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Assessing the consequence of land use change on agricultural productivity in China

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ABSTRACT

China's cultivated land has been undergoing dramatic changes along with its rapidly growing economy and population. The impacts of land use transformation on food production at the national scale, however, have been poorly understood due to the lack of detailed spatially explicit agricultural productivity information on cropland change and crop productivity. This study evaluates the effect of the cropland transformation on agricultural productivity by combining the land use data of China for the period of 1990–2000 from TM images and a satellite-based NPP (net primary production) model driven with NOAA/AVHRR data. The cropland area of China has a net increase of 2.79 Mha in the study period, which causes a slightly increased agricultural productivity (6.96 Mt C) at the national level. Although the newly cultivated lands compensated for the loss from urban expansion, but the contribution to production is insignificant because of the low productivity. The decrease in crop production resulting from urban expansion is about twice of that from abandonment of arable lands to forests and grasslands. The productivity of arable lands occupied by urban expansion was 80% higher than that of the newly cultivated lands in the regions with unfavorable natural conditions. Significance of cropland transformation impacts is spatially diverse with the differences in land use change intensity and land productivity across China. The increase in arable land area and yet decline in land quality may reduce the production potential and sustainability of China's agro-ecosystems.

1. Introduction

Land use activities, primarily for agricultural expansion and economic growth, have transformed one third to one half of our planet's land surface in the form of forest clearance, agricultural practice and urban expansion, which made profound impacts on ecosystem service, food production and environment (GLP, 2005; Vitousek et al., 1997; Foley et al., 2005). Being home to one out of every five people in the world, China has been undergoing dramatic modifications due to the unprecedented combination of economic and population growth since the early 1980s (Liu et al., 2003; Chen, 1999). The loss of cultivated land due to widespread construction activities was considered to be one of the most serious problems affecting China's food security (FAO, 2002). In the recent years, a good number of studies have highlighted impacts of land use change on China's potential to maintain food self-sufficiency (Brown, 1995; Rozelle and Rosegrant, 1997; Heilig, 1999; Feng et al., 2005). Some previous studies have analyzed and assessed China's cropland area change and its influences on crop yield using census data at both national and provincial levels (Yang and Li, 2000). Such aggregated assessments, however, lack a detailed analysis of the variation of agricultural productivity caused by various forms of land transformation (such as urbanization and reclamation) and regional variability. Owing to the spatial heterogeneity of land use change caused by highly diverse natural and socio-economic conditions across China, accurate information on both cropland area and spatially explicit quantification of agricultural productivity are of critical importance for policy makers to assess the impacts of land use modification on national food security (Fischer et al., 1998; Verburg et al., 2000).

Satellite remote sensing is a significant data source for quantifying vegetation productivity, as it is able to detect actual vegetation dynamics top-down over large areas directly. It is helpful in avoiding the problems associated with "scaling up" in process-based modeling which extrapolates data from point measurements since the detailed information on factors such as climate, soil, and especially management of agro-ecosystems are not always available at the national scale (Schimel, 1995; Field et al., 1995; Reeves et al., 2005). Moreover, the measurement of photosynthetic production from remote sensing using net primary productivity (NPP) provides a common unit of production among the different crop types and hence it is a more useful approach in quantifying the impacts of land transformation (Bounoua et al., 2004). Furthermore, satellite remote sensing has been used significantly for monitoring and assessing land use change at large scales in the last two decades. Liu et al. (2002, 2005a), for instance, used LANDSAT TM/ETM to construct 1:100,000 scale China's National Land-Use/Land-Cover Dataset (NLCD hereafter) and to detect land use information across China for the period of 1990–2000 at a spatial resolution of 30 m. From the result of their study, for the first time, an unambiguous and spatially explicit understanding of the degree to which the whole nation's cropland has been converted was obtained.

In this study, we have quantified the influences of cropland transformation on the agricultural productivity of China during the

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1990s in a spatially explicit form. By integrating land use change data from NLCD and agricultural productivity data derived from satellite remote sensing images at a resolution of 8 km, the impacts of cropland transformation on agricultural productivity from the impacts of climate change and management measures for the period of 1991–2000 were distinguished. In addition, the spatial heterogeneity of agricultural productivity variation caused by various types of cropland transformation was differentiated in detail, and its implications for food security and agro-ecosystem sustainability were examined. In the analysis, our focus was particularly on five widely occurring land transformation types, namely: conversions of cropland to urban, cropland to forest and grassland, grassland to cropland, and forest to cropland. NPP is taken as the measure of agricultural productivity in this study and defined as the production per unit crop area, with a unit of g C m^{-2} yr^{-1}, while P (total productivity) refers to the summed NPP over the crop area in each geographic unit and has a unit of g C for pixels or Mt C (10^{12} g C) for regions.

2. Materials and methods

2.1. Land use change data

To characterize the spatial and temporal patterns of land use/land cover changes across China during the 1990s, the Chinese Academy of Sciences initiated a nationwide land cover/land use project in the late 1990s. Land use datasets for the periods of the end of the 1980s (NLCD80) and the end of the 1990s (NLCD90) with a mapping scale of 1:100,000 were developed. NLCD80 was derived from LANDSAT TM images at the end of 1980s and/or the beginning of 1990s, and NLCD90 was produced from remotely sensed images taken in 1999/2000. According to the land-cover classification system for NLCD, the land cover was categorized into 6 types: cropland, forest, grassland, water bodies, unused land, and built-up land including urban areas (Liu et al., 2002, 2003, 2005a).

The accuracy of NLCD dataset was evaluated with about 8000 pictures which were taken by cameras equipped with global position system (GPS) from an extensive field survey along transects of more than 75,000 km across China. The accuracy of TM images derived cropland was 94.9%, while that of built-up area had the highest accuracy of 96.3%. The accuracy for forest and grassland was 90.1% and 88.1%, respectively. A more detailed description of the data sources and methods used for developing NLCD dataset and for evaluating the accuracy of the dataset have been reported by Liu et al. (2002, 2003, 2005a).

2.2. NPP estimation

For establishing the link between satellite data and NPP, a production efficiency model (GLO-PEM) has been developed to estimate plant PAR absorption, light use efficiency, and autotrophic respiration (Prince, 1991; Prince and Goward, 1995; Cao et al., 2004). GLO-PEM was designed to run with both biological and environmental variables derived from satellite images (Prince and Goward, 1995; Goetz and Prince, 2000). Hence, it is a suitable tool to incorporate the effects of both climate change and crop management measures on crop growth activity into NPP estimation at the same resolution as satellite data. GLO-PEM consists of linked components that describe the processes of canopy radiation absorption, utilization, autotrophic respiration, and the regulation of these processes by environmental factors such as temperature, water vapor pressure deficit, and soil moisture (Prince and Goward, 1995; Goetz et al., 2000; Cao et al., 2004). In the model, the following relationship is used to determine NPP:

$$NPP = \sum_t \left[(S_t \cdot N_t)\varepsilon_g - R \right] \tag{1}$$

where S_t is the incident PAR in time t, N_t is the fraction of incident, photosynthetically active radiation (PAR) absorbed by vegetation canopy (Fapar) at time t (as demonstrated by Prince and Goward (1995), N_t can be calculated as a linear function of NDVI), ε_g is the light utilization efficiency of PAR absorbed by vegetation within the context of gross primary production, and R is the autotrophic respiration calculated as a function of standing aboveground biomass, air temperature, and photosynthetic rate (Prince and Goward, 1995; Goetz et al., 2000). Plant photosynthesis depends on both the capacity of photosynthetic enzyme to assimilate CO_2 (Farquhar et al., 1980; Collatz et al., 1991) and the stomatal conductance to CO_2 from the atmosphere into the intercellular spaces (Harley et al., 1992; Gollan et al., 1992). The two factors are affected by environmental factors, such as air temperature, water vapor pressure deficit (VPD), soil moisture, and atmospheric CO_2 concentration. For this, the following relationship can be used to determine ε_g:

$$\varepsilon_g = \varepsilon_g^* \cdot \sigma \tag{2}$$

where ε_g^* is the maximum possible light utilization efficiency of PAR absorbed by vegetation determined by photosynthetic enzyme kinetics, which is a function of photosynthetic pathway, temperature and CO_2/O_2 ratio, and σ is the reduction of ε_g^* caused by environmental factors that control stomatal conductance and can be determined from the following relationship:

$$\sigma = f(T)f(\delta q)f(\delta\theta) \tag{3}$$

where $f(T)$, $f(\delta q)$ and $f(\delta\theta)$ represent the stresses of air temperature, VPD, and soil moisture to stomatal conductance, respectively.

GLO-PEM is driven with the Pathfinder AVHRR (Advanced Very High Resolution Radiometers) data at a spatial resolution of 8 km and temporal of 10 days. These were obtained from AVHRR sensors aboard the National Ocean and Atmosphere Administration (NOAA) satellites. The algorithms to calculate NDVI, Fapar, biomass, air temperature, and VPD from the AVHRR data are included in the model (Prince and Goward, 1995; Goetz and Prince, 1999). Detailed descriptions of the algorithms for determining the interrelationship among model variables and satellite data preprocessing were given in the studies of Prince and Goward (1995), Goetz et al. (2000), and Cao et al. (2004). In this study, we use GLO-PEM and the NOAA/NASA Pathfinder AVHRR Land (PAL) data at resolutions of 8 km and 10 days to estimate NPP for the end of the 1990s (1998 and 1999) and that of the 1980s (1988 and 1989) for the purpose of matching with land use change data in temporal dimension.

The validation of the results yielded from GLO-PEM over a large scale was difficult because field measurements are not available to evaluate remotely sensed measures. The county-level census data for production and planted area of major crops over China was obtained from the national natural resource database (www.naturalresources.csdb.cn). These provided a comprehensive, independent measure of carbon uptake throughout the growing season of plants for comparison with the satellite-derived estimates (Malmstrom et al., 1997). Based on the statistic data, the method proposed by Lobell and Hicke (2002) was employed to estimate the cropland NPP for all counties across China. In this study remote sensing data for 1996 were used due to the availability of agricultural census data for that year. In order to minimize errors in regions with sparse agriculture, comparison of our result was limited to those of counties where cropland area accounts for more than 30% of the total county area according to 1996 statistic data. For the same reason, selection of crops was limited to those types growing on more than one million ha according to 1996 statistic data. Hence, a total of 1171 counties were sampled for comparisons. The results of correlation analyses showed that the estimates of crop NPP at county level were consistent with the NPP derived from county-level statistics (correlation coefficient $R = 0.68$). Although the crop yield from agricultural statistics are likely biased due to uncertainty in cropland area, the use of data at the county level still provided a large number of samples for evaluating remote sensing estimates of NPP.

We also compared NPP from provincial statistics data against GLO-PEM model derived NPP over the 1981–1996 years for 29 provinces of China. According to Table 1, the correlation coefficient (R, measuring interannual variation similarity) between modeled-NPP and statistic-derived NPP are high in those provinces suitable for intensive cropping due to favorable temperature and rainfall conditions. The large plain areas, the central part of China, had highest correlation coefficient (such as, $R=0.86$ in Hunan Province and $R=0.83$ in Jiangxi Province); while correlation coefficient was low at hilly and arid area, especially at north-west part of China (such as Gansu and Ningxia provinces) where model usually did not take into account a significant amount of NPP contributed by residue and weeds on abandoned land which eventually influenced the NDVI signals (Lobell and Hicke, 2002). Moreover, differences between estimates were also attributed to potential shortcomings in the statistic based estimate. It is also clear from Table 1 that 16 provinces had $R>0.6$ while 23 out of 29 provinces were with $R>0.35$ for model evaluation. The high correlation coefficients in most areas suggest that GLO-PEM was able to estimate NPP at an acceptable level.

2.3. Data fusion between land use change and NPP

To combine the cropland area data from NLCD in a vector format with the NPP estimated from GLO-PEM in a raster format, the cropland data in vector format were converted to raster format with 8 km resolution using a data fusion technique developed by Liu et al. (2002). The converted raster format data recorded the percentage of cropland area or converted area between cropland and other land cover types in each 8 km×8 km pixel, the area of each type in the 8×8 km grid is therefore consistent with the counterpart in the original, high-resolution vector data. Such data fusion technique enables the conversion of vector data into raster data without destroying the acreage information. The impacts of land use change on agricultural productivity were further analyzed based on the spatially matched land use change and NPP data.

Table 1
Correlation coefficients between modeled-NPP and statistic-derived NPP during 1981–1996 in 29 provinces of China.

Region	Province	Correlation coefficient	Percentage of cropland	Percentage of plain
North-East	Inner Mongolia	0.76	9.9	45.7
	Liaoning	0.55	44.4	42.4
	Jilin	0.37	39.3	66.2
	Heilongjiang	0.63	35.3	64.8
North	Beijing	0.62	29.7	69.8
	Tianjin	0.63	60.7	100
	Hebei	0.65	51.9	59.3
	Shanxi	0.22	39.0	13.1
	Shandong	0.77	66.7	65.2
	Henan	0.68	65.3	67.8
South-East	Shanghai	0.08	67.0	100
	Jiangsu	0.62	68.6	93.2
	Zhejiang	0.57	26.7	35.2
	Fujian	0.77	17.9	8.2
	Guangdong	0.73	25.1	48.6
Central	Anhui	0.80	57.4	74.5
	Jiangxi	0.83	27.1	40.0
	Hubei	0.75	37.6	57.4
	Hunan	0.86	28.9	38.6
South-West	Guangxi	0.68	21.9	30.8
	Sichuan	0.66	25.0	12.5
	Guizhou	0.52	28.2	2.3
	Yunnan	0.41	18.0	2.7
	Tibet	0.23	0.4	2.0
North-West	Shannxi	0.23	34.9	10.3
	Gansu	−0.44	17.5	10.7
	Qinghai	−0.21	1.2	4.6
	Ningxia	−0.05	35.3	26.9
	Xinjiang	0.11	3.6	71.2

2.4. Discrimination of agricultural productivity change caused by cropland transformation

It is known that changes in agricultural production often originate from either change in cropland area or in the crop production per unit land area. In this study, the total agricultural production is defined as the product of crop area and NPP in the form of:

$$P = A \cdot NPP = c \cdot A_g \cdot NPP \tag{4}$$

where P is the total agricultural production, NPP is the production per unit crop area (g C m^{-2} yr^{-1}), A is cropland area that equals to the product of the proportion of cropland in each pixel (c) and pixel area ($A_g = 64$ km^2). In the calculation of the changes of P, we took the value of NPP in 1988 and 1989 as the NPP level at the end of the 1990s (NPP_1) so as to maintain consistency with the land cover change data; similarly, the average value of NPP in 1998 and 1999 was regarded as the NPP level at the end of the 1980s (NPP_2). Each pixel has one NPP value derived from GLO-PEM model, while the heterogeneous landscape induced errors were neglected, because the fraction of non-vegetated area in 8 km×8 km pixel was very little within the land transformation types we focused in this study.

To evaluate the effects of cropland area changes on agricultural production, we applied the following method proposed by Hicke et al. (2004) to determine the fractional contributions of cropland area (A) and/or NPP to P:

$$\Delta A = A_2 - A_1 \tag{5}$$

$$\Delta NPP = NPP_2 - NPP_1 \tag{6}$$

$$\begin{aligned} \Delta P = P_2 - P_1 &= A_2 \cdot NPP_2 - A_1 \cdot NPP_1 \\ &= (A_1 + \Delta A) \cdot (NPP_1 + \Delta NPP) - A_1 \cdot \mathrm{NPP}_1 \\ &= \Delta NPP \cdot A_1 + \Delta A \cdot NPP_1 + \Delta A \cdot \Delta NPP \end{aligned} \tag{7}$$

where, A_1 and A_2 represent the cropland area at the end of the 1980s and 1990s, respectively. Rearranging Eq. (7) and dividing ΔP by P_1 result in:

$$\Delta P / P_1 = \Delta A / A_1 + \Delta NPP / NPP_1 + \Delta A \cdot \Delta NPP / P_1. \tag{8}$$

Thus, the fractional increase in P is the sum of the fractional increases in area A, NPP and an interaction term between A and NPP.

3. Results and analyses

According to the land use change data, China's cropland had a net increase of 2.79 Mha during the 1990s since the newly cultivated land was 5.97 Mha while 3.18 Mha out of the total cropland was modified for other uses especially for urban expansion, grassland and forest. The result calculated from Eq. (8) shows that China's total agricultural productivity had an increase of 150.16 Mt yr^{-1} in the 1990s, within which 6.96 Mt yr^{-1} was attributed to cropland transformation due to increased cropland area, while 142.99 Mt yr^{-1} to an increased NPP, and a negligible fraction to the area–NPP interaction (Table 2). In next two sub-sections, spatial distribution and extent of effects of land use changes on agricultural productivity are analyzed and described.

3.1. Contributions of cropland area on agricultural productivity contrasting to NPP change

China's newly cultivated cropland, as presented in Fig. 1, is mainly distributed in the Northeast Region (Zone I), the Inner Mongolia Region (Zone II) and the Gan-Xin Region (Zone VIII). Croplands that were modified for other uses were found largely in Southern China. Spatial variation patterns of the total agricultural productivity and its two fractions (area-induced and NPP-induced) across China in the 1990s

Table 2
Effects of cropland area change and NPP on total production (Unit: Mt).

Zone	Agricultural region	Cropland area	NPP	NPP–area interaction
I	Northeast Region	11.78	9.78	0.91
II	Inner Mongolia and the Great Wall Region	2.05	7.20	0.28
III	Huang-Huai-Hai Region	−2.31	32.09	−0.38
IV	Loess Plateau Region	0.12	−0.45	−0.003
V	Middle and lower reaches of the Yangtze River drainage basin	−3.23	57.35	−0.54
VI	Southwest Region	−0.25	21.33	−0.03
VII	South China Region	−1.33	1.59	−0.09
VIII	Gan-Xin Region	0.08	−0.22	0.08
IX	Tibet Region	0.08	−0.002	−0.003
	Whole China	6.96	142.99	0.21

are presented in Fig. 2. Although land conversion was responsible for crop production increase in northern China and decrease in South China, its effects on the total agricultural production change were spatially scattered due to NPP-induced total agricultural production change. Most of the cropland with reduced total agricultural production were found in northwestern China, except for some areas in the Yangtze River and the Pearl River deltas (parts of Zone V and VII) (Fig. 2A). By comparing Fig. 2B and C, the relative contributions of cropland area and NPP to change in agriculture productivity can be determined. In the Yangtze River delta and the Pearl River delta, land conversion had a strong negative impact causing the total production to decrease significantly, while it resulted in a positive impact on the western side of the Song-Nen Plain (part of Zone I). The negative effects of land conversion in most southern regions have been cancelled out by the increase in NPP. In the Loess Plateau Region (Zone IV), however, the newly cultivated cropland could not compensate for the loss of productivity caused by a reduction in NPP. It can also be observed from Fig. 2 that the area-induced decrease in agricultural production occurred largely in the northern and eastern regions of China where NPP showed an increasing trend, mainly in the Huang-Huai-Hai Plain region (Zone III) and the Yangtze River drainage basin (Zone V). In the western part of the Song-Nen Plain (part of Zone 1), however, NPP had a decreasing trend although a large amount of land has been newly cultivated.

The shrinking of cropland occurred widely in the Huang-Huai-Hai Plain region (Zone III), the lower and middle areas of the Yangtze River drainage basin (Zone V), the Southwest Region (Zone VI) and the Southern China Region (Zone VII). The cropland area in the above mentioned four regions has decreased by 4684 km^2, 5174 km^2, 1963 km^2 and 587 km^2, respectively, which reduce the total production by 2.32, 3.24, 1.33 and 0.26 Mt C, correspondingly. However, the increased NPP in the four regions has not only offset the negative effects of cropland transformation but has also enhanced the crop production, resulting in improved total production by 18.6%, 23.7%, 15.2% and 12.7%, respectively.

In the Loess Plateau Region (Zone IV) and the Gan-Xin Region (Zone VIII), the land resources are generally of poor quality with heavy soil erosion, lower NPP and susceptibility to degradation. Although there were 1376 km^2 and 3389 km^2 of newly cultivated cropland respectively in the two regions, the reduced NPP still made the total production decrease slightly. In the Northeast Region (Zone I) and the Inner Mongolia Region (Zone II), both cropland area and NPP had a positive influence on productivity, but the influence from newly cultivated cropland were more significant than that from the increase in NPP in the Northeast Region (Zone I).

3.2. Agricultural productivity variations caused by five major cropland conversion forms

As stated earlier, the increase in crop production gained from land use transformation, 6.96 × 10^6 ton, is the net result of the positive effects of new cultivation and the negative effects of urbanization or natural vegetation restoration. The loss from the reduced cropland area has been compensated by the wide range of new cultivation in northern China. Among various forms of land transformation, it was found that there are five types that play a dominant role. They are the conversions of cropland to urban, forest, and grassland, grassland to cropland, and forest to cropland (Liu et al., 2005b). During the ten-year period, urbanization has caused a decrease of 7.84 Mt in crop production, while the cropland transformed into forest and grassland has reduced crop production by 2.64 Mt C and 1.69 Mt, respectively. Conversely, the increase in crop production from newly cultivated cropland transformed from forest and grassland was 8.34 Mt C and 10.13 Mt, respectively.

Among the above mentioned five major types of land use changes, the transformation of grassland to cropland exhibited the most significant positive effects on food production, and it was followed by the transformation of forest to cropland. Meanwhile, urban sprawl appears to be the most influencing human activity on crop production decrease, whose negative impact on crop production was almost double the sum of the loss of crop production resulting from the transformation of cropland to forest and grassland (Table 3). Furthermore, most of the area losses in cropland due to urbanization were of good quality and with high productivity, while the newly developed cropland was generally from area of poor land quality and with low productivity. This can be seen through comparing the changes in cropland area and the resulting productivity with the changes in urban sprawl and the transformation of grassland to cropland (Fig. 3). Of the resulting productivity change by cropland transformation, there was 22.8% lost to urbanization, while 29.5% was gained from the newly cultivated land from grassland. However, all the cropland lost to urbanization accounted

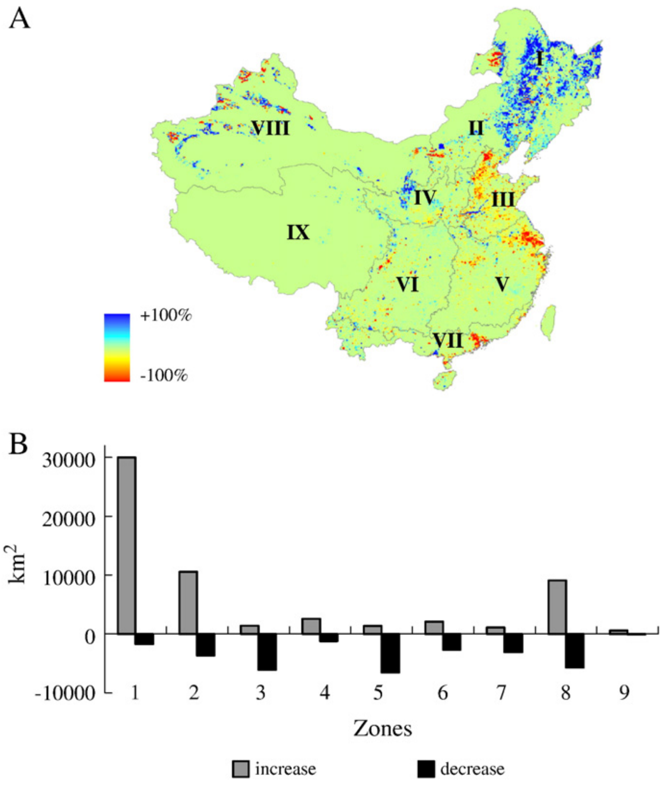

Fig. 1. Cropland transformation in China during the 1990s. A is spatial distribution of cropland transformation, where the pixel value is the proportion of transformed cropland area within each 8 km × 8 km pixel, positive value means cropland area increased and negative value means cropland area decreased. B presents the sum of cropland area of newly cultivated and modified for other uses within the 9 agricultural regions. The corresponding agricultural regions' names are presented in Table 2.

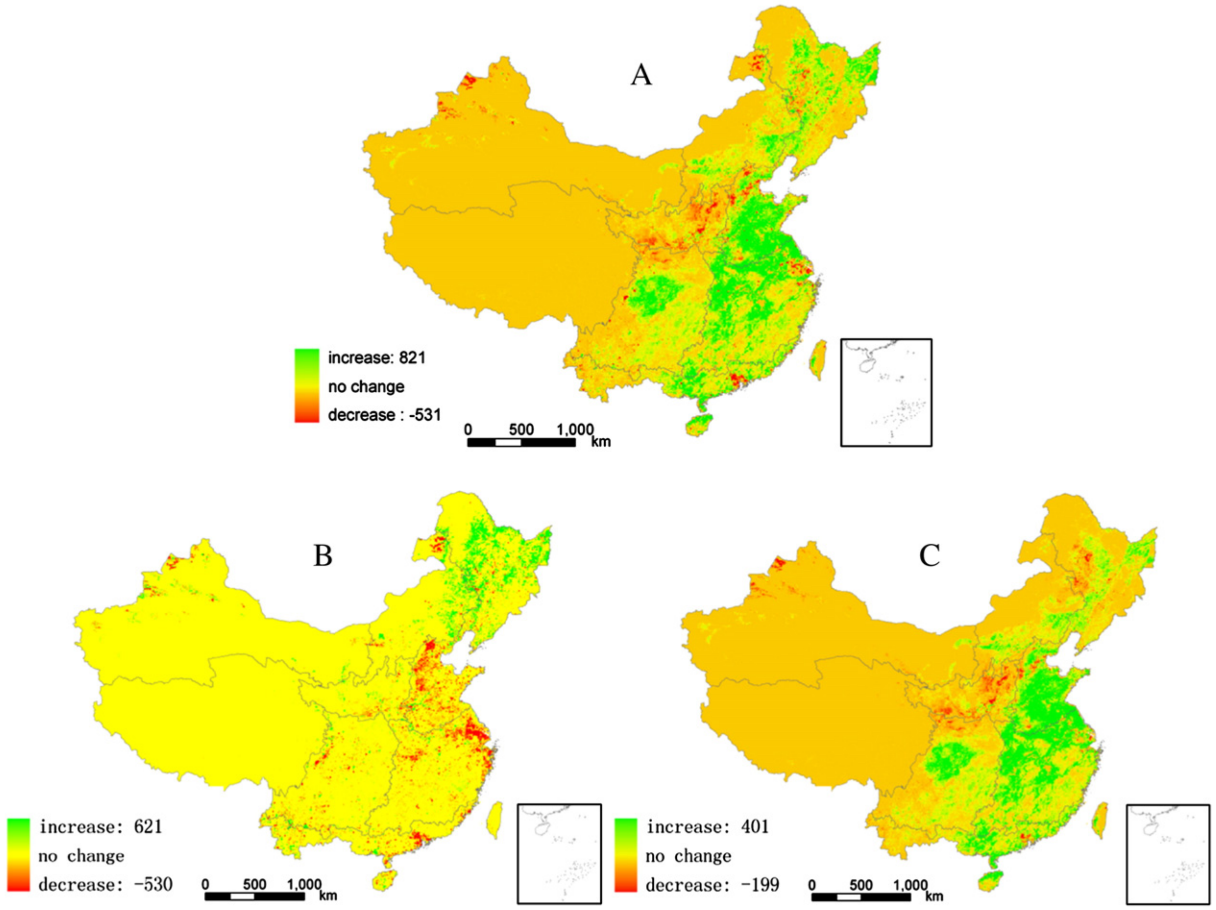

Fig. 2. Effects of land use change and NPP on total productivity in China during the 1990s (Unit: g C), A: total productivity change, B: land use transformation induced change, and C: NPP-induced change.

for only 16.6% of the total transformed area, while the total cropland transformed from newly cultivated grassland was 38.8% of the total transformed cropland area. That is to say, an occupation of 1 ha cropland by urban requires cultivating 1.8 ha grassland to compensate the resulted production loss.

Land use change is highly diverse across the whole country, so are its impacts on agricultural productivity due to natural and socio-economic differences in different geographical regions (Fig. 4). In the Northeast Region (Zone I), the agricultural production resulting from cropland transformation was as high as 11.8 Mt C, to which the most contributed land use change types were grassland and forestland cultivation, including 5.8 Mt C resulted from an increase in forest area and 5.2 Mt C from an increase in grassland cultivation. The Inner-Mongolia and the Great Wall Region (Zone II) is a typical farm and pasture interleaving area, where intensive land conversions of cropland to grassland and grassland to cropland occurred simultaneously. In this region, the agricultural productivity has gained a net increase of 2.1 Mt C, to which the most significant contributions were 2.9 Mt C gain from grassland cultivation and 0.9 Mt C loss from converting cropland into grassland. Cropland transformation has caused a loss of 2.3 Mt C in agricultural productivity in the Huang-Huai-Hai Plain Region (Zone III), within which the rapid urbanization has caused a loss of 2.63 Mt, mainly happened in the Beijing–Tianjin–Tangshan economic area, while the new cultivation in the region only has had limited potential to compensate the loss. In the Loess Plateau Region (Zone IV), the large area of newly cultivated cropland

Table 3
Impacts of the different forms of land use change on the total agricultural productivity of China during the 1990s.

Land use changes	Area induced productivity variation (%)
Cropland to forest land	−7.7
Cropland to grassland	−4.9
Cropland to built-up land	−22.8
Forest land to cropland	24.3
Grassland to cropland	29.5
Others	11.0

Positive values indicate land use changes make agricultural productivity increase. Negative values indicate land use changes make agricultural productivity decrease.

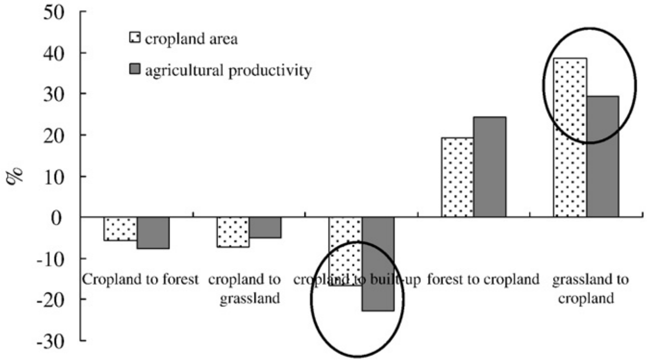

Fig. 3. Proportions of 5 major forms of cropland transformation and the induced agricultural productivity change in China during the 1990s.

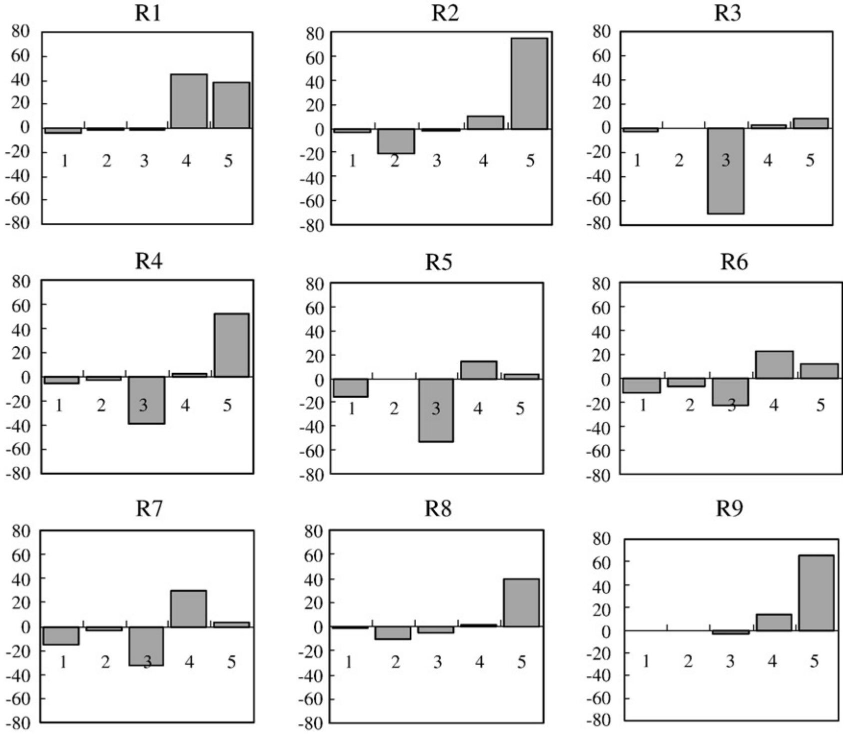

Fig. 4. Agricultural productivity changes caused by 5 major types of cropland transformation across 9 agricultural regions in China during the 1990s. R1–R9 represent the 9 corresponding agricultural regions demonstrated in Fig. 1. The horizontal axis is the 5 focused land use change types: 1.Cropland to forest, 2. Cropland to grassland, 3. Cropland to build-up land, 4. Forest to cropland, 5. Grassland to cropland; the vertical axis is the proportion of changed area of a certain land use change type within the total changed area in every agricultural regions.

transformed from grassland has yielded an increase in production by 0.54 Mt C during 1990–2000. At the same time, the occupied cropland by built-up area resulted in a reduction in agricultural production by 0.4 Mt. As a whole, land transformation had a weak positive effect on agricultural productivity with only 0.12 Mt C increase in the Loess Plateau Region. Urbanization has brought about a significant impact on agricultural sustainability in the lower and middle reaches of the Yangtze River drainage basin (Zone V), especially in the Yangtze River delta area. There was 2.73 Mt C of agricultural productivity lost to urban sprawl in Zone V, while a small fraction of scattered cropland was converted into forest in this region, by which the loss in crop productivity can be nearly counteracted by newly cultivated cropland. Consequently, a loss of 3.24 Mt C resulted from cropland transformation in the lower and middle reaches of the Yangtze River drainage basin (Zone V). Agricultural productivity was reduced by 0.26 Mt C in the Southwest Region (Zone VI), an area where the five major types of cropland transformation have all taken place with the impacts of intensive forest cultivation and urbanization being more significant than those of the other three. In Southern China Region (Zone VII), the cropland transformation was characterized with urbanization in the Pearl River delta area and deforestation and afforestation in parts of the Guangxi Province. Of the loss of 1.33 Mt C in crop production due to cropland transformation, 1.09 Mt C was due to urban sprawl. In Gan-Xin Region (Zone VIII), a small part of oasis was recovered into grassland while the grassland around oasis has been reclaimed again, resulting in an increase of 0.08 Mt C in agricultural productivity.

4. Discussion and conclusions

The nation-wide impacts of China's cropland transformation on agricultural productivity were evaluated through integrating TM derived land use data and NPP model driven with satellite remote sensing data at a spatial resolution of 8 km. Our findings showed that in the 1990s, the cropland transformation in China led to an increase in agricultural productivity of 6.96×10^6 ton. This implies that there was a national increase of 5% in total agricultural productivity resulting in less pressure on national food security from the continual increase in population.

However, we found that change in China's arable land was characterized by a significant loss to urban sprawl in southern China but by a significant gain from the new cultivation in northern China, and the productivity of arable land occupied by urban expansion is 80% higher than that of the newly cultivated lands in the regions where the quality of newly cultivated lands was poor. This implies that the increase in the nation's agricultural production induced by land transformation during the 1990s resulted mainly from the expansion of poor quality land into cropland. This is not a healthy, sustainable way for development and, if no appropriate measures are implemented, it can make the food production potentials and sustainability of China's agro-ecosystems decline drastically in the near future.

Because of the highly diverse nature of China's physical environment and socio-economic development, the impacts of land use change on agricultural production have revealed different patterns across China in the 1990s. Significant impacts of cropland transformation on agricultural production occurred mainly in the Northeast Region (Zone I) (where large area of newly cultivated land has been developed) and in the regions with rapid urban expansion, typically the delta of the Pearl River (part of Zone VII), the delta of the Yangtze River (part of Zone V) and the Beijing–Tianjing–Tangshan Region (part of Zone III). In the Loess Plateau Region (Zone IV), the Gan-Xin Region (Zone VIII), and the Song-Nen Plain Region (part of Zone I), however, the increase in the agricultural productivity owing to the newly cultivated land could not compensate for the decreases in crop productivity caused due to the loss of cropland. In the Huang-Huai-Hai Plain (Zone III) and most of the regions in southern China, the negative effects of the reduction in arable land was concealed by the increases in the crop productivity.

Our results are generally in accordance with those of other scientists who have observed from census data, that decreases in cropland area caused by urban sprawl have reduced agricultural production in Huang-Huai-Hai plain (Yao et al., 2004). Our findings also confirm that recovery of cropland to forest or grassland at western China did not result in significant loss of agricultural production (Feng et al., 2005). In comparison with the work of Deng et al. (2006) on national scale, although we had some similar conclusions that the land use conversion did not bring negative impacts in recent years on total agricultural productivity due to the enlarged cropland area, however, our results slightly differed from theirs, because AEZ model used in their study evaluated potential productivity based on physical conditions and managements for crop growth, while GLO-PEM estimated actual productivity based on satellite observations.

Land use and management practices largely govern the sustainability of a given land (Foley et al., 2005), therefore cropping intensity and improved management (e.g., crop varieties, irrigation, fertilizer, etc.) have profound influences on crop production and environment as well as land use transformation (Ortiz-Monasterio and Lobell, 2007). In this study we have explored the influences of land use transformation on agricultural productivity and its implication on environment. Crop production and environmental impacts of agricultural land management still depend on how effectively we understand their changes on temporal and spatial scale and the social and ecological elements of agricultural ecosystems.

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