

The influences of spatiotemporal change of cultivated land on food crop production potential in China

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Received: 21 September 2015 / Accepted: 6 April 2017 / Published online: 14 May 2017
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Abstract The impact of changes in cultivated land on the production potential of food crops in China during the period of 1990–2010 was studied using land use data and the Global Agro-ecological Zones (GAEZ) model. The contribution of crop production potential per unit cultivated land area (PPCLA) to the total food-energy based production potential (TPP) of food crops was further investigated. From 1990 to 2010, China has experienced a net increase of cultivated land, resulting from a net increase in northern China and a smaller net decrease in the south. However, the TPP reduced by 9.64×10^{12} kcal despite an overall cultivated land increase for crops. This was attributed to the spatial heterogeneity of PPCLA in the cultivated land, whereby the average PPCLA of the newly cultivated land was much lower than that of the lost land. The PPCLA gap between the newly developed land and the lost cultivated land expanded from 3.16×10^6 kcal/ha in the first decade (1990–2000) to 6.49×10^6 kcal/ha in 2000–2010. Contributions of PPCLA to TPP varied among regions,

and the regions with the largest contributions were consistent with those with the largest PPCLA gaps. Such regions included the Sichuan Basin and surrounding region in 1990–2000, and the Huang-Huai-Hai Plain during 2000–2010. Based on these research findings, key implications for land use policies in relation to major food crops in China are discussed.

Keywords Cultivated land · GAEZ model · Production potential · Spatial heterogeneity · China

Introduction

Changes in land use caused by expansion of urban areas and extensive deforestation have significant impacts on land productivity globally through altering the quantity, quality and structure of cultivated land (Foley et al. 2005). Land use change has attracted extensive attention due to its worldwide threat to food security, and particularly in China (Rozelle and Rosegrant 1997; Tan and Peng 2003; Liu et al. 2010b; Tschardt et al. 2012; Anderson and Strutt 2014). China is the world's most populous nation, and it currently feeds approximately 22% of world population with only 7% of the world's cultivated land. Tracking the changes in cultivated land areas and their impacts on agricultural productivity in China is a prerequisite to the better guarding of national food security.

China has experienced a rapid growth in urban areas since the start of implementation of its reform and opening policy in 1978. The proportion of the urban population to total population in China had increased from 18% in 1978 to 50% in 2010 (Beijing Statistics Bureau 2011), with a growth rate that has been more than double the world average. As a result, large amounts of cultivated (cropped) land have been converted to urban use, especially in central and eastern coastal areas of China (Cai et al. 2013). To prevent a decrease of cultivated

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land area nationally, the Government of China implemented the Cultivated Land Acquisition and Compensation Balance (CLACB) policy in 1997, and further codified it into the Land Management Law in the following year. According to the CLACB policy, if the cultivated land in one province has been altered for non-agricultural uses, a land area of equal quantity and quality in the same province must be ‘compensated’ through the conversion of other types of land into cultivated land. Such compensated land has been mainly sourced from grassland, woodland and unused land through processes of land reclamation, consolidation, and rehabilitation. During the same period, another cultivated-land-related campaign, the Grain for Green Project, was also implemented. Aiming to protect and improve the ecological environment in western China, this project involved 25 provinces in central and western China. In these regions, sloping cultivated land and degraded farmland were allocated for restoration with natural vegetation, and parts of them have been planted with grass and trees, according to their climate, soil, moisture and terrain conditions. By the end of 2010, 7.86×10^6 ha of cultivated land were allocated for afforestation (State Forestry Administration 2012).

Rapid urbanization in China, along with the implementation of these land policies and ecological protection campaigns, has resulted in changes to the quantity and quality of cultivated land (Chen 2007; Pijanowski and Robinson 2011; Yan et al. 2012; Qin et al. 2013; Tian and Qiao 2014). Several previous studies have investigated these changes in cultivated land and their impacts on the total production potential (TPP) of food crops (Cai et al. 2013). During 1999–2008, a total of 2.10×10^6 ha of cultivated land was lost due to urbanization and economic development, while 2.77×10^6 ha of new cultivated land was obtained from land exploitation, consolidation, and rehabilitation (Song and Pijanowski 2014). From 1986 to 2000, the impact of the conversion of cultivated land on the total agricultural potential in China was found to be insignificant in that the conversion of cultivated land to other uses had not imposed threats to China’s national food security (Deng et al. 2006). However, during 1990–2010, Liu et al. (2014c) estimated that potential food crop production had decreased by approximately 34.9 million t (which accounted for 6.52% of China’s total actual production), mostly as a result of urban expansion. The net decrease of production potential caused by changes in cultivated land was only 2.97 million t or 0.29% of national total actual crop production in 2010 (Liu et al. 2015). Although this previous research was based on different data sources, most of these studies identified obvious changes in both the cultivated land area and agricultural production potential. Changes to agricultural production potential were attributed to both the change in amount of cultivated land and the spatial heterogeneity of production potential per unit cultivated land area (PPCLA). Most of these previous studies

focused on changes in quantity of cultivated land, with little effort made to identify the impacts of PPCLA.

With this background, our study aimed to assess the impacts of changes with cultivated land on agricultural production potential in China. In particular we addressed the influences caused by spatial heterogeneity of PPCLA, with an emphasis on major food crops, especially cereals that are grown on most of the cultivated land. The findings will provide useful guidance for the optimal use of land resources and the development of informed agricultural policies in the future.

Materials and methods

Materials

The data used in this study included land use/cover data, meteorological data, and regional agricultural data for China.

Land use/cover data

The land use/land cover dataset, with a mapping scale of 1:1,000,000, was developed by the Chinese Academy of Sciences (CAS). The primary data source for the land use/cover dataset was derived from Landsat MSS/TM/ETM+ images. Images from the China-Brazil Earth Resources Satellite (CBERS), the Small Satellite Constellation for Environment and Disaster Monitoring and Forecasting (SSCEDMF), and the HJ-1 satellite were also used as supplementary data sources for the areas not covered by Landsat images. Land use data were classified into 25 categories and then grouped into six classes: farmland, woodland, grassland, water body, built-up land, and unused land. Detailed information about this land use database can be found in previous studies by Liu et al. (2010a, 2012). Data on cultivated land for the years 1990, 2000 and 2010 were extracted from the land use/cover dataset and then used to assess the influence of change in cultivated land on the production potential of agricultural crops in China during 1990–2010.

Meteorological data

Meteorological data from 1990 to 2010, which included the monthly maximum air temperature, minimum air temperature, precipitation, relative humidity, wind speed at a height of 10 m, and sunshine hours were obtained from agrometeorological stations maintained by the Chinese Meteorological Administration (CMA) (<http://cdc.cma.gov.cn>). The impacts of topography on the interpolation of the meteorological data were also considered because of the diverse terrain across China. The ANUSPLIN software (Hutchinson 1998) was used in this study to interpolate the

meteorological data based on the terrain elevation dataset. Monthly data for the above six key plant growth factors were interpolated to $1 \times 1 \text{ km}^2$ resolution maps using the ANUSPLIN software based on the digital terrain model of China.

Regional agricultural data

Regional agricultural data were used to investigate the spatio-temporal patterns of cultivated land and how their change may affect the potential production of food crops. China was divided into nine agricultural regions at provincial level, according to the endowment of farmland resources and the characteristics of land use change (Fig. 1 and Table 1) (Qin et al. 2013). Regions A-E are known as the major crop production areas in China, while regions F-H are covered by the Grain for Green Project emphasized by Central Government. To ensure regional integrity, the Qinghai-Tibet Plateau region (I) was also included, although the area of cultivated land in this region is less than 1% of the national total (Liu et al. 2005).

Methods

Global agro-ecological Zones (GAEZ) model

Crop production potential is the maximum attainable yield per unit land area that can be achieved by a particular crop cultivar in an ideal environment where pests and diseases are

effectively controlled and nutrients are limitation free (Evans 1993). To estimate crop production potential, many methods have been developed (Fischer et al. 2002, 2005, 2006; Mahmood et al. 2004; Lobell et al. 2009; Licker et al. 2010), of which a method based on Agro-ecological Zones (AEZ) is the most commonly used due to its simplicity and reliability. This model was developed by the Food and Agriculture Organization of the United Nations (FAO) in collaboration with the International Institute for Applied Systems Analysis (IIASA) in the 1970s, and subsequently it was further developed into the Global Agro-ecological Zones (GAEZ) model. The GAEZ model can serve as an assessment framework for biophysical constraints (light, temperature, water and soil) and production potential for all major food and fiber crops under specified levels of inputs and management conditions (Fischer et al. 2002, 2005, 2006). Initially, existing climate data, soil type data and the development level of technology were used to predict Land Utilization Types (Liu et al. 2014a, b, 2015). Then the data on Land Utilization Types along with other factors, such as the length of growing cycle and harvest indexes, were input into the model to determine which crops were the most suitable ones for each cell through a step-wise limiting process. Consequently, the potential production can be calculated based on all the related data.

The GAEZ model was employed in this study to evaluate potentials of crop production at a grid of $1 \times 1 \text{ km}^2$. The main crops covered by this research were wheat, maize, rice, sweet potato and soybean, which accounts for 97.7% of the total

Fig. 1 Map of agricultural regions in China

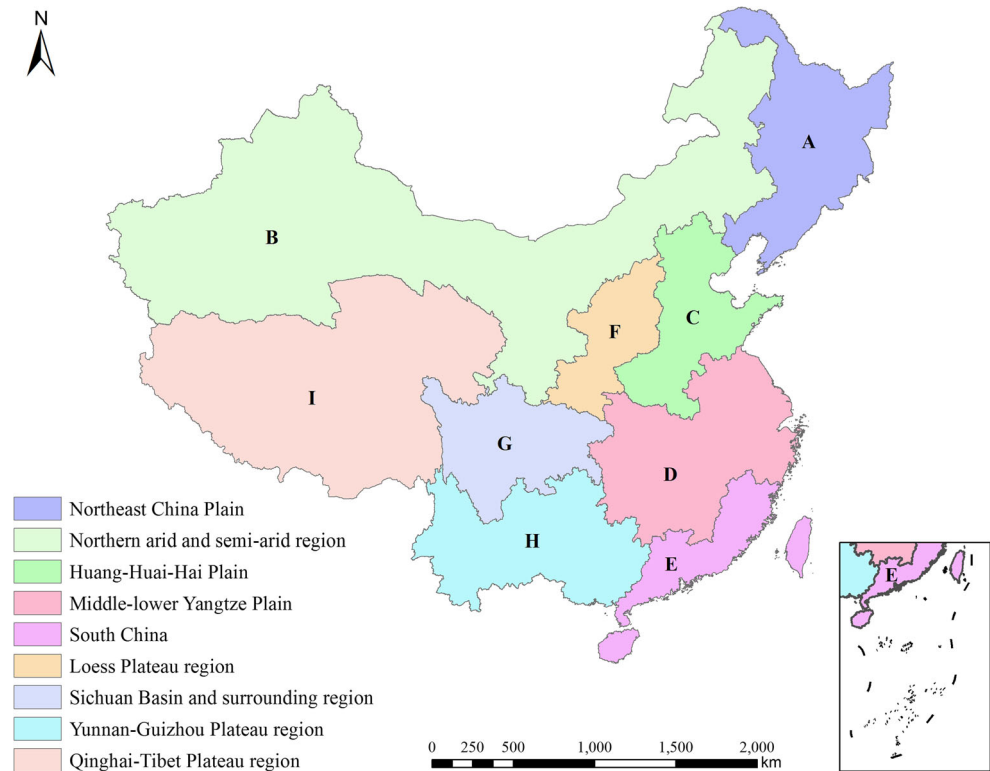


Table 1 Provinces in each agricultural region in China

Code	Agricultural Region	Provinces included in each agricultural region
A	Northeast China Plain	Heilongjiang, Jilin, Liaoning
B	Northern arid and semi-arid region	Xinjiang, Inner Mongolia, Ningxia, Gansu
C	Huang-Huai-Hai Plain	Beijing, Tianjin, Hebei, Shandong, Henan
D	Middle-lower Yangtze Plain	Shanghai, Jiangsu, Anhui, Hubei, Hunan, Zhejiang, Jiangxi
E	South China	Guangdong, Fujian, Hainan, Taiwan
F	Loess Plateau region	Shaanxi, Shanxi
G	Sichuan Basin and surrounding region	Sichuan, Chongqing
H	Yunnan-Guizhou Plateau region	Yunnan, Guizhou, Guangxi
I	Qinghai-Tibet Plateau region	Qinghai, Tibet

food output in China (Chen et al. 2012). Meteorological information, terrain elevation, soil and farmland distribution data were also used as model inputs. Grid cells were considered only when their cultivated land areas were larger than 0.05 km² and their actual yields were higher than 20% of potential yields. Both irrigated and rain-fed conditions were considered for most crops while only irrigated conditions were possible for irrigated rice paddies. Both winter and spring wheat, and both maize and warm-season maize were tested in each grid cell so that the crop type with the higher yield was selected. An ‘optimal’ crop combination was determined by simulating yields for all possible crop combinations and selecting the crop combination with the highest yield in each grid cell under the average climatic conditions between 1990 and 2010. The number of crop types in a combination was determined according to the customary multiple cropping index, including single cropping per year, triple cropping over two years, double cropping per year, and triple cropping per year.

Under the assumption of no water stress in irrigated areas, crop yields within each grid cell were calculated by summing the yields under both rain-fed and irrigated conditions (Eq. (1)).

$$yield_{total} = yield_{rain-fed} \times (1-i) + yield_{irrigated} \times i \quad (1)$$

where $yield_{total}$ is the crop yield of a grid cell (kg/ha); $yield_{rain-fed}$ is the yield under rain-fed conditions (kg/ha); $yield_{irrigated}$ is the yield under irrigated conditions (kg/ha); and i is the ratio of irrigated land areas to the total cultivated areas. County-based irrigation statistics from the Chinese Agriculture Ministry underlie the i calculation.

The GAEZ model forecasts the production potentials, and thus there exist gaps between the modeled potentials and the actual production of crops. Using the actual production yields from more than 2000 counties, we investigated the relationships between the forecast potential and the actual production based on data for 2010. As a result, a fairly high correlation was found ($r = 0.82$). The calculation of r was achieved by following three steps from our previous research (Liu et al.

2015). First, the actual yields at county level from official statistics for the year 2010 were extracted. Second, the potential production in 2010 at county level were aggregated using Spatial Analyst Tools in ArcGIS 10.2. Third, a regression between the production potentials and actual yields was calculated based upon more than 2000 samples at county level, covering more than 90% of China’s cultivated land area.

The investigation of impacts of cultivated land change on production potential did not take any change in climate into consideration. Therefore, the average climate conditions from 1990 to 2010 were used to simulate the production potentials using the average monthly maximum air temperature, minimum air temperature, precipitation, relative humidity, wind speed and sunshine hours.

Potential calories produced

Different crops have different yields, so movement of a plot of land from a low yielding crop to a high yielding crop is registered as an “improvement”. But crops also have differences in food energy (calories), so a plot of land could move from a high yield to a lower yield crop and that change could provide more calories. Since food energy is more relevant than food quantity to discussions of food security, we applied food energy (kilocalories; kcal) as the measure of potential productivity.

In this study, crop yields under rain-fed conditions and irrigated conditions at different times were modelled separately. Each modelling situation corresponded to a crop distribution. For example, in the first season of 1990 under rain-fed conditions, wheat was the most widespread crop, while maize came second. Rice was only distributed in southeastern China. Based on the spatial pattern, it was possible to change the measurement of the modelled yield from quantity to energy (calories) by the general coefficients on calories per kg of different cereal crops provided in the food balance sheets from FAO (Table 2).

Table 2 General coefficients on calories per kg of different cereal crops

Crop	Coefficients (kcal/kg)
Wheat	3340
Rice paddy	2800
Maize	3560

From FAO: <http://www.fao.org/docrep/003/x9892e/X9892e05.htm>

Contribution index (CI)

In order to quantitatively measure the influences of the PPCLA variance on the TPP, a contribution index (CI, Eq. (2)) was developed based on the simulated and actual TPPs. To construct the index, the regional simulated TPP (TPP_{simu} , Eq. (3)) was first calculated under the scenario where the PPCLA of the converted cultivated land was constant.

$$CI = \frac{TPP_{actual} - TPP_{simu}}{TPP_{actual}} \times 100\% \quad (2)$$

Where CI is the contribution index, TPP_{actual} and TPP_{simu} are the regional actual and simulated TPPs, respectively.

$$TPP_{simu} = AREA_{net} \times PPCLA_{uni} \quad (3)$$

Where $AREA_{net}$ is the net change of regional cultivated land, and $PPCLA_{uni}$ is the average PPCLA of the converted cultivated land.

Results and discussion

Characteristics of cultivated land change in China

During the period of study, China brought into cultivation about 8.83×10^4 km² of new farmland, while 7.53×10^4 km² of already cultivated land was

transformed for other uses, resulting in a net increase of cultivated land by about 1.30×10^4 km².

During 1990–2000, the total cultivated land in China increased by 2.63×10^4 km². An area of 6.51×10^4 km² of newly cultivated land was mainly located in the Northeast China Plain, and the Northern Arid and Semi-arid region. A decrease of 3.87×10^4 km² of cultivated land occurred in the Northern Arid and Semi-arid region, the Middle-lower Yangtze Plain and the Huang-Huai-Hai Plain (Fig. 2a). During 2000–2010, a net decrease of 1.33×10^4 km² cultivated land was calculated. The decrease occurred in most regions (6 out of 9) except for the Northern Arid and Semi-arid region and the Northeast China Plain (Fig. 2b). Similar to the first decade (1990–2000), the increase of 2.33×10^4 km² in newly cultivated land was again concentrated in the Northeast China Plain and the Northern Arid and Semi-arid region. The decrease of cultivated land during 2000–2010 was mainly distributed in the Middle-lower Yangtze Plain, the Huang-Huai-Hai Plain and the Northern Arid and Semi-arid region, and together they accounted for 61.55% of the total decrease in cropped land.

Net changes in cultivated land exhibited clear spatial heterogeneity with a net increase in the north of China and a net decrease in southern China (Fig. 3). During 1990–2000, the areas with a net increase in cultivated land were mostly concentrated in the Northeast China Plain and the Northern Arid and Semi-arid region. In contrast, the net decreases of cultivated land were distributed mainly in southern and eastern China. In the period 2000–2010, most counties across China experienced a net increase in cultivated land, mainly in the Northeast China Plain and the Northern Arid and Semi-arid region. During the same period, net decreases in cultivated land were detected again in most of the counties in southern China.

The decrease of cultivated land during the two decades was primarily attributed to construction development, which was driven by rapid population growth, economic development, and intensified urbanization (Cai et al. 2013; Liu et al. 2014c). The conversion of

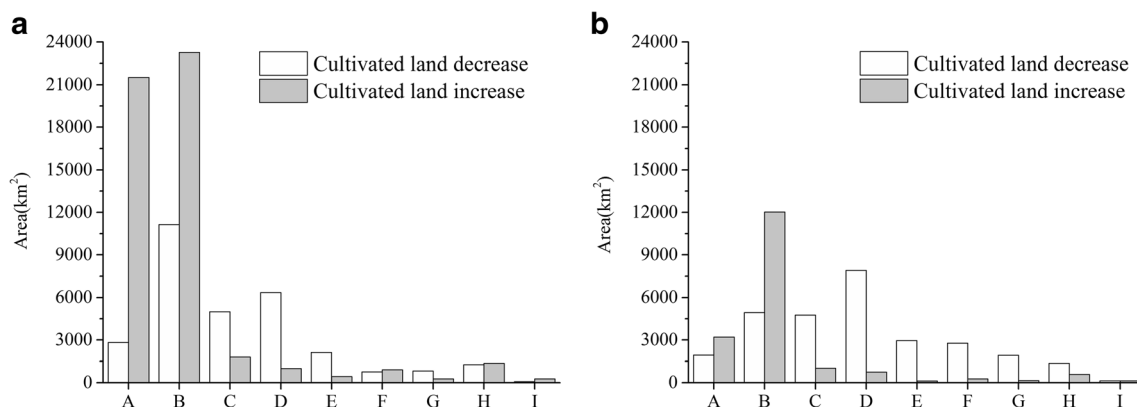


Fig. 2 Changes in cultivated land area in the nine agricultural regions (A–I) of China during **a** 1990–2000 and **b** 2000–2010

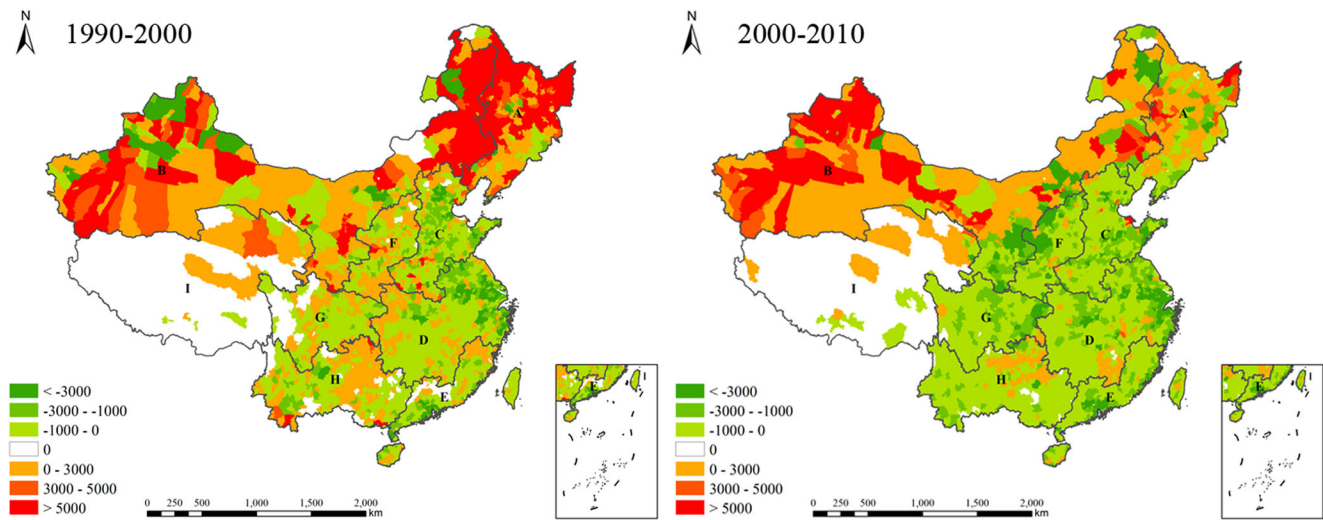


Fig. 3 Maps of net changes (km^2) in the area of cultivated land over counties in China during 1990–2000 (left) and 2000–2010 (right)

cultivated land for construction use accounted for 39% of the total cultivated land decrease in 1990–2000. Cultivated land decrease caused by construction accelerated during 2000–2010 when this proportion increased to 53%. During that decade, nearly 80% of the decrease in cultivated land in eastern China was attributed to construction development, especially in the regions of the Huang-Huai-Hai Plain, the Middle-lower Yangtze Plain and South China.

The conversion of cultivated land to either woodland or grassland was another major factor contributing to the decrease of cultivated land. This occurred mainly in northern and western China where the eco-environment is often fragile and where national ecological projects have been prioritized. During 1990–2000, the Grain for Green Project was implemented only in the Northern Arid and Semi-arid region and Yunnan-Guizhou Plateau region as a pilot project, and much of the decrease of cultivated land in those regions was attributed to the allocation of degraded farmland to this project. In 2000–2010, more of the decrease of cultivated land in the Northern Arid and Semi-arid region, the Loess Plateau region and Yunnan-Guizhou Plateau region was attributed to the conversion of cultivated land to woodland or grassland. This was because of the scaling up of the national ecological project after the year 2000 in the above-mentioned agricultural regions (Huang et al. 2013). The increase of cultivated land was still mainly from the reclamation of woodland and grassland, but their contribution dropped from 83% in the first decade (1990–2000) to 67% in 2000–2010. The implementation of the Grain for Green Project was the main reason for the slowed increase of cultivated land since more effort was devoted to environmental protection than agricultural development in regions such as the Loess Plateau region.

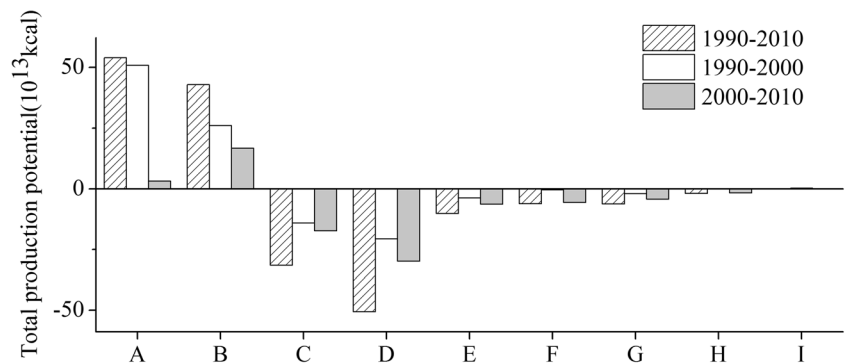
Effects on the TPP

Using the GAEZ model, the TPP in China was calculated based on the average climatic conditions from 1990 to 2010, and significant correlations were also identified between the change of the TPP and the change of cultivated land.

Overall in China, the addition of newly cultivated land during 1990–2010 resulted in a 1.48×10^{14} kcal increase in the TPP, while the lost cultivated land offset the national TPP increase by 1.58×10^{14} kcal. This indicated that although the total cultivated land increased (a net increase of 1.30×10^6 ha) during the two decades of this study, the national TPP was reduced by 9.64×10^{12} kcal. The highest net increases in TPP occurred in the Northeast China Plain (5.39×10^{13} kcal) and the Northern Arid and Semi-arid region (4.28×10^{13} kcal). However, the highest net decreases in TPP occurred in the Middle-lower Yangtze Plain and the Huang-Huai-Hai Plain, with drops of 5.05×10^{13} kcal and 3.15×10^{13} kcal, respectively. The least change in TPP (a net increase of 8.38×10^{10} kcal) occurred in the Qinghai-Tibet Plateau region where cultivated land accounted for less than 1% of national farmland area (Figs. 4 and 5).

During 1990–2000, the changes to cultivated land in China resulted in a net increase of 3.58×10^{13} kcal in TPP, with an increase in the TPP that was 1.43-fold of the decrease in the TPP. The areas with increased TPP were mainly distributed in the Northeast China Plain and the Northern Arid and Semi-arid region, with increases of 5.82×10^{13} kcal and 4.57×10^{13} kcal, respectively. The increased TPP in these two regions accounted for 88% of the total TPP increase in China. The increased TPPs were mainly achieved by the reclamation of woodland and grassland, and their conversion to cropping. In contrast, the regions that experienced decreased TPP were mainly located in the Middle-lower Yangtze Plain, the Huang-Huai-Hai Plain and the Northern Arid and Semi-

Fig. 4 Net changes in the energy-based total production potential (TPP) of food crops among agricultural regions (A–I) of China from 1990 to 2010



arid region, where the decreased TPPs were 2.37×10^{13} , 2.01×10^{13} and 1.97×10^{13} kcal. The decreased TPP in these three regions accounted for 77% of the national total decrease in TPP. Decreases to TPP in the Middle-lower Yangtze Plain and the Huang-Huai-Hai Plain were mainly attributed to urban expansion (Tan et al. 2005). In contrast, the decreased TPP in the Northern Arid and Semi-arid region was mainly caused by the Grain for Green Project (Feng et al. 2005; Long et al. 2006; Yan et al. 2012).

During 2000–2010, the change to cultivated land resulted in a 4.55×10^{13} kcal net decrease in the TPP in China, of which the decreased TPP was 2.2-fold of the increase. The areas which experienced decreased TPP were mainly distributed in the Middle-lower Yangtze Plain and the Huang-Huai-Hai Plain, with decreases of 3.17×10^{13} and 1.88×10^{13} kcal, respectively. Rapid urban expansion was the major factor that caused the TPP to decrease over this decade. The reduced TPP in these two regions accounted for 61% of the total TPP decrease in China. In contrast, the areas with increased TPP were mainly located in the Northern Arid and Semi-arid region, where the TPP increased by

2.44×10^{13} kcal. This increase accounted for 64% of the national total TPP increase, which was also mainly a result of the conversion of woodland and grassland.

Contributions of the spatial variation of the PPCLA

The production potential per unit cultivated land area (PPCLA) of cultivated land varied spatially. From 1990 to 2010, the average PPCLA of newly cultivated land failed to match those of land that was lost from cultivation. On average, the PPCLA of newly cultivated land was 1.68×10^7 kcal/ha, which was lower than that of the lost cultivated land (2.09×10^7 kcal/ha). The lost cultivated land was mainly distributed on the periphery of cities, and this was especially the case for the decrease in land area in China’s eastern regions (Cai et al. 2013) where much of the land that was lost was endowed with favorable climate, terrain and soil conditions for crop production (Chen 2007; Li et al. 2013). The PPCLA gap between the newly-developed and lost cultivated lands was further expanded, shifting from

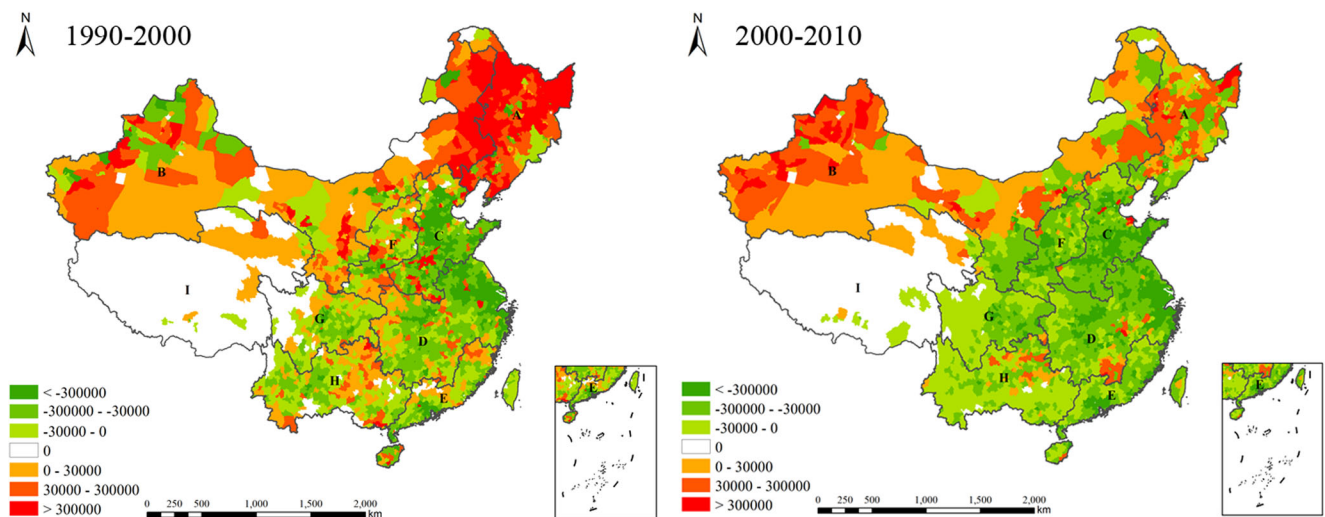
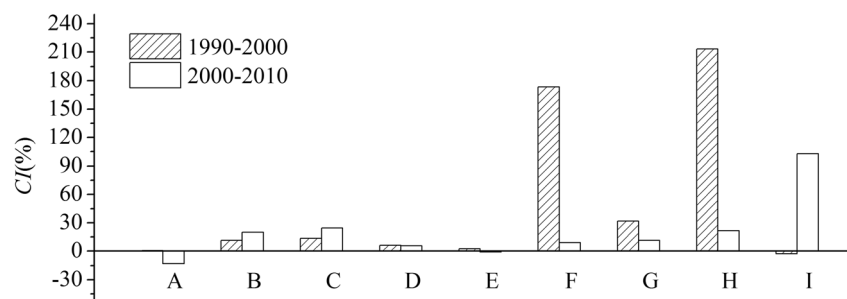


Fig. 5 Maps of the distribution of total production potential (TPP) net changes (kcal/ha) among counties during 1990–2000 (left) and 2000–2010 (right)

3.16×10^6 kcal/ha in the first decade studied to 6.49×10^6 kcal/ha in 2000–2010. This was because in most of the agricultural regions the average PPCLA of lost cultivated land exceeded that of newly cultivated land. Two regions were the exception; the Northern Arid and Semi-arid region and the Northeast China Plain. The largest gap in 1990–2000 was found in the Sichuan Basin and surrounding region. However, during 2000–2010 the largest gap was in the Huang-Huai-Hai Plain where the average PPCLA was 1.12×10^7 kcal/ha in the newly-cultivated land and 3.09×10^7 kcal/ha in the land lost from cultivation.

To further quantify the contributions of the spatial variation of the PPCLA to the TPP, *CI*s among the agricultural regions were calculated. As shown in Fig. 6, *CI*s in three agricultural regions were extremely high; they were the Yunnan-Guizhou Plateau and the Loess Plateau during 1990–2000, and the Qinghai-Tibet Plateau during 2000–2010. For these regions in the corresponding periods, net increases in cultivated land occurred (ranging from 5 km² to 184 km²), but net decreases in the TPP were detected. This indicated that the mismatch of PPCLA between newly cultivated and land lost from cultivation reversed the TPP change caused by the gain in cultivated land. The *CI*s among other agricultural regions ranged from –13% to 32%. The highest *CI*s in the period 1990–2000 were found in the Sichuan Basin and its surrounding region (*CI* = 31.85%), and also in the Huang-Huai-Hai Plain during 2000–2010 (*CI* = 24.53%). The regions with high *CI*s were consistent with the regions with large gaps of PPCLA between the newly cultivated land and the land lost from cultivation. In the case of the Northeast China Plain, the *CI* shifted from 0.64% during the 1990–2000s to –12.89% during 2000–2010. However, both the cultivated land and TTP in this region increased during those two periods. This indicated that spatial variation of the PPCLA among the converted cultivated land reduced the increase in TPP induced by the net increase in cultivated land. In contrast, both the cultivated land and TPP also increased in the Northern Arid and Semi-arid region, while *CI*s in the two periods were positive, which indicated that spatial variation of the PPCLA enhanced the TPP increase in this region.

Fig. 6 Contribution Index (*CI*) among agricultural regions in China during 1990–2000 and 2000–2010



Limitations of using the GAEZ model

In this study we assumed that the soil condition remained unchanged during the study period, which might bring some errors to the simulated results. For example, along with the implementation of ecological projects, both afforestation and reforestation may improve the local soil conditions through increasing soil moisture, altering soil texture and alleviating soil erosion (Xiao et al. 2015) but also the degradation of farmland (including soil alkalization and desertification) will also lead to soil change. Thus, updated soils data are needed to improve the accuracy of modelled estimations in future studies.

Other possible uncertainties came from the input data. Although all computations were performed based on a 1×1 km² grid, the input data were actually sourced at different spatial scales. The scale integration of data from multiple sources may have brought errors. For example, land use data were derived from remote sensing images with a resolution of 30 m, while meteorological data were interpolated from the records of 752 meteorological stations throughout China. Although we have considered possible terrain impacts on the interpolation of the meteorological variables, it is still unlikely to achieve perfect consistency between these two data sets. Further studies on scale effects are needed.

Implications for China's land use policy

The Cultivated Land Acquisition and Compensation Balance (CLACB) policy in China was given high priority for land management. According to this policy, any non-agricultural use of farmland should be strictly compensated for by land of equal quantity and quality brought into cultivation at a provincial level. However, according to our study, the amount of compensated cultivated land has failed to match the loss of cultivated land caused by construction development in eastern China. For example, from 2000 to 2010, the amount of cultivated land taken for construction was 3.71 times that of newly developed cultivated land in the Huang-Huai-Hai Plain. Thus, the area of newly developed cultivated land was much less than the farmland lost because of construction development. The mismatch was even more serious in the Middle-lower

Yangtze Plain and South China where the ratios of lost farmland to newly-developed land were 8.81 and 20.38 respectively. For these regions, the reserves of farmland resources were low, and it was not possible to balance the compensation and the loss at a provincial level. Moreover, these regions produce higher economic output per unit of construction land, and lead China's economic development. Thus, it would be more practical for the CLACB policy to be implemented beyond provincial boundaries, which means land compensation can be made across different provinces. Alternatively, land compensation targets should be adjusted based on the role of a province in the economic development of its region. For example, for the national key development areas (Fan et al. 2010), such as the Jing-Jin-Ji and Yangtze River Delta regions, their land compensation targets should be adjusted by taking the utilization efficiency per unit construction land into consideration.

In order to preserve national food security, the government of China proposed a "redline" of total farmland area in the 11th Five-Year Plan, supported by strict land policies. However, this study has shown that although the total amount of cultivated land has increased during the two-decade period we studied, the TPP decreased due to the mismatch of the PPCLA between the newly cultivated and lost farmland. In some agricultural regions, the decrease of TPP showed an accelerated trend. This reminds us that additional to the farmland area 'redline', much attention should be paid to variation in crop production potential caused by the conversion of cultivated land to other uses.

Conclusions

This study estimated the conversions of cultivated land and the induced TPP change in China using satellite-based land use data and the GAEZ model. The spatial heterogeneity of PPCLA and its contribution to the change in TPP across China were further assessed. The key implication drawn from our research findings is that land use policy in China has to be further adjusted based on the economic development role of a province in its region. The defined provincial boundary on CLACB policy by Central Government needs to be reconsidered given that limited reserves of farmland were found in many Chinese provinces.

China has seen a net increase of 1.30×10^6 ha in cultivated/cropped land from 1990 to 2010, resulting from a net increase of 2.63×10^6 ha in the period from 1990 to 2000, but a net decrease of 1.33×10^6 ha during 2000 to 2010. These changes in cultivated land varied spatially, with the increased area located mainly in the Northeast China Plain and the Northern Arid and Semi-arid region, while the area decrease was mostly in the middle-lower Yangtze Plain and the Huang-Huai-Hai Plain. The decrease in cultivated land was mainly attributed to construction development, while the land increase was mainly

sourced from the conversion of woodland and grassland areas to cropping. Along with the implementation of the Grain for Green Project across China, the conversion and reclamation of woodland and grassland slowed down in the study period, especially for the Loess Plateau region.

In contrast to the increase of farmland area during the research period, China has seen a net decrease of TPP of 9.64×10^{12} kcal over this time. Furthermore, the decrease of TPP occurred in most agricultural regions due to the spatial heterogeneity of PPCLA. More specifically, this was because the average PPCLA of the lost cultivated land was higher than that of the new land converted to cultivation at the national level, and their gap in PPCLA increased by 105.6% in the second decade of our study, i.e., 2000–2010. The contributions of spatial heterogeneity of the PPCLA varied spatially, and the largest contributions tended to be in accordance with the largest gap in PPCLA between the newly-converted and the land lost from cultivation. Based on our results, we have made several suggestions to improve China's land use policy in relation to crop production.

Acknowledgements This research was supported and funded by the National Key Project of Scientific and Technical Supporting Programs (No.2013BAC03B01), Key Deployment Project of the Chinese Academy of Sciences (No. KJZD-EW-TZ-G10) and Cultivate Project of the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science (No. TSYJS03). We particularly appreciate the help of Günther Fisher from IIASA for his GAEZ model. He also made substantial contributions to the estimations of production potentials for China. We would like to thank the Editors of Food Security and two anonymous reviewers for their valuable comments and constructive suggestions on this paper.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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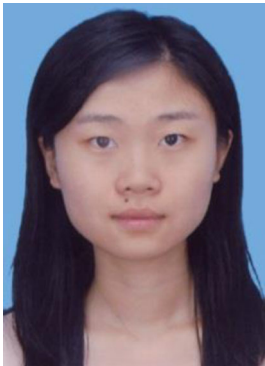
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