Food Sec. (2015) 7:33–43
DOI 10.1007/s12571-014-0411-z

ORIGINAL PAPER

Assessing the impact of urban expansion on potential crop yield in China during 1990–2010

Luo Liu · Xinliang Xu · Xi Chen

Received: 20 February 2014 / Accepted: 2 December 2014 / Published online: 19 December 2014

Abstract Rapid urbanization in China has raised great concerns regarding food security caused by conversion of limited cultivated land to urban use. In this study, the loss of potential crop yield due to urban expansion in China during 1990–2010 was calculated by the Global Agro-Ecological Zones (GAEZ) model. Over this period, potential yield decreased by approximately 34.90 million tons due to urban expansion, accounting for 6.52 % of China's total actual production. The decrease was 13.07 and 21.83 million tons during the first and second decade, respectively. Key areas of lost potential yield were primarily in the Middle-lower Yangtze Plain and the Huang-Huai-Hai Plain. However, South China became a new key area of lost potential yield during the second decade. These findings provide useful information for the development of land use policy, protection of suitable arable land resources and urban development plans in China.

Keywords Urban expansion · Potential yield · GAEZ · China

Introduction

The urbanization process is one of the most important aspects of global change, which is associated with the immigration from rural residential land to urban areas, accompanied by the clearing of forests and the conversion of cropland to urban construction land (Burke et al. 1991; Qiao et al. 2013a; Tian and Qiao 2014). China has undergone rapid urbanization due to population growth, economic development and changing land use over the last few decades (Deyong et al. 2009). It is worth noting that the percentage of the population in urban areas of China reached 50 % in 2010, whereas it was just 17 % in 1978 (Tian and Qiao 2014). The acceleration of urban population growth has not only resulted in the encroachment on cropland, but has also led to greater food demand. For China with nearly 20 % of the global population, it is extremely important for the country to maintain the ability to feed itself. Thus, tracking the impacts of urbanization on cropland and agricultural yield is a prerequisite for better guarding the food supply, especially as China is predicted to continue its rapid urbanization over the next few decades (Brown 1995; Godfray et al. 2010).

During the last two decades, urban areas in China have increased exponentially, the greatest area of increase changing from the Northeastern provinces in the 1990s to the Southeast coast in the 2010s. Urban areas were mostly converted from croplands, and amounted to approximately 17,750 km^2, mainly distributed over the flat-lying, more economically developed and densely populated areas, including the Huang-Huai-Hai Plain, Yangtze River delta, Pearl River delta, and Sichuan basin (Wang et al. 2012). The speed of urban expansion in the second decade (2000–2010) was 2.14 times that in the first decade (1990–2000) (Liu et al. 2003, 2005a, b, 2010, 2012; Qiao et al. 2013a, b). During recent years, a number of studies at the regional and national scales have investigated the characteristics of urbanization and consequent cropland and agricultural production loss (Jinwei et al. 2010; Qin et al. 2013; Zhiqiang et al. 2004). Some of these studies have assessed and analyzed China's urbanization process and its influences on crop yields, using census data at national and provincial levels

L. Liu · X. Xu (✉)
State Key Laboratory of Resources and Environmental Information Systems, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
e-mail: xuxl@lreis.ac.cn

L. Liu · X. Chen
State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China

L. Liu
University of Chinese Academy of Sciences, Beijing 100049, China

(Shi et al. 2013; Tao et al. 2012). Such assessments, however, lack detailed analysis of the variation of yield loss caused by the urbanization process. Owing to the spatial heterogeneity of urban expansion caused by highly diverse natural and socio-economic conditions across China, accurate information on both the area of arable land and the spatial quantification of yield are of critical importance for policymakers in order for them to assess the impacts of the urbanization process on national food security. Based on land use data derived from Landsat-TM, Tan et al. (2005) summarized the characteristics of urban expansion and consequent loss of cropland of 145 major cities in China. Yan et al. (2009) and Deng et al. (2006) analyzed the impact of change of land use, especially cropland dynamics, on agricultural yield in China from 1990 to 2000. Tian and Qiao (2014) estimated the loss of Net Primary Productivity (NPP) due to the transformation from cropland to urban land.

In this study, the agricultural potential yield in China was calculated using the Global Agro-Ecological Zones Model (GAEZ) in order to reveal the impact of urban expansion on potential yield from 1990 to 2010. The objectives of the paper were therefore to address the following questions: (1) how has urban expansion impacted the national potential crop yield of China? and (2) what are the differences in the losses of potential yield due to the impact of urban expansion among the different regions? The results provide important information for the development of land use policy and urban development plans in China.

Data sources and methodology

Data sources

The data sources used for this study included terrain elevation, soil, change of land use/cover, meteorological data and agricultural regional data.

Terrain elevation data

The terrain elevation dataset derived from the Shuttle Radar Topography Mission (SRTM) C-band was the first publicly available near-global, high-resolution raster Digital Elevation Model (DEM). The SRTM data have a 90 m spatial resolution, reduced from the original 30 m resolution via averaging and sub-sampling. Numerous worldwide applied studies have used SRTM data for environmental analysis (Shortridge and Messina 2011). The SRTM Version 2 data (by naming convention SRTM3 for 3 arc sec data) was sourced from the Jet Propulsion Laboratory (http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp).

Soil data

Soil data were used to calculate the soil-water balance, which determined the potential and actual evapotranspiration for a reference crop and the length of its growing period (LGP, days). Soil data included soil type, effective soil depth and soil water-holding capacity. A nation-wide soil dataset at the scale of 1:1,000,000 was provided by the Data Center for Resources and Environmental Sciences at the Chinese Academy of Sciences (RESDC).

Change of land use/cover

A change of land use/cover database with a mapping scale of 1:1,000,000 was developed by CAS (The Chinese Academy of Sciences). The database includes five time periods: the late 1980s (named "1990"), the mid-1990s (named "1995"), the late 1990s (named "2000"), the mid-2000s (named "2005") and 2010. The primary data source was Landsat TM/ETM CCD digital images. CBERS (the China-Brazil Earth Resources Satellite) and HJ-1 (a small satellite constellation for environment and disaster monitoring) images were also used as supplements for some areas not covered by Landsat. The land-use data were classified into 25 categories, which were subsequently grouped into six classes: cropland, woodland, grassland, water body, built-up area and unused land. Detailed information about this database can be found in previous papers (Liu et al. 2003, 2005a, b, 2010, 2012). In this study, the remote sensing urban dynamic datasets were derived from the above national land-use database. Three time period data were used to analyze the process of urban expansion, including 1990, 2000 and 2010.

Meteorological data

Meteorological data, which included the monthly maximum air temperature, minimum air temperature, precipitation, relative humidity, wind speed at 10 m height and sunshine hours from 1980 to 2010, were obtained from the national agro-meteorological stations of China, maintained by the Chinese Meteorological Administration (CMA) (http://cdc.cma.gov.cn). Because of the diverse terrain across China, the impact of topography on the interpolation of the meteorological data was also considered. ANUSPLIN software (Hutchinson 1998a, b), which was designed for spatial interpolation of climate data, was used to interpolate the meteorological data with the terrain elevation dataset. These data, measured monthly for the above six key factors of plant growth, were interpolated by ANUSPLIN to 10 km resolution based on the digital terrain model of China.

Regional agricultural data

Regional agricultural data were used to investigate the differences in the urban expansion process and its effects on potential yield of farmland across China during 1990–2010. China is divided into nine agricultural regions (Fig. 1 and Table 1: (Qin et al. 2013).

Methodology

The simulation of farmland potential yield was performed at 1 km spatial resolution using the Global Agro-Ecological Zones Model (GAEZ) (Fischer et al. 2005, 2006; Fischer and Sun 2001), which was developed in the 1970s, and updated in 2010 by the Food and Agriculture Organization (FAO) of the United Nations and the International Institute for Applied Systems Analysis (IIASA). The main crops include wheat, maize, rice, sweet potato and soybean, representing 97.7 % of China's total food output. Land evaluation by the GAEZ approach utilizes meteorological data, terrain elevation data, soil data and farmland distribution data to calculate the potential yield, which is basic information for the supply of water, energy, nutrients and physical support for plants.

In the GAEZ model, agro-climatic potential yields are mainly determined by the availability of solar radiation and seasonal temperature, while the actual attained rain-fed yields are further limited by water availability, soil characteristics and terrain slopes. Figure 2 shows a flowchart used to calculate farmland yield based on the GAEZ model.

To ensure the assessment of heat stress occurred only in areas suitable for agriculture, grid cells were only considered when attainable yields were≥20 % of potential yields and at least 5 % of the land in a grid cell was cultivated. Irrigated rice was considered as this is the usual method of its cultivation. For other crops both irrigated and rain-fed conditions were considered. In the latter, the date of sowing is highly dependent on there being sufficient soil moisture available for seed germination and seedling establishment. Both winter and spring wheat and both maize and warm-loving maize were tested in each grid cell and the crop type with the highest yield was selected.

Fig. 1 China's agricultural regions

Table 1 Agricultural regions and provinces of China

Agricultural region	Provinces included in the agricultural regions
North East China Plain	Heilongjiang, Jilin, Liaoning
Huang-Huai-Hai Plain	Beijing, Tianjin, Hebei, Shandong, Henan
Middle-lower Yangtze Plain	Shanghai, Jiangsu, Anhui, Hubei, Hunan, Zhejiang, Jiangxi
Southern China	Guangdong, Fujian, Hainan, Taiwan
Northern arid and semi-arid region	Xinjiang, Inner Mongolia, Ningxia, Gansu
Loess Plateau region	Shaanxi, Shanxi
Sichuan Basin and surrounding regions	Sichuan, Chongqing
Yunnan-Guizhou Plateau regions	Yunnan, Guizhou, Guangxi
Qinghai-Tibet Plateau regions	Qinghai, Tibet

China is one of the largest countries in the world and has succeeded in achieving the highest multiple cropping index (Yan et al. 2005). The optimal crop combinations were considered in the calculation of the potential yield, based on actual agriculture production in China. These were determined by simulating yields for all possible crop combinations and then selecting the highest yield in each grid cell under average climatic conditions between 1980 and 2010. The possible combinations were decided by two factors: crop structure and customary multiple cropping index. The crop structure included one or more crops selected from the five main crops mentioned above and the multiple cropping index included single cropping per year, triple cropping per 2 years, double cropping per year and triple cropping per year.

Under the assumption that there was no water stress on the irrigated area, the simple equation used to calculate crop yields within each grid cell under rain-fed and irrigated conditions was determined as follows:

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

Here, $yield_{total}$ is the crop yield under rain-fed and irrigated conditions (kg/ha); $yield_{rain-fed}$ is yields under rain-fed conditions (kg/ha); $yield_{irrigated}$ is yield under irrigated conditions (kg/ha); and i (%) is the ratio of irrigated to cultivated area over cultivated area (Tatsumi et al. 2011).

There are many factors affecting food yield and, in order to dissect the effects of urban expansion on potential yield in China during 1990–2010, the GAEZ model was used to calculate the food potential yield under the assumption that land use changed and other factors, including climate

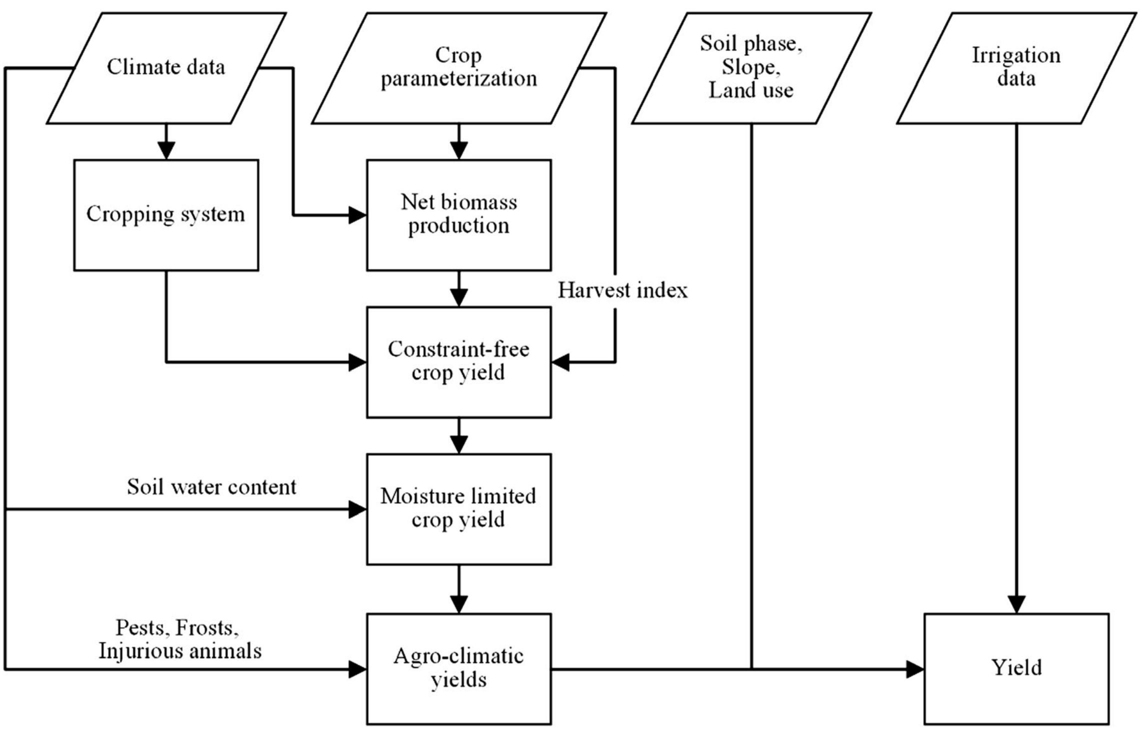

Fig. 2 Flowchart used to calculate yield in the GAEZ model

conditions, terrain elevation, and soil conditions, remained unchanged. The urban expansion data were extracted from the China time series datasets of changed land-use/cover in 1990–2000 and 2000–2010. The unchanged climate conditions were the average climate from 1980 to 2010. Other factors were assumed to be constant.

Results and analysis

Verification

To verify the accuracy of the calculated results, the farmland potential yield in 2010 was compared with the actual yield from official statistics at county level of more than 2,000 counties. The average potential yield per hectare was 8,316 kg in 2010, which was nearly 1.55 times as much as the actual yield. Figure 3 shows the correlation between the calculated potential yield and the actual yield at county level in 2010. The cross-correlation coefficient is 0.82 and the standard deviation is 7.4 thousand tons, which indicate that there is an excellent correlation. Consequently, the trends of the potential yield change, to a great extent, does reflect the actual yield change.

The impact of urban expansion on arable land

Due to rapid urban expansion during 1990–2010, the area of arable land converted to urban use was relatively large - approximately 4.18 million hectares - 1.50 million hectares during the first decade and 2.68 million hectares during the second decade The annual encroachment rate increased by 0.06 %, from 0.08 % during 1990–2000 to 0.14 % during 2000–2010, but there was considerable variation among regions. For example in the Huang-Huai-Hai Plain and Middle-lower Yangtze Plain, it was 530.16 and 466.07 thousand hectares, in 1990–2000, respectively and 668.40 and 1,079.71 thousand hectares in 2000–2010, respectively. These figures represent a 131.66 % and a 210.65 % increase in the second decade compared with the first for the Huang-Huai-Hai Plain and Middle-lower Yangtze Plain, respectively. In contrast, the rate of loss of arable land in the Northern arid and semi-arid region had decreased by 19.64 % from 127.48 thousand hectares in 1990–2000 to 102.44 in 2000–2010 (Table 2).

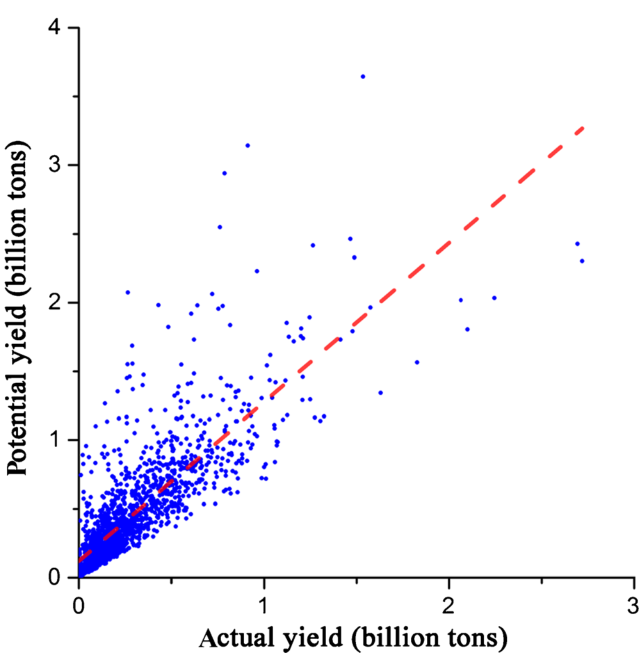

Fig. 3 The correlation between the potential yield and the actual yield at county level in 2010

Potential yield loss due to urban expansion at the national level

According to our estimates, from 1990 to 2010, the potential total yield, loss due to urban expansion, was approximately 34.90 million tons, which accounts for 6.52 % of China's total actual production and 3.29 % of China's total potential production in 2010 (Table 2). The potential total yield loss was approximately 13.07 million tons during the first decade, the areas where most of the loss of potential yield occurring mainly in the Huang-Huai-Hai Plain and Middle-lower Yangtze Plain (39.02 % and 36.80 % of the total loss of potential yield, respectively; Fig. 4) These are areas where the economy was relatively well developed and where, according to our statistics, the average potential yield per hectare of cropland developed for urban use was approximately 9.54 and 9.49 ton, respectively. On the other hand, little potential yield loss occurred in the Qinghai-Tibet Plateau, as only a small area of agricultural land was encroached upon. Consequently there was little loss of potential yield in this poor and sparsely populated region (Table 2).

The potential total yield loss increased significantly by approximately 21.83 million tons during the second decade, 8.76 million tons more than the first decade. The key areas of lost potential were again in the Huang-Huai-Hai Plain (28.72 %) and the Middle-lower Yangtze Plain (45.49 %; Fig. 5), core areas of urbanization and encroachment on cropland areas. Loss of potential yield in this second decade increased by 1.17 (22.92 %) and 5.12 (106.47 %) million tons in the Huang-Huai-Hai Plain and Middle-lower Yangtze Plain, respectively. In contrast, potential loss decreased by 0.17 (24.98 %) million tons in the Northern arid and semi-arid region. South China emerged as a new key area of lost potential at 2.1 million tons, an increase

Table 2 The loss area of the arable land and the loss of potential yield caused by urban expansion in China during two recent decades

Main agricultural region	Loss area (Thousand hectares)		Loss potential yield (million tons)	
	1990–2000	2000–2010	1990–2000	2000–2010
Northeast China Plain	52.86	87.60	0.37	0.64
Yunnan-Guizhou Plateau	57.71	56.34	0.35	0.36
Northern arid and semi-arid region	127.48	102.44	0.69	0.52
South China	131.00	406.94	0.67	2.10
Sichuan Basin and surrounding regions	71.70	155.66	0.55	1.17
Middle-lower Yangtze Plain	466.07	1,079.71	4.81	9.93
Qinghai-Tibet Plateau	3.77	8.27	0.01	0.04
Loess Plateau	60.84	116.87	0.49	0.85
Huang-Huai-Hai Plain	530.16	668.40	5.10	6.27
Total	1,501.59	2,682.23	13.07	21.83

of 1.43 million tons over the previous decade (213.25 %) and 9.61 % of the total loss. There was also some change in the Qinghai-Tibet Plateau, an increase in loss of 0.04 tons from 0.01 tons (Table 2).

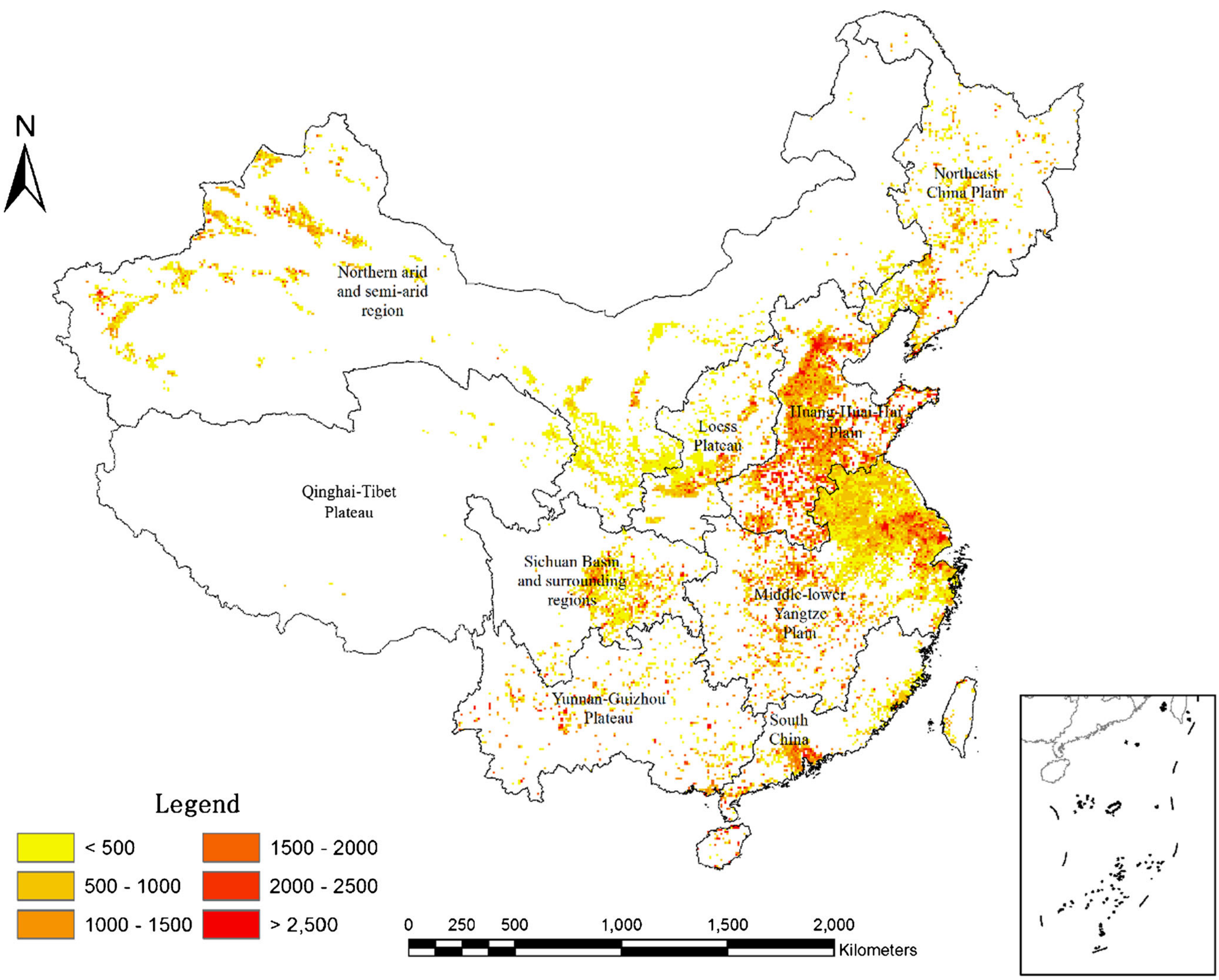

Fig. 4 Potential yield loss from 1990 to 2000 (kg/hm^2)

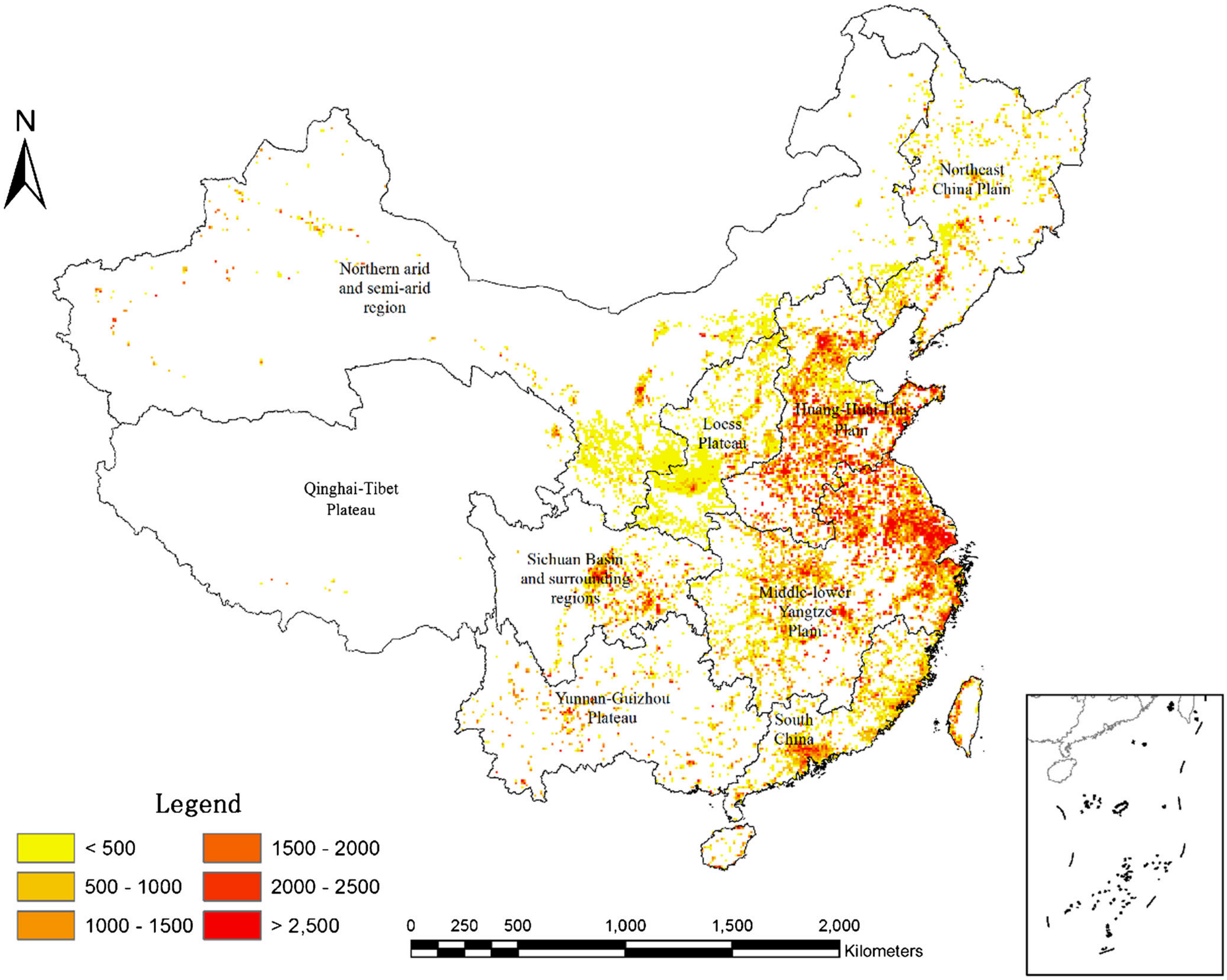

Fig. 5 Potential yield loss from 2000 to 2010 (kg/hm^2)

Potential yield loss at the provincial level due to urban expansion

Potential yield loss caused by urban expansion was also analyzed at the provincial scale (Table 3, Fig. 6). Due to the urbanization process and economic growth, provinces in eastern China were facing conflict between agriculture and urban use of land. During 1990–2000, Jiangsu, Hebei, Shandong, Henan and Anhui were the provinces with the most potential yield loss caused by urbanization; 2.26, 1.86, 1.23, 1.20 and 1.11 million tons, respectively. However, the provinces with the largest losses during the second decade were Jiangsu, Shandong and Zhejiang; 3.46, 2.88 and 2.54 million tons, respectively. During the two decades, the provinces with the most potential yield loss per area were always Anhui, Beijing, Henan, Hubei, Jiangsu and Shandong - 10.33, 9.87, 10.25, 10.20, 9.81 and 9.54 tons per hectare, respectively.

In general, the potential yield loss caused by urban expansion increased in most provinces from the first decade to the second decade, except for Hebei, Xinjiang, Guangxi, Beijing and Hainan. Among these provinces, potential yield loss in Hebei decreased most from 1.86 million tons to 1.05 million tons because of state strategic macro-control of arable land resources. Zhejiang experienced rapid urban expansion, and its potential yield loss consequently jumped from 0.50 million tons to 2.54 million tons, an increase of 2.04 million tons, the most of all provinces. The potential yield loss in Shandong, Jiangsu, Guangdong, Fujian and Jiangxi increased by more 0.5 million tons - 1.65, 1.20, 0.74, 0.59 and 0.53 million tons, respectively. Potential yield losses in other provinces caused by urban expansion were relatively stable (Table 3).

Conclusions and discussion

During two recent decades, 1990–2000 and 2000–2010, China's population growth and economic development has

Table 3 Potential yield loss in provinces

Provinces	Total potential yield loss (thousand tons)			Potential yield loss per area (tons / hectare)		
	1990–2000	2000–2010	1990–2010	1990–2000	2000–2010	1990–2010
Anhui	1112.89	1398.40	2511.28	10.47	10.22	10.33
Beijing	708.67	677.95	1386.63	9.68	10.07	9.87
Chongqing	107.73	368.38	476.11	6.43	6.10	6.17
Fujian	70.33	664.94	735.27	4.29	4.88	4.82
Gansu	107.68	122.18	229.86	4.70	4.42	4.55
Guangdong	518.67	1255.87	1774.53	5.18	5.19	5.19
Guangxi	157.94	110.27	268.21	5.35	5.02	5.21
Guizhou	31.77	34.33	66.10	6.43	5.81	6.10
Hainan	70.26	49.24	119.50	8.02	6.77	7.46
Hebei	1860.72	1053.96	2914.68	9.35	8.92	9.19
Heilongjiang	92.68	145.72	238.40	5.96	5.96	5.96
Henan	1196.46	1303.92	2500.38	10.46	10.07	10.25
Hubei	300.06	645.58	945.63	10.46	10.08	10.20
Hunan	171.51	422.13	593.64	9.81	9.61	9.66
Inner Mongolia	28.17	104.25	132.42	3.99	4.14	4.11
Jiangsu	2259.19	3460.34	5719.53	10.07	9.65	9.81
Jiangxi	127.15	655.96	783.11	9.69	9.71	9.71
Jilin	94.77	188.42	283.19	6.89	6.67	6.74
Liaoning	188.37	309.29	497.66	8.24	8.76	8.56
Ningxia	35.68	182.29	217.96	6.18	6.46	6.42
Qinghai	10.34	31.16	41.49	3.29	5.03	4.45
Shaanxi	334.38	496.90	831.28	9.51	9.23	9.34
Shandong	1232.85	2878.74	4111.59	10.06	9.34	9.54
Shanghai	365.54	851.89	1217.43	9.33	8.79	8.95
Shanxi	162.86	362.92	525.78	6.55	5.71	5.95
Sichuan	448.67	806.22	1254.88	8.31	8.40	8.37
Taiwan	15.23	127.71	142.94	6.29	6.28	6.28
Tianjin	61.90	274.66	336.56	8.34	6.22	6.53
Tibet	1.18	4.09	5.27	2.05	2.17	2.14
Xinjiang	530.04	95.39	625.43	5.89	4.79	5.69
Yunnan	165.61	210.14	375.76	7.39	7.31	7.35
Zhejiang	500.70	2536.76	3037.46	8.52	8.09	8.16

been unprecedented. As a result, urbanization has been rapid with the result that large tracts of land, suitable for arable use, have been given over to urban construction with significant implications for the country's food security. This has been studied quantitatively using the GAEZ model. Conclusions from the work are as follows:

(1) During the recent two decades studied, the area of conversion of arable land to urban use was approximately 4.18 million hectares, 1.50 million hectares during the first decade, and 2.68 million hectares during the second. The loss of arable land was primarily in the Huang-Huai-Hai Plain and the Middle-lower Yangtze Plain (Table 1).

(2) As a result, the potential yield decreased by approximately 34.90 million tons, accounting for 6.52 % of China's total actual production. Approximately 13.07 million tons of this occurred during the first decade and the rest in the second. Key areas of loss were in the Huang-Huai-Hai Plain and Middle-lower Yangtze Plain. During the second decade South China became a new key area for loss of potential yield (Table 2; Figs. 4 and 5).

(3) Conversion of arable land to urban use and consequent loss of potential yield was also studied by Province (Table 3 and Fig. 6) The area of potential yield loss due to urbanization were mainly located in Anhui, Guandong, Hebei, Henan, Jiangsu and

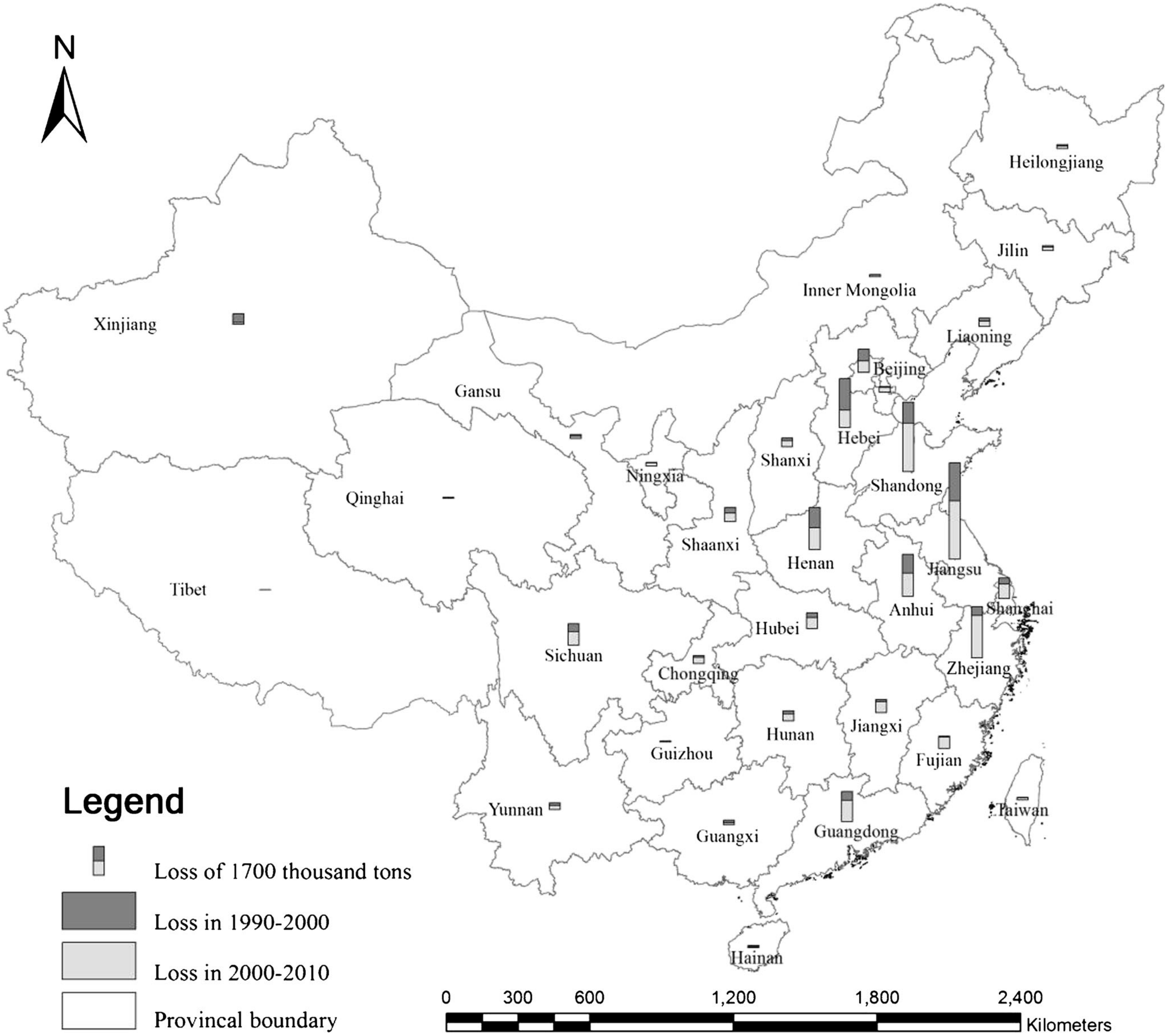

Fig. 6 The distribution map of potential yield losses in the provinces of China

Shandong, with large increases in the second decade of the study in Guandong, Jiangsu, Shandong and Zhejiang. The potential yield loss caused by urbanization increased in most provinces from 1990–2000 to 2000–2010, except for Beijing, Guangxi , Hainan, Hebei and Xinjiang. The most potential yield loss per area was always located in Anhui, Beijing, Henan, Hubei, Hunan, Jiangsu, Jiangxi, Shaanxi and Shandong.

Against the background of the global food security crisis, great attention has been paid to research on the impact of urban expansion on potential yield by Governments and Communites. Since the 1990s, the total area of the arable land in China has decreased permanently owing to conversion to other uses of which conversion to urban use made up just over half. This has led to to a downward trend in potential yield (Liu et al. 2012).

Our study has explicitly revealed the impacts of urban expansion on potential yield in China and is an important update of the research of Yan et al. (2009). Four aspects are manifest: (1) The newest national urban expansion data was used (2000–2010) a decade of the most rapid expansion. (2) Yan used an NPP (net primary production) model to estimate the agricultural yield in China. NPP contains the biomass of crop residues and therefore does not represent crop yield. In this study, we employed the more powerful and realistic yield assessment tool GAEZ to simulate the yield. Moreover, farmland potential yield was verified using actual yields from official statistics at county level. (3) The land-use map with a mapping scale of 1:1,000,000 was used to extracted urban expansion data, which has a higher spatial resolution than Yan's. (4) The study explicitly considered the effect of many kinds of factors, especially the multiple cropping index, thus more effectively simulating potential yield.

Urban development in China has always been subject to national development planning. As mentioned above, the conversion of arable land to urban use is directed by the emphasis of national development. Other factors, such as economic development, population growth and migration, have also impacted the transformations. These may have resulted in the conversion of cropland of high quality to urban use rather than land of lower quality. According to the urban development plan in China, the Chinese government will put the emphasis on urbanization in the central, eastern, and coastal regions in the future, making cropland in these locations vulnerable to encroachment. However, in China, cropland protection has always held a high priority in national development. Since the 1990s, the central government has promulgated several strict cropland reservation regulations, such as the dynamic balance of total farmland policy in 1998. This policy stipulates that local governments should reclaim the same amount of cropland as that commandeered for urban use. It is therefore one of the major means of relieving rising pressure on arable land resources from the fast developing Chinese economy. As such it guarantees the "red line" of arable land and maintains a balance between arable and urban land thus aiding food security. It should also be noted that new-type urbanization in China has emphasized population urbanization and optimization of urban land structure. This trend may, to a certain extent, mitigate the loss of cropland caused by urban development in the future. On the other hand, under the influence of building ecological security and strengthening ecological protection, the phenomenon of urban expansion extensively encroaching on suitable arable land may gain control in China in the future.

China faces challenges in its efforts to ensure food security resulting from an increasing population and the decreasing availability of land for agriculture. Climatic variability and reduction of arable land are two important factors that put Chinese food security at risk. GAEZ modelling can take multiple factors into consideration, including light, temperature, moisture, CO_2 fertilizer application, pests, diseases, soil, topography and agricultural management measures. Thus it can help to reveal the impact of climate change and human activity on farmland potential yield. By means of simulation with the GAEZ model, it should be possible optimize adaptation to the changing conditions under which crops will need to be grown in the future, increasing yields and strengthening food security.

Acknowledgments This research was supported and funded by the National Key Project of Scientific and Technical Supporting Programs (No.2013BAC03B01), project of CAS action-plan for West Development (No. KZCX2-XB3-08-01) and important National Project of high-resolution Earth observation system (No.05-Y30B02-9001-13/15-10). We are particularly indebted to Günther Fisher from IIASA for his GAEZ model. He made substantial contribution to the production potential estimation of China.

References

Brown, L. R. (1995). *Who will feed China?: Wake-up call for a small planet*. Washington, DC: WW Norton & Company.

Burke, I., Kittel, T., Lauenroth, W., Snook, P., Yonker, C., & Parton, W. (1991). Regional analysis of the central Great Plains. *BioScience, 41*, 685–692.

Deng, X. Z., Huang, J. K., Rozelle, S., & Uchida, E. (2006). Cultivated land conversion and potential agricultural yield in China. *Land Use Policy, 23*, 372–384.

Deyong, Y., Hongbo, S., Peijun, S., Wenquan, Z., & Yaozhong, P. (2009). How does the conversion of land cover to urban use affect net primary yield? A case study in Shenzhen city, China. *Agricultural and Forest Meteorology, 149*, 2054–2060.

Fischer, G., Shah, M., Tubiello, F. N., & Van Velhuizen, H. (2005). Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. *Philosophical Transactions of the Royal Society, B: Biological Sciences, 360*, 2067–2083.

Fischer, G., Shah, M., Velthuizen, H., & Nachtergaele, F. (2006). *Agro-ecological zones assessments. Land use and land cover. Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO*. Oxford: Eolss Publishers [http://www.eoloss.net].

Fischer, G., & Sun, L. X. (2001). Model based analysis of future land-use development in China. *Agriculture, Ecosystems & Environment, 85*, 163–176.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. *Science, 327*, 812–818.

Hutchinson, M. F. (1998a). Interpolation of rainfall data with thin plate smoothing splines. Part I: two dimensional smoothing of data with short range correlation. *Journal of Geographic Information and Decision Analysis, 2*, 139–151.

Hutchinson, M. F. (1998b). Interpolation of rainfall data with thin plate smoothing splines. Part II: analysis of topographic dependence. *Journal of Geographic Information and Decision Analysis, 2*, 152–167.

Jinwei, D., Jiyuan, L., Wenjiao, S. (2010). China's sloping land conversion program at the beginning of 21st century and its habitat suitability in typical region of Loess Plateau. *Journal of Resources and Ecology, 1*, 37–44.

Liu, J., Liu, M., Tian, H., Zhuang, D., Zhang, Z., Zhang, W., Tang, X., & Deng, X. (2005a). Spatial and temporal patterns of China's cropland during 1990–2000: an analysis based on Landsat TM data. *Remote Sensing of Environment, 98*, 442–456.

Liu, J., Liu, M., Zhuang, D., Zhang, Z., & Deng, X. (2003). Study on spatial pattern of land-use change in China during 1995–2000. *Science in China Series D: Earth Sciences, 46*, 373–384.

Liu, J., Tian, H., Liu, M., Zhuang, D., Melillo, J. M., & Zhang, Z. (2005b). China's changing landscape during the 1990s: large-scale land transformations estimated with satellite data. *Geophysical Research Letters, 32*, L02405.

Liu, J., Zhang, Q., & Hu, Y. (2012). Regional differences of China's urban expansion from late 20th to early 21st century based on remote sensing information. *Chinese Geographical Science, 22*, 1–14.

Liu, J., Zhang, Z., Xu, X., Kuang, W., Zhou, W., Zhang, S., Li, R., Yan, C., Yu, D., & Wu, S. (2010). Spatial patterns and driving forces of land use change in China during the early 21st century. *Journal of Geographical Sciences, 20*, 483–494.

Qiao, Z., Tian, G., & Xiao, L. (2013a). Diurnal and seasonal impacts of urbanization on the urban thermal environment: a case study of Beijing using MODIS data. *ISPRS Journal of Photogrammetry and Remote Sensing, 85*, 93–101.

Qiao, Z., Yang, X., Liu, J., & Xu, X. (2013b). Ecological vulnerability assessment integrating the spatial analysis technology with algorithms: a case of the wood-grass ecotone of Northeast China. *Abstract and Applied Analysis, 2013*, 8.

Qin, Y., Yan, H., Liu, J., Dong, J., Chen, J., & Xiao, X. (2013). Impacts of ecological restoration projects on agricultural yield in China. *Journal of Geographical Sciences, 23*, 404–416.

Shi, W., Tao, F., & Liu, J. (2013). Changes in quantity and quality of cropland and the implications for grain production in the Huang-Huai-Hai Plain of China. *Food Security, 5*, 69–82.

Shortridge, A., & Messina, J. (2011). Spatial structure and landscape associations of SRTM error. *Remote Sensing of Environment, 115*, 1576–1587.

Tan, M., Li, X., & Lu, C. (2005). Urban land expansion and arable land loss of the major cities in China in the 1990s. *Science in China Series D: Earth Sciences, 48*, 1492–1500.

Tao, F., Zhang, Z., Zhang, S., Zhu, Z., & Shi, W. (2012). Response of crop yields to climate trends since 1980 in China. *Climate Research, 54*, 233–247.

Tatsumi, K., Yamashiki, Y., Valmir da Silva, R., Takara, K., Matsuoka, Y., Takahashi, K., Maruyama, K., & Kawahara, N. (2011). Estimation of potential changes in cereals production under climate change scenarios. *Hydrological Processes, 25*, 2715–2725.

Tian, G., & Qiao, Z. (2014). Assessing the impact of the urbanization process on net primary yield in China in 1989–2000. *Environmental Pollution, 184*, 320–326.

Wang, L., Li, C., Ying, Q., Cheng, X., Wang, X., Li, X., Hu, L., Liang, L., Yu, L., & Huang, H. (2012). China's urban expansion from 1990 to 2010 determined with satellite remote sensing. *Chinese Science Bulletin, 57*, 2802–2812.

Yan, H., Liu, J., & Cao, M. (2005). Remotely sensed multiple cropping index variations in China during 1981–2000. *Acta Geographica Sinica-Chinese Edition, 60*, 559.

Yan, H., Liu, J., Huang, H. Q., Tao, B., & Cao, M. (2009). Assessing the consequence of land use change on agricultural yield in China. *Global and Planetary Change, 67*, 13–19.

Zhiqiang, G., Jiyuan, L., Mingkui, C., Kerang, L., & Bo, T. (2004). Impacts of land use and climate change on regional net primary yield. *Journal of Geographical Sciences, 14*, 349–358.

Luo Liu is a geographer specializing in agriculture, land use change, geographic information systems and climate change. He is a Ph. D. candidate from the University of the Chinese Academy of Sciences, focussing on the contributions of land use change and climate change to agriculture.

Xinliang Xu is a geographer and associate researcher in the State Key Laboratory of Resources and Environmental Information Systems, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences. He is engaged in research on land use/cover change, resources, environmental remote sensing and geographic information systems.

Xi Chen is a scientist engaged in remote sensing, geographic information systems and resource environment. He is the director of Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. He is a recipient of the special government allowance for outstanding youth of the CAS.