in India is highly influenced by the seasonal pattern of precipitation. Precipitation together with temperature divides the cropping systems in India into three types: (1) Zaid (summer crop; starting from March to June), (2) *Kharif* (rainy season crop; starting from July to October) and (3) *Rabi* (winter crop or dry season crop; starting from October to March). The sizes of cropland parcels in India vary substantially across landscapes, and often are small, segmented and with irregular shapes.

3. Satellite images and ancillary data

3.1 Description of MODIS data

Moderate Resolution Imaging Spectroradiometer (MODIS) is an optical sensor onboard the Terra and Aqua satellites. MODIS scans the entire surface of the Earth every 1 to 2 days, acquiring data in 36 spectral bands. Of the 36 spectral bands, seven are designed for the study of vegetation and land surfaces: blue (459–479 nm), green (545–565 nm) red (620–670 nm), near-infrared (NIR1: 841–875 nm, NIR2: 1230–1250 nm), and shortwave infrared (SWIR1: 1628–1652 nm, SWIR2: 2105–2155 nm). Daily global imagery is provided at spatial resolutions of 250 m (red and NIR1) and 500 m (blue, green, NIR2, SWIR1, SWIR2). The MODIS Land Science Team provides a suite of standard MODIS data products to users, including the eight-day composite MODIS Surface Reflectance Product (MOD09A1). There are 46 eight-day composites in a year, starting with Julian date of 1 January each year. The MOD09A1 data are organized in tile fashion and freely available to the public from the US Geological Survey (USGS) Earth Resources Observation and Science (EROS) Data Center (EDC) (http://edc.usgs.gov).

We downloaded the MDO09A1 datasets in 2005 from the USGS EDC website. For each MODIS eight-day composite the following four indices are calculated: (1) Normalized Difference Vegetation Index (NDVI; Tucker 1979); (2) Enhanced Vegetation Index (EVI; Huete *et al.* 2002); (3) Land Surface Water Index (LSWI; Xiao *et al.* 2005b) and (4) Normalized Difference Snow Index (NDSI; Hall *et al.* 2002), using surface reflectance values (ρ) from the blue, green, red, NIR1 and SWIR1 bands (denoted by the subscripts below; see equations (1–4)).

$$NDVI = \frac{\rho_{NIR1} - \rho_{RED}}{\rho_{NIR1} + \rho_{RED}}$$
(1)

$$EVI = 2.5 \frac{\rho_{\rm NIR1} - \rho_{\rm RED}}{\rho_{\rm NIR1} + 6\,\rho_{\rm RED} - 7.5\,\rho_{\rm BLUE} + 1}$$
(2)

$$LSWI = \frac{\rho_{NRI1} - \rho_{SWIR1}}{\rho_{NIR1} + \rho_{SWIR1}}$$
(3)

$$NDSI = \frac{\rho_{GREEN} - \rho_{NIR1}}{\rho_{GREEN} + \rho_{NIR1}}$$
(4)

All these four indices are used in a number of large-scale agricultural studies (Xiao *et al.* 2005a, 2006). Cloudy observations within a year (46 eight-day composites) were identified and gap-filled, following the procedure described in earlier studies (Xiao *et al.* 2005a, 2006).

3.2 Description of agricultural statistical and census data

National and sub-national level agricultural census data for India in 2004–2005 (from June 2004 to May 2005) came from the Directorate of Economics and Statistics (DES), Ministry of Agriculture, Government of India. The database contains district, state and country level statistics on crop sown area, irrigated and arable land area, multiple-cropping area (area sown more than once), total cropland area and total sown area. The collection of agriculture statistics in India is based on the land records. Therefore, the agricultural census is conducted mainly on the information available in the land records collected at very small units called *Patwaris* (village revenue agency). The village land records include tenancy, land use, irrigation, sources of irrigation, crop types, cropping pattern, intensity, etc.

The basic unit of data collection is the operational holding. The data collected at this smallest unit are up-scaled to the entire country through village, community development blocks, *tehsil* (also called *Talukas*), districts and states. Based on information availability and records maintained, the various states in the country have been grouped into two main categories: land record states and non-land record states. Land record states have comprehensive information on land and its use, cropping patterns, etc., which is not the case for non-land record states. The information collected in the case of former states is pooled for all parcels of an operational holding irrespective of its location but it restricted to *tehsil* level only. In the states where comprehensive land records are not maintained the cropland data are collected through a sample survey on household enquiry approach.

The agriculture census follows a census-cum-sample approach, and the census is divided into three phases (Phases I, II and III). Phase I and Phase II collect key data on operational holdings. Phase III is an input survey which is conducted in 7% of the villages with information related to number of parcels of land, multiple cropping, irrigated and rain-fed areas, fertilizer application, livestock, agriculture implements and machinery.

The Indian monsoon climate is characterized by tropical wet (rainy) and dry seasons; the rainy season starts in May and December to March are the driest months. Agricultural activities closely follow the monsoon climate; and the annual agricultural census data are therefore reported for the period of June–May (agricultural year), not in a calendar year (January–December).

3.3 Description of field ground-truth data

Precise knowledge of land use and land cover on the ground is essential to the interpretation of all remote sensing products for the purposes of training, mapping and accuracy assessment. In 5 August–28 September 2005, a large number of the

ground-truth datasets were collected for the Global Irrigated and Rainfed Area Mapping project at the International Water Management Institute (IWMI), and these field data are made available through the IWMI data storehouse pathway (http:// www.iwmidsp.org; also see Thenkabail et al. (2005)) in standard geographical information system (GIS) formats. For a large country such as India, random or systematic sampling is not feasible due to limited resources available (Muchoney and Strahler 2002). Therefore, ground-truth points were selected based on accessibility (road network) and stratified across the states with an emphasis to cover all categories of agricultural land use systems. Stratified sampling over a homogeneous agricultural patch across the transect route was carried out; a representative area of 90 m \times 90 m or larger was selected for sampling (Thenkabail et al. 2005, Biggs et al. 2006). The land use class for a field site was assigned by looking across the sampling unit and by interacting with farmers regarding the cropping pattern and cropping intensity for the previous and current years. The precise locations of the sample sites were recorded by global positioning system (GPS) in the Universal Transverse Mercator (UTM) system and the latitude/longitude coordinate system with a common datum of WGS84. At each location land use, land cover, crop type, crop calendar, crop growth stages, cropping intensity, etc., were recorded and later on the detailed ground-truth digital database was developed for further analysis. The ground-truth mission in 2005 covered north-south and east-west about 1600 km, and 807 sample points were collected (figure 1). The major variables collected at each field location were:

- 1. location information (GPS position, location name, date of collection);
- 2. land use/land cover type (class name);
- per cent areas of individual land cover types such as cropped canopy and noncanopy area (water, fallow lands and weeds);
- 4. crop types, cropping pattern and cropping calendar: for *Kharif*, *Rabi* and *Zaid* seasons;
- 5. agricultural intensification, sources of water, and presence of irrigated, rain-fed and supplemental irrigation; and
- 6. digital photographs.

4. Methods

4.1 MODIS-based phenology algorithm: temporal profile analysis approach

Seasonal dynamics of EVI, NDVI and LSWI were carefully examined in forests, cropland and grasslands in China, USA and Brazil (Xiao *et al.* 2005c, Li *et al.* 2007, Mahadevan *et al.* 2008, Wu, *et al.* 2008, 2009, Yan *et al.* 2009). Figure 2 shows the seasonal dynamics of three vegetation indices (NDVI, EVI and LSWI) in 2005 at three cropland sites and three non-cropland sites in India. Vegetation indices (NDVI and EVI) in both the grassland and shrubland sites started to grow in June as the rain season came. For the evergreen forest site, vegetation indices (NDVI and EVI) had high values in dry periods but low values in the rainy season, because of frequent cloud cover in the rainy season. For the single cropping site, vegetation indices started to increase in June, which suggests that crops were planted when the rainy season (*Kharif*) arrived, reached a peak value (see EVI time series data) in August, and then declined gradually until harvest took place in November. For the double-cropping site, vegetation indices show bimodal dynamics; the first modal represents the crop cycle in February–April (*Rabi*), and the second model represents the crop cycle in



Figure 2. The seasonal dynamics of three vegetation indices in 2005 at three cropland sites and three natural vegetation sites in India. (*a*) Single crop $(16^{\circ} 28' 43.38'' \text{ E}; 76^{\circ} 6' 43.25'' \text{ N});$ (*b*) double crop $(27^{\circ} 54' 34.92'' \text{ E}; 78^{\circ} 37' 36.13'' \text{ N});$ (*c*) triple crop $(28^{\circ} 7' 17.21'' \text{ E}; 76^{\circ} 14' 15.23'' \text{ N});$ (*d*) evergreen forest $(26^{\circ} 54' 41.34'' \text{ E}; 93^{\circ} 17' 23.913'' \text{ N});$ (*e*) shrubland $(16^{\circ} 47' 37.69'' \text{ E}; 73^{\circ} 30' 2.14'' \text{ N});$ (*f*) grassland $(17^{\circ} 21' 33.76'' \text{ E}; 74^{\circ} 42' 45.09'' \text{ N})$. The vegetation index data in this figure are the original data calculated from the MODIS surface reflectance of individual bands, including cloudy observations. Cloudy observations have low NDVI values.

June–early December (*Kharif*). For the triple-cropping site, vegetation indices show triple-modal dynamics, clearly indicating three crop rotations in a year (*Rabi, Zaide* and *Kharif*). As January–May is a dry period, the crop cycles in that period for the double cropping site and the triple cropping site are likely to be associated with irrigation. LSWI is sensitive to vegetation and soil moisture (Zarco-Tejada *et al.* 2003, Xu 2006), and has also been used to map vegetation phenology (Delbart *et al.* 2006). As shown in figure 2, LSWI values were low (<0.0) at both the beginning and ending periods of a crop cycle; these are the troughs in the LSWI time series data for a plant-growing cycle.

In several earlier studies we identified and mapped paddy rice agriculture in China, India and South-East Asia through the temporal profile analysis, of NDVI, EVI and LSWI time series data for individual pixels (Xiao *et al.* 2005a, 2006). Recently, the anomaly between EVI and LSWI was also used to map flooding events in Cambodia and Vietnam (Sakamoto *et al.* 2007).

For identifying multiple-cropping cycles in an image pixel, our temporal profile analysis of vegetation indices (EVI, NDVI and LSWI) has three procedures:

- 1. Identify the highest EVI value (EVI0) in a year (N = 46 observations in a year), then search for the trough (the lowest value; Date0) of the LSWI time series before the date with the maximum EVI, and the trough (the lowest value; Date2) of LSWI after the date with the maximum EVI. The first vegetation growth cycle is defined by the trough dates (with a length of *m* observations between two troughs from Date0 to Date2) of LSWI time series data.
- 2. Identify the highest EVI value (EVI2) in the remaining EVI time series data (N-m observations), then search for the trough of the LSWI time series before the date with the EVI2 and the trough of LSWI times series after the date with the EVI2. The second vegetation growth cycle is defined by the trough dates (with a length of k observations between the dates of two troughs) of LSWI time series data.
- 3. Identify the highest EVI value (EVI3) in the remaining EVI data (N m k observations), and then repeat the procedure of trough search as described in steps (1) and (2). The third vegetation growth cycle is defined using the trough dates of the LSWI time series.

This computational algorithm is applied to all individual pixels for delineating number of cropping cycles in a year. We assume that those pixels with two and triple vegetation growth cycles in a year as double-and triple-cropping croplands, respectively.

4.2 Regional implementation of the phenology algorithm

The implementation of our MODIS-based phenology algorithm at the continental scale is a challenging task, and requires careful consideration of many factors that could potentially affect the seasonal dynamics of vegetation indices, including snow cover, clouds, cloud shadow, water bodies and other vegetated land cover types. We have developed a procedure for regional implementation of the algorithm by generating various masks for clouds, snow cover, water bodies and evergreen vegetation in an effort to minimize their potential impacts (figure 3). Detailed descriptions of cloud, snow cover, water body and evergreen vegetation masks were given in two earlier publications (Xiao *et al.* 2005a, 2006). The cloudy observations in time series vegetation index data for individual pixels were gap-filled using clear-day observations before and after the cloudy observation (Xiao *et al.* 2005a, 2006).

India has a total land area of 2.97 million km², and 10 tiles of MOD09A1 data are used to cover the entire Indian territory. In this study, we use land surface reflectance data (MOD09A1) from 2005. We computed the four indices (EVI, NDVI, LSWI and NDSI; see equations (1)–(4)), generated the masks and ran the phenology algorithm for all the individual MODIS tiles that cover the study area. We then used an administrative boundary map of India to generate a summary of cropping intensity at national, state and district levels.

4.3 Statistical analysis for comparison and evaluation

In general, accuracy assessment of moderate-resolution (500 m to 1 km) land cover products is a challenging task, as these land cover maps can overestimate or



Figure 3. The schematic diagram for regional implementation of the phenology-based algorithm for identifying and mapping multiple-cropping croplands, using the eight-day MODIS land surface reflectance product (MOD09A1).

underestimate areas of land cover types due to the fragmentation and sub-pixel proportion of individual land cover types. Because of budget constraints and human resource limitations, we were not able to conduct extensive field surveys for collection of sitespecific data. Through international collaboration with the researchers at International Water Management Institute (IWMI), we have access to a large number of *in situ* field data collected by the researchers at IWMI over the last few years (see section 3.2).

We evaluated the MODIS-based cropping intensity dataset in two ways: (1) agricultural census data at national, state and district levels in 2004/2005; and (2) groundtruth data collected at individual sites over the past few years (http://www.iwmidsp.org/iwmi/info/main.asp; Thenkabail *et al.* 2005). Considering the similarity between the grasslands/shrublands and single-cropped agricultural fields in terms of the seasonal dynamics of vegetation indices (figure 2), in this study we have used only areas sown more than once (multiple cropping) in a year for the comparison study.

The agricultural census data collected from national sources (DES 2007) are used for evaluation of the MODIS-based estimates of multiple-cropping areas at the state level. Note that we have district-level census data of cropping intensity only for a few states. In this study only the state Andhra Pradesh is considered for evaluation of MODIS-based cropping intensity maps at the district level due to lack of availability of data at district level for rest of the states. The statistical analyses were carried out to compare the MODIS-based estimates of cropping intensity with those from the agricultural census data.

5. Results

5.1 Spatial distribution of multiple-cropping fields in India

Figure 4 shows the spatial distribution of double-and triple-cropping fields in 2005 in India at 500-m spatial resolution. The multiple-cropped fields occur extensively over the country but are largely concentrated in the floodplain and valleys of major rivers in India, for example, the Ganges and Indus river basins. In those large river basins there exist extensive irrigation systems, which could provide irrigation water for crops during the dry season.



Figure 4. The spatial distribution of multiple-cropping croplands in India in 2005, as estimated by the MODIS-based mapping algorithm, using the eight-day MODIS land surface reflectance product (MOD09A1) in 2005 at 500-m spatial resolution. The red dots in the figure are the ground-truth points for double cropping, and the yellow dots are the ground-truth points for triple cropping (also see figure 1 for spatial distribution of ground-truth points).

The MODIS-based phenology algorithm estimates 56.7 million ha of double cropping fields and 1.1 million ha of triple-cropping fields in 2005. The total area of triple-cropping fields in 2005 is approximately 2% of the double-cropping area. As the agricultural census data report multiple-cropping area (no separation between double-and triple-cropping fields), we also aggregated the areas of double cropping together with the area of triple cropping into the multiple-cropping area. The MODIS-based algorithm estimates a total area of 57.8 million ha of multiple-cropping fields in 2005, which is approximately 6.4% higher than the estimate (54.3 million ha) of multiple-cropping fields from the agricultural census data in 2004/2005 (table 1).

| States and union territories | Total land area $(\times 10^3 ha)$ | Multiple cropping area in 2004/ 2005 by agricultural census $(\times 10^3 \text{ ha})$ | Multiple cropping area in 2005 by MODIS-based mapping (×10 ³ ha) | | | |
|------------------------------|--|--|---|--|--|--|
| Andhra Pradesh | 27 507 | 2191 | 2257 | | | |
| Arunachal Pradesh | 8374 | 91 | 111 | | | |
| Assam | 7844 | 1209 | 1120 | | | |
| Bihar | 9416 | 1827 | 4595 | | | |
| Chhattisgarh | 13 519 | 946 | 277 | | | |
| Goa | 370 | 36 | 9 | | | |
| Gujarat | 19 602 | 1570 | 1455 | | | |
| Haryana | 4421 | 2898 | 3523 | | | |
| Himachal | 5567 | 415 | 394 | | | |
| Pradesh | | | | | | |
| Jammu & | 22 224 | 349 | 514 | | | |
| Kashmir | | | | | | |
| Jharkhand | 7972 | 0 | 53 | | | |
| Karnataka | 19 179 | 2308 | 632 | | | |
| Kerala | 3886 | 841 | 229 | | | |
| Madhya Pradesh | 30 825 | 5228 | 8145 | | | |
| Maharashtra | 30 771 | 1041 | 2339 | | | |
| Manipur | 2233 | 0 | 48 | | | |
| Meghalaya | 2243 | 46 | 69 | | | |
| Mizoram | 2108 | 0 | 58 | | | |
| Nagaland | 1658 | 71 | 43 | | | |
| Orissa | 15 571 | 2979 | 458 | | | |
| Punjab | 5036 | 3583 | 4399 | | | |
| Rajasthan | 34 224 | 4514 | 5249 | | | |
| Sikkim | 710 | 0 | 5 | | | |
| Tamil Nadu | 13 006 | 792 | 1804 | | | |
| Tripura | 1049 | 0 | 39 | | | |
| Uttar Pradesh | 24 093 | 16683 | 17 631 | | | |
| Uttaranchal | 5348 | 468 | 334 | | | |
| West Bengal | 8875 | 4149 | 1977 | | | |
| Union Territories | 1096 | 43 | 75 | | | |
| Total (India) | 328 727 | 54 276 | 57 841 | | | |

 Table 1. State-level comparison of the multiple-cropping area (sown more than once in a year over a unit land area) between the estimates from the national agricultural census in 2004–2005 and the estimates in 2005 from the MODIS-based mapping in this study.

5.2 Evaluation of MODIS-based multiple-cropping map at the state and district levels

India has 28 states and seven union territories. As the land areas of the seven union territories are small ($\sim 1.1 \times 10^6$ ha), they are lumped together into one category for the purpose of simplicity of presentation (table 1). The agricultural census data were reported at the state and district levels. We aggregated the MODIS-based multiplecropping area by state and district, which enables a direct comparison between the MODIS-based dataset and the agricultural census dataset. Hereafter we refer to the MODIS-based cropping intensity dataset as the MOD-CI dataset and the census-based cropping intensity dataset as the ACD-CI dataset.

According to the MOD-CI dataset, Uttar Pradesh state has the largest area of multiple-cropping fields, approximately 17.6 million ha, followed by Madhya Pradesh state (8.1 million ha) and Rajasthan state (5.2 million ha). Four states



Figure 5. The state-level comparison in the area of multiple cropping croplands between the agricultural census dataset in 2004/2005 and the MODIS-based dataset in 2005.

(Uttar Pradesh, Punjab, Bihar and Haryana) in the Great Plain of North India had a total area of 30.1 million ha of multiple-cropping croplands, accounting for 52% of the total area of multiple-cropping croplands in India in 2005 (table 1). Figure 5 shows the comparison in multiple cropping area at the state level between the MOD-CI data in 2005 and the ACD-CI dataset in 2004/2005 (coefficient of determination, $R^2 = 0.90$; N = 27).

The 28 states and seven union territories of India are further divided into 612 districts. For the district-level comparison, we focused on Andhra Pradesh state, where agricultural census data from 23 districts are available (table 2). According to the MOD-CI dataset, Andhra Pradesh has a total of 2.3 million ha of multiplecropping croplands. Figure 6 shows the spatial distribution of multiple-cropping fields at the district level from both the MOD-CI and ACD-CI datasets. There is some similarity in spatial distribution of multiple-cropping areas in this state (figure 6). Figure 7 shows the linear relationship in the district-level area of multiple-cropping croplands between the MOD-CI and ACD-CI datasets ($R^2 = 0.45$; N = 23). Although multiple-cropping areas at the state level are similar between the agricultural census dataset (2.19 million ha) and the MODIS-based map (2.25 million ha), there are relatively large discrepancies at the district level between these two datasets.

5.3 *Pixel-level accuracy assessment of cropping intensity using* in situ ground observations

A total of 731 ground-truth points collected across the country in August–September 2005 are used in accuracy assessment of the cropping intensity map (MOD-CI) derived from MODIS data in 2005. Among the 731 field sites, 39 sites were recorded

| Districts | Total land area $(\times 10^3 ha)$ | Multiple-cropping area in 2004/2005 by agricultural census (×10 ³ ha) | Multiple-cropping area in 2004/2005 by MODIS-based mapping (×10 ³ ha) | | | | |
|----------------|--|--|--|--|--|--|--|
| Adilabad | 1611 | 6 | 24 | | | | |
| Anantapur | 1913 | 65 | 7 | | | | |
| Chittoor | 1515 | 39 | 68 | | | | |
| Cuddapah | 1536 | 55 | 66 | | | | |
| East Godavari | 1081 | 317 | 258 | | | | |
| Guntur | 1139 | 171 | 438 | | | | |
| Hyderabad | 22 | 0 | 0 | | | | |
| Karimnagar | 1182 | 90 | 22 | | | | |
| Khammam | 1603 | 41 | 123 | | | | |
| Krishna | 873 | 205 | 272 | | | | |
| Kurnool | 1766 | 83 | 53 | | | | |
| Mahbubnagar | 1843 | 56 | 18 | | | | |
| Medak | 970 | 94 | 6 | | | | |
| Nalgonda | 1424 | 87 | 142 | | | | |
| Nellore | 1308 | 40 | 135 | | | | |
| Nizamabad | 796 | 113 | 23 | | | | |
| Prakasam | 1763 | 63 | 193 | | | | |
| Rangareddi | 749 | 27 | 5 | | | | |
| Srikakulam | 584 | 106 | 39 | | | | |
| Vishakhapatnam | 1116 | 76 | 25 | | | | |
| Vizianagaram | 654 | 114 | 11 | | | | |
| Warangal | 1285 | 102 | 13 | | | | |
| West Godavari | 774 | 240 | 314 | | | | |
| State total | 27 505 | 2191 | 2257 | | | | |

| Tabl | e 2. | Dis | trict-lev | el compa | rison (| of the m | ultipl | e-cropping | , area | (sow | n more | than | once in | n a |
|---|------|-----|-----------|-----------|---------|----------|--------|------------|--------|------|----------|------|---------|-----|
| year) | in | the | Andhra | 1 Pradesł | n state | betwee | n the | estimates | from | the | agricult | ural | census | in |
| 2004–2005 and the estimates in 2005 from the MODIS-based mapping in this study. | | | | | | | | | | | | | | |

as triple-cropping sites, and 236 sites as double-cropping sites. The accuracy assessment of the MODIS map is carried out for double and triple cropping. Out of 197 MODIS pixels that geographically correspond to the 197 ground-truth points of double-cropping sites (figure 4), 160 MODIS pixels are identified as double-cropping pixels (81% agreement in double-cropping) and 19 MODIS pixels are identified as triple-cropping pixels. Of 39 MODIS pixels that geographically correspond to the 39 ground-truth points of triple-cropping sites, 14 are identified as triple-cropping pixels (36% agreement in triple cropping) and 19 as double-cropping. Note that in those field sites identified as triple crops in a year, one crop is often vegetables; consequently, the MODIS algorithm may fail to identify it, because of the short vegetable growing cycle and small areas of vegetable cultivation within a 500-m pixel. When we merged double-and triple-cropping sites together as the multiple-cropping category, of 236 MODIS pixels that geographically correspond to the 236 multiple-cropping sites from the field work, 212 are identified as multiple-cropping pixels (90% agreement in multiple-cropping).

6. Discussion and summary

Agriculture is the most extensive land use and water use on the Earth (Vitousek *et al.* 1997). Because of the diverse range of natural environments and human needs,



Figure 6. The spatial distribution of multiple cropping croplands at the district level India in 2005, and Andhra Pradesh state. (*a*) Map of administrative districts with MODIS-derived multiple cropping pixels in India; (*b*) spatial distribution of multiple cropping fields (double and triple crops), as estimated by the MODIS-based mapping algorithm and MODIS data in 2005 at 500-m spatial resolution (MOD-CI); (*c*) area of multiple cropping croplands as reported by the agricultural census data (ACD-CI) (\times 103 ha); (*d*) area of multiple cropping croplands as estimated by the MODIS-based mapping algorithm and MODIS imagery in 2005 at 500-m spatial resolution (MOD-CI) (\times 103 ha).

agriculture is also the most complicated land use and water use system, which poses an enormous challenge to the scientific community, the public and decision-makers. Updated and geo-referenced information on crop intensity (number of crops per year), calendar (planting date, harvesting date) and irrigation is critically needed to better understand the impacts of agriculture on biogeochemical cycles (e.g. carbon, nitrogen and trace gases), water and climate dynamics.

Several earlier studies used wavelet methods to generate smoothed time series of vegetation indices from MODIS imagery and identify crop phenology (Sakamoto



Figure 7. District-level comparison in the area of multiple-cropping croplands in Andhra Pradesh state between the agricultural census dataset in 2004/2005 and the MODIS-based dataset in 2005.

et al. 2006, Galford *et al.* 2008). In this study, we used a temporal profile analysis of MODIS-derived vegetation indices (NDVI, EVI and LSWI) to identify cropping intensity (double-and triple-cropping per year) at individual pixels over large spatial domains. This approach takes advantage of MODIS-derived time series data (at eight-day intervals) of vegetation indices that vary seasonally and are correlated with biophysical and biochemical properties of vegetation and the land surface. NDVI is sensitive to the seasonal dynamics of leaf area index (Begue 1993, Turner *et al.* 1999) and is used to map cropland (Agrawal *et al.* 2003, Thenkabail *et al.* 2005, Biggs *et al.* 2006). EVI is sensitive to light absorption by leaf chlorophyll (Zhang *et al.* 2005, 2006). LSWI is sensitive to land surface water content and has been used to map inundation of paddy rice fields (Xiao *et al.* 2005a, 2006, Sakamoto *et al.* 2005, 2007).

The approaches to land cover classification and mapping at moderate spatial resolution (hundreds of metres to 1 km) can be simply divided into two groups. The first group is based on the spatial clustering of vegetation indices, including the use of multi-temporal data. It often calculates spectral Euclidian distances between the pixels in a study area, generates spectral clusters, and then interprets and labels an individual cluster as a land cover type. This space-oriented approach is the dominant paradigm in the remote sensing community and originates from land cover classification at fine spatial resolution (tens of metres), for example, Landsat Thematic Mapper (TM)/Enhanced Thematic Mapper Plus (ETM)+ images. It is widely used for mapping land cover at the global scale (Loveland *et al.* 2000, Friedl *et al.* 2002, Bartholome and Belward 2005) and agriculture at regional scales (Thenkabail *et al.* 2005, Biggs *et al.* 2006). One of the disadvantages of the space-oriented approach is that

interpretation and labelling of a spectral cluster into a land cover depends upon the experience of the users (Biggs et al. 2006). The second group of research approaches is based on the temporal profile analysis of vegetation indices at individual pixels. This time-oriented approach, which can also be called a phenology-based approach, is relatively new and evolving. It labels a pixel as a land cover, based on a unique physical feature of the land cover type at time t and its corresponding unique characteristics of vegetation indices. For example, the temporal profile analysis of three vegetation indices (NDVI, EVI and LSWI) was applied to map paddy rice fields in Southern China (Xiao et al. 2005a), Vietnam (Sakamoto et al. 2006) and South-East Asia (Xiao et al. 2006). In this study, we applied the temporal profile analysis of vegetation indices to generate a geospatial dataset of cropping intensity in 2005 in India, using MODIS data at 500-m spatial resolution and eight-day temporal resolution in 2005. One of the advantages of the time-oriented approach is that the classification of a land cover type can be automated and is independent from users. It is also important to note that the time-oriented approach is still in its early stages and requires an intensive, detailed study of individual land cover types over time (Xiao et al. 2002) in order to identify unique physical and spectral features of individual land cover types over time (within the plant growing cycles).

According to the annual statistics from FAOSTAT (Food and Agriculture Organization of the United Nations, http://faostat.fao.org), India had 159.9 million ha of arable land in 2001. The Directorate of Economics and Statistics (DES) of India estimated an irrigated area of 57.2 million ha in 2001/2002. In this study, the double-and triple-cropping areas as estimated by the MODIS-based mapping algorithm with MODIS imagery in 2005 at 500-m resolution comprise 57.8 million ha. As the monsoon climate in India has distinct dry and wet seasons, those areas of double-and triple-cropping fields are likely to be irrigated in the dry season. Therefore, geospatial datasets of double-and triple-cropping areas in India as reported in this study could be used to help other research activities that aim to map irrigation, for example, in global irrigation area mapping (Siebert *et al.* 2005, Biggs *et al.* 2006).

The spatial pattern of multiple cropped areas derived from the MODIS images at 500-m pixel resolution (figure 4) generally agrees with that of national agricultural census data (see table 1 and figure 5); however, there are differences in some states at the state level (Bihar, Orissa and West Bengal). These state-level regional differences could be the result of the differences in methodology used and aggregation of agricultural census data. For Orissa and West Bengal states, MODIS-based estimates of multiple cropping areas were lower than the agricultural census data, which might be attributed to the small parcel sizes of croplands in these two states; and MODIS data at 500-m spatial resolution do not capture sub-pixel dynamics of small parcel croplands. For Bihar state, MODIS-based estimates of multiple cropping areas were higher than the agricultural census data, which might be attributed to the underreporting of agriculture census data in Bihar state. Similarly, a district-level comparison is done for the state Andhra Pradesh (23 districts); there is some discrepancy between the MODIS-based estimates and the agricultural census data (figure 5 and table 2). Discrepancy between the MODIS-based estimate and agricultural census estimates in some states and district administrative units can be attributed to: (1) the methods used in aggregation of two or more crops per year from the small farm holdings and inconsistent approach and estimation methods from state to state; and (2) limitations of the 500-m resolution MODIS-based algorithm in identifying small patches of agricultural field sizes. Note that MODIS sensors have two spectral bands (red and near-infrared bands) at 250-m spatial resolution, and additional research could be done in the near future to use the MODIS images at 250-m spatial resolution to indentify and map cropping intensity in India.

In summary, here we report a simple approach that aims to map and monitor multiple-cropping areas, using multi-temporal MODIS image data at 500-m spatial resolution (figure 3). In this article, we generate geospatial datasets of cropping intensity in India in 2005 at 500-m spatial resolution. The resultant geospatial dataset of multiple-cropping area, together with irrigation (e.g. paddy rice data; see Xiao *et al.* (2006)), could be used to address many important questions relevant to science and policy of global changes, including hydrology (Doll and Siebert 2002), climate and health (Gilbert *et al.* 2007, Gilbert *et al.* 2008).

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