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NET PRIMARY PRODUCTION OF CHINESE CROPLANDS FROM 1950 TO 1999

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Abstract. Considerable efforts have been made to assess the contribution of forest and grassland ecosystems to the global carbon budget, while less attention has been paid to agriculture. Net primary production (NPP) of Chinese croplands and driving factors are seldom taken into account in the regional carbon budget. We studied crop NPP by analyzing the documented crop yields from 1950 to 1999 on a provincial scale. Total NPP, including estimates of the aboveground and belowground components, was calculated from harvested yield data by (1) conversion from economic yield of the crop to aboveground mass using the ratio of aboveground residue production to the economic yield, (2) estimation of belowground mass as a function of aboveground mass, and (3) conversion from total dry mass to carbon mass. This approach was applied to 13 crops, representing 86.8% of the total harvested acreage of crops in China. Our results indicated that NPP in Chinese croplands increased markedly during this period. Averaging for each decade, the amount of NPP was 146 ± 32, 159 ± 34, 260 ± 55, 394 ± 85, and 513 ± 111 Tg C/yr (mean ± SD) in the 1950s, 1960s, 1970s, 1980s, and 1990s, respectively. This increase may be attributed to synthetic fertilizer application. A further investigation indicated that the climate parameters of temperature and precipitation determined the spatial variability in NPP. Spatiotemporal variability in NPP can be well described by the consumption of synthetic fertilizer and by climate parameters. In addition, the total amount of residue C and root C retained by the soils was estimated to be 618 Tg, with a range from 300 to 1040 Tg over the 50 years.

Key words: *agricultural statistics; China; crop yield; net primary production; spatiotemporal variability.*

INTRODUCTION

The CO_2 emitted to the atmosphere by fossil fuel burning and land use change is apparently greater than the amount remaining in the atmosphere and removed by the known sinks (Sundquist 1993). The magnitude, geographical distribution, and causes of a northern midlatitude terrestrial carbon sink are uncertain (Houghton and Hackler 2003). Recent studies suggest a net sink of 1–2.5 Pg C/yr distributed relatively evenly between North America and Eurasia (Prentice et al. 2001, Schimel et al. 2001, Gurney et al. 2002).

Much attention was paid to the contribution of forest and grassland ecosystems to the C sink (Parton et al. 1995, Fan et al. 1998, Houghton et al. 2000, Fang et al. 2001, Janssens et al. 2003), while less attention was paid to agriculture. Prince et al. (2001) estimated net primary production (NPP) from agricultural harvest yield data and indicated that 4–17 $Mg \cdot ha^{-1} \cdot yr^{-1}$ (in dry mass) was produced in U.S. Midwest croplands. Compared with forest and grassland ecosystems, the agriculture ecosystem is artificially controlled to a greater degree through changing cropping systems, fertilization, and irrigation to approach higher production. With the best management practices, Schimel et al. (2000) suggested that U.S. agriculture could remain a modest sink for decades to come. Such sinks are of great importance but have been difficult to quantify.

China is the world's third largest country, most of it within northern midlatitudes. The arable land in 1999 was 124.14 Mha distributed across a vast area spanning wide regions of temperate, subtropical, and tropical climates (Food and Agricultural Organization of the United Nations Statistical Database, FAOSTAT, *available online*).[4] Rice, wheat, maize, rapeseed, soybean, and potato are the main crop species (FAOSTAT). Single-cropping rotations are common in northern, northeastern, and northwestern China, while multi-cropping rotations dominate in central, southeastern, and southern China, where more than one harvest occurs per year on a given patch of cropland. An assessment of NPP in Chinese croplands is helpful in recognizing the role of worldwide agriculture in the global carbon budget. The objectives of this paper are to estimate the amount of NPP in Chinese croplands and the conversion of crop residues to soil organic carbon from 1950 to 1999, to quantify spatiotemporal variability in NPP, and to discuss the potential impact of global warming on NPP

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Table 1. Parameters used for estimating crop net primary production.

Crop, product	Carbon fraction		Dry matter fraction†	Residue : economic product ratio‡	Root : shoot ratio‡
	Product	Residue			
Rice, grain	0.38	0.42	0.85	1.32 (0.38)	0.10 (0.02)
Wheat, grain	0.39	0.49	0.85	1.72 (0.59)	0.11 (0.04)
Millet, grain	0.39	0.46	0.85	1.61 (0.62)	0.11 (0.04)
Maize, grain	0.39	0.47	0.78	1.27 (0.30)	0.09 (0.06)
Sorghum, grain	0.45	0.45	0.91	1.59 (0.50)	0.09 (0.04)
Rapeseed, seed	0.42	0.45	0.90	2.94 (1.04)	0.06 (0.02)
Cotton, unginnned	0.40	0.39	0.90	1.61 (0.68)	0.06 (0.02)
Legume, bean	0.40	0.45	0.85	1.30 (0.46)	0.08 (0.03)
Sesame, seed	0.40	0.45	0.85	5.88 (2.42)	0.15 (0.04)
Potatoes, tuber	0.39	0.42	0.20	0.40 (0.04)	
Sugar beet, tuber	0.39	0.42	0.20	0.45 (0.02)	
Peanut, tuber	0.38	0.38	0.86	1.35 (0.55)	
Sugarcane, stalk	0.42	0.42	0.32	0.80 (0.13)	0.05 (0.02)

Sources: Zhang and Zhu (1990), Miao et al. (1998), Shen (1998), Li et al. (1999), Wan and Kuang (1999), Intergovernmental Panel on Climate Change (2000), Ding et al. (2001), and Zhao and Li (2001).

† We simply assumed the fraction of dry matter in the economic product and in the residue to be the same.

‡ Values in parentheses are standard errors.

in Chinese croplands and the effect of climate and soil on residue conversion.

Materials and Methods

We used crop yield data from the National Agriculture Database (Statistics Bureau of China 2000) to estimate the NPP in croplands. The database documented annual trends from 1950 to 1999 on a provincial scale. Synthetic fertilizer consumption from the same database was used to address the temporal variability in the NPP. The climate database from the China Meteorological Administration was used to evaluate the impact of temperature and precipitation on NPP. Crops studied include rice, wheat, maize, rapeseed, barley, sorghum, legume, sesame, cotton, peanuts, potatoes, sugar beet, and sugarcane, representing 86.8% of the total harvested acreage of crops in China. Because the rest of the cropped area (13.2% of the total) is mainly planted vegetables for which related data sets are not available, no estimates of NPP for these areas were made in this study.

Net primary production was calculated annually for each crop ($i = 1, 2, \ldots, 13$) and each province ($j = 1, 2, \ldots, 30$). Hong Kong, Macao, and Taiwan regions were not taken into account due to a lack of an available database. The total amount of NPP in Chinese croplands was estimated by the summation of NPP for each sector as follows:

$$C = \sum_{j=1}^{30} \sum_{i=1}^{13} C_i S_i \qquad (1)$$

where C is the total amount of NPP, C_i and S_i represent the amount of NPP per unit harvested area and the total harvested area for a given crop, respectively. We calculated the NPP of the economic yield (C_{iy}), aboveground residues (C_{is}), and belowground component (C_{ir}) for each crop. The economic yield referred to unginned cotton for the cotton crop; tubers for the potatoes, sugar beet, and peanut; stalk for sugarcane; and grain for the others. The NPP for a given crop, including rice, wheat, maize, rapeseed, barley, sorghum, legume, sesame, cotton, and sugarcane, was determined by a summation of these three components. Because the economic yield of potatoes, sugar beet, and peanut is the belowground component, NPP for these crops was calculated as a summation of C_{iy} and C_{is}:

$$C_{iy} = y_i \times F_{id} \times F_{icy} \qquad (2)$$

$$C_{is} = y_i \times F_{id} \times R_{iry} \times F_{ics} \qquad (3)$$

$$C_{ir} = y_i \times F_{id} \times (1 + R_{iry}) \times R_{irs} \times F_{icr} \qquad (4)$$

$$C_i = C_{iy} + C_{is} + C_{ir} \qquad (5)$$

where y_i refers to the economic yield per unit harvested area. F_{id} is the dry matter fraction. F_{icy}, F_{ics}, and F_{icr} are the C fractions of the economic yield, residues, and root, respectively, for a given crop. R_{iry} represents the ratio of residue to the economic yield. R_{irs} is the ratio of root to shoot. Table 1 shows the details for these parameters.

Because wide variations existed in the residue/economic product ratio R_{iry} and the root : shoot ratio R_{irs} (Table 1), the lower and upper estimates of NPP were computed under the scenarios of $R_{iry} - \mathrm{SE}$ with $R_{irs} - \mathrm{SE}$ and $R_{iry} + \mathrm{SE}$ with $R_{irs} + \mathrm{SE}$ (Eqs. 3 and 4), respectively. Assuming that 25% of aboveground crop residues (Li et al. 2003) and all the roots in crops of rice, wheat, barley, maize, sorghum, legume, rapeseed, sesame, and cotton were left in the soil, the amount of carbon added into the soil C pools was calculated as follows:

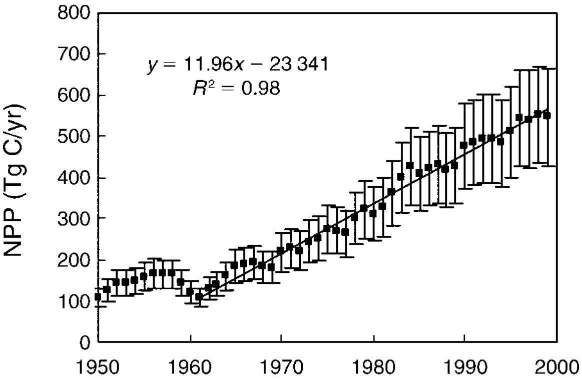

FIG. 1. Changes in crop net primary production (NPP) in China from 1950 to 1999. The vertical bars represent ±SE.

$$C_{\mathrm{soil}} = (0.25 \times C_{\mathrm{res}} + C_{\mathrm{root}}) \times F \quad (6)$$

where C_{soil} is the total amount of residue C and root C retained by the soils (C_{res} and C_{root} are residue C and root C, respectively). The lower and upper estimates of C_{res} and C_{root} were computed via $R_{i\mathrm{ry}}$ ± SE and $R_{i\mathrm{rs}}$ ± SE (Eqs. 3 and 4), respectively. F is a fraction of residue and root carbon converted to soil organic carbon (SOC).

Linear regression and nonlinear regression (SPSS 2000) were used to estimate the relationships between NPP and climate as well as fertilizer use.

RESULTS

Spatiotemporal characteristics of NPP

There has been a considerable increase in NPP observed in Chinese croplands since 1950 (Fig. 1). Averaging for each decade, the amount of NPP was estimated to be 146 ± 32, 159 ± 34, 260 ± 55, 394 ± 85, and 513 ± 111 Tg C/yr (mean ± SD) in the 1950s, 1960s, 1970s, 1980s, and 1990s, respectively. During the period from 1960 to 1999, a steady increase in NPP was observed from 122 ± 37 Tg C/yr in 1960 to 547 ± 119 Tg C/yr in 1999 with a rate of ~12 Tg C/yr (Fig. 1).

On a per unit area basis, NPP was calculated for each decade on a provincial scale to further identify the spatiotemporal patterns. In the 1990s, the area-weighted mean of NPP for different crops was 6.0 ± 1.3 Mg C·ha^{-1}·yr^{-1}. The highest and the lowest amounts were 10.7 ± 1.8 Mg C·ha^{-1}·yr^{-1} in Guangdong and 2.1 ± 0.5 Mg C·ha^{-1}·yr^{-1} in Gansu Province, respectively. Compared with the average value of 1.5 ± 0.3 Mg C·ha^{-1}·yr^{-1} in the 1950s, NPP per unit area increased by approximately 17%, 102%, 212%, and 309% in the 1960s, 1970s, 1980s, and 1990s, respectively.

The spatial distribution of NPP is characterized by higher values in southern and southeastern regions and lower NPP in western, northeastern, and northwestern regions (Fig. 2). An apparent reason is that the climate conditions in the southern and southeastern regions are

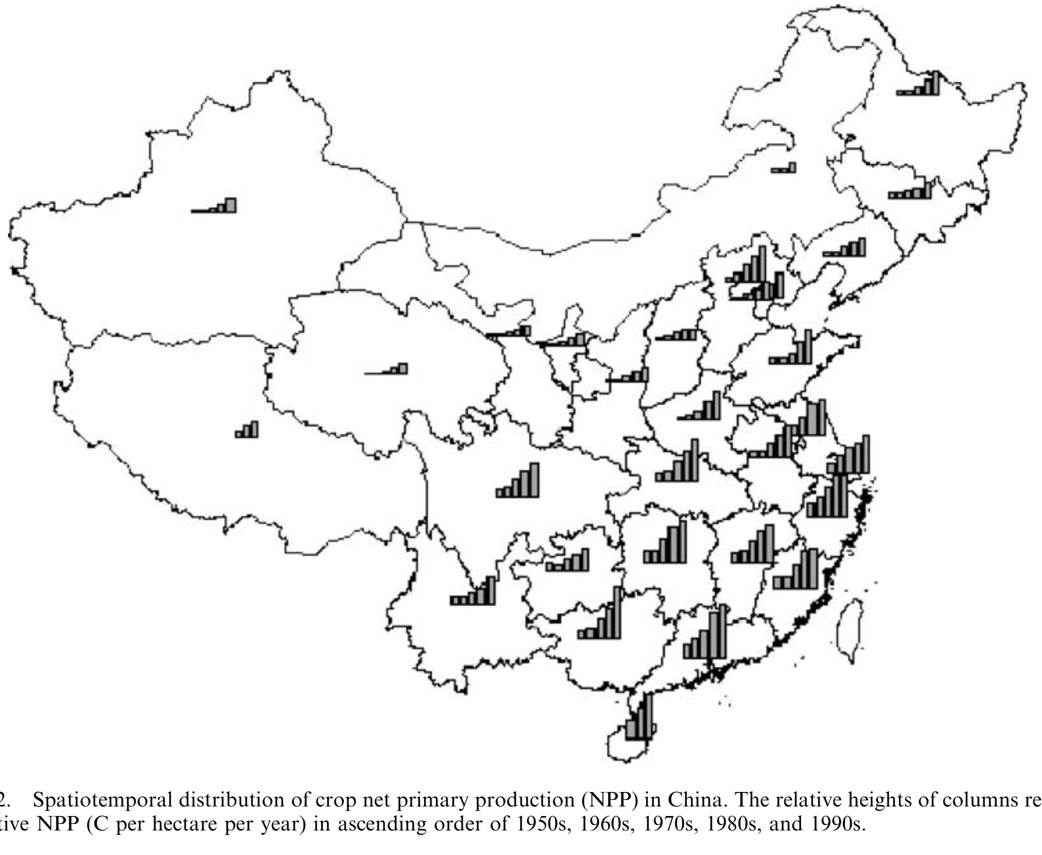

FIG. 2. Spatiotemporal distribution of crop net primary production (NPP) in China. The relative heights of columns represent the relative NPP (C per hectare per year) in ascending order of 1950s, 1960s, 1970s, 1980s, and 1990s.

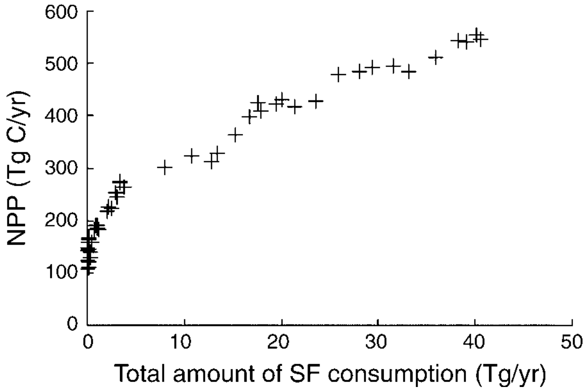

FIG. 3. Relation of net primary production (NPP) to synthetic fertilizers (SF) consumption.

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. Triple crops of rice–rice–rapeseed rotation, for example, prevail in Guangxi province located in southern China, while one harvest is a dominant cropping system in Heilongjiang province located in northeastern China, where lower temperature and less precipitation occur.

NPP with synthetic fertilizer consumption and climate

Consumption of synthetic fertilizers (SF, the sum of synthetic N, P_2O_5, and K_2O) increased markedly over the 50 years. Averaging for each decade, the amount of SF consumption was 0.1, 0.6, 4.2, 17.8, and 34.2 Tg/yr in the 1950s, 1960s, 1970s, 1980s, and 1990s, respectively. Obviously, the increasing application of SF contributed greatly to the NPP (Fig. 3).

In order to assess the impact of climate on NPP, regional means of the accumulated temperature above 0°C (in degree-days) and the total amount of precipitation (in millimeters) were respectively calculated by weighting the areas covered by meteorological stations for each province. Regression analyses indicated that NPP is proportional to the accumulated temperature (Fig. 4a) and the precipitation (Fig. 4b), respectively. Moreover, the proportion expressed as the slope of the liner regression increased with time (Fig. 4, Table 2). This increased proportion was associated with the consumption of SF (Table 2).

Temporal variation in NPP (Y, in megagrams of C per hectare per year) correlated well with the consumption of synthetic fertilizers (SF, in kilograms per hectare per year) for each province by $Y = C_0 \times (1 - B \times \mathrm{EXP}[-k \times \mathrm{SF}])$. Parameters C_0, B, and k are empirical coefficients. The coefficient C_0 represents the maximum amount of NPP for a given province when the supply of synthetic fertilizers is not restricted. Fig. 5 shows the relationships between NPP and SF consumption for the three provinces of Guangxi, Jiangsu, and Hebei. The values of C_0 were estimated to be 18.8, 8.4, and 5.8 Mg C·ha^{-1}·yr^{-1} for the three provinces, respectively. Note that the C_0 is dependent upon the temperature or the precipitation for a given province (Fig. 5), suggesting that great potential in NPP exists in the regions where higher temperature or plentiful precipitation occur. The results shown in Fig. 5 are in accordance with those of Fig. 4.

Based on the results of Figs. 4 and 5, NPP was further correlated with decade-mean climate and yearly fertilizer use on a national scale. Values of the model determination coefficient (R^2) in Table 3 suggest that 38% and 80% of spatiotemporal variability of NPP in Chinese croplands can be explained by climate (either precipitation or temperature) and fertilizer use, respectively. The combination of climate and fertilizer use explained ~90% of the variability (Table 3). There were no improvements in the model determination when the precipitation and temperature were inserted into a single model (Table 3), because the two parameters are linearly

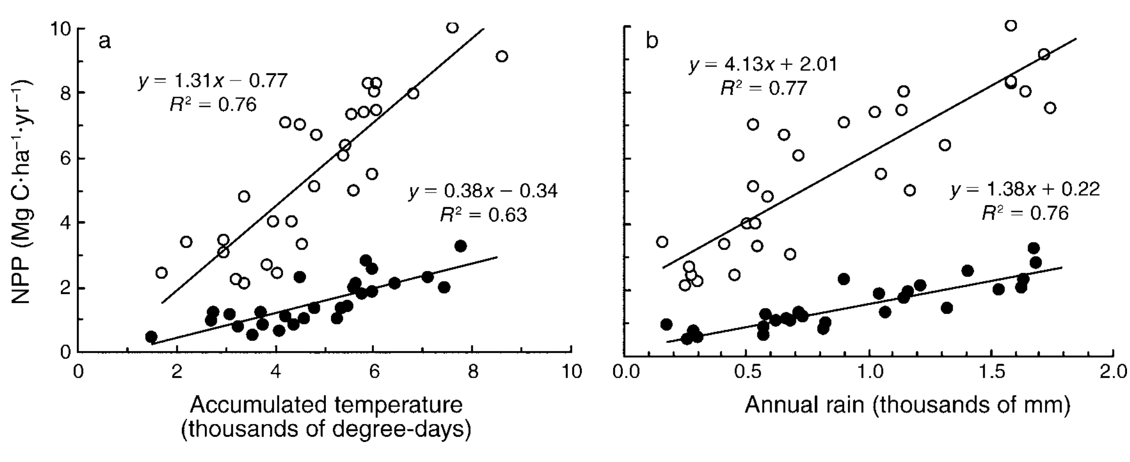

FIG. 4. Correlation of net primary production (NPP) to (a) annual accumulated temperature and (b) annual precipitation. Solid and open circles represent data sets in the 1950s and 1990s, respectively.

TABLE 2. Parameters of net primary production (Y) related to the annual accumulated temperature (T_a), the annual precipitation (p), and the consumption of synthetic fertilizers (SF).

	$Y = K_1 \times T_a + \beta_1$			$Y = K_2 \times p + \beta_2$				
Decade	K_1	β_1	R^2	K_2	β_2	R^2	n	Consumption of SF ($\text{kg·ha}^{-1}\text{·yr}^{-1}$)
1950s	0.38	−0.34	0.63***	1.28	0.22	0.76***	27	1
1960s	0.53	−0.79	0.64***	1.82	0.17	0.69***	27	6
1970s	0.72	−0.52	0.64***	2.73	0.52	0.77***	30	41
1980s	1.06	−0.80	0.66***	4.06	0.77	0.80***	30	188
1990s	1.31	−0.77	0.76***	4.13	2.01	0.77***	30	361

Notes: NPP (=Y) is measured as Mg $\text{C·ha}^{-1}\text{·yr}^{-1}$; annual accumulated temperature is measured as thousands of degree-days; annual precipitation is measured as thousands of mm. The sample size is n.

*** $P < 0.001$.

correlated ($R^2 = 0.78$, $n = 150$). Higher temperature generally accompanied plentiful precipitation in the areas studied.

Contribution of NPP to soil organic carbon from 1950 to 1999

Most studies find the fractions of residue carbon converted to SOC in the range of 0.14–0.22 (e.g., Rasmussen and Collins 1991, Balesdent and Balabane 1996, Lin 1998, Bolinder et al. 1999). The yearly carbon added into the soil C pools via crop residues and roots was calculated by employing Eq. 6 under four scenarios of lower estimates of C_{res} and C_{root} with a smaller conversion factor of 0.14, lower estimates of C_{res} and C_{root} with a larger conversion factor of 0.22, upper estimates of C_{res} and C_{root} with a smaller conversion factor of 0.14, and upper estimates of C_{res} and C_{root} with a larger conversion factor of 0.22, respectively. The yearly mean and standard deviation of residue C and root C retained by the soils were determined from the four scenarios.

The quantity of residue C and root C retained by soil increased gradually (Fig. 6) with the values of 62 ± 32, 67 ± 34, 110 ± 56, 166 ± 85, and 214 ± 111 Tg in the 1950s, 1960s, 1970s, 1980s, and 1990s, respectively. The rates were 0.06 ± 0.03 Mg $\text{C·ha}^{-1}\text{·yr}^{-1}$ in the 1950s and 0.23 ± 0.12 Mg $\text{C·ha}^{-1}\text{·yr}^{-1}$ in the 1990s, respectively. The total amount of residue C and root C retained was estimated to be 618 Tg with a range from 300 Tg to 1040 Tg over the 50 years.

DISCUSSION

Potential impact of global warming on NPP in Chinese croplands

On a global scale, the largest ecosystem differences in NPP are associated with variation in climate and vegetation structure. The NPP of forests correlates most strongly with precipitation and also increases with

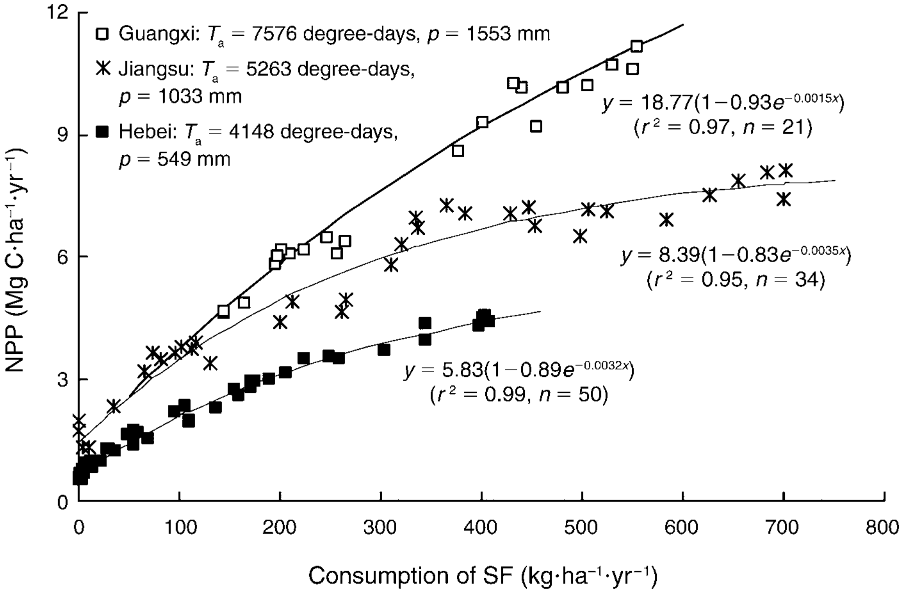

FIG. 5. Correlation of net primary production (NPP) to the consumption of synthetic fertilizers (SF). T_a and p represent the accumulated temperature and annual precipitation, respectively.

TABLE 3. Models and corresponding parameters.

Model	Parameters					
	C_0	C_1	C_2	B	k	R^2
$Y = C_0 + C_1 \times X_1$	−0.95 (0.21)	1.00 (0.04)				0.38***
$Y = C_0 + C_2 \times X_2$	1.11 (0.13)		3.13 (0.13)			0.38***
$Y = C_0 + C_1 \times X_1 + C_2 \times X_2$	−0.20 (0.24)	0.55 (0.08)	1.62 (0.26)			0.41***
$Y = C_0 \times (1 - B \times \mathrm{EXP}(-k \times \mathrm{SF}))$	10.85 (0.09)			0.89 (0.007)	2.10 (0.45)	0.80***
$Y = (C_0 + C_1 \times X_1) \times (1 - \mathrm{B} \times \mathrm{EXP}(-k \times \mathrm{SF}))$	1.98 (0.20)	1.12 (0.03)		0.81 (0.007)	3.54 (0.18)	0.90***
$Y = (C_0 + C_2 \times X_2) \times (1 - B \times \mathrm{EXP}(-k \times \mathrm{SF}))$	4.01 (0.13)		3.47 (0.08)	0.81 (0.006)	4.14 (0.18)	0.92***
$Y = (C_0 + C_1 \times X_1 + C_2 \times X_2) \times (1 - B \times \mathrm{EXP}(-k \times \mathrm{SF}))$	3.11 (0.19)	0.33 (0.06)	2.62 (0.16)	0.81 (0.007)	4.11 (0.18)	0.92***

Notes: Key to variables: Y, net primary production; X_1, annual accumulated temperature; X_2, annual precipitation; SF, synthetic fertilizer use. C_0, C_1, C_2, B, and k are regression coefficients. Values in parentheses are standard errors ($n = 988$ samples).

*** $P < 0.001$.

increasing temperature (Chapin et al. 2002). It is not surprising that NPP of Chinese croplands is positively correlated with temperature (Fig. 4a) and precipitation (Fig. 4b), because the crop rotation index, defined as the cropping cycles within one year for a given arable soil, increased with temperature (Fig. 7a) and precipitation (Fig. 7b). Consequently, NPP increased as the crop rotation index increased (Fig. 8).

The globally averaged surface temperature is projected to increase by 1.4–5.8°C over the period 1990 to 2100 (IPCC 2001). The corresponding atmospheric CO_2 concentrations by 2100 are 540 ppm and 970 ppm, respectively. Under the scenario of a 1.4°C increase, the crop rotation index would increase by 0.118 when the relationship in Fig. 7a is employed. As a result, NPP of Chinese croplands will increase by 11% as compared with that in 1999. When we take CO_2 fertilization (Chapin et al. 2002) into account, NPP will increase by 9% to 19%. Thus, an overall increase in NPP of Chinese croplands would be 20–30% under the scenario of 1.4°C increase in temperature and atmospheric CO_2 concentration of 540 ppm.

Global warming would 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. According to the People's Republic of China Initial National Communication on Climate Change, global warming would expand the triple cropping region by ~500 km northward in China and the corresponding acreage would increase by 22.5% (China Climate Change Info-Net, *available online*).[5] From this point of view, crop NPP in China would benefit from global warming. However, increased temperature may accelerate plant respiration, resulting in less than optimal conditions for NPP. Moreover, if the temperature increases, a shortage of available soil water in some regions would occur because of increasing evapotranspiration. The increased plant respiration and the reduced available soil water will have a negative impact on crop NPP. Besides, crops may become acclimatized when global warming occurs gradually. Impacts of global warming on NPP are complex and have great importance, but have been difficult to evaluate. It is therefore necessary to take both positive and negative impacts into account so that the uncertainties in addressing the influence of global warming on NPP could be reduced.

Effect of climate and soil on residue conversion

There is no doubt that the increasing NPP in Chinese croplands (Fig. 1) augmented the amounts of residue and root conversion to SOC (Fig. 6), but the conversion efficiency may vary in different regions. Several long-term field experiments indicate a wide range of the residue C conversion coefficients (Table 4). It is noteworthy that the values of the coefficient depend on the mean annual temperature in general, while neither on the annual precipitation nor on the initial concentration of SOC. Higher conversion efficiency occurred in the cold regions (Table 4). Soil texture is known to affect the retention of organic matter from crop residues. With the same input of organic material, clay soils usually contain more organic carbon than sandy soils (Jenkinson 1988). Annual increase in SOC

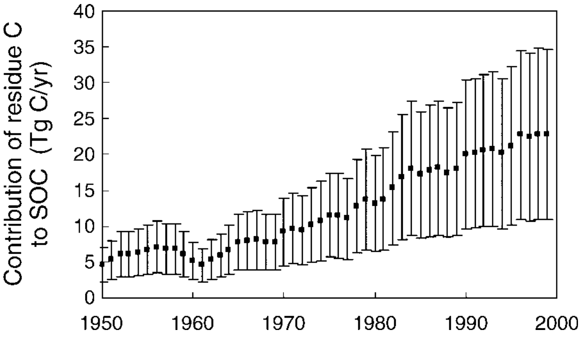

FIG. 6. Contribution of net primary production carbon to soil organic carbon (SOC) from 1950 to 1999. Vertical bars represent ±SD from four calculations.

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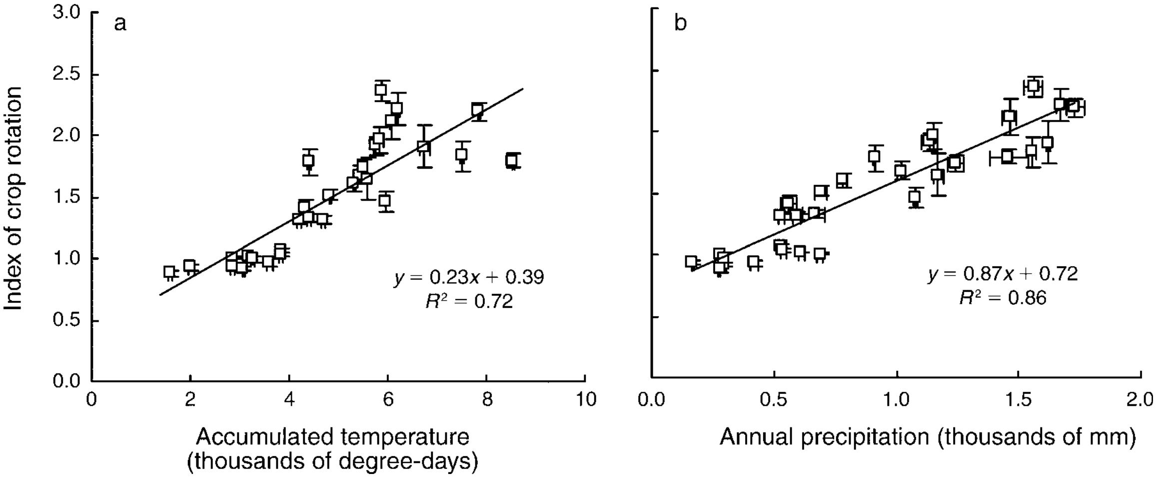

FIG. 7. Dependence of crop rotation index on (a) temperature and (b) precipitation. Error bars indicate ±SD from the records of the five decades. See *Discussion: Potential impact of global warming on NPP in Chinese croplands* for a description of the crop rotation index.

was found to positively correlate with clay content of the soil (McConkey et al. 2003). In addition, composition of the residue C source (Bolinder et al. 1999, Martens 2000) and tillage (Duiker and Lal 1999, Allmaras et al. 2004) are also known to affect the residue conversion.

Temperatures in China generally increase from north to south with an annual mean of ~8.6°C on a national scale. The temperature gradient is ~28.5°C from Heilongjiang Province in the northernmost region to Hainan Province in the southernmost region (Chinese Academy of Sciences 1990). With respect to the soils, 12 categories of soil texture were documented in China where loamy, sand, and clay soils account for approximately 60%, 20%, and 20% of the total area, respectively (Office for Soil Survey of China 1998). The great diversities in temperature and soil texture might have introduced spatial uncertainties in the quantity of C retained in this study, though we adopted the conversion factors of 0.14 and 0.22 to estimate a range for the residue C retained. Underestimation in northern China and/or overestimation of the residue C retained by soils in southern China are possible in view of temperature distribution. Further studies on the conversion factor associated with climate and soils are necessary to get a more reliable estimation of the residue conversion to SOC.

TABLE 4. Residue C conversion coefficients summarized from 14 studies.

				Soil
Site	Location	T	p (mm)	Depth (cm)
Mishan, Heilongjiang, China	45°33′ N, 131°52′ E	3.2	493	0–20
St-Lambert, Québec, Canada	45°30′ N, 73°30′ W	4.0	1200	0–30
Fukang, Xinjiang, China	44°17′ N, 87°55′ E	6.6	164	0–25
Rosemount, Minnesota, USA	44°40′ N, 93°07′ W	7.0	820	0–15
Akron, Colorado, USA	40°25′ N, 103°25′ W	9.2	424	0–15
Halle, Germany	51°31′ N, 12°00′ E	9.2	465	0–65
Sterling, Stratton and Walsh, Colorado, USA	40°22′ N, 103°08′ W–37°14′ N, 102°10′ W	9.5–11.8	410–440	0–10
Zunhua, Hebei, China	40°12′ N, 117°57′ E	10.4	775	0–20
Ludhiana, India	30°54′ N, 75°08′ E	10.5	800	0–15
Waterman Farm, Ohio, USA	40°00′ N, 83°01′ W	11.0	932	0–10
Fengqiu, Henan, China	35°00′ N, 114°24′ E	13.9	605	0–20
Davis, California, USA	38°32′ N, 121°52′ W	15.5	462	0–15
Ponta Grossa, Paraná State, Brazil	25°20′ S, 50°20′ W	18.7	1545	0–10
Tibagi, Paraná State, Brazil	24°36′ S, 50°23′ W	20.7	1532	
Barrackpore, India	22°45′ N, 88°26′ E	26.9	1698	0–30
Akola, India	20°42′ N, 77°02′ E	27.1	825	0–30

Note: Key to variables and abbreviations: T, mean annual temperature; p, mean total annual precipitation; SCL, silt clay loam; SL, silty loam; SDL, sandy loam; CL, clay loam; L, loam; LS, loamy sand; SCL, silty clay loam; FL, fine loamy; C, clayey; SDCL, sandy clay loam; SOC, soil organic carbon; na, not available.

† Calculated as the ratio of SOC change to total C input.

‡ Estimated from the nonlinear relationship between aboveground stover inputs and SOC (Sherrod et al. 2003).

While estimating the residue C retained, it is not possible from this study, nor is it the intention, to quantify carbon sequestration, because losses of carbon from decomposition offset some of the gain from residue conversion to soil C. Moreover, the carbon loss from decomposition is complex (Jenkinson 1988, Chapin et al. 2002), and no simple approach could be applied to estimate the carbon losses from Chinese croplands that are distributed across a vast area with various climates, soils, and cropping systems. Nevertheless, the estimation of residue conversion to soil C in this study is helpful in understanding the contribution of crop NPP to SOC.

Some investigations (Lal 2002, Li et al. 2003, Wu et al. 2003) suggested that Chinese agricultural soils are losing C, while more recent investigation conducted by Huang and Sun (2006), who pooled and analyzed a mass of data sets from 132 articles published since 1993, indicated that the concentration of topsoil (20 cm) organic carbon increased in 53–59%, decreased in 30–31%, and stabilized in 4–6% of the Chinese croplands. An overall increase in SOC was estimated to be 311–401 Tg over the last two decades (Huang and Sun 2006). Our estimation suggested that the total amount of residue C and root C retained by the soils was 300–1040 Tg with a mean value of 618 Tg over the last 50 years. It must be noted that the manure amendment was not taken into account in the current estimates, though the manure comes partly from the crop residues. Gao et al. (2002) reported that 22.6% of harvested crop residue was used as animal fodder in China. According to Li et al. (2003), the amount of manure C incorporation into the croplands in China is ~45% higher than the residue C inputs, which should contribute to SOC greatly.

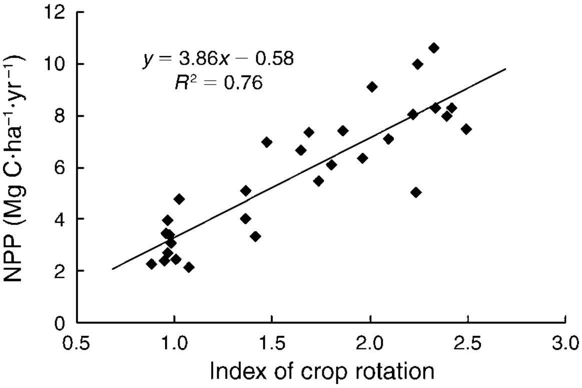

FIG. 8. Dependence of net primary production (NPP) on crop rotation index in the 1990s.

CONCLUSION

With an increasing application of synthetic fertilizer, NPP in Chinese croplands increased markedly from 1950 to 1999. The amount of NPP was 146 ± 32 Tg C/yr in the 1950s and 513 ± 111 Tg C/yr in the 1990s. Consequently, the total amount of residue C and root C retained by the soils was estimated to be 618 Tg, with a range from 300 to 1040 Tg over the 50 years. Net primary production was spatially determined by the climate parameters of temperature and precipitation and temporally determined by the consumption of synthetic fertilizer. The spatiotemporal variations of NPP can be mathematically described by a combination of climate and synthetic fertilizer use. Under the scenario of a 1.4°C increase in temperature and atmospheric CO_2 concentration of 540 ppm, increase in NPP of Chinese croplands would be possible, but great uncertainties remain.

TABLE 4. Extended.

Soil		Years of experiment	Conversion coefficient (%)	Source
Surface texture	Initial SOC (g/kg)			
SCL	20.3	9	21.8†	Tian et al. (2004)
SL	33	15	17	Bolinder et al. (1999)
CL	4.5	9	17.6†	Zhou and Wang (2003)
SL	~28	13	11–26	Allmaras et al. (2004)
SL	6.9	11	11–30	Halvorson et al. (1999)
SDL	14.9	37	31	Flessa et al. (2000)
CL, L, LS, SDL, SCL	2.7–19.2	13	~25‡	Sherrod et al. (2003)
FL	7.1	8	10.7–12.5†	Han et al. (2003)
LS	3.6	11	6.6–10.4†	Yadvinder-Singh et al. (2004)
SL	~8.5	8	8–10	Duiker and Lal (1999)
SL	5.8	13	10.2	Meng et al. (2005)
SL, SCL	na	10	7.6	Kong et al. (2005)
C	na	10–22	~11.9	Sá et al. (2001)
SDCL	7.1	29	6.1†	Manna et al. (2005)
C	4.6	14	14†	Manna et al. (2005)

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