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Impacts of ecological restoration projects on agricultural productivity in China

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Abstract: The changes in cropland quantity and quality due to land use are critical concerns to national food security, particularly for China. Despite the significant ecological effects, the ecological restoration program (ERP), started from 1999, has evidently altered the spatial patterns of China's cropland and agricultural productivity. Based on cropland dynamic data from 2000 to 2008 primarily derived from satellite images with a 30-m resolution and satellite-based net primary productivity models, we identified the impacts on agricultural productivity caused by ERP, including "Grain for Green" Program (GFGP) and "Reclaimed Cropland to Lake" (RCTL) Program. Our results indicated that the agricultural productivity lost with a rate of 132.67×10^4 t/a due to ERP, which accounted for 44.01% of the total loss rate caused by land use changes during 2000–2005. During 2005–2008, the loss rate due to ERP decreased to 77.18×10^4 t/a, which was equivalent to 58.17% of that in the first five years and 30.22% of the total loss rate caused by land use changes. The agricultural productivity loss from 2000–2008 caused by ERP was more attributed to GFGP (about 70%) than RCTL. Although ERP had a certain influence on cropland productivity during 2000–2008, its effect was still much less than that of urbanization; moreover, ERP was already converted from the project implementation phase to the consolidation phase.

Keywords: ecological restoration; agricultural productivity; remote sensing; Grain for Green; Reclaimed Cropland to Lake

1 Introduction

In history, land use/cover change was dominated by substantial increase of cropland and built-up land and great decrease of forest to meet increasing resources requirement of human

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being to some extent, which impacted the agricultural productivity by changing the quantity, quality and land use structure of cropland resources (Foley *et al*., 2005). In China, food security has always been a concern because of the challenge of lack of cropland, increasing population and water shortage (Tao *et al*., 2009). During the past 50 years, remarkable achievement in agricultural production was reached, although China is facing a great challenge of land scarcity to feed the largest population with cropland per capita far below the world average (Chen, 2007). The cereal production has increased steadily with an annual growth rate of 3.7%, which is substantially higher than the world mean growth rate of 2% during the period (Fan *et al*., 2012). Although the great promotion in cereal production mainly resulted from the yield increase, it was still attributed to cropland expansion, especially in Northeast and Northwest China (Liu *et al*., 2005, 2009; Wang *et al*., 2009). According to National Bureau of Statistics (NBS, hereafter), China's cropland area increased by about 30% during 1978–2000 (http://www.stats.gov.cn/tjsj/ndsj/). Based on the cropland dynamics monitoring through Landsat TM/ETM images at a spatial resolution of 30 m, cropland increased about 2.79 million ha in China during 1990–2000, which was mainly in the Northeast and Northwest regions and was primarily due to reclamation of grassland and deforestation (Liu *et al*., 2005). However, under tremendous pressure on land and food demand, excessive cropland reclamation had resulted in a series of ecological and environmental problems that offset a large part of the acquired achievement (Shi *et al*., 2011). Most of the primary forest and wetland in China has been depleted, and a high percentage of new cultivated land and grassland has been degraded (WWF, 2003; Yin *et al*., 2005). Unreasonable cropland reclamation exacerbated water shortage in the north area (State Council of People's Republic of China, 2008) and the newly added cropland always had poor quality (Liu *et al*., 2005; Dong *et al*., 2010). Excessive wetland reclamation shrunk water area, induced soil degradation and deteriorated the stability of regional ecosystem significantly (Li *et al*., 2006; Zheng *et al*., 2006). Compared with cropland, afforested area had enhanced vegetation structure, species diversity, soil nutrients and anti-erodibility (Jiao *et al*., 2010; Li *et al*., 2010), and increased storages of soil organic carbon and nitrogen (Liu *et al*., 2004), just like the grassland restoration (Wang *et al*., 2011). National level ecological restoration program (ERP) was triggered in China by severe droughts in 1997 and huge floods in 1998.

ERP program include "Grain for Green" Program (GFGP) (Zhang *et al*., 1999; Loucks *et al*., 2001; Xu *et al*., 2006; Liu *et al*., 2008) and "Reclaimed Cropland to Lake" (RCTL, hereafter) Programs. ERP is one of the world's largest ecological restoration programs and plays an important role in global conservation efforts. After pilot in Sichuan, Shaanxi and Gansu in 1999, ERP was widely carried out in 2000. During the first 5 years, the ERP was dominated by ecological construction that a large area of cropland not suitable for cultivation was reversed to ecological land, such as forest, grassland and wetland. Due to the great change in supply-demand relationship and increasing food price in the international grain market in 2003, the attention of ERP was gradually turned to the consolidation of the recovered ecological land after 2005 (Huang *et al*., 2010; State Council of People's Republic of China, 2007), and the cropland loss rate caused by ERP slowed down. Cropland database at the scale of 1:100,000, derived from Landsat images with a 30-m resolution, could clearly depict the spatial and temporal patterns and dynamics of China's cropland since the end of the 1980s (Liu *et al*., 2003, 2009), particularly ERP. Every coin has two sides; the conversion of cropland to ecological land potentially affected the agricultural production. Although the effects of ecological restoration on agricultural production could be not severe, as its negative effects were offset by new land reclamation in Northeast and Northwest China (Deng *et al*., 2005, 2006), more concern is needed to evaluate the impacts or implications of these ecological restoration programs on food security of China. Remote sensing is increasingly used in monitoring agricultural productivity and land use dynamics (including deforestation and afforestation, cropland reclamation and abandonment, urban expansion, etc.) (Doraiswamy *et al*., 2003; Tao *et al*., 2005; Liu *et al*., 2005; Morton *et al*., 2006; Yan *et al*., 2009; Gibbs *et al*., 2010), which enable large-scale and real-time monitoring cropland area and agricultural productivity. Agricultural productivity of different crops were expressed as accumulated dry matter in net primary productivity (NPP), which could provide a unified measure standard for crop productivity; so, it is an effective and feasible measuring index for agricultural productivity change analysis. Satellite-based light use efficiency models have been an important and widely accepted method to calculate ecosystem NPP (Potter *et al*., 1993; Prince *et al*., 1995; Lobell *et al*., 2002). Therefore, the regional agricultural production could be estimated by cropland area and NPP.

This study aimed to estimate the ERP's impacts on agricultural productivity during 2000–2005 and 2005–2008 on national scale, by combining satellite-based light use efficiency models with cropland dynamics due to ERP. The impacts of GFGP and RCTL on agricultural productivity were distinguished to well understand the spatial and temporal patterns and regional discrepancies of the reduced agricultural productivity in China.

2 Data and methods

2.1 Cropland change data

In order to investigate the impact of land use change process on cropland resources across China, a research team led by the author Liu J Y, has carried out national Land-Use/Cover Change monitoring through remote sensing since the early 1990s. The state and change of cropland was identified as the core of the monitoring. The National Land-Use/Cover Change Data sets (NLCD, hereafter) were also developed based on satellite images and a variety of other data including soil type, DEM, roads, rivers and climate. The state and dynamic grid data contained information on the percent area of cropland with a resolution of 1 km×1 km was obtained since the end of the 1980s (Liu *et al*., 2002, 2005, 2009). Each grid land-use vector data were acquired first by remote sensing images interpretation through a computer-aided, interactive procedure (Liu *et al*., 2003, 2005). Then, the vector data and a vector fishnet with 1 km × 1 km cells were intersected, and the area percentage of land-use dynamics in every cell was calculated and finally, the cells were converted into raster grid, contained information of area percentage of land-use dynamics. This aggregation process can help for not only effective data fusion but also maintaining the acreage information without information loss (Liu *et al*., 2005). The cropland data in 2000 was primarily interpreted from Landsat TM/ETM images in 1999/2000, while cropland data in 2005 and 2008 were interpreted from Landsat TM/ETM images and CBERS images in 2004/2005 and 2007/2008, respectively.

To characterize the ERP's impact on cropland productivity, we used data converted from cropland in this study, including cropland converted to forest, cropland to grassland and cropland to water body during 2000–2005 and 2005–2008. In the NLCD, cropland is defined as "identifiable reclaimed cropland in remote sensing images"; while in the investigation rules of Ministry of Land and Resources, new reclamation of wasteland to be cultivation for more than 3 years could be identified as cropland.

2.2 Agricultural productivity data

GLO-PEM is a productivity efficiency model driven mainly by National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometers (AVHRR) data. The model consists of several interrelated components about the processes of canopy radiation absorption, utilization, autotrophic respiration and the regulation of these processes by environmental factors. The structure principle of GLO-PEM as well as its application in agricultural productivity estimation in China was discussed in detail (Yan *et al*., 2009). VPM (Vegetation Photosynthesis Model) is an ecosystem productivity estimation model based on MODIS (Moderate Resolution Imaging Spectroradiometer) data (Yan *et al*., 2007, 2012). The climate data that drive VPM model came from daily surface climate dataset during 2000–2005 provided by China Meteorological Data Sharing Service System of National Meteorological Administration (http://cdc.cma.gov.cn/). The average temperature index of daily data of 752 ground meteorological stations and automatic stations were used in this study through spline interpolation by using ANUspline software.

2.3 Impacts of ERP on agricultural productivity

The agricultural production per unit area estimated from the satellite-based ecosystem productivity models and cropland dataset with a spatial resolution of 1 km in grid cell provided precise distribution and area information. So it is possible to calculate the total agricultural productivity based on the raster data containing cropland area information and the estimated production per unit area which was represented as the average net primary productivity (NPP) during 1982–2005. The total agricultural productivity of two periods was calculated according to equation (1), respectively.

$$P = c \times NPP \times A \tag{1}$$

where P is the total agricultural productivity (Ton C); NPP is the cropland production per unit area (gC/m^2/yr); c is the proportion of cropland in each grid cell, and A is the grid area. The change of total agricultural productivity (ΔP) is equal to the changed productivity caused by cropland area change (ΔA) and cropland production per unit area.

To investigate the difference of ecological restoration effects on agricultural productivity in spatial and temporal patterns across China during 2000–2008, we divided the land of China into 8 regions (Figure 1): Northeast China Plain region (Ⅰ1) including: Heilongjiang, Jilin and Liaoning; Huang-Huai-Hai Plain region (Ⅰ2) including: Beijing, Tianjin, Hebei, Shandong and Henan; Middle-lower Yangtze Plain region (Ⅰ3) including: Shanghai, Jiangsu, Anhui, Hubei, Hunan, Zhejiang and Jiangxi; South region (Ⅰ4) including: Guangdong and Fujian; Northern arid and semi-arid region (Ⅰ5) including: Xinjiang, Inner Mongolia, Ningxia and Gansu; Loess Plateau region (Ⅱ1) including: Shaanxi and Shanxi; Sichuan Basin and surrounding regions (Ⅱ2) including: Sichuan and Chongqing;

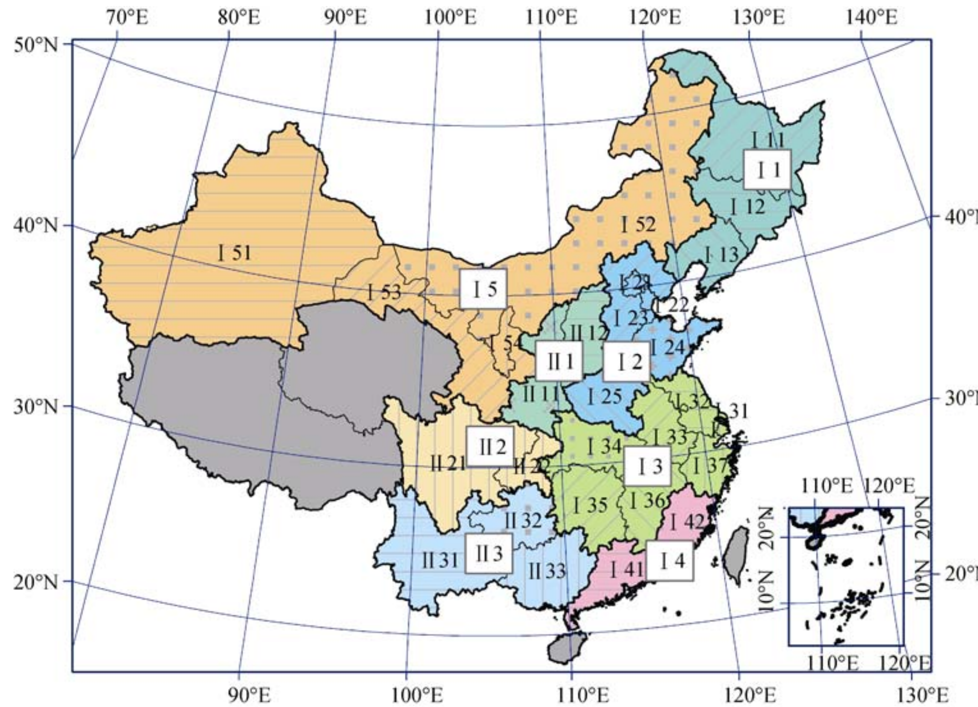


Figure 1 China's agricultural regionalization. Northeast China Plain region includes: Ⅰ11-Heilongjiang, Ⅰ12-Jilin and Ⅰ13-Liaoning; Huang-Huai-Hai Plain region includes: Ⅰ21-Beijing, Ⅰ22-Tianjin, Ⅰ23-Hebei, Ⅰ24-Shandong and Ⅰ25-Henan; Middle-lower Yangtze Plain region includes: Ⅰ31-Shanghai, Ⅰ32-Jiangsu, Ⅰ33-Anhui, Ⅰ34-Hubei, Ⅰ35-Hunan, Ⅰ36-Jiangxi and Ⅰ37-Zhejiang; South region includes: Ⅰ41-Guangdong and Ⅰ42-Fujian; Northern arid and semi-arid region includes: Ⅰ51-Xinjiang, Ⅰ52-Inner Mongolia, Ⅰ53-Gansu and Ⅰ54-Ningxia; Losses Plateau region includes: Ⅱ11-Shaanxi and Ⅱ12-Shanxi; Sichuan Basin and surrounding regions includes: Ⅱ21-Sichuan and Ⅱ22-Chongqing; Yunnan-Guizhou Plateau includes: Ⅱ31-Yunnan, Ⅱ32-Guizhou and Ⅱ33-Guangxi.

Yunnan-Guizhou Plateau region (Ⅱ3) including: Yunnan, Guizhou and Guangxi. Ⅰ1-Ⅰ5 were the major agricultural production regions and Ⅱ1-Ⅱ3 were the major regions under the implementation of GFGP. For each region, we analyzed the ERP's effect on agricultural productivity during 2000–2005 and 2005–2008.

Provinces in gray color were not included in this study, including Qinghai, Tibet, Hainan, Taiwan, Hong Kong and Macao.

3 Results

3.1 Agricultural productivity loss due to ERP at national level

As the attention of ERP was converted from ecological construction to consolidation of the reversed ecological land, the agricultural productivity loss rate was about 132.67×10^4 t/a during 2000–2005 and 77.18×10^4 t/a during 2005–2008 which was about 58.17% of that in the first period. Compared with RCTL, the agricultural productivity loss caused by ERP was more attributed to GFGP, which accounted for about 70% of the agricultural productivity loss in each period (Table 1).

During 2000–2005, the lost agricultural productivity was mainly distributed in Northern arid and semi-arid region (25.17% of the total loss of agricultural productivity due to ERP), Middle-lower Yangtze Plain (21.06%) and Loess Plateau (13.51%) (Tables 1 and 2). Because of the serious ecological problem in western regions, such as severe soil erosion and desertification, excessive reclamation for cropland, GFGP was arrayed as the key strategy in the "Western Development" and induced great agricultural productivity loss with the rate about 92.34×10^4 t/a, especially in Northern arid and semi-arid region (24.40%) and Loess Plateau (12.45%). Agricultural productivity loss rate was about 40.34×10^4 t/a caused by RCTL, mainly distributed in eastern China with dense population and great demand for food, especially in Middle-lower Yangtze Plain (15.87%) and Huang-Huai-Hai Plain (7.59%) where lakes shrunk quickly due to excessive cropland reclamation for a long time (An *et al*., 2007).

Table 1 Agricultural productivity loss rate caused by GFGP, RCTL and ERP and their ratio to total loss rate due to ERP during 2000–2005 and 2005–2008

	2000–2005		2005–2008	
	Agricultural productivity loss rate (10^4 t/a)	Ratio to total loss rate (%)	Agricultural productivity loss rate (10^4 t/a)	Ratio to total loss rate (%)
GFGP	92.34	69.60	56.49	73.19
RCTL	40.34	30.41	20.69	26.81
ERP	132.67	100.00	77.18	100.00

Table 2 Ratio of the agricultural productivity loss caused by GFGP, RCTL and ERP in each agricultural region to total agricultural productivity loss due to ERP in China during 2000–2005 and 2005–2008 (%)

Main agricultural region	2000–2005			2005–2008		
	GFGP	RCTL	ERP	GFGP	RCTL	ERP
Northeast China Plain	6.80	0.78	7.58	17.62	2.34	19.95
Huang-Huai-Hai Plain	0.80	7.59	8.40	2.08	5.32	7.40
Middle-lower Yangtze Plain	5.19	15.87	21.06	4.26	9.72	13.98
South China	1.67	3.45	5.13	0.60	1.03	1.64
Northern arid and semi-arid region	24.40	0.77	25.17	8.39	1.48	9.86
Loess Plateau	12.45	1.06	13.51	8.18	1.45	9.63
Sichuan Basin and surrounding regions	9.49	0.20	9.69	9.73	2.69	12.42
Yunnan-Guizhou Plateau	8.44	0.30	8.73	22.19	2.16	24.35
Total	69.24	30.03	99.27*	73.06	26.18	99.24*

* Qinghai, Tibet, Hainan, Taiwan, Hong Kong and Macao are not included.

Compared with the first 5 years, agricultural productivity loss rate decreased significantly during 2005–2008 (Tables 1 and 2), and the key areas of the lost agricultural productivity were changed to Yunnan-Guizhou Plateau (24.35%) with obvious rocky desertification and Northeast China Plain (19.95%) with substantial cropland reclamation (Liu *et al*., 2002; An *et al*., 2007). Agricultural productivity loss rate caused by GFGP decreased to 56.49×10^4 t/a, and the key areas were shifted to Yunnan-Guizhou Plateau (22.19%) and Northeast China Plain (17.62%). Agricultural productivity loss rate decreased to 20.69×10^4 t/a caused by RCTL, while the key areas were still in Middle-lower Yangtze Plain and Huang-Huai-Hai

Plain, but the ratio declined to 9.72% and 5.32%, respectively.

3.2 Agricultural productivity loss at provincial level due to ERP

3.2.1 Total loss due to ERP

Unlike eastern provinces with good natural conditions, provinces in central and western China were facing various kinds of ecological and environmental problems and attracted widely implement of ERP for soil and water conservation, which leaded to the most agricultural productivity loss (Figures 2a and 2b). During 2000–2005, Inner Mongolia, Shaanxi, Hubei, Gansu, Sichuan and Guizhou were the provinces with the most agricultural productivity loss rates caused by ERP, about 19.09×10^4 t/a, 14.82×10^4 t/a, 10.47×10^4 t/a, 8.93×10^4 t/a, 7.53×10^4 t/a and 7.04×10^4 t/a, or 14.39%, 11.17%, 7.89%, 6.73%, 5.68% and 5.30% of the total agricultural productivity loss due to ERP in China, respectively (Figures 2a and 2c). However, the provinces with the largest loss rates were changed to Heilongjiang, Yunnan and Guizhou during 2005–2008, about 14.19×10^4 t/a, 8.52×10^4 t/a and 8.37×10^4 t/a, with the ratio of 18.39%, 11.04% and 10.84%, respectively (Figures 2b and 2c).

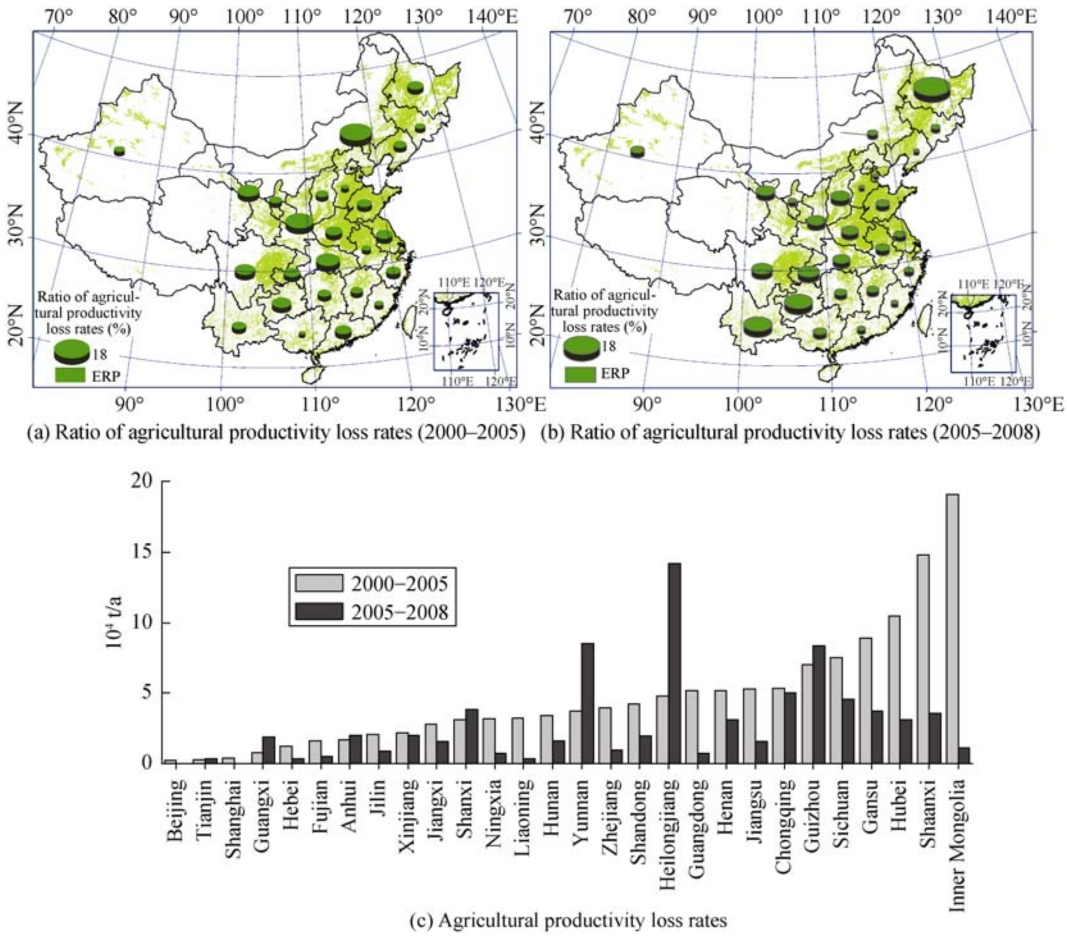


Figure 2 Agricultural productivity loss rates (c) in provinces and their ratio to total agricultural productivity loss rate (a and b) due to ERP in China

In general, agricultural productivity loss rates caused by ERP decreased in the most provinces in the early 21st century, except for Heilongjiang, Yunnan, Guizhou, Shanxi, Anhui, Guangxi and Tianjin (Figure 2c). Among these provinces, agricultural productivity loss rate in Heilongjiang increased the most, from 4.79×10^4 t/a to 14.19×10^4 t/a because of structural adjustment of agricultural production, and the ratio to the total agricultural productivity loss rate increased from 3.61% to 18.39%. For a long time, agricultural products in Heilongjiang were relative surplus and vulnerable to market volatility, and high quality forestry/fruit industry and animal husbandry were encouraged to promote economic growth and to improve soil loss and ecological environment (Huang *et al*., 2010). As the main regions of rocky desertification in Southwest China, Yunnan, Guizhou and Guangxi experienced enhanced ERP and agricultural productivity loss rates increased by about 4.77×10^4 t/a, 1.33×10^4 t/a and 1.10×10^4 t/a, respectively. ERP was strengthened in Shanxi to reduce sediment into the Yellow River and agricultural productivity loss rate increased by 0.75×10^4 t/a. The agricultural productivity loss in Anhui and Tianjin caused by ERP was stable in small amount.

3.2.2 Loss due to GFGP

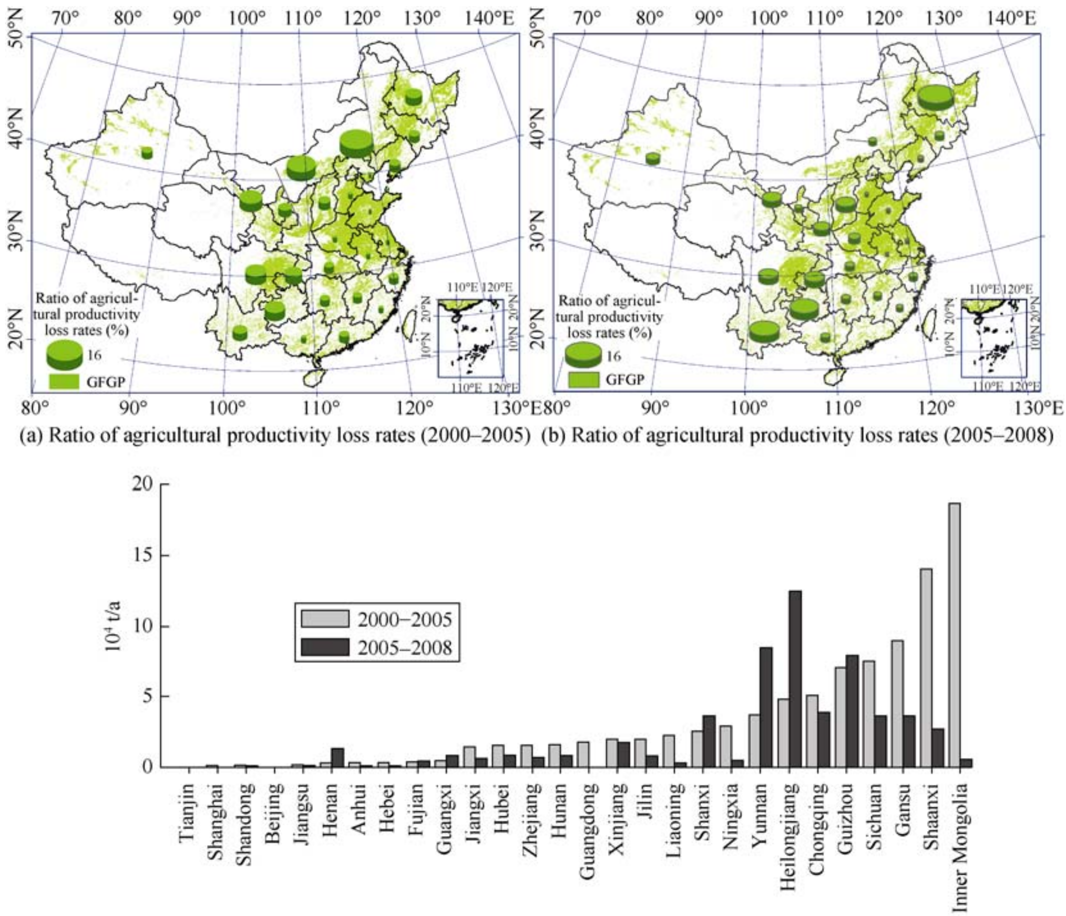
As the main component of ERP, GFGP was mainly located in central and western provinces and presented discrepant trends in the early 21st century (Figures 3a and 3b). During 2000–2005, the largest agricultural productivity loss rates were mainly located in Inner Mongolia, Shaanxi, Gansu, Sichuan and Guizhou, about 18.57×10^4 t/a, 13.99×10^4 t/a, 8.91×10^4 t/a, 7.50×10^4 t/a and 7.01×10^4 t/a (Figure 3c) with the ratio of 14.00%, 10.54%, 6.71%, 5.66% and 5.29% of total agricultural productivity loss caused by ERP in China. Then the largest agricultural productivity loss rates were shifted to Heilongjiang, Yunnan and Guizhou with the loss rates about 12.45×10^4 t/a, 8.40×10^4 t/a and 7.89×10^4 t/a and the ratio about 16.13%, 10.88% and 10.22%, respectively. The agricultural productivity loss rates caused by GFGP declined in the most provinces except for Heilongjiang, Yunnan, Shanxi, Henan, Guizhou, Guangxi and Fujian, especially the largest increase in Heilongjiang (7.67×10^4 t/a) and Yunnan (4.69×10^4 t/a).

3.2.3 Loss due to RCTL

RCTL was mainly concentrated in central and eastern provinces where a large area of abundant wetland was exploited to cropland for food demand, and extended toward western provinces during 2005–2008 (Figures 4a and 4b). The largest agricultural productivity loss rates were in Hubei, Jiangsu, Henan, Shandong and Guangdong, about 8.91×10^4 t/a, 5.11×10^4 t/a, 4.88×10^4 t/a, 4.07×10^4 t/a and 3.38×10^4 t/a (Figure 4c) with the ratio of 6.71%, 3.85%, 3.67%, 3.07% and 2.55% of total agricultural productivity loss rate caused by ERP in China during 2000–2005, and then were changed to Hubei, Anhui, Shandong, Henan and Heilongjiang with the decreased loss rates about 2.27×10^4 t/a, 1.91×10^4 t/a, 1.82×10^4 t/a, 1.76×10^4 t/a and 1.74×10^4 t/a and the ratio about 2.26%–2.95% during 2005–2008, respectively. During the two periods, the agricultural productivity loss rates caused by RCTL in Heilongjiang, Sichuan, Chongqing, Guangxi, Anhui and Guizhou increased the most, about $(0.46–1.74)\times10^4$ t/a.

4 Conclusions and discussion

At the turn of the century, China's land use was entering a new stage focusing on both "strict



(a) Ratio of agricultural productivity loss rates (2000–2005) (b) Ratio of agricultural productivity loss rates (2005–2008)

(c) Agricultural productivity loss rates

Figure 3 Agricultural productivity loss rates (c) in provinces and their ratio to total agricultural productivity loss rate (a and b) due to GFGP in China

protection of cropland" and "ecological environment construction". Large-scale ecological protection policies, e.g., Returning Cropland to Forest, make cropland dynamics present reverse transformation compared with the historical trends (Zhang *et al*., 2000; Liu *et al*., 2008; Goldstein *et al*., 2012). China's cropland area and agricultural production therefore faced with a new great strike for ecological and environmental protection, which no doubt leaded to significant change in cropland productivity (Liu *et al*., 2003, 2005, 2009; Chen, 1999). Cropland transformation data used in this study including cropland converted to forest, cropland to grassland and cropland to water body, which was interpreted from Landsat TM/ETM images with a resolution of 30 m during 2000–2005 and 2005–2008. The cropland dynamic data, combined with cropland productivity estimated from satellite-based NPP models, was used to identify national ERP's impacts on cropland productivity and its regional distribution discrepancies.

(1) The agricultural productivity loss rate was about 132.67×10^4 t/a during 2000–2005, as ERP was gradually stepped from ecological construction phase to ecological consolidation phase, the agricultural productivity loss rate decreased to 77.18×10^4 t/a during 2005–2008,

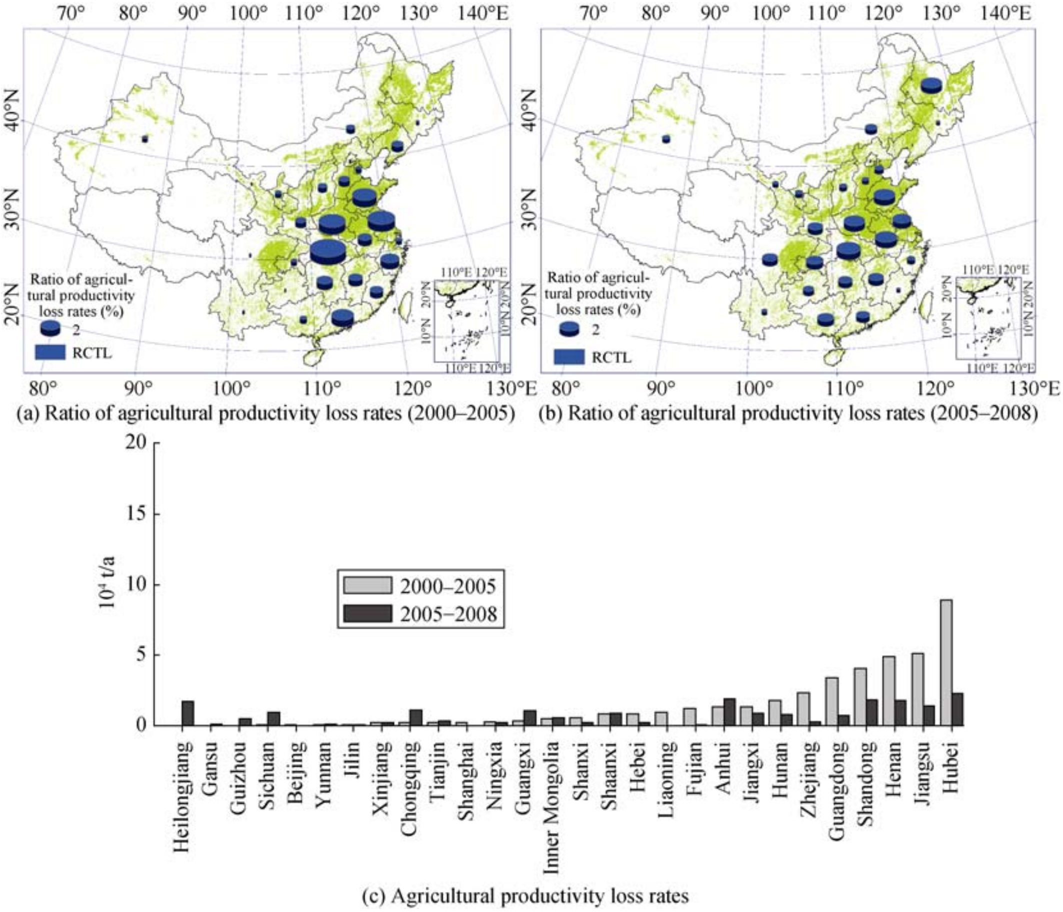


Figure 4 Agricultural productivity loss rates (c) in provinces and their ratio to total agricultural productivity loss rate (a and b) due to RCTL in China

about 58.17% of that occurred in the first five years. About 70% of the agricultural productivity loss due to ERP was devoted by GFGP, much larger than RCTL's effect.

(2) The lost cropland due to ERP and its impacts on agricultural productivity loss had obvious spatial and temporal discrepancies. The effects of GFGP on the agricultural productivity were limited in central and western provinces during 2000–2008, while the effects of RCTL were mainly located in central and eastern provinces in the first period and then toward western provinces in the second period. The largest agricultural productivity loss rates due to ERP were mainly located in Inner Mongolia, Shaanxi, Hubei, Gansu, Sichuan and Guizhou, between 19.09×10^4 t/a and 7.04×10^4 t/a, then were shifted to Heilongjiang, Yunnan and Guizhou with the rates between 14.19×10^4 t/a and 8.37×10^4 t/a. As the major component of ERP, GFGP presented the similar spatial and temporal effects on agricultural productivity as ERP. While the key areas of the lost agricultural productivity caused by RCTL were mainly located in Middle-lower Yangtze Plain and Huang-Huai-Hai Plain, the ratio declined from 15.87% and 7.59% to 9.72% and 5.32% of the total cropland productivity loss due to ERP, respectively.

(3) Great achievement had obtained in ecological protection through ERP during

2000–2008 (Lv *et al*., 2011; Lv *et al*., 2012; Zhang *et al*., 2012). The criterion for enrolling in the GFGP is for the slope of cropland in southwestern China to be >25° and cropland in northwestern China to be >15°. Most of the cropland plots selected for ERP had lower productivity, compared to those that were not retired (Xu *et al*., 2002; Xu *et al*., 2004a, 2004b) and converted to built-up land. Based on our monitoring results, the average productivity of cropland selected for ERP was about 5073.51 kg/ha, much lower than that of cropland converted to built-up land (6476.64 kg/ha). The lost agricultural productivity due to ERP accounted for 80.70% and 43.90% of that caused by cropland converted to built-up land, and about 44.01% and 30.22% of total productivity loss caused by land use change during 2000–2005 and 2005–2008, respectively. According to NBS, the cereal yield in China stabilized at 4.40×10^8 t/a during 2000–2003, and increased continuously to 5.29×10^8 t in 2008 (http://www.stats.gov.cn). The agricultural production in 11 provinces, with the largest agricultural productivity loss caused by ERP during 2000–2008, was kept stable or increasing except Guangdong province. Such crop yield increase trend also indicated that although ERP had a certain influence on cropland productivity during 2000–2008, ERPs had no obvious adverse effect on China's food security.

References

An S Q, Li H B, Guan B H *et al*., 2007. China's natural wetlands: Past problems, current status, and future challenges. *Ambio*, 36(4): 335–342.

Chen B M, 1999. The existing state, future change trends in land-use and food production capacities in China. *Ambio*, 28(8): 682–686.

Chen J, 2007. Rapid urbanization in China: A real challenge to soil protection and food security. *Catena*, 69(1): 1–15.

Deng X Z, Huang J K, Rozelle S *et al*., 2006. Cultivated land conversion and potential agricultural productivity in China. *Land Use Policy*, 23(4): 372–384.

Deng X Z, Huang J K, Scott R, 2005. Change of cultivated land and its impacts on agricultural bioproductivity in China: Implications to national grain security. *China Soft Science Magazine*, 5: 65–70. (in Chinese)

Dong J W, Liu J Y, Yan H M *et al*., 2010. Spatio-temporal pattern and rationality of land reclamation and cropland abandonment in mid-eastern Inner Mongolia of China in 1990–2005. *Environmental Monitoring and Assessment*, 179(1–4): 137–153.

Doraiswamy P C, Moulin S, Cook P W *et al*., 2003. Crop yield assessment from remote sensing. *Photogrammetric Engineering and Remote Sensing*, 69(6): 665–674.

Fan M S, Shen J B, Li X Y *et al*., 2012. Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. *Journal of Experimental Botany*, 63(1): 13–24.

Foley J A, DeFries R, Asner G P *et al*., 2005. Global consequences of land use. *Science*, 309(5734): 570–574.

Gibbs H K, Ruesch A S, Achard F *et al*., 2010. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings of the National Academy of Sciences of the United States of America*, 107(38): 16732–16737.

Goldstein J H, Caldaroneb G, Duarte T K *et al*., 2012. Integrating ecosystem-service tradeoffs into land-use decisions. *Proceedings of the National Academy of Sciences of the United States of America*, 109(19): 7565–7570.

Huang S L, Zhou H J, Wang J A *et al*., 2010. Driving forces of returning cultivated land to forest and grass in China at different scales. *Journal of Arid Land Resources and Environment*, 24(4): 112–116. (in Chinese)

Jiao J Y, Zhang Z G, Bai W J *et al*., 2012. Assessing the ecological success of restoration by afforestation on the Chinese Loess Plateau. *Restoration Ecology*, 20(2): 240–249.

Li C B, Qi J G, Feng Z D *et al*., 2010. Quantifying the effect of ecological restoration on soil erosion in China's

Loess Plateau region: An application of the MMF approach. *Environmental Management*, 45(3): 476–487.

Li Y C, Liu C M, Yu J J, 2006. Tradeoff of conflict between wetland protection and farmland reclamation in the Sanjiang Plain, Heilongjiang Province. *Journal of Beijing Forestry University*, 28(1): 39–42. (in Chinese)

Liu J G, Li S X, Ouyang Z Y *et al*., 2008. Ecological and socioeconomic effects of China's policies for ecosystem services. *Proceedings of the National Academy of Sciences of the United States of America*, 105(28): 9477–9482.

Liu J Y, 1996. Macro-scale Survey and Dynamic Study of Natural Resources and Environment of China by Remote Sensing. Beijing: China Science and Technology Press. (in Chinese)

Liu J Y, Deng X Z, Liu M L *et al*., 2002. Study on the spatial patterns of land-use change and analysis of driving forces in northeastern China during 1990–2000. *Chinese Geographical Science*, 12(4): 299–308.

Liu J Y, Liu M L, Tian H Q *et al*., 2005. Spatial and temporal patterns of China's cropland during 1990–2000: An analysis based on Landsat TM data. *Remote Sensing of Environment*, 98(4): 442–456.

Liu J Y, Liu M L, Zhuang D F *et al*., 2003. Study on spatial pattern of land-use change in China during 1995–2000. *Science in China* (*Series D*), 46(4): 373–384.

Liu J Y, Wang S Q, Chen J M *et al*., 2004. Storages of soil organic carbon and nitrogen and land use changes in China: 1990–2000. *Acta Geographica Sinica*, 59(4): 483–496. (in Chinese)

Liu J Y, Zhang Z X, Xu X L *et al*., 2010. Spatial patterns and driving forces of land use change in China during the early 21st century. *Journal of Geographical Sciences*, 20(4): 483–494.

Lobell D B, Hicke J A, Asner G P *et al*., 2002. Satellite estimates of productivity and light use efficiency in the United States agriculture, 1982–1998. *Global Change Biology*, 8(8): 722–735.

Loucks C J, Lv Z, Dinerstein E *et al*., 2001. Giant pandas in a changing landscape. *Science*, 294(5546): 1465–1465.

Lv Y H, Fu B J, Feng X M *et al*., 2012. A policy-driven large scale ecological restoration: Quantifying ecosystem services changes in the Loess Plateau of China. *Plos One*, 7(2): e31782, doi: 10.1371/journal.pone.0031782.

Lv C H, Wang Q, Ma J F, 2011. Effects of the ecological construction in the hilly Loess Plateau. *Journal of Arid Land Resources and Environment*, 25(10): 28–31. (in Chinese)

Morton D C, DeFries R S, Shimabukuro Y E *et al*., 2006. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, 103(39): 14637–14641.

Potter C S, Randerson J T, Field C B *et al*., 1993. Terrestrial ecosystem production: A process model based on global satellite and surface data. *Global Biogeochemical Cycle*, 7(4): 811–841.

Prince S D, Goward S N, 1995. Global primary production: A remote sensing approach. *Journal of Biogeography*, 22(4/5): 815–835.

Shi M J, Ma G X, Shi Y, 2011. How much real cost has China paid for its economic growth? *Sustainability Science*, 6(2): 135–149.

State Council of People's Republic of China, 2007. The Notice of State Council on Improving "Grain for Green" Policy. (in Chinese)

State Council of People's Republic of China, 2008. Medium- and Long-term Plan of China's Food Security (2008-2020). (in Chinese)

Tao F L, Yokozawa M, Liu J Y *et al*., 2009. Climate change, land use change, and China's food security in the twenty-first century: An integrated perspective. *Climatic Change*, 93(3/4): 433–445.

Tao F L, Yokozawa M, Zhang Z *et al*., 2005. Remote sensing of crop production in China by production efficiency models: Models comparisons, estimates and uncertainties. *Ecological Modelling*, 183(4): 385–396.

Wang Y F, Fu B J, Lu Y H *et al*., 2011. Effects of vegetation restoration on soil organic carbon sequestration at multiple scales in semi-arid Loess Plateau, China. *Catena*, 85(1): 58–66.

Wang Z M, Song K S, Zhang B *et al*., 2009. Shrinkage and fragmentation of grasslands in the West Songnen Plain, China. *Agriculture Ecosystems & Environment*, 129(3): 315–324.

WWF (World Wide Fund for Nature), 2003. Report suggests China, Grain-to-Green plan is fundamental to managing water and soil erosion. http://www.wwfchina.org/english/loca.php?loca=159

Xu J T, Cao Y Y, 2002. Efficiency and sustainability of converting cropland to forest and grassland in the western region. In: Xu J T, Katsigris E, White T A (eds.). Implementing the natural forest protection program and the sloping land conversion program: Lessons and policy implication CCICED-WCFGTF. Beijing: China Forestry Publishing House, 71–81. (in Chinese)

Xu J T, Tao R, Xu Z G, 2004a. Sloping land conversion: cost effectiveness, structural adjustment, and economic sustainability. *China Economics Quarterly*: 4(1): 139–162. (in Chinese)

Xu J T, Yin R S, Li Z *et al*., 2006. China's ecological rehabilitation: Unprecedented efforts, dramatic impacts, and requisite policies. *Ecological Economics*, 57(4): 595–607.

Xu Z G, Bennett M T, Tao R *et al*., 2004b. China's sloping land conversion program four years on: Current situation and pending issues. *International Forestry Review*, 6(3/4): 317–326.

Yan H M, Fu Y L, Xiao X M *et al*., 2004. Modeling gross primary productivity for winter wheat-maize double cropping system using MODIS time series and CO_2 eddy flux tower data. *Agriculture. Ecosystems and Environment*, 129(4): 391–400.

Yan H M, Liu J Y, Cao M K *et al*., 2007. Spatial pattern and topographic control of China's agricultural productivity variability. *Acta Geographica Sinica*, 62(2): 171–180. (in Chinese)

Yan H M, Liu J Y, Huang H Q *et al*., 2009. Assessing the consequence of land use change on agricultural productivity in China. *Global and Planetary Change*, 67(1/2): 13–19.

Yan H M, Liu J Y, Huang H Q *et al*., 2012. Impacts of cropland transformation on agricultural production under urbanization and Grain for Green Project in China. *Acta Geographica Sinica,* 67(5): 579–588. (in Chinese)

Yin R S, Xu J T, Li Z *et al*., 2005. China's ecological rehabilitation: The unprecedented efforts and dramatic impacts of reforestation and slope protection in western China. *China Environment Series*, 7: 17–32.

Zhang G L, Dong J W, Xiao X M *et al*., 2012. Effectiveness of ecological restoration projects in Horqin Sandy Land, China based on SPOT-VGT NDVI data. *Ecological Engineering*, 38(1): 20–29.

Zhang P, Zhou X, Wang F, 1999. Introduction to Natural Forest Conservation Program. Beijing: China Forestry Publishing House. (in Chinese)

Zhang P C, Shao G F, Zhao G *et al*., 2000. China's forest policy for the 21st century. *Science*, 288(5474): 2135–2136.

Zheng F L, 2006. Effect of vegetation changes on soil erosion on the Loess Plateau. *Pedosphere*, 16(4): 420–427.