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Simulating Crop Net Primary Production in China from 2000 to 2050 by Linking the Crop-C model with a FGOALS's Model Climate Change Scenario

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ABSTRACT

Net primary production (NPP) of crop represents the capacity of sequestrating atmospheric CO_2 in agro-ecosystem, and it plays an important role in terrestrial carbon cycling. By linking the Crop-C model with climate change scenario projected by a coupled GCM FGOALS via geographical information system (GIS) techniques, crop NPP in China was simulated from 2000 to 2050. The national averaged surface air temperature from FGOALS is projected to increase by 1.0°C over this period and the corresponding atmospheric CO_2 concentration is 535 ppm by 2050 under the IPCC A1B scenario. With a spatial resolution of 10×10 km^2, model simulation indicated that an annual average increase of 0.6 Tg C yr^{-1} (Tg=10^{12} g) would be possible under the A1B scenario. The NPP in the late 2040s would increase by 5% (30 Tg C) within the $98{\times}10^6$ hm^2 cropland area in contrast with that in the early 2000s. A further investigation suggested that changes in the NPP would not be evenly distributed in China. A higher increase would occur in a majority of regions located in eastern and northwestern China, while a slight reduction would appear in Hebei and Tianjin in northern China. The spatial characteristics of the crop NPP change are attributed primarily to the uneven distribution of temperature change.

Key words: crop NPP, Crop-C, FGOALS, simulation, climate change, GIS

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1. Introduction

Climate has undoubtedly changed over recent decades and will continue to change, which is greatly attributed to the increase in the atmospheric greenhouse gases including CO_2, CH_4 and N_2O (IPCC, 2001). On the one hand, climate warming could extend the length of the potential growing season, allowing earlier planting of crops in the spring, earlier maturation and harvesting, and the possibility of completing two or more cropping cycles during the same season (Xu et al., 1999; Zhang and Miao, 2001). On the other hand, climate change encompasses gradually increasing average temperatures and may locally increase frequency and magnitude of extreme weather events (Mirza, 2003), which would most likely have a negative impact on crop grain yield (Matsui et al., 2001; Peng et al., 2004). Nevertheless, crop photosynthesis, and hence NPP (net primary production), is expected to benefit from increasing atmospheric CO_2 (Amthor, 2001; Kimball et al., 2002; Kim et al., 2003). Impacts of climate change on crop NPP, and hence yield, are complex, have great importance, but have been difficult to evaluate.

Over recent decades, a considerable number of investigations have been carried out to predict the impacts of climate change on crop production. By using county-level cross-sectional data on climate, agricultural net revenue, and other economic and geographical data for 1275 agriculture-dominated coun-

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ties, Liu et al. (2004a) found that under most climate change scenarios both higher temperature and more precipitation would have an overall positive impact on China's agriculture from an economic view. Several model studies suggested that climate change would have a negative effect on crop production in China (e.g., Wang et al., 2003; Ju et al., 2005) although these studies primarily focused on grain yields or the production potential of photo-temperatures of a specific crop, and the direct effect of increasing CO_2 was not taken into account. Studies have shown that increasing CO_2 has a positive effect on crop biomass (Anten et al., 2004; Ainsworth and Long, 2005), but its net effect on crop yield depends on possible yield reductions associated with increasing temperature (Ziska et al., 1997; de Costa et al., 2003). To better understand the contribution of agro-ecosystem to regional carbon budget, simulation models of crop NPP have been developed well since 1970s (e.g., Jone et al., 2003; van Ittersum et al., 2003). However, few models have been successfully put into practice in the agro-ecosystem of China, which is mainly due to the unavailability of model inputs and verification of reliability in different regions of China. Huang et al. (2006) recently developed Crop-C for simulating crop NPP. Model validation indicated that crop NPP can be well simulated from weather, soil, atmospheric CO_2 and N fertilization in various regions of China (Wang et al., 2006).

China is the world's third largest country, with cropland distributed across a vast area spanning wide regions of temperate, subtropical and tropical climates. Recognizing the role of croplands in the regional carbon budget and food supply, an evaluation of crop NPP under climate change scenario is of great importance. In this paper, crop NPP in China from 2000 to 2050 is predicted by linking the Crop-C model with the output of a coupled GCM called FGOALS (Flexible Global Ocean-Atmosphere-Land System model) for IPCC (Intergovernmental Panel on Climate Change) A1B scenario (Yu et al., 2004). The objective is to quantitatively evaluate the impacts of climate change on the capacity of sequestrating atmospheric CO_2 in Chinese agriculture.

2. Model description

2.1 *Crop-C model*

Crop-C is a process-level model dedicated to simulating NPP of rice, wheat, maize, cotton, rapeseed and soybean crops planted in approximately two thirds of agricultural soils in China (Huang et al., 2006). The model includes two main functional modules: photosynthesis and respiration, and nitrogen transport within soil-plant system.

The processes of photosynthesis and respiration are determined by environmental variables of temperature, solar radiation, precipitation, atmospheric CO_2 concentration and crop tissue nitrogen as follows (Huang et al., 2006):

$$P_n(i) = G(i) - [R_{\mathrm{G}}(i) + R_{\mathrm{M}}(i)] \,, \tag{1}$$

$$G(i) = 12 \times 10^{-6} \times P(i) \times W_{\mathrm{L}}(i) \times D_{\mathrm{L}}(i) \,, \tag{2}$$

$$P(i) = P_{\max}(i) \times F_{\mathrm{Q}}(i) \times F_{\mathrm{T}}(i) \times F_{\mathrm{W}}(i) \times F_{\mathrm{CO_2}} \,, \tag{3}$$

$$R_{\mathrm{G}}(i) = R_{\mathrm{g}} \times G(i) \,, \tag{4}$$

$$R_{\mathrm{M}}(i) = 12 \times 3600 \times 24 \times 10^{-6} \times R_{\mathrm{m}} \times Q_{10}^{\frac{T(i)-25}{10}} \times \sum_i P_n(i-1) \,, \tag{5}$$

where $P_n(i)$ and $G(i)$ represent the daily amounts of crop net photosynthesis and gross photosynthesis (g m^{-2} d^{-1}, in term of C weight whenever biomass was mentioned), respectively. $R_{\mathrm{G}}(i)$ and $R_{\mathrm{M}}(i)$ are the daily amounts of growth respiration and maintenance respiration (g m^{-2} d^{-1}); $P(i)$ is photosynthesis rate (μmol CO_2 g^{-1} h^{-1}) regulated by crop photosynthetic capacity ($P_{\max}(i)$, μmol CO_2 g^{-1} h^{-1}) and environmental variables, i.e. solar radiation $F_{\mathrm{Q}}(i)$, temperature $F_{\mathrm{T}}(i)$, soil water supply $F_{\mathrm{W}}(i)$ and atmospheric CO_2 concentration $F_{\mathrm{CO_2}}$; $D_{\mathrm{L}}(i)$ is the day length in hours; $W_{\mathrm{L}}(i)$ is green leaf mass (g m^{-2}); $P_{\max}(i)$ is a function of crop leaf nitrogen content; R_{g} (g g^{-1}) and R_{m} (μmol CO_2 g^{-1} s^{-1}) are the coefficients of growth respiration and maintenance respiration, respectively. The coefficient of growth respiration, R_{g}, has a value between 0.18 and 0.38 (g g^{-1}) depending on crop species. For that of maintenance respiration, R_{m} (μmol CO_2 g^{-1} s^{-1}), it is a function of crop tissue nitrogen concentration (Sun et al., 2007). Q_{10} is a temperature coefficient for maintenance respiration, given a value of 2.0.

The transportation of nitrogen within soil-plant system is determined by simulating the processes of crop nitrogen uptake (Eq. 6) and soil nitrogen mineralization and synthetic nitrogen release (Eq. 7) as follows (Huang et al., 2006):

$$\Delta N_{\mathrm{u}} = \min[\Delta N(i), \Delta D_{\mathrm{N}}(i)] \,, \tag{6}$$

$$\Delta N(i) = \Delta N_{\mathrm{S}}(i) + \Delta N_{\mathrm{N}}(i) \,, \tag{7}$$

where $\Delta N_{\mathrm{u}}, \Delta D_{\mathrm{N}}(i)$ and $\Delta N(i)$ represent the daily N amounts of uptake, demand and supply (g m^{-2} d^{-1}), respectively; $\Delta N_{\mathrm{S}}(i)$ and $\Delta N_{\mathrm{N}}(i)$ are the daily amounts of soil nitrogen mineralization and synthetic nitrogen release (g m^{-2} d^{-1}), respectively.

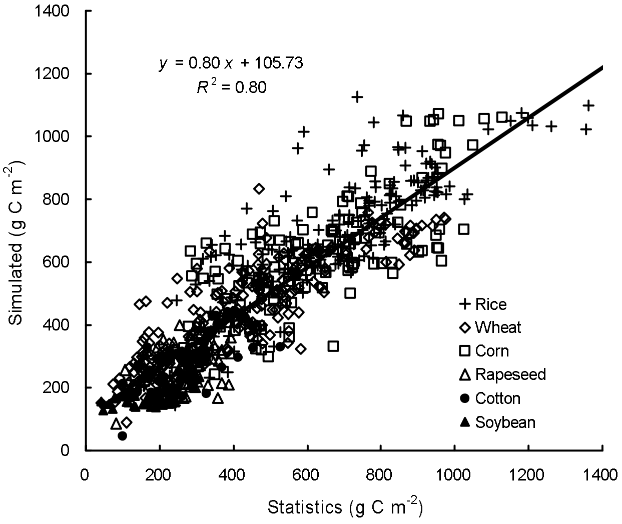

Fig. 1. Comparison of the simulated biomass against official statistics of crops in China from the 1950s to the 1990s (Wang et al., 2006).

Crop-C has been validated against independent datasets. In the study of Wang et al. (2006), statistical grain yields of the six crops (rice, wheat, corn, rapeseed, cotton, and soybean) of 20 counties in 15 provinces all over the crop cultivation area of China were used to validate Crop-C on a regional scale. The statistical data were transformed into crop biomass via ratios of crop biomass to grain yields in order to compare with the model outputs (Fig. 1). The simulated data were in general agreement with the independent datasets with the statistical R^2 of 0.80.

2.2 *Climate change scenario predicted by FGOALS*

FGOALS was developed by scientists at the Institute of Atmospheric Physics, Chinese Academy of Sciences. The FGOALS model is able to simulate the observed spatial distribution and annual cycles of temperature and precipitation for East Asia reasonably well (Yu et al., 2002, 2004) and has been widely applied in studies of climate variability, air-sea interaction and monsoon (e.g., Yu et al., 2000; Liu et al., 2004b; Yu and Liu, 2004; Li et al., 2005; Liu et al., 2006; Jian et al., 2006).

Simulation of climate change under A1B scenario was carried out by FGOALS. The A1B scenario comes from A1 scenario family that describes a future world of very rapid economic growth, global population that peaks mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies (IPCC, 2001). The output of FGOALS to drive Crop-C model was adopted in the present study.

3. Spatial databases and model up-scaling

Up-scaling was carried out by linking Crop-C to the spatial databases of soils, cropping system, agricultural activities and climate change scenario with a resolution of 10 × 10 km^2. A GIS technique was used to create the spatial databases. The soil database consists of bulk density, soil sand/clay fraction, pH, water capacity and initial concentrations of total nitrogen and organic carbon. The agricultural activities mainly include the sowing and harvesting dates of crops and the dates and rates of synthetic nitrogen application. Because the climate change scenario by FGOALS has a lower resolution of 2.8° × 2.8°, it was scaled down to 10 × 10 km^2 grids (see section 3.4).

3.1 *Soil features*

Spatial grid datasets from the Institute of Soil Science, Chinese Academy of Sciences, were adopted. More than 6000 soil profile measurements were used to create the spatial raster datasets. These measurements were conducted in the Second National Soil Survey of China, completed in the early 1980s.

3.2 *Cropping system*

Rice, wheat, maize, soybean, cotton and rapeseed are dominant crops with the cultivation acreage of 103 × 10^6 hm^2 in the 98 × 10^6 hm^2 arable lands, representing approximately 82% of the total harvested acreage of crops in China. The rest of the cropped area (18% of the total) is mainly planted with vegetables and fruit/tea trees (National Bureau of Statistics of China, 2001). The spatial distribution of arable

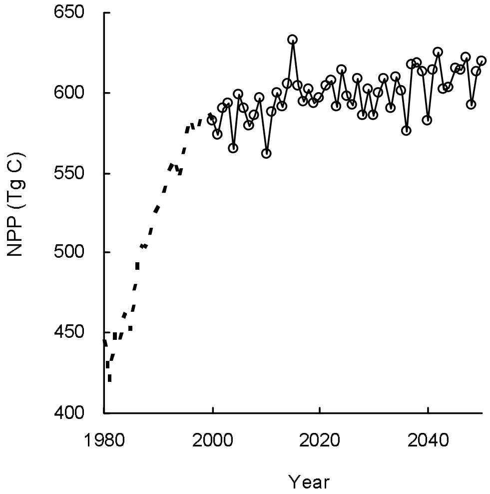

Fig. 2. Changes in the simulated crop NPP of China from 1980 to 2050 (simulated NPP from 1980 to 2000 taken from Wang et al., 2006).

Table 1. Main cropping system in China.

Region	Crop rotation	Arable area ($\times 10^3$ hm^2)
Mainly in northeastern and western China	Rice	10766
	Wheat	8130
	Maize	16730
	Soybean	11898
	Cotton	3155
	Rapeseed	4498
Eastern and northern China	Wheat-rice	2819
	Wheat-maize	8221
	Wheat-soybean	192
	Wheat-cotton	2272
	Other crops-rice	48
	Other crops-maize	58
	Other crops-rapeseed	270
	Soybean-rapeseed	142
	Other crops-soybean	463
	Other crops-cotton	219
	Rapeseed-rice	1871
	Rapeseed-maize	409
Southern China	Rice-rice	3579
	Soybean-rice-rice	51
	Rapeseed-rice-rice	86
	Other crops-rice-rice	3443
	Other crops	18719
	Total	98039

Note: other crops include potato, sugarcane, peanut etc.

land was obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC, CAS). The original datasets were 1×1 km^2 grids but were aggregated into 10×10 km^2 grid. By overlaying the spatial distribution raster of arable land with the county level datasets of crop cultivation acreage, crop rotation patterns were produced for each 10×10 km^2 grid to run the Crop-C model. Table 1 shows the main cropping system in China.

Crop-C is able to simulate NPP of rice, wheat, maize, cotton, rapeseed and soybean crops. Average value of the model parameters was given to simulate the NPP of other crops in Table 1.

3.3 *Crop phenology and agricultural management*

The Maps of Agriculture Phenology in China (Zhang et al., 1987) were digitized and interpolated by TIN (Triangular Irregular Network) techniques of GIS to obtain the spatial distribution of crop phenology. Based on the digitized crop phenology, the accumulated temperature from planting/transplanting to heading and from heading to maturity was calculated for each crop in each grid with the interpolated daily mean temperature.

The application rates of synthetic fertilizer nitrogen in 2000 were obtained from Chinese Academy of Agricultural Sciences at county level. The county level datasets were linked to the administrative boundary map of China and projected onto each grid.

3.4 *Down-scaling of climate change scenario*

The output of FGOALS represents a meteorological representation with large grids (2.8° × 2.8° for each grid). To downscale the surface air temperatures (daily mean, maximum and minimum temperature) into 10×10 km^2 grids, a correction factor was calculated for each grid [Eq. (8)].

$$V_m = \frac{1}{1461}\left(\sum_{i=1}^{1461} M_{\rm S}(i) - \sum_{i=1}^{1461} M_{\rm L}(i)\right) , \tag{8}$$

where $V_{\rm m}$ is the correction factor, representing an average difference between the historically recorded temperature and the projected temperature in the same period from 2000 to 2003. $M_{\rm S}(i)$ of a given 10×10 km^2 grid is interpolated with the recorded daily temperature. $M_{\rm L}(i)$ is the projected daily temperature by FGOALS in a corresponding grid. The constant 1461 in Eq. (8) is the length in days from 1 January 2000 to 31 December 2003.

Daily precipitation from the FGOALS model is not, to a certain extent, a likely representation of ac-

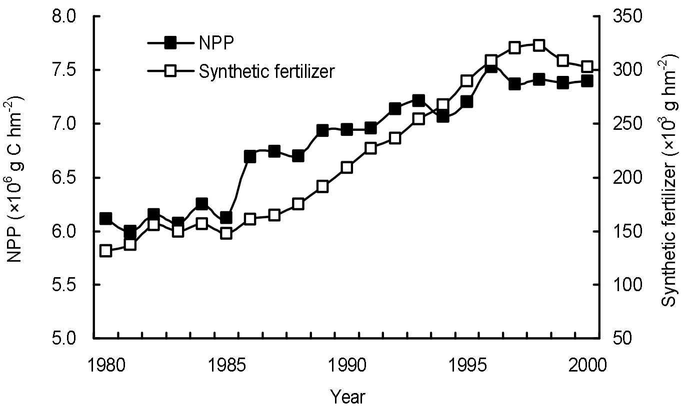

Fig. 3. Synthetic fertilizer application and simulated crop NPP (application rate of synthetic fertilizer taken from the National Bureau of Statistics of China, 2000, 2001).

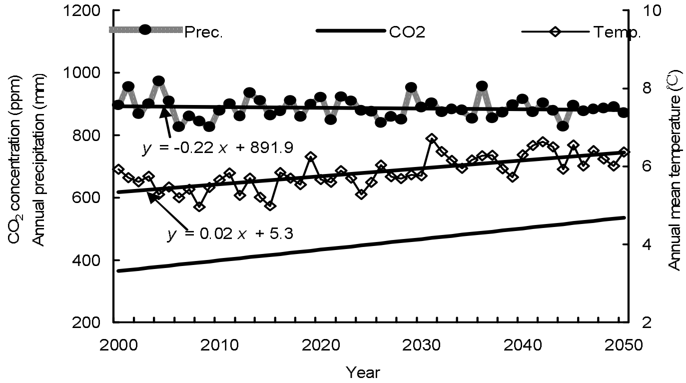

Fig. 4. Predicted changes in temperature, precipitation and atmospheric CO_2 concentration under the A1B scenario.

tual rainfall making it look as though the precipitation occurs every day. To make it more accurate, we first determined annual precipitation and counted the total days of rainfall occurrence from the spatialized climate database. The ratios of the annual precipitation from FGOALS to the current precipitation were then calculated for each 10×10 km^2 grid. The total days of rainfall occurrence for a given year in the period from 2000 to 2050 were determined via these grid-oriented ratios. The daily precipitation from FGOALS was reallocated according to the daily occurrence of precipitation while the annual amount of precipitation was kept unchanged.

Because the surface solar radiation was not directly output by FGOALS, a method by Thornton et al. (2000) was adopted to estimate daily solar radiation. The method was calibrated beforehand with historical observations from 11 meteorological stations in China to ensure its validity.

3.5 *Model performance*

With the assumption that the application rates of synthetic fertilizer nitrogen in different regions are the same as that in 2000, the Crop-C model was run from 2000 to 2050 for each grid with a daily step. Requirements of the accumulated temperature for completing developmental phases from planting/transplanting to heading and from heading to maturity were used to identify the actual crop-growing season. According to the threshold temperature for winter crops, the average temperature of 7 sequential days identifies the beginning dates for growth ending in the winter season and re-growth in the early spring. In most regions of northern and northwestern China, proper irrigation is usually conducted to keep crops grow well. Because the related records are not available, it was assumed that the soil water reduction function of F_w in Eq. (3) has a value of 0.7 when it is lower than 0.7 in these regions (Yang et al., 2004; Gong and Li, 2000).

4. Results and discussion

4.1 *Temporal change in crop NPP*

Model calculation showed that the crop NPP of China would increase from 580 Tg C in the early 2000s to 610 Tg C in the late 2040s with an augment of 30 Tg C (Fig. 2), an increase of around 5%. The annual rate of increase is approximately 0.6 Tg C yr^{-1}, much lower than that from 1980 to 2000 (Fig. 2). A recognized reason is that the augment of synthetic fertilizer application contributed greatly to NPP (Fig. 3). The application rate of synthetic fertilizer (referred to the sum of synthetic N, P_2O_5 and K_2O) was 130 kg hm^{-2} in 1980 and increased to 300 kg hm^{-2} in 2000, and as a result, the NPP increased greatly (Fig. 3). In contrast with the changes in NPP from 1980 to 2000, the predicted annual variations from 2000 to 2050 are mainly induced by climate change in that the application of synthetic fertilizer during this period was assumed to be the same as that in 2000.

Several model predictions suggested that global warming would accelerate crop development and induce a shortage of available soil water in some regions of China due to increasing evapotranspiration. As a result, crop yields would tend to decrease (Raes et al., 2006; Yu et al., 2006). However, other studies have shown that plant photosynthesis will increase by 20%–40% under doubled CO_2 concentration (Chapin et al., 2002), and crop yield will also increase by around 31% (Amthor, 2001) under these circumstance. The national averaged surface temperature is projected by FGOALS to increase by 1.0°C over the period from 2000 to 2050 and the atmospheric CO_2 concentration will correspondingly reach 535 ppm by 2050 (Fig. 4). While both the rising temperature and the increasing atmospheric CO_2 concentration were taken into account in Crop-C, the net effect of the climate change was predicted that the NPP of Chinese croplands would slightly increase [Fig. 2 and Eq. (3)].

Climate change might cause unfavorable conditions (e.g., extreme maximum temperature and drought) and most likely crop yield would be reduced by high-temperature-induced spikelet sterility (Matsui et al., 2001) but crop biomass production might not be reduced as CO_2 concentration increases (Matsui et al., 1997). It is therefore necessary to take both positive and negative impacts into account so that the uncertainties in assessing the influence of climate change on NPP can be reduced.

4.2 *Spatial distribution of crop NPP in 2000*

The spatial distribution of crop NPP in 2000 is characterized by higher values in southern and southeastern regions and lower in western, northeastern and northwestern regions (Fig. 5), which is mainly attributed to an integrated impact of climate (temperature, solar radiation and precipitation), soils and agricultural practices (crop species and rotation, fertilizer application and irrigation). Climate conditions in the southern and southeastern regions are more favorable for crop production. Favorable climate conditions such as higher temperature and solar radiation, and plentiful precipitation allow for multiple crop rotations within one year. For example, triple crop rotation prevails in Guangdong Province (southern China) while one crop harvest is dominant in Heilongjiang Province in northeastern China (Table 1). In addition to climate conditions, the application rates of synthetic fertilizer also contributed greatly to regional crop NPP. Lower application rates of synthetic fertilizer in northeastern China (e.g., Heilongjiang Province), southwestern China (e.g., Yunnan Province) and northwestern China (e.g. Gansu Province) resulted in lower crop NPP (Fig. 6).

4.3 *Comparison of NPP between the early 2000s and the late 2040s*

Annual air temperatures in the period from 2000 to 2004 and in the period from 2046 to 2050 were averaged for each grid respectively. The crop NPP for these periods was also averaged to remove inter-annual variations.

Figure 7 shows the temperature difference between the early 2000s and the late 2040s. It appears that the increase in temperature would not be evenly distributed under the A1B scenario (Fig. 7). The most significant increase would occur in the regions of the Tibet Plateau and Xinjiang in western China with values of 0.6–1.6°C up until the late 2040s (Fig. 7). Regions in northern and northeastern China would also face significant temperature increase (0.4–0.6°C), while a slight decline would appear in southwestern China. The remaining regions, including southern and eastern China, would have a slight increase or would remain stable (Fig. 7).

Driven by the uneven distribution of temperature change (Fig. 7), the crop NPP simulated by Crop-C also shows a notable spatial variation (Fig. 8). Compared to that in the early 2000s, crop NPP in the late 2040s would increase by 400–700 kg C hm^{-2} in the regions of eastern China (Shanghai, Jiangsu, Zhejiang, and Fujian) and of northwestern China (Gansu, Ningxia, Shanxi, and Shaanxi), while it would decrease by 15–30 kg C hm^{-2} in the regions of northern China (Hebei and Tianjin). These results are consistent with the predicted changes in temperature, i.e., no significant changes in eastern and northwestern China

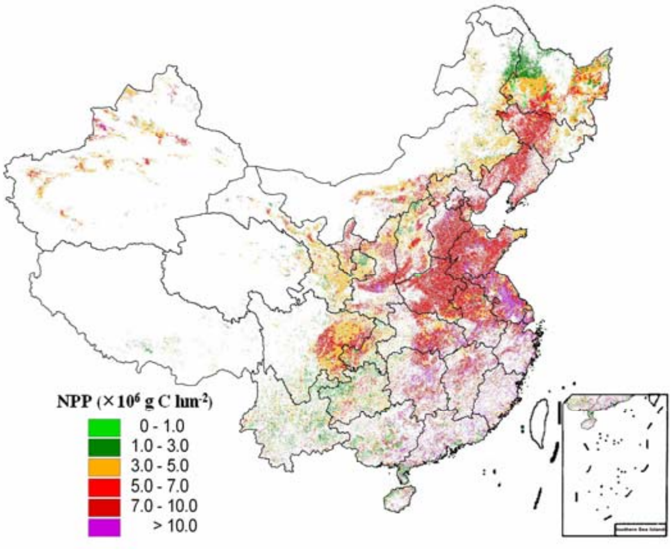

Fig. 5. Spatial distribution of simulated crop NPP in 2000.

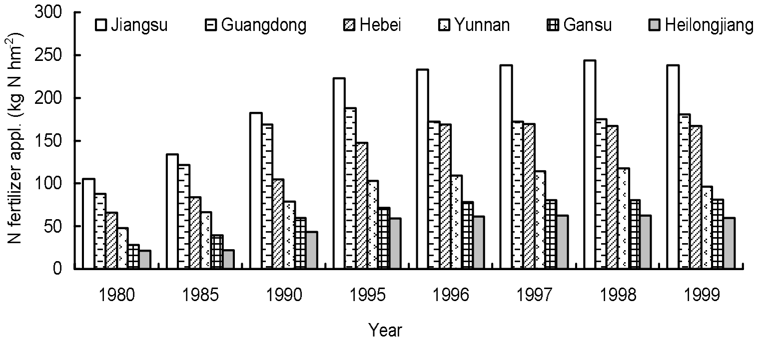

Fig. 6. The application of nitrogen fertilizer in several representative provinces (fertilizer application data taken from National Bureau of Statistics of China, 2000).

but significant increase in northern China (Fig. 7). Crop NPP in the regions of northeastern China (Heilongjiang and Jilin) may also benefit from the climate change. A possible reason is that the increased temperature may favor crop photosynthesis.

On a provincial scale, NPP was predicted to increase by a range of $(0.3-0.7)\times10^6$ g C hm^{-2} in the provinces of Shanghai, Zhejiang, Jiangsu, Fujian, Sichuan, Heilongjiang, Ningxia, Gansu, Qinghai, Shaanxi, Shanxi and Xinjiang. An increase of $(0.2-0.3)\times10^6$ g C hm^{-2} would occur in the provinces of Liaoning, Jilin, Inner Mongolia, Shandong, Henan, Yunnan, Guizhou, Chongqing, Hainan, Guangdong and Guangxi, and $(0.1-0.2)\times10^6$ g C hm^{-2} in the provinces of Hubei, Hunan, and Anhui. NPP would not change greatly in Jiangxi Province but would decline slightly in the provinces of Hebei and Tianjin (Fig. 9).

4.4 *Estimation uncertainties*

Projections of climate change are affected by a range of uncertainties (IPCC, 2001), but an evaluation of these uncertainties is not included in this study. The fact is that the uncertainties in projections of climate change contributed to the estimation uncertainties of Crop-C. Nearly all of the climate change projections believed that both global atmospheric CO_2 abundance and temperature would rise quantitatively with great uncertainties in the future, but that precipitation would vary greatly from one place to another. Usually irrigations are conducted against droughts in the main crop cultivation areas of China. However parameterization of the field irrigation on regional scale is difficult and $F_{\rm w}\geqslant0.7$ was simply assumed (Yang et al., 2004; Gong and Li, 2000). This assumption may over-estimate the increment of crop NPP in the future.

Crop-C combine available knowledge with the pro-

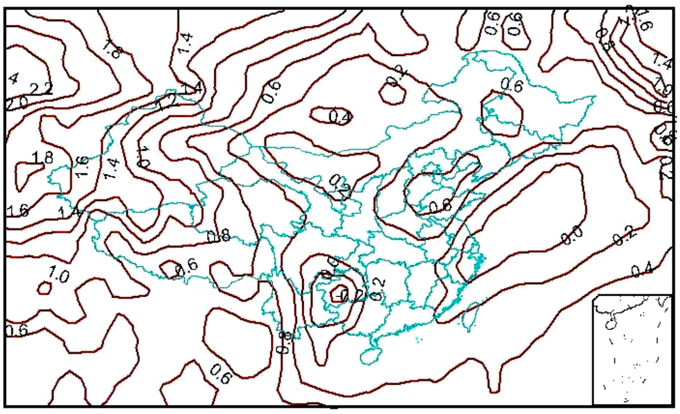

Fig. 7. Predicted changes in air temperature between the early 2000s and the late 2040s (°C).

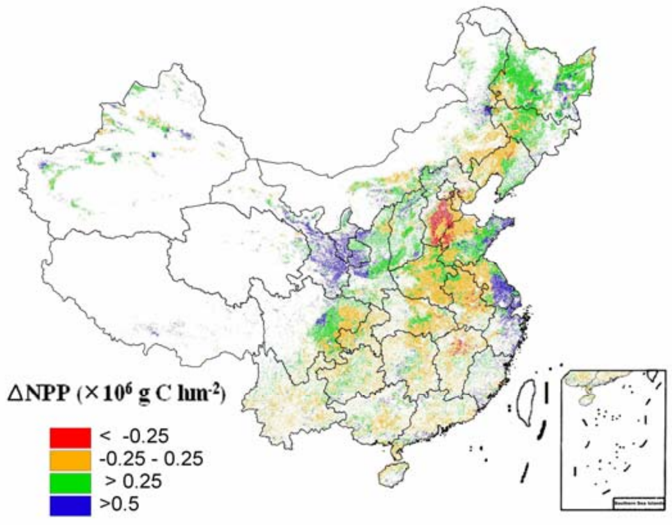

Fig. 8. Changes in simulated crop NPP between the early 2000s and the late 2040s.

cesses involving crop photosynthesis, respiration and partitioning of assimilate. It is difficult to simulate the processes in great detail, and hence simplification is inevitable. Although Crop-C has been validated against observations and statistic data (Wang et al., 2006) showing that the model's performance was reliable in simulating the crop growth of China's main cultivation areas, there are still processes and influences of some factors such as incidence and distribution of pests and pathogens were not included.

Crop physiology may adjust more rapidly to long-term change in the environment and adapt to the changed environments. Bunce (1995) reported that with long-term exposure to high CO_2, the stimulation of plant photosynthesis declined slightly. Usually, the optimum temperature for photosynthesis is at a lower temperature for C3 plants compared to C4 plants (Stone, 2001). Whether these optimum temperatures change in the future as environment temperature increases is not yet clear.

There are other factors that cause uncertainties in crop NPP prediction, including land use change, precision of fertilizer application and soil characteristics etc. To reduce uncertainty caused by these factors, high quality spatial databases of model parameters are expected to be available.

5. Conclusion

Crop NPP in China was simulated from 2000 to 2050 by linking the Crop-C model with climate change scenario projected by the FGOALS model. An annual average increase of 0.6 Tg C yr^{-1} would be possible under A1B scenario. NPP in the late 2040s would increase by 5% (30 Tg C) in contrast with that in the early 2000s. Changes in the NPP would not be

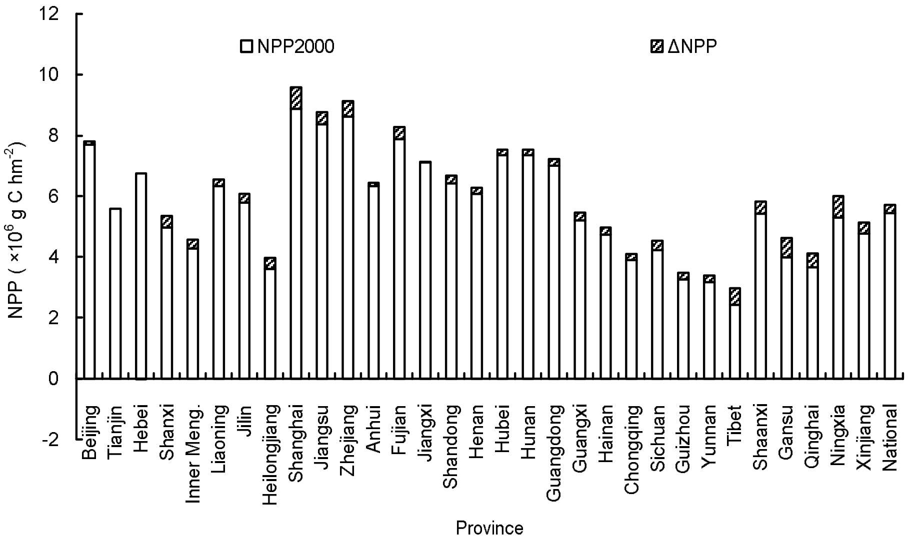

Fig. 9. Changes in simulated crop NPP on a provincial scale.

evenly distributed in China. A higher NPP increment would occur in most regions of eastern and northwestern China, while a slight reduction would appear in the provinces of Hebei and Tianjin in northern China. The spatial characteristics are attributed to the uneven distribution of temperature change.

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