Applied Geography 79 (2017) 212–222

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Mapping cropping intensity trends in China during 1982–2013

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ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form
5 January 2017
Accepted 6 January 2017
Available online 19 January 2017

Keywords:
Cropping intensity
MODIS
China
Continuous wavelet transform
Spatiotemporal continuous datasets

ABSTRACT

Long range continuous monitoring information of cropping intensity is useful for sustainable agricultural management but still limited. This study filled this information gap through delivering spatiotemporal continuous datasets of cropping intensity in China during the past 30 years. Cropping intensity data were derived by a wavelet features-based method based on the long-term weekly global EVI2 (Enhance Vegetation Index with two bands) at 0.05° spatial resolution (5 km) from 1982 to 1999 and 8-day composite 500 m Moderate Resolution Imaging Spectroradiometer (MODIS) surface reflectance products from 2001 to 2013. The remote-sensing estimated images in 2013 agreed well with field survey data (overall accuracy = 91.63%) and the national agricultural census data ($r^2 = 0.89$). Results revealed that the cropping intensity remarkably increased during 1982–1999 but slightly declined during 2001–2013. The overall cropping intensity increased from 1.34 in the 1980s to 1.41 in the 1990s, and then dropped to an average of 1.36 after 2000. From 1982 to 1999, approximately 93,225 km^2 single-cropped areas changed to double-cropping, primarily those located in the North China plain. However, 39,883 km^2 double-cropped areas were turned back into single-cropping areas from 2001 to 2013, principally located in the North China plain, the Middle-lower Yangtze River plain, and the hill regions of the southern Yangtze River. This reverse trend of cropping intensity was due to combined effects from the corresponding reverse variations in agricultural population, increasing agricultural mechanical power, positive agricultural policy. The agricultural duty free policy has only immediate effects on stabilizing cropping intensity in croplands with more favorable biophysical conditions.

1. Introduction

Asia is home to the most intensively farmed cropland on earth in order to meet the growing demand for agricultural products with limited room for expansion (Gray et al., 2014; Plourde, Pijanowski, & Pekin, 2013). For example, agriculture in China feeds 33% of the world's population with only 7% of the world's arable land (Piao et al., 2010). Multiple cropping is widely utilized to increase food production in Asian countries. However, intensification might have significant environmental and social impacts, which need careful evaluation (Plourde et al., 2013; Qiu et al., 2003; Robinson, Ericksen, Chesterman, & Worden, 2015; Wang, Zhang, & Fu, 2016). Timely and spatially continuous information of cropping intensity (CI) is required for sustainable agricultural and environmental management (Challinor, Parkes, & Ramirez-Villegas, 2015; Iizumi & Ramankutty, 2015). However, there are a limited number of cropping intensity datasets and crop-specific information in current global land cover products (Iizumi & Ramankutty, 2015; Qiu, Qi, Tang, Chen, & Wang, 2016a, 2017; Wang et al., 2016).

Considerable remote sensing-based research efforts have been undertaken to characterize agricultural intensification, especially cropping intensity (Ding et al., 2016; Gray et al., 2014; Jain, Mondal, DeFries, Small, & Galford, 2013; Wang et al., 2016; Yan et al., 2014). On a global scale, a global map of irrigated areas and rain-fed crop areas provides information on irrigation status and cropping intensity (Thenkabail et al., 2009). In the United States, the U.S.

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http://dx.doi.org/10.1016/j.apgeog.2017.01.001
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Department of Agriculture's (USDA) Cropland Data Layer provides a means to assess the acreage of major crops, finding evidence of increased monoculture cropping (Plourde et al., 2013). In Asia, a recent study developed 500 m Asian Cropping Intensity CI maps using MODIS images for years 2009–2012 and revealed significant challenges in mapping CI (with overall accuracy of 11%) (Gray et al., 2014). In China, 0.5° resolution distribution maps of single and multi-crop rotations in mainland China have been generated through combining agricultural census data and 1995-96 Landsat Thematic Mapper data (Qiu et al., 2003). Recently, cropping intensity in 2012 was derived from MODIS data based on the peak-detection method with reference to agro-meteorological observations (Yan et al., 2014). From 2005 to 2012, the annual agricultural intensity in mainland China at 500 m spatial resolution was obtained using an iterative moving-window method and evaluated through comparing a visually interpreted time series (Li et al., 2014).

Besides the research efforts of mapping cropping index, trends of agricultural (cropping) intensity over time have also been documented (Robinson et al., 2015). For example, cropping intensity increased from the early 1980s to the late 1990s in China based on 8 km AVHRR NDVI images (Yan, Liu, & Cao, 2005). The mean multiple cropping index over the whole of northern China increased from 107% to 115% throughout the 1980s and 1990s based on 8 km Global Inventory Modeling and Mapping Studies (GIMMS) NDVI datasets (Ding et al., 2016). Farmers moved from single-to double-cropping in order to increase yields during the 2000s in Mato Grosso, Brazil (Arvor, Jonathan, Meirelles, Dubreuil, & Durieux, 2011).

Despite these research efforts, mapping cropping intensity is relatively understudied compared to mapping the amount of cropland and irrigation (Gray et al., 2014). There are several challenges involved in undertaking these studies. First, validation and accuracy assessment conducted with ground truth datasets is arguably essential when considering the complexity of the MODIS Vegetation Indices (VI) time series across different regions. It is recognized that trajectories of MODIS Vegetation Indices time series in croplands are highly variable over large areas (Qiu, Zeng, Tang, & Chen, 2013, Qiu et al. 2017). Second, most of these datasets cannot be easily utilized to identify changes since they only provide a snapshot in time (Gray et al., 2014). Third, the inter-annual spatiotemporal trends and the influencing factors for relatively longer periods are rarely investigated (Ding et al., 2016).

Given the importance of cropping intensity in balancing the food productions and increasing demands of land for rapid urbanizations, studies on the country-wide spatiotemporal trends in cropping intensity are essential for a better understanding of food security and agriculture-related decision-making in China (Ding et al., 2016). Previous research has failed to provide temporally and spatially continuous monitoring and neglected the spatial heterogeneity of cropping intensity (Ding et al., 2016). This study aims to fill this gap by developing broad scale spatiotemporal continuous datasets of cropping intensity in China during the past 3 decades (1982–2013) based on vegetation indices time series with better spatial and temporal resolutions. We aim to answer the following questions: how did multiple-cropping croplands vary spatially and inter-annually from 1982 to 2013? Is there any overall decreasing or increasing trends? What are the primary spatio-temporal trends and the implications?

2. Data sources and methodology

2.1. Study region

China has tremendous altitudinal and climatic diversity (Fig. 1(a)). Croplands span temperate, subtropical, and tropical climates. Primary large arable lands are located in several plains: the Northeast China Plain, the North China Plain, the Middle-lower Yangtze River Plain, the Pearl River Delta Plain, and the Sichuan Basin. The mountainous and hilly areas in South China are characterized with relatively small patches of croplands. According to the distribution of farmland and its cropping intensity, climatic and topographic conditions, the whole country is subdivided into 11 regions (Fig. 1(b)). Single cropping is common in northern China, while multi-cropping rotations dominate south of 40°N (Piao et al., 2010). Triple cropping is generally practiced in tropical regions, particularly Hainan and Taiwan islands (see locations in Fig. 2(a)).

2.2. Data sources

The vegetation index (VI) time series utilized from 2001 to 2013 (2001–2013) were 8-day composite 500 m Moderate Resolution

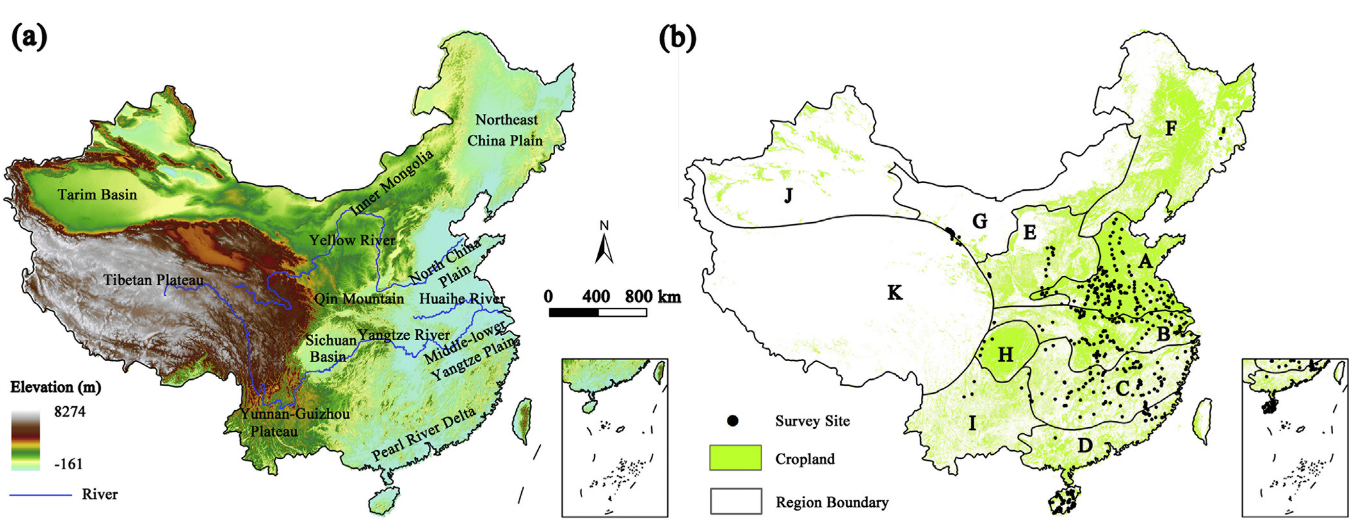

Fig. 1. The spatial distribution of elevation (a), croplands, and survey sites (b). Notes: Regions A-K represented the North China plain, the Middle-lower Yangtze River plain, the southern Yangtze hill region, the Pearl River Delta, the loess plateau, Northeast China, the Inner Mongolia Plateau, the Sichuan basin, the Yunnan-Guizhou plateau, the Tibet-Qinghai plateau, and Xinjiang region, respectively.

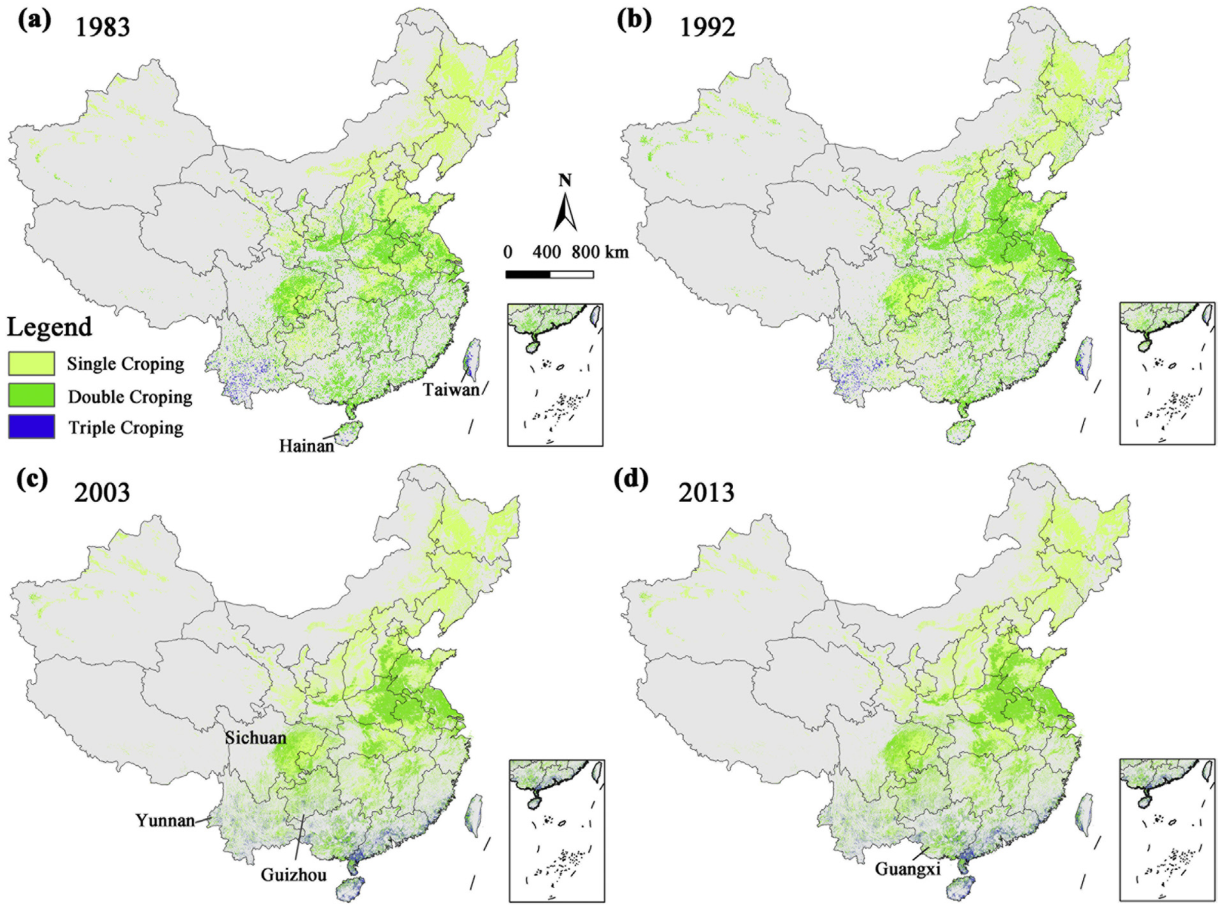

Fig. 2. The spatial distribution maps of cropping intensity for mainland China in 1983, 1992, 2003, and 2013.

Imaging Spectroradiometer (MODIS) surface reflectance products (MOD09A1). The two-band Enhanced Vegetation Index (EVI2) was calculated (Jiang, Huete, Didan, & Miura, 2008). The long-term weekly global EVI2 at the 0.05° spatial resolution (5 km) from 1982 to 1999 was also applied, downloaded from the University of Arizona (http://vip.arizona.edu/). These datasets have been generated from an advanced, very high resolution radiometer (AVHRR), using the vegetation isoline equations in order to eliminate soil brightness effects (Yoshioka, Miura, & Obata, 2012).

The 1 km land use/cover map in 2000 was utilized to derive the cropland mask. It was provided by the Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn), and detailed descriptions can be found in related studies (Ren, Li, Lu, & Li, 2012). The DEM datasets were from Shuttle Radar Topography Mission data with a spatial resolution of 90 m.

Field surveys were primarily carried out from July to September 2012–2014 and from December to March 2013–2014, and concern the farming practice of the preceding two years (see locations in Fig. 1(b)). UniStrong G138 or MG858 hand-held GPS receivers were utilized for the ground survey at the field sites. At each sampling site, we recorded the cropping patterns and their corresponding phonological stages.

Besides the field survey data, agricultural census data for grain sown areas were used for validation and evaluation. Other social-economic datasets included agricultural population and mechanical power. The agricultural census data were downloaded from the National Bureau of Statistical of China (NBSC) (http://www.stats.gov.cn/tjsj/ndsj).

2.3. Methodology

2.3.1. Extracting cropping intensity based on continuous wavelet transform

For each pixel of cropland, a daily continuous EVI/EVI2 dataset was developed through linear interpolation. For MODIS datasets, the linear interpolation process was conducted using date of observations based on cloud-free observations. The minimum reflectivity in the MODIS bands provided good separability in which cloud cover could be removed (Thenkabail, Schull, & Turral, 2005). We used minimum blue band reflectivity of 21% or above to identify cloud cover. For the determination and calculation of cropping intensity, a wavelet features-based method was applied (Qiu, Zhong, Tang, & Wang, 2014, Qiu et al. 2016b). The cropping index was identified based on three main features, the skeleton width, maximum number of strong brightness centers and the intersection of their scale intervals, derived from wavelet spectra (Qiu et al., 2014, 2016b).

Despite of their simplification and widely utilizations (Ding et al., 2016; Galford et al., 2008; Jain et al., 2013), the VI peak-based algorithms are difficult to be engaged with uncertainties introduced by various situations such as data noise and varieties of different cultivations over large areas (Galford et al., 2008). The challenges of intra-class variability of vegetation indices temporal profiles could not easily be delivered by the VI peak-based algorithms. However, the wavelet features-based method can successfully cope with these challenges through continuous wavelet transform and efficient feature extraction based on wavelet isolines (Qiu et al., 2014, 2016b). The wavelet features-based method has

Table 1
Accuracy assessment of MODIS-estimated results in 2013 using ground truth data.

Ground truth data	Cropping intensity			Producer accuracy (%)
	Single	Double	Triple	
Single	177	15	0	92.1875
Double	47	660	8	92.4370
Triple	3	5	28	77.78
User accuracy (%)	77.93	97.06	77.78	
Overall accuracy: 91.63%				

been proved to be efficient to extract the cropping index and therefore was applied in this study.

2.3.2. Spatiotemporal trends of cropping intensity

In order to investigate the spatiotemporal trends of cropping intensity, the trend and the breakpoints of cropping intensity were identified. First, the magnitude of total change during the study period was calculated based on the non-parametric Sen's method (Sen, 1968). Then, the Mann-Kendall nonparametric test was applied to recognize significant trends in cropping intensity. After that, the heuristic segmentation method was utilized to locate the timing of change points/breakpoints (change year). Following is a brief introduction of the heuristic segmentation method: divide the original time series (time series x(t), t = 1, 2, …, N) into two separate parts (left time series and right time series) from location i, then calculate the mean and standard deviation of both sides, and compute the difference of the mean values between the two divided time series that could be tested through its t value; After repeating the above process for every location (from 1 to N) of the original time series x(t), a new time series T(t) was obtained, and large values in time series T(t) indicate distinct difference/breakpoints in mean values of those two divided left and right time series at that specific location. Finally, for each pixel with significant trends, the specific changes in cropping intensity, i.e., from double cropping to single cropping, are identified based on the primary cropping index before and after the change year.

2.3.3. Driving forces analysis from the socio-economic, topographic, and water conditions

We further investigated the driving forces of primary spatiotemporal trends in cropping intensity from 1982 to 2013. First, we analyzed the relationship between the overall trends of cropping intensity and the total agricultural population and mechanical power for the whole country during the past four decades. Next, we investigated the primary spatiotemporal trends in regions A, B and C and evaluated examined their association with topographic conditions and agricultural policy for each year from 2001 to 2013. Finally, we also explored their connection with cities and water conditions in regions A, B, C and E (see locations in Fig. 1(b)).

3. Results

3.1. Accuracy assessment and validation

The spatial distribution map of cropping intensity of China in 2013 shows some expected patterns (Fig. 2). From north to south, the cropping intensity patterns changed from single cropping to double cropping, and then to a mixture of single, double, and triple cropping in South China. Double cropping was prevalent in the North China plain. The climatic conditions in South China allowed for multiple cropping. However, only around 50% of croplands were multiple-cropped in the Middle-lower Yangtze River plain, southern Yangtze hill region and the Pearl River Delta. In all, a total of 34.83% croplands were multi-cropped in China in 2013. Among them, only 9.30% croplands were triple-cropped. Remote-sensing estimated maps of cropping index in 1983, 1992, and 2003 are also given in Fig. 2.

We evaluated the MODIS-derived cropping intensity map based on ground truth data and agricultural census data. Data from a total of 943 survey sites were collected. The survey sites covered South, East, and Central China (see locations in Fig. 1). Northeast China was not extensively investigated due to the long stable history of single cropping. The evaluation results with survey data are shown in Table 1. A high proportion of single and double cropping areas are correctly classified with a producer's accuracy of over 92%. The overall accuracy is 91.63%.

Due to the limitations of field survey data in recent years and easily accessible areas, accuracy evaluation was also conducted with national agricultural census data. The total sown areas at the provincial level were calculated based on a remote sensing-derived cropping intensity map with reference to land use/cover data. The remote sensing estimated sown areas were then compared to those from NBSC datasets. These two datasets agreed reasonably well, with an r-squared value of 0.89 in 2013 (Fig. 3). Considerable good agreement was also obtained in 1983, 1992, and 2003, with R^2 values of 0.93, 0.87, and 0.88, respectively Fig. 3. Although consistency was examined between those two datasets in most provinces, considerable overestimates were observed in Yunnan, Guizhou, and Sichuan provinces (region I, Fig. 3(c) and (d)).

3.2. Overall cropping intensity trends from 1982 to 2013

The cropping index was calculated for the whole country from the remote-sensing images-estimated data from 1982 to 2013 (Fig. 4). An obvious increase trend was observed from 1982 to 1999, from an average value of 1.34 during the 1980s to 1.41 during the 1990s. Nevertheless, the estimated cropping index from 2001 to 2013 was much steadier and only a slight decline was observed. The cropping intensity ranged between 1.32 and 1.42 from 2001 to 2013, with an average value of 1.36.

High-frequency temporal variations might be blurred by some outliers. Considerably more frequent outliers were examined from 1982 to 1999. Several years, such as 1993, 1999, and 2012, exhibited extremely higher values compared with their neighboring years. For example, the estimated cropping index in 2012 was 1.42. But it was only 1.34 to 1.35 in its neighboring years. These outliers might be introduced by the data quality of remote sensing images. This problem was further investigated in the following discussion section.

The proportion of different cropping patterns from 1982 to 2013 is also provided in Fig. 5. Single cropping decreased from 56 to 64% during the 1980s to 51–60% during the 1990s, and then increased slightly from an average of 55% from 2001 to 2005 to around 57% during the 2010s. Double cropping increased from approximately 34.80% in the 1980s to an average 40.10% in the 1990s, and then decreased from around 36.36% in the 2000s to 34.99% in the 2010s. Triple cropping croplands occupied only a small proportion (less than 4%) of croplands. The averaged proportion of triple cropping croplands was 1.63% from 1982 to 1999. From 2001 to 2013, it increased slightly from 2.71% during the 2000s to 3.19% in the early 2010s (2010–2013). In sum, the average percentages of multi-cropped croplands increased from 36.23 in the 1980s to 41.91 in the 1990s, and then decreased from 39.07 in the 2000s to 38.18 in the 2010s. There were relatively fewer fallow croplands from 1982 to 1999 (less than 4% except 1982 and 1989). However, averaged 5.48% croplands were fallow from 2001 to 2013.

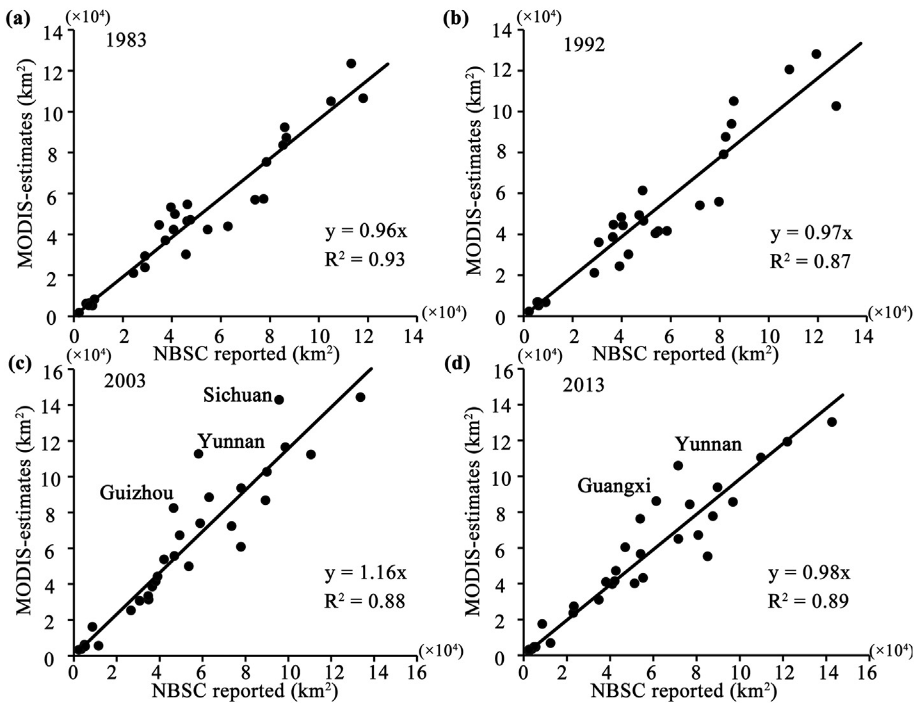

Fig. 3. Correlation of agricultural sown areas between NSBC reports and MODIS-estimates at the provincial level.

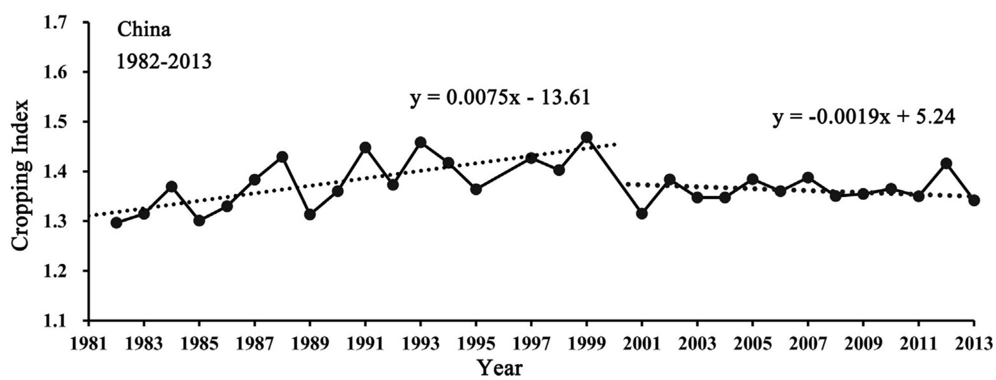

Fig. 4. Cropping intensity variations across the whole country from 1982 to 2013.

3.3. Spatiotemporal trends of cropping intensity

The trend of cropping intensity was evaluated through a per-pixel strategy for the late 20th century and the early 21st century time periods (Fig. 6). From 1982 to 1999, a total of 107,850 km^2 areas acquired positive trends (Fig. 6 (a)). This cropland intensification (positive trend) was mainly distributed in the North China plain (region A). Only 7200 km^2 areas obtained a negative trend, scattered in South China.

From 2001 to 2013, a total of 132,139 km^2 areas (6.72% croplands) presented significant trends (Fig. 6(b)). Among them, approximately 72,692 km^2 areas obtained a positive trend. Specifically, croplands intensification (positive trend) was principally located in the loess plateau (region E, 29.28%), the North China plain (region A, 16.78%), and the Middle-lower Yangtze River (region B, 11.39%). A total of 59,447 km^2 areas acquired a decreasing trend (Fig. 6(b)). Of these areas, around one-quarter (26.38%) were observed in the North China plain (region A). Over one-fifth (22.11%) were located in the Middle-lower Yangtze River (region B). Others were primarily located in Southern Yangtze hilly region (13.25%, region C), Sichuan basin (10.08%, region H), and the loess plateau (8.06%, region E).

4. Discussion

4.1. Uncertainties introduced from data quality

The cloud cover ratio was calculated for each year from 2001 to 2013 in order to allay the uncertainties introduced from the data quality (Fig. 7). Although cloud cover generally occurred across the whole country, it differed in different regions and years. From 2001 to 2013, the highest cloud cover ratio was found in 2012. Considerably heavy cloud cover generally occurred in Northeast China (region F), Sichuan basin (region H), Yunnan-Guizhou plateau (region I), and the Pearl River Delta (region D), which was consistent with related studies (Qiu et al., 2013). In contrast, among these important cultivated areas, relatively high quality datasets could be expected in the North China plain (region A) and loess plateau

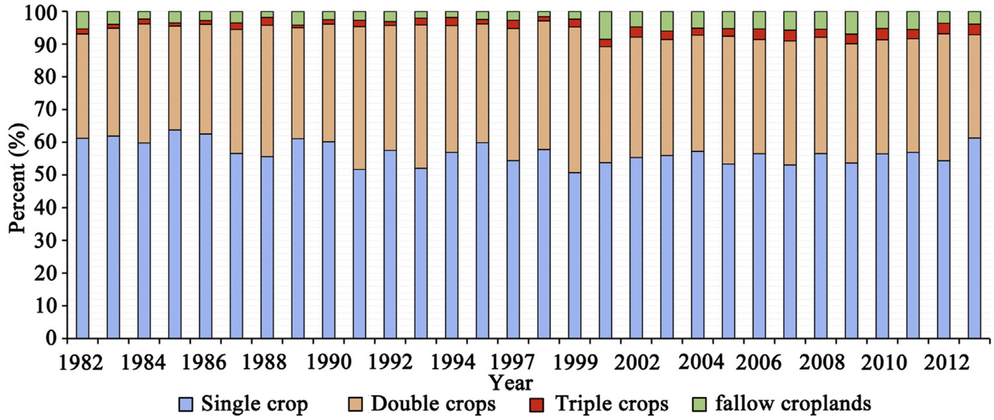

Fig. 5. Changes in the proportion of single, double, triple, and fallow croplands in China from 1982 to 2013.

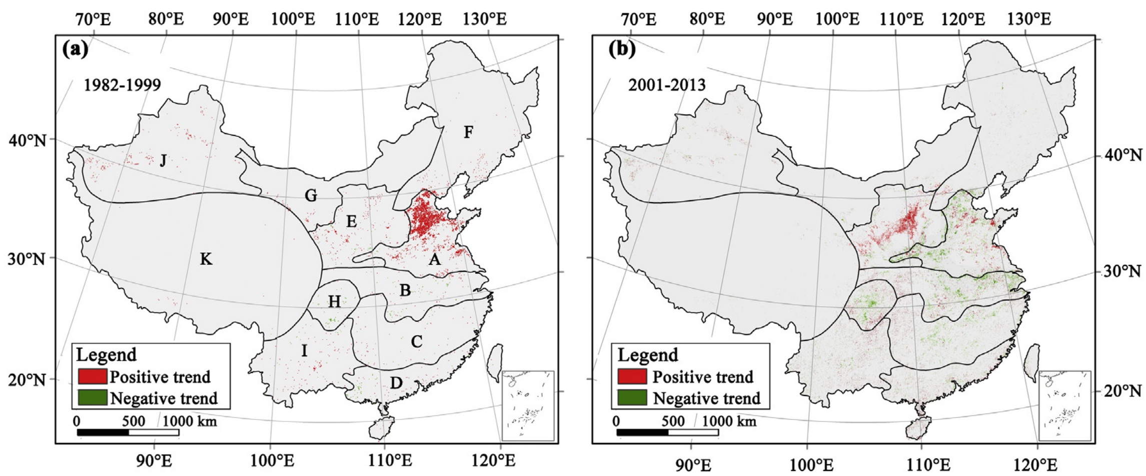

Fig. 6. Map of significant trends of cropping intensity from 1982 to 1999 (a) and 2001–2013 (b).

(region E). Considerably reliable datasets could also be acquired in the Middle-lower Yangtze River plain (region B) and the southern Yangtze hill region (region C) during several years (e.g., 2004, 2007, and 2013). Therefore, we further performed detailed investigation into their primary spatiotemporal trend and driving forces for these four regions in subsequent sessions.

A higher cloud cover ratio indicated higher uncertainties of the estimated results. Underestimates or overestimates might be introduced depending on the length and period of missing data in different cropping areas. For example, long periods of missing data associated with the Asian monsoon were found to be the main cause for cropping intensity underestimates, because entire crop cycles might be missed due to persistent cloud cover (Gray et al., 2014). Overestimates might also be introduced by regular summer cloud cover in tropical and subtropical regions, which resulted in two or more false peaks of the vegetation indices temporal profiles (Qiu et al., 2013).

4.2. Primary spatiotemporal trends from 1982 to 2013

We further explored the primary spatiotemporal trends from 1982 to 2013. From 1982 to 1999, the primary variation was from single to double cropping (88.83%). Around 93,225 km^2 single-cropped areas changed to double cropping. Others included the change pattern from fallow to single cropping cropland (7.24%, 7600 km^2). The increased cropping intensity from 1982 to 1999 was obviously acquired through increased double cropping.

From 2001 to 2013, the dominant positive change patterns were single to double cropping (52.50%) and fallow to single cropping (37.03%) (Fig. 8). A total of 38,163 km^2 single-cropped areas changed to double cropping and 26,917 km^2 croplands were re-cultivated (fallow to single cropping). Other positive change patterns consisted of double-to triple-cropping patterns (6.94%, 5045 km^2) and single-to triple-cropping patterns (2.24%, 1628 km^2). The major negative change pattern was from double to single cropping (78.30%), single cropping to fallow (9.40%), and double cropping to fallow (7.51%). A total of 46,547 km^2 double-cropped areas were turned into single-cropping. And 5588 km^2 single-cropped and 4464 km^2 double-cropped areas changed to fallow. Other negative change patterns were triple-to double-cropping (2.63%) and triple-to single-cropping (1.08%). Compared with croplands intensification (positive trend), croplands extensification (negative trend) was more decentralized distributed.

From 2001 to 2013, the key change patterns of cropping intensity were between single and double cropping. These two primary change patterns principally occurred in the North China plain (region A), Middle-lower Yangtze River plain (region B), and the southern Yangtze hill region (region C) (see locations in Fig. 8). A positive change pattern from single-to double-cropping was more decentralized distributed, principally located in the loess plateau (region E). In the following sections, we discuss our further investigation of these four regions.

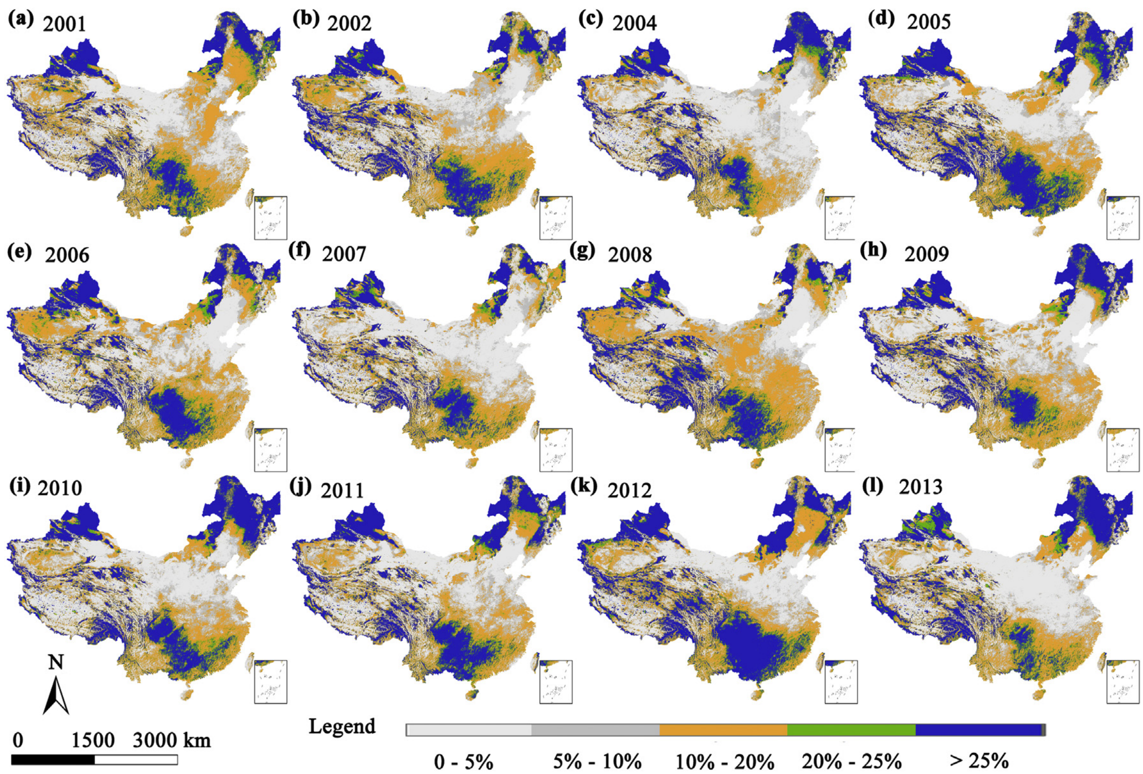

Fig. 7. Spatial distribution map of the cloud cover ratio from 2001 to 2013.

In the North China plain, a remarkable increasing trend was also observed from 1982 to 1999. The cropping index increased from 1.43 to 1.65 during the 1980s to 1.69–1.86 during the 1990s. The estimated cropping intensity from 2001 to 2013 was much more stable. It generally varied between 1.61 and 1.72 from 2001 to 2013. On the whole, a slightly decreased trend was exhibited from 2001 to 2013. Over 99% croplands were cropped. Specifically, less than 50% of croplands were double-cropped during the early 1980s (44.20–46.81%), which increased to over 50% during the mid- and late 1980s (53.92–64.95%). In the 1990s, the proportion of double cropping continuously increased to over 70% in the early 1990s and even 80% in the late 1990s. The percentage of double cropping ranged between 65.6% and 72.8% from 2001 to 2013.

In the Middle-lower Yangtze River Plain, the cropping intensity was considerably lower compared with the North China plain. The average values were 1.53, 1.55, 1.53 and 1.48 during the 1980s, 1990s, 2000s and 2010s, respectively. Over 97% of croplands were single/double-cropped. In 2011 and 2013, less than half of the croplands were multi-cropped.

In the southern Yangtze hill region, the cropping index varied from 1.55 to 1.74 during the 1980s to 1.61–1.79 during the 1990s. It then changed from 1.57 to 1.74 from 2001 to 2007 to 1.56–1.67 from 2008 to 2013. The percentage of double-cropping croplands increased from 67.57% in the 1980s to 68.15% in the 1990s.

In the above three regions, there was an increasing trend of cropping intensity from 1982 to 1999 but a reverse trend from 2001 to 2013. However, in the loess plateau (region E), the cropping intensity continuously increased from 2001 to 2013. It increased from 0.61 to 0.84 in the 2000s to 0.79–0.89 in the early 2010s. Most (98.01%) positive change patterns were from fallow to single cropping. Therefore, the increased cropping intensity in the loess plateau was obtained through the reduction of fallow.

It has been reported that roughly half of the cropland in China was multi-cropped from 1982 to 1999 (Qiu et al., 2003). Our study further revealed that the proportion of multiple cropping changed every year and ranged within 39.31–46.91 during 1990s (Fig. 5). Therefore, great uncertainties might be introduced when evaluating the trends of cropping intensity over time with only two periods of data. Annual continuous datasets of cropping intensity were highly recommended for this purpose.

4.3. Possible influence of socio-economic factors, topography and water conditions

The trends of agricultural population and mechanical power in China are provided in Fig. 9. The agricultural population kept increasing from 1982 until it reached its peak in 1996, and then decreased continuously from 1996 to 2013. This opposite variation in agricultural population might explain the reverse trends of cropping intensity in China during these two periods. For mechanical power, only a slight increase was observed from 1982 to 1995. But after 1995, there was a steady, remarkable increase. Capital intensity and the proportion of machinery showed an increasing trend in China since 1980 (Chen, Li, Tian, & Tan, 2009). A linear regression model was established based on the variables of agricultural population and agricultural mechanical power (Function (1)):

$$Y = 0.0899 \times X_1 + 0.0271 \times X_2 + 0.5101 \quad \left(R^2 = 0.4857;\ p < 0.001\right) \tag{1}$$

where Y denoted the cropping intensity, and X_1, X_2 represented the variables of agricultural population and agricultural mechanical power, respectively. Both agricultural population and agricultural mechanical power positively associated with the cropping intensity. A recent study also revealed that agricultural investments and farm mechanization positively contributed to the

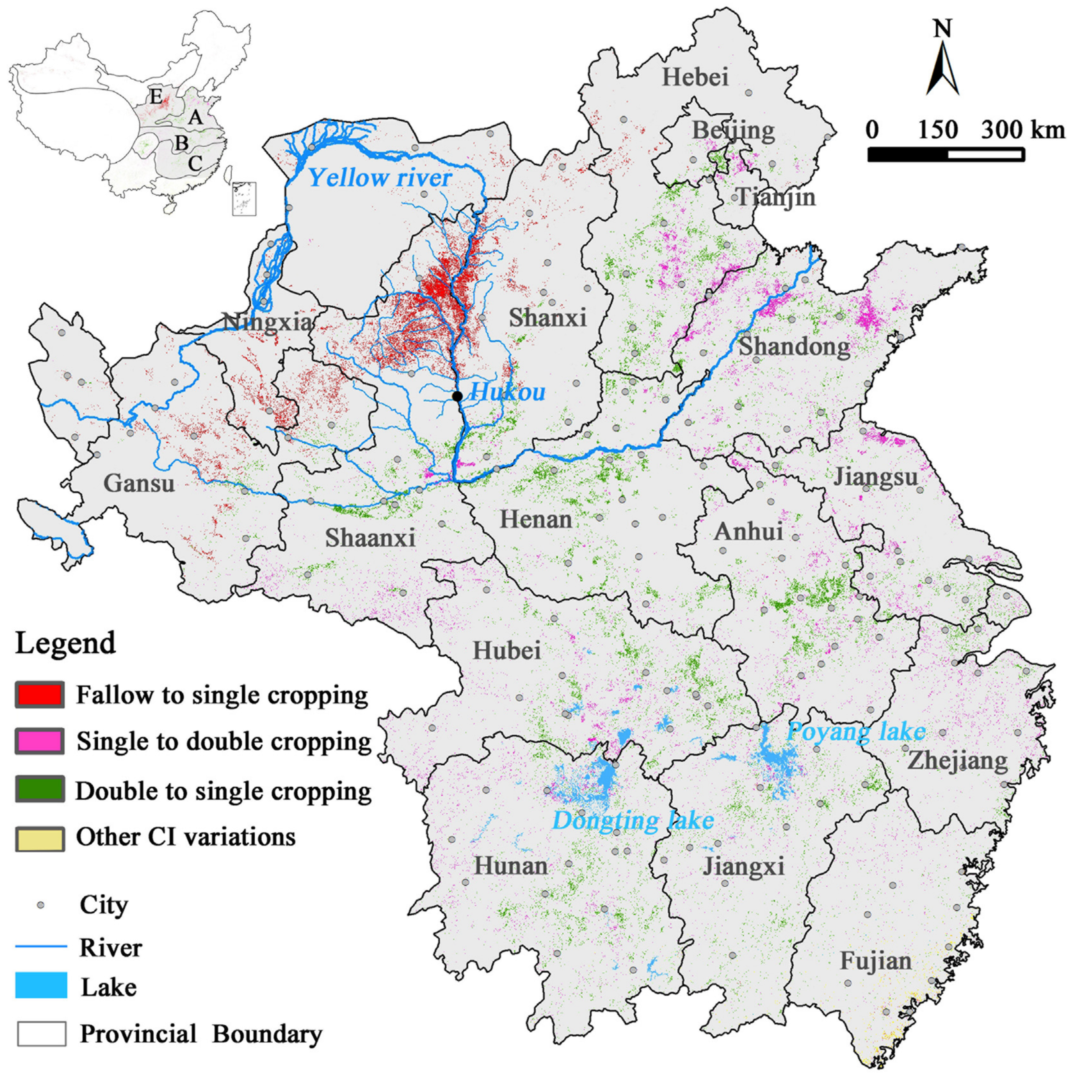

Fig. 8. Primary spatiotemporal trends of cropping intensity in regions A, B, C and E in China from 2001 to 2013. Notes: Regions A, B, C and E represented the North China plain, the Middle-lower Yangtze River plain, the southern Yangtze hill region, and the loess plateau, respectively.

intensification of agricultural land use (Jiang, Deng, & Seto, 2013; Kale, Nathani, & Chandra, 2016). It could also explain the fact that the cropping intensity only obtained a slight decrease from 2001 to 2013 despite the sharp drop in agricultural population.

In regions A, B and C, the primary change patterns were from double to single-cropping (27,262 km^2), and single to double cropping (22,494 km^2). In order to further explore the driving forces of these two primary change patterns, the change point/year for each pixel with significant trends was identified. The total numbers of pixels with these two primary change patterns were

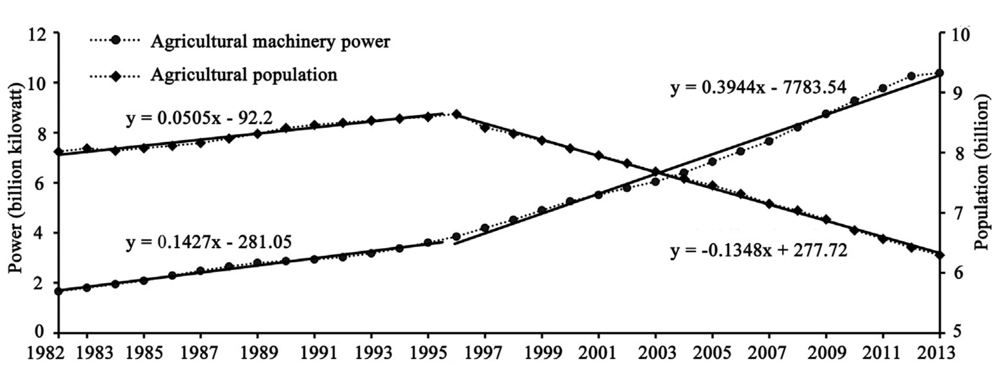

Fig. 9. The trend of agricultural population and mechanical power in China from 1982 to 2013.

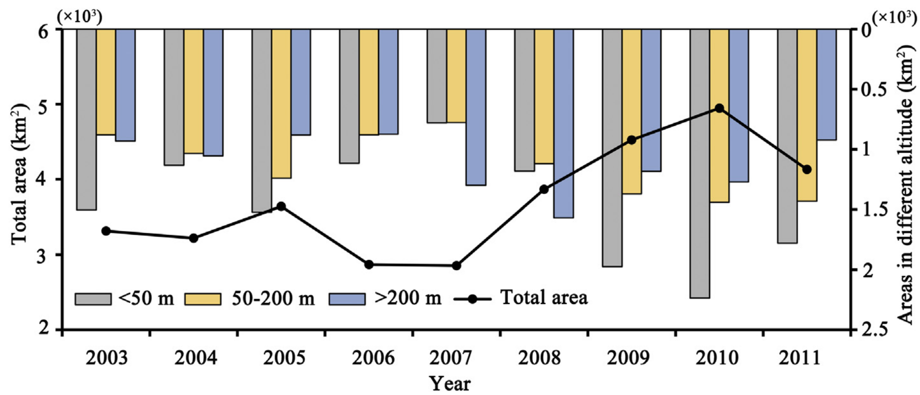

Fig. 10. Areas from double-to single-cropping on the whole and at different altitudes (<50 m, 50–200 m and >200 m) for each year from 2001 to 2013 in regions A, B and C.

calculated for each specific year for relatively lower (<50 m), medium (50–200 m) and high altitudes (>200 m) (Figs. 10 and 11), which occupied 46.79%, 30.52%, and 22.69% of croplands, respectively. On the whole, double-cropped areas turned to single-cropping primarily during the late 2000s (2008–2010) and less during the mid- 2000s (2006–2007). In 2005, the Chinese government established an agricultural duty free policy in order to stimulate cultivation. This policy had a significant effect on stabilizing cropping intensity. The total areas with negative trends per year decreased immediately after 2005. However, the agricultural duty free policy had more direct influence on croplands on plains (<200 m) (Fig. 10). Furthermore, the influences of this policy weakened two to three years later, and more areas exhibited decreased cropping intensity after then (Fig. 10).

Considerably more single-cropped areas turned to double-cropping during the early and late 2000s, particularly in 2004, 2005, 2008, and 2010 (Fig. 11). A relatively less increasing trend took place from 2006 to 2007. For the single-to double-cropping pattern, a large proportion (45%) was observed within a lower altitude (<50 m), and around 26.41% and 28.59% were acquired within medium (50–200 m) and higher altitudes (>200 m), respectively. Therefore the increasing trend primarily occurred within the lower altitude (<50 m) compared with the negative trend.

For the North China plain (region A) and Middle-lower Yangtze River plain (region B), we also explored the relationship of trends and the distance to nearest cities (municipal level). For each pixel with significant trends, its distance to nearest cities (the geometric center of cities) was calculated and summed (Fig. 12). As the distance to nearest cities increased, the areas of both negative and positive trend increased gradually, reached their peaks within 80 km, and then declined steadily. A study based on panel econometric methods found that urban expansion was associated with a decline in agricultural land use intensity (Jiang et al., 2013). Our study further revealed its double effects on cropping intensity and indicated that the negative trends were generally obtained at areas closer to cities compared to the positive trends.

The primary change pattern of cropping intensity in the Loess Plateau (region E) was re-cultivation. A total of 18,805 km^2 fallow areas were single-cropped from 2001 to 2013. For the Southern Yangtze hilly region (region C) and the Loess Plateau (region E), we explored the relationship between the primary change patterns and distances to nearest water sources (Fig. 13). In the Southern Yangtze hilly region, single-cropped areas closer to nearest lakes were prone to be double-cropped (Fig. 13(a)). In the Southern Yangtze hilly region (region C), the Dongting and Poyang lake plains were famous lands of fish and rice in China (Qiu, Li, Tang, Chen, & Qi, 2015). The central and local governments have promoted double rice cultivation through an agricultural subsidy policy in recent years. Our study revealed the policy effects on stimulating cropland intensification and further implicated that it had greater effects on areas closer to these great lakes (within 30 km). In the Loess Plateau, areas closer to the outlet (near Hukou waterfall, seen location in Fig. 8) of the middle basin (Shanxi and Shaanxi Gorge Reach) tended to be re-cultivated earlier (Fig. 13(b)). Vegetation improvements in Loess Plateau were also evidenced in a recent study based on MODIS NDVI time series (Jiang et al., 2014). Our study further disclosed its close relationship with water accessibility.

The socioeconomic driving mechanisms of cropping intensity were also documented in related studies (Ding et al., 2016; Li & Wang, 2003). For example, it was revealed that economic comparative profit drives farmers to increase the intensity level for agricultural production in the western provinces at present but not forever (Li & Wang, 2003). The cropping intensity was affected by the changing agricultural population, deployment of food policies, and methods introduced for maximizing farmer benefits (Ding et al., 2016). In addition to these above influencing factors, the trends in cropping intensity might also correspond to climate warming in some regions (Iizumi & Ramankutty, 2015; Zhang et al., 2013). Areas with good terrain and climate conditions were generally associated with multiple cropping (Jiang et al., 2013). Detailed information on cropping intensity is essential for understanding this process, and further investigations are needed in future research (Iizumi & Ramankutty, 2015; Qiu et al., 2016a). Our study made contributions in this aspect through providing spatio-temporal continuous datasets of cropping intensity during the past 30 years with fairly good spatiotemporal resolution in China. Up till now, there is no long-term annual continuous spatial distribution map covering the whole country with a spatial resolution no less than 5 km. Most existing studies either focused on local scale or only covered several individual years or a short period (Ding et al., 2016). Our study disclosed and confirmed the reverse trends in cropping intensity covering the whole country and broad scale (1982–2013) with full considerations of data uncertainty. It was hope to deliver a better understanding on guaranteeing long-term sustainability of agricultural productions in China.

4.4. Future work

Future studies could be conducted on the following aspects: (1) Radar images could be applied to those areas with regular cloud cover in order to better characterize spatiotemporal trends in cropping intensity during the past decades; (2) Time series imagery

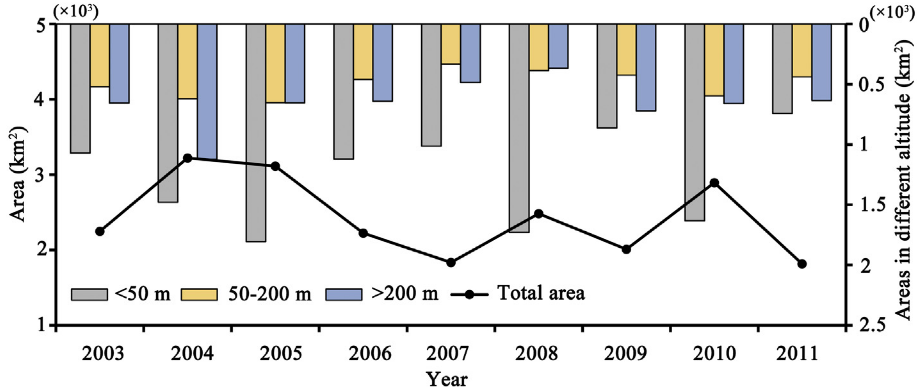

Fig. 11. Areas from single-to double-cropping on the whole and at different altitudes (<50 m, 50–200 m and >200 m) for each year from 2001 to 2013 in regions A, B and C.

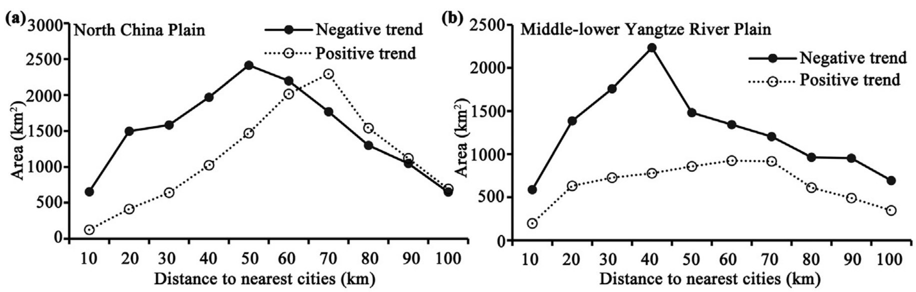

Fig. 12. Patterns of cropping index trends associated with distances to nearest cities in North China plain (a) and Middle-lower Yangtze River plain (b).

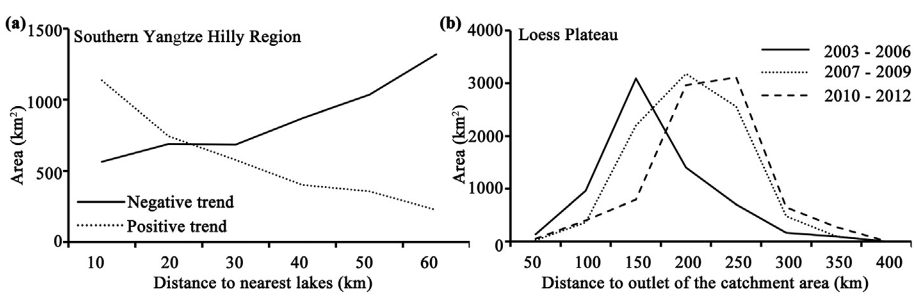

Fig. 13. Patterns of cropping index trends associated with distances to nearest water sources in Southern Yangtze hill region (a) and Loess Plateau (b).

with higher spatial resolution could be utilized to obtain more reliable results for small farms, especially in the southern hilly and mountainous areas; (3) Updated and high quality land cover data might be exploited to acquire more reliable cultivated land mask every year if possible; (4) further investigations would be conducted on the driving mechanisms on spatiotemporal variations of cropping intensity with full considerations of natural, technical and socio-economic factors (i.e. agricultural labors, food price, agricultural policy, introductions of new technologies and climatic changes) and possible stratified heterogeneity (Wang et al., 2016); and (5) Spatiotemporal approaches could be adopted to assess the agricultural and environmental consequences and implications of cropping intensity variations. A number of questions should be asked. How will the cropping intensity change in the near future? How is the crop yield associated with cropping intensity over these past decades? Among these trends of cropping intensity from 0 to 1 or vice versa, to what extent are they related to land use changes? What cultivated areas are being converted to non-cultivated lands?

5. Conclusions

This study explored the trends and primary change patterns based on spatiotemporal continuous datasets of cropping intensity during 1982–2013. From 1982 to 1999, the cropping intensity significantly increased through a key change pattern from single to double cropping primarily occurred in the North China plain. From 2001 to 2013, the cropping intensity slightly decreased with a main change pattern from double to single cropping or reverse principally took place in the North China plain, the Middle-lower Yangtze River plain, and the hill regions of the southern Yangtze River, and re-cultivation in the Loess Plateau. The reverse trends in cropping intensity might be associated with the corresponding variations of agricultural population in China. Thanks to the remarkable increase of mechanical power and the agricultural duty free policy, only a slight decrease in cropping intensity was found from 2001 to 2013. Our study provided valuable information on the spatiotemporal trends of cropping intensity in the past 30 years and contributed to deliver insightful solutions on stabilizing cropping intensity in China in the future.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (grant no. 41471362).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2017.01.001.

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