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ARTICLE

Effects of nitrogen input and climate trends on provincial rice yields in China between 1961 and 2003: quantitative evaluation using a crop model

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Abstract Analyses of the technological and climatic factors that influence regional yield can provide insights into how production systems can be improved in the future. We analyzed the effects of changes in climate and nitrogen input on the time course of rice yields of nine rice-producing provinces in China for the period between 1961 and 2003. We developed a regional-scale model that considered both climate and nitrogen flow in the rice paddy. Observed yields (Y_{obs}) tripled during the period, of which 65 % of the increase was accounted for by the estimated yield (Y_{est}) based on changes in nitrogen input and climate. The remaining 35 % was attributed to other technological factors ($\alpha = Y_{obs}/Y_{est}$), which include improvements in cultivars and pest management, for example. Contribution of α became pronounced after 1980 and accounted for 69 and 90 % of the yield increases in the 1980s and 1990s, respectively. Nitrogen input had much greater impacts on Y_{est} (90 %) than did climate, but Y_{est}/nitrogen input dropped substantially. Significant positive effects were observed for CO_2 fertilization effects, which differed significantly among provinces; their relative contribution to the increase in Y_{est} ranged from 1.0 to 7.4 %. The effect of temperature change on Y_{est} was negative and significant in three provinces, but not for the overall average. To meet future rice demand and to improve nitrogen use efficiency, full use of possible positive interactions among cultivars, nitrogen management, and climate is required.

Keywords Crop model · Global environmental change · N fertilizer · *Oryza sativa* L. · Provincial yield

Introduction

Rice (*Oryza sativa* L.) is the primary staple food for more than half of the world's population, produced and consumed mainly in Asia (FAO 2013). The world rice production has almost tripled since 1960, owing primarily to increases in yield per unit area rather than in production area. Demand for rice is expected to increase by about 30 % from 2005/2007 to 2050 (Alexandratos and Bruinsma

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2012). However, the increases in rice yield have started to slow in some Asian countries (Cassman et al. 2003; Horie et al. 2005; Peng et al. 2009). Vulnerability of the rice production system to climate change will also have significant impacts on the world food market and even a small variation in production can result in substantial fluctuation in price (IPCC 2014). Technological development to meet demand under the effects of climate change is one of the major challenges faced by food production systems.

The dramatic increase in grain yield in the second half of the twentieth century resulted from a number of factors, including improved cultural practices, breeding, agricultural chemical use, climate trends, and combinations of these factors (Evans 1993; Cassman et al. 2003). A quantitative understanding of how these factors contribute to regional yields is useful for identification of current problems and future directions for improvement of productivity. Statistical analyses have been a common approach to evaluate the trends and/or fluctuations in past yields (e.g. Lobell et al. 2011), but because multiple factors have changed concurrently, it is often difficult to untangle the effects of single factors and interactions among them.

Nitrogen (N) fertilizer is a major driver of the increase in crop production. It increases leaf area, canopy light interception, and the rate of photosynthesis per unit leaf area, all of which lead to an increase in biomass. On the other hand, heavy use of N has increased the environmental load from rice agriculture (Cassman et al. 2003; Shindo et al. 2006; Shindo 2013). Future rice production must meet the growing food demand while reducing the environmental load from agriculture. In particular, this has become a major concern in China, which accounts for about 28 % of world rice production and 34 % of global N fertilizer consumption (as of 2011; FAOSTAT http://faostat3.fao.org/).

Statistical analyses of recent climate trends on rice yields have detected some significant effects of climatic factors, but they often differed in magnitude and even in sign depending on the region (Tao et al. 2006, 2008; Zhang et al. 2010; Zhou et al. 2013). Climatic factors affect rice growth and yield via multiple processes and their effects are often nonlinear. The effects can also be modulated by management or cultivars, and these interactions are difficult to determine with empirical models that do not consider the mechanisms of these effects. Crop models that account for crop responses to climate and management factors are a useful tool for quantifying the factors responsible for change in production over years. Recent studies have attempted to identify the effects of climate trends or cultivar improvements on the historical yield change using crop models (Xiong et al. 2012; Yu et al. 2012; Xiao and Tao 2014). However, because efficient use of resources such as nutrients and water will become a central issue for food production, there is a need to implement model analyses to explore productivity and resource use efficiency under global climate changes.

Previously, we developed a crop model for regional rice yield in rain-fed lowland areas based on crop water use (Hasegawa et al. 2008). This model is useful for estimating crop yield with a small number of environmental variables, but does not account for two important factors that influence crop production under limited resources: N balance (soil N supply, N fertilizer use, and crop N uptake), which is essential for evaluation of environmental load from arable land, and the effect of atmospheric CO_2 concentration on crop water use. On the other hand, field-scale detailed simulation models are already available for rice (e.g., Hasegawa and Horie 1997), but they require data for a number of field- and cultivar-specific parameters if they are to be applied to a regional scale.

In this study, we first modified our regional model to evaluate the effect of crop management and climatic factors on the historical changes in crop production based on our regional-scale rice yield model (Hasegawa et al. 2008) by incorporating a simple nitrogen dynamics in rice paddy field (Hasegawa and Horie 1997). We then applied this model to quantify the effects of factors associated with the time course of rice production in East Asia, using the example of China, which experienced a very rapid change in crop production and N use in the second half of the twentieth century. Because crop responses to climatic factors or N inputs are often nonlinear, we predicted that contributions of the factors would differ depending on climate zones and/or input levels.

Materials and methods

Model structure

We combined two existing models into a new simulation model driven by agrochemical and crop water use for regional-scale agricultural productivity (SACRA). SACRA is principally based on our previous regional-scale model (Hasegawa et al. 2008), but incorporates N dynamics from a field-scale rice model (Hasegawa and Horie 1997). SACRA also accounts for the effects of atmospheric CO_2 concentration ($[CO_2]$) on crop water use and water use efficiency (WUE). The main features of the model are summarized below.

N dynamics in a rice field

The model assumes a single inorganic N pool (N_{pool}) in the soil as a source of N supply to the plants. N_{pool} varies during the crop growing season owing to the inflow and outflow to and from N_{pool}. In the actual paddy ecosystems, the inflow includes fertilizer N supply, mineralized soil and manure N, N from the atmosphere (deposition) and in irrigation water, whereas the outflow includes N uptake by plants and N loss to the atmosphere, ground or surface water outside the paddy fields. In croplands, fertilizers and soil organic matter generally dominate other sources of N (Liu et al. 2011), although recent studies show nonnegligible contributions from the atmosphere (He et al. 2010; Katayanagi et al. 2013) and irrigation water (Kyaw et al. 2005). In this study, we used the following components to estimate daily changes in the N_{pool} in the plow layer $\mathrm{d}N_{\mathrm{pool}}/\mathrm{d}t$:

$$\mathrm{d}N_{\mathrm{pool}}/\mathrm{d}t = N_{\mathrm{f}} + \mathrm{d}N_{\mathrm{m}}/\mathrm{d}t - \mathrm{d}N_{\mathrm{up}}/\mathrm{d}t - \mathrm{d}N_{\mathrm{loss}}/\mathrm{d}t, \tag{1}$$

where t is the unit of time for calculation (day), and $\mathrm{d}N_{\mathrm{m}}/\mathrm{d}t$, $\mathrm{d}N_{\mathrm{up}}/\mathrm{d}t$, and $\mathrm{d}N_{\mathrm{loss}}/\mathrm{d}t$ are the rates of soil N mineralization, crop N uptake, and N loss from rice fields, respectively. Organic N is a major source for crop N uptake and the rate of change in mineralization of soil and manure N is given as the first-order rate equation (Sugihara et al. 1986)

$$\mathrm{d}N_{\mathrm{m}}/\mathrm{d}t = k_{\mathrm{m}} N_{\mathrm{o}} \mathrm{e}^{-k_{\mathrm{m}} t} \tag{2}$$

$$k_{\mathrm{m}} = A_{\mathrm{m}} \mathrm{e}^{-E_{\mathrm{m}}/(R(T+273))}, \tag{3}$$

where A_{m} is a constant for wet soil, E_{m} is apparent activation energy for $\mathrm{d}N_{\mathrm{m}}/\mathrm{d}t$, T is temperature in °C, R is the gas constant, and N_{o} is the mineralization potential, which represents the capacity of soil N supply during the growing season. In this study, we also account for organic fertilizer applied:

$$N_{\mathrm{o}} = N_{\mathrm{o,soil}} + N_{\mathrm{o,manure}}, \tag{4}$$

where $N_{\mathrm{o,soil}}$ is the N_{o} from the indigenous soil organic matter and $N_{\mathrm{o,manure}}$ is that from the applied manure. $N_{\mathrm{o,soil}}$ may vary with soil type, but in this study we fixed this value as 70 kg ha^{-1}, which is commonly observed in the paddy field in temperate regions (Toriyama 2002). $N_{\mathrm{o,manure}}$ is expressed as a function of applied organic manure, which we derived from various incubation studies by Sugihara et al. (1986):

$$N_{\mathrm{O,manure}} = -3.34 \times 10^{-8} \mathrm{N}_{\mathrm{ma}}^{3} + 1.68 \times 10^{-5} N_{\mathrm{ma}}^{2} - 2.07 \times N_{\mathrm{ma}} + 0.172, \tag{5}$$

where N_{ma} is manure N fertilizer input (g m^{-2}).

Crop N uptake is limited by crop demand for N or soil N supply (Seligman et al. 1975). The crop demand for N (N_{dem}) is driven by the daily biomass gain and maximum crop N concentration ($\mathrm{NC}_{\mathrm{max}}$, g g^{-1}).

$$\mathrm{d}N_{\mathrm{dem}}/\mathrm{d}t = NC_{\mathrm{max}} \times \mathrm{d}W/\mathrm{d}t \tag{6}$$

$\mathrm{NC}_{\mathrm{max}}$ decreases as the crop biomass increases (Greenwood et al. 1991) and is expressed as:

$$NC_{\mathrm{max}} = 0.0040\mathrm{e}^{-c_1 B}, \tag{7}$$

where B is the total biomass (g m^{-2}), and c_1 is an empirical constant. The rate of crop N uptake ($\mathrm{d}N_{\mathrm{up}}/\mathrm{d}t$) is limited by the smaller of N_{dem} or N available in the N pool (N_{avl}):

$$\mathrm{d}N_{\mathrm{up}}/\mathrm{d}t = \min(dN_{\mathrm{dem}}/\mathrm{d}t, \mathrm{d}N_{\mathrm{avl}}/\mathrm{d}t) \tag{8}$$

$$N_{avl} = N_{pool} \times f(B), \tag{9}$$

where $f(B)$ is the empirical function for relative degree of root system development, with the maximum being 1:

$$f(B) = \min(c_2 \times \mathrm{e}^{c_3 B}, 1) \tag{10}$$

where c_2 and c_3 are constants. The loss of N from rice fields can occur through several pathways such as denitrification, volatilization, runoff, and leaching, but we assumed that N_{loss} is proportional to the N_{pool}. We set the relative loss rate at 0.03 day^{-1} as used in Hasegawa and Horie (1997).

Crop growth

Leaf area development and fraction of light intercepted by canopy

Leaf area index (LAI) increase is highly dependent on N availability in the soil. The allometric relation between leaf area and crop N has been used in some crop models (Hasegawa and Horie 1997; Yin et al. 2003; Lemaire et al. 2007). When N supply is limited, old leaves translocate their N to developing leaves (Yoneyama and Sano 1978; Gastal and Lemaire 2002), so that leaf area continues to grow at the expense of decreased N concentration in the crop organs (i.e., dilution). Translocation can occur without the death of lower leaves as long as N concentration exceeds the lowest limit of plant N concentration. Expansion of leaf area at a given N availability is also dependent on temperature (Hasegawa et al. 1999). Daily LAI increase was principally expressed as a function of daily N uptake and daily temperature as follows:

$$\mathrm{dLAI}/\mathrm{d}t = \mathrm{LPN} \times \mathrm{d}N_{\mathrm{up}}/\mathrm{d}t \times (1 - (\mathrm{DVI}/1.8)^{c_4} \times (1 + \mathrm{e}^{-c_5 \times (T - c_6)})^{-1}, \quad \text{when } \mathrm{d}N_{\mathrm{up}} < N\mathrm{a}_{\mathrm{vl}}, \tag{11}$$

where LPN is the maximum LAI production per unit N uptake, T is temperature, c_4 to c_6 are empirical coefficients, and DVI is the value of the developmental index from the crop phenology model. The amount of N that can be transferred for leaf development is described as

$$N_{\mathrm{trans}} = TN_{\mathrm{up}} - NC_{\mathrm{min}} \times B \tag{12}$$

$$\mathrm{dLAI}/\mathrm{d}t = \mathrm{LPN} \times \left(\frac{\mathrm{d}N_{\mathrm{up}}}{\mathrm{d}t} + N_{\mathrm{trans}}/c_7\right) \times (1 - (\mathrm{DVI}/1.8)^{c_4} \times (1 + \mathrm{e}^{-c_5 \times (T - c_6)})^{-1}, \quad \text{when } dN_{\mathrm{up}} \geq N_{\mathrm{avl}}, \tag{13}$$

where N_{trans} is the translocated N, TN_{up} is the total amount of crop N uptake for leaf development, and c_7 is a time constant for translocated N. The enhanced canopy cover accelerates daily biomass gain by increasing the light interception. The fraction of light interception (FLI) by the canopy is obtained using Beer's Law:

$$\mathrm{FLI} = 1 - \mathrm{e}^{-k \times \mathrm{LAI}}, \tag{14}$$

where k is the extinction coefficient of the canopy, which we set to a constant value of 0.55.

Crop water use, biomass accumulation, and grain yield

Crop carbon assimilation results from canopy CO_2 exchange and the conversion of photosynthate into biomass. These processes are mainly driven by three environmental factors: solar radiation, CO_2 supply, and water, and most existing crop models incorporate these factors. In this study, we used a water-driven approach to model rice growth as in Hasegawa et al. (2008) and Steduto et al. (2009), because this approach approximates well the resource-limited growth and yield (Steduto et al. 2009).

Biomass (B) increases in proportion to crop water use so that WUE is relatively unaffected by other environmental factors (Gregory 2004). However, vapor pressure deficit (VPD) has a strong effect on WUE and should be considered when the model is applied to a range of climatic zones. To account for the effect of VPD, we first converted VPD (hPa) to vapor concentration deficit (VCD; kg m^{-3}) using the equation of the state of an ideal gas and then calculated the adjusted WUE ($\mathrm{WUE_v}$; g kg^{-1}) using VCD (Sinclair et al. 1984):

$$\mathrm{VCD} = \frac{n\mathrm{VPD}}{R(T + 273)} \tag{17}$$

$$\mathrm{WUE_v} = K_{\mathrm{t}}/\mathrm{VCD}, \tag{18}$$

where n is the molecular weight of water, R is the gas constant, T is the temperature in degrees Celsius, K_{t} is the proportionality factor of crop water use to biomass (uncorrected WUE). We set K_{t} at 30.8×10^{-3} g m^{-3} based on the observation of rice plants by Adachi (1997). Atmospheric CO_2 concentration ($[CO_2]$) has a significant effect on WUE through enhancement of CO_2 assimilation. This effect needs to be incorporated in a long-term yield analysis as $[CO_2]$ has increased by as much as 25 % in the period between 1960 and 2009 (http://www.esrl.noaa.gov/gmd/ccgg/trends/). WUE can sometimes be approximated by a linear function of $[CO_2]$, but this could potentially overestimate the effect of $[CO_2]$ because under high $[CO_2]$ assimilation is not limited by CO_2 supply (Farquhar et al. 1980). We therefore used a Michaelis–Menten-type rectangular hyperbola function for the $[CO_2]$-dependent WUE ($\mathrm{WUE_{cv}}$):

$$\mathrm{WUE_{cv}} = \mathrm{WUE_v} \times c_8[\mathrm{CO_2}]/(\mathrm{K_c} + [\mathrm{CO_2}]) \tag{19}$$

where K_{c} is the Michaelis–Menten coefficient, and c_8 is an empirical parameter. We estimated c_8 and K_{c} based on a free-air CO_2 enrichment experiment, in which WUE increased by 19 % with an increase in CO_2 concentration of 200 μmol mol^{-1} (Yoshimoto et al. 2005) ($c_8 = 1.882$; $K_{\mathrm{c}} = 341.283$). Crop water use depends on three factors: physical evaporative demand, canopy establishment, and stomatal conductance. The physical evaporative demand can be approximated by the Food and Agriculture Organization of the United Nations (FAO) reference evapotranspiration (mm day^{-1}) modified by Ishigooka et al. (2008) ($\mathrm{ET_0}$). We used FLI to represent the degree of canopy cover. $[CO_2]$ also affects transpiration of the canopy via decreased stomatal conductance. Taken collectively, crop water use (CWU; mm day^{-1}) can be approximated as:

$$\mathrm{CWU} = \mathrm{ET_o} \times (c_9[\mathrm{CO_2}] + c_{10}) \times \mathrm{FLI}, \tag{20}$$

where c_9 and c_{10} are empirical coefficients. Parameters c_9 and c_{10} were also estimated based on the FACE experiment (Yoshimoto et al. 2005), where transpiration decreased by 8.2 % in response to $[CO_2]$ elevated by 200 μmol mol^{-1} ($c_9 = -0.00041$, $c_{10} = 1.15867$).

Finally, biomass growth and grain yield (Y) are determined as:

$$\mathrm{d}B/\mathrm{d}t = \mathrm{WUE_{cv}} \times \mathrm{CWU} \tag{21}$$

$$Y = \mathrm{HI} \times B, \tag{22}$$

where HI is the harvest index, set at 0.488 as a representative value for modern high-yielding varieties planted in Asian countries, based on the mean HI observed in a variety trial (Cui et al. 2000). HI has been substantially improved through breeding over the period studied (Evans 1993), but we have rather used the fixed HI to evaluate technological improvement including breeding as detailed in the subsequent section for analysis of factors that affected historical yield change.

Study area

We selected nine major rice-growing provinces in China (Table 1), which produced about 80 % of the total rice production in 2004. The nine provinces ranged from about 20 to 50°N and thus covered the range of climates in the major rice-growing regions of East Asia.

Table 1 Climatic variables, N fertilizer input, cropping systems, and trends in temperature, and N fertilizer application in the nine major rice-producing provinces in China

Province	Latitude of the capital city	Mean air temperature from April to November[a,b]	Mean daily solar radiation from April to November[a,b,c]	Statistical yield[d,g]	Nitrogen fertilizer input[e,g]	Ratio of area for each cropping type[f,g]			Temperature trend (±S.E.)[h]	Nitrogen fertilizer trend (±S.E.)[h]
	°N	°C	MJ m^{-2}	t ha^{-1}	kg ha^{-1}	Early	Inter-mediate	Late	°C $decade^{-1}$	kg ha^{-1} $decade^{-1}$
Heilongjiang	48.0	10.9	15.2	5.66	67.8	–	1.00	–	0.31 ± 0.070***	18.6 ± 1.07***
Jilin	43.7	13.2	15.3	7.01	181.0	–	1.00	–	0.23 ± 0.071**	53.6 ± 2.65***
Liaoning	41.1	15.7	16.1	7.21	220.9	–	1.00	–	0.18 ± 0.066**	58.7 ± 4.23***
Jiangsu	32.9	20.0	15.4	7.83	269.2	0.00	0.92	0.08	0.16 ± 0.061*	78.6 ± 3.04***
Anhui	31.8	20.9	14.7	5.74	161.4	0.19	0.60	0.22	0.14 ± 0.061*	47.2 ± 2.25***
Zhejiang	29.2	21.8	14.5	6.01	199.0	0.36	0.22	0.41	0.09 ± 0.054	55.8 ± 4.05***
Fujian	25.9	23.7	14.7	5.13	223.8	0.37	0.27	0.36	0.11 ± 0.054*	61.9 ± 4.45***
Guangxi	23.6	24.9	14.6	5.06	114.2	0.47	0.06	0.47	0.11 ± 0.043*	29.6 ± 2.88***
Guangdong	23.4	25.2	15.0	5.57	219.1	0.48	0.01	0.51	0.15 ± 0.041***	61.9 ± 3.72***

*, ** and *** indicate that changes (regression slopes) are significantly different from zero at $P = 0.05$, 0.01 and 0.001, respectively

[a] Source: China Meteorological Administration from 1961 to 2003

[b] Roughly corresponds to the growing season

[c] Estimated using a function to convert sunshine duration to solar radiation

[d] Original data were obtained from the International Rice Research Institute (IRRI) statistical database (http://ricestat.irri.org:8080/wrs2/entrypoint.htm)

[e] Original data were from Provincial Local Statistical Year Books

[f] *Source* China Agriculture Yearbook. Ratios relative to the total planted area per year are shown

[g] Data are averaged values from 1990 to 2003

[h] The values are the slope of the linear regression against years and its standard error (S.E.) for the period from 1961 to 2003

Data

Climate data

Climate data were obtained from China Meteorological Administration, China (http://cdc.cma.gov.cn/home.do). The database includes daily climate data from approximately 200 stations across the country. We used data from all weather stations (3–4 stations in each province) in the nine provinces. The meteorological dataset included average temperature, sunshine duration, precipitation, vapor pressure, and wind speed from 1961 to 2003. Solar radiation data were not available, so we estimated it by converting sunshine duration to daily solar radiation using the equation proposed by Xu et al. (2011). For [CO_2], we used annual mean [CO_2] data measured at Mauna Loa from the National Oceanic and Atmospheric Administration (NOAA, http://www.esrl.noaa.gov/gmd/ccgg/trends/co2_annmean_mlo.txt).

Nitrogen input

We used data for both inorganic and organic N fertilizer sources. The amounts of inorganic N applied were obtained from Provincial Local Statistical Year Books (National Bureau of Statistics of China, 1981–2004). These series of statistics cover provincial-level N consumption in agriculture from 1980 to 2003. Inorganic N application before 1980, however, was available only at the national level (FAOSTAT, http://faostat3.fao.org/). The N input data between 1961 and 1979 at the provincial level were estimated from the national-scale N data by weighting fertilizer use in each province relative to the national total use in 1980, assuming that the values were unchanged between 1961 and 1980. Note that the changes in the rank and relative fertilizer used among provinces were little changed between 1980 and 2003. The decadal change in the manure N consumption data in major production areas was obtained from Zou et al. (2009).

Phenology and crop calendar

Crop phenology, timing and progress of crop development as affected by climatic variables is an essential component of a crop growth model and is highly sensitive to changes in temperature and cultivars used (Ritchie and NeSmith 1991; Horie 1994). Various types of crop phenology models have been developed and used in rice growth models (reviewed by Zhang and Tao 2013), but those used for a wide range of environmental conditions generally include functions of temperature and day length to account for photoperiod and temperature sensitivities (Nakagawa and Horie 1995; Yin et al. 1997; Sawano et al. 2008). In these models, parameters are specific to each cultivar estimated from controlled-environment or field experiments. Unfortunately, information is limited on rice cultivars specifically planted in the target regions during the period of interest. Therefore, we used phenology models and/or parameters reported for both *japonica* -type and *indica*-type cultivars planted in four different latitudinal zones, in a similar manner to that of Zhang and Tao (2013), though the latter authors defined three zones across China. For short-duration *japonica*–type cultivars planted in a northeastern province (Heilongjiang), we used a crop clock model by Shimono et al. (2007) for Kirara 397. In Jilin and Liaoning, a short to intermediate-duration *japonica* cultivar, Akitakomachi, was assumed with a similar model to that of Shimono et al. (2007) with the parameters estimated from the data of Kim et al. (2003). These two cultivars are adapted to relatively high latitudes and therefore are non-photoperiod-sensitive. In three provinces in central China along the Yangtze River (Jiangsu, Anhui, and Zhejiang), a late *japonica*-type cultivar, Hinohikari, was assumed and in three southern provinces (Fujian, Guangxi, and Guangdong), IR36, an indica cultivar adapted to tropical climates was used. For these photoperiod-sensitive cultivars, a phenology model proposed by Horie et al. (1995) and Nakagawa and Horie (1995) was used. The parameters for Hinohikari in the Nakagawa and Horie (1995) model were obtained from Hasegawa et al. (1995).

Planting time is another important element in the crop calendar and could be a primary adaptation measure under climate change. Earlier or later planting than at present can make a significant difference in growth duration in response to climate change (Zhang and Tao 2013). Planting time also varies from field-to-field within each region. Frequency distribution of transplanting time within a target area is an effective means to improve model performance for regional-scale yield estimation (Stehfest et al. 2007; Sawano et al. 2008). Previously, we expressed a frequency distribution of planting time as a function of precipitation for the rain-fed lowland production system (Sawano et al. 2008), but in the present study, because irrigated lowland is the most common system, we assumed a fixed normal distribution in each province with the initial and terminal dates given in Yan et al. (2003).

Provincial yield data

Rice production data in each province were obtained from the International Rice Research Institute (IRRI) statistical database (http://ricestat.irri.org:8080/wrs2/entrypoint.htm). The database provides planted area, production, and yield data in each province from 1951 to 2004. Where double cropping is available, planted areas for the first and second crops were obtained from the China Agriculture Yearbook (China Agriculture Press 1981–2004). In southern provinces such as Fujian, Guanxi and Guandong, triple cropping is also practiced in the paddy ecosystem. In most of the triple cropping, however, two rice crops are combined with another crop such as vegetables (Frolking et al. 2002), and triple rice cropping is not explicitly shown in the year book.

Calculation of provincial yield

We calculated provincial yield in the following steps. First, the model calculated growth and grain yield for a crop planted on a given date with daily climate data and seasonal N input. This was repeated from the onset and final dates of transplanting at weather stations in each province. They were then weighted by the ratio of area transplanted on each date. Where double cropping is practiced, we repeated these steps for both early and late crops. Finally, annual regional yield was estimated by weighting the average by the ratio of land area between cropping seasons. To test whether the model accounts for the spatial variation in grain yield, we ran SACRA for the period between 1990 and 2003 in nine major rice-producing provinces (Table 1).

Analysis of factors that affected historical yield change

The model developed here accounts for the effects of changes in the amount of N fertilizer and climatic factors such as temperature and [CO_2], which have changed over the past decades (Table 1). In addition, technological factors other than N input could make significant contributions to regional yield increase for the same period, but the current model is not capable of simulating the effects of these technological factors. We therefore analyzed these factors associated with the regional yield via two steps. First, we estimated the regional yields (Y_{est}) of each province using the real climate and N input data during the period from 1961 to 2003. Because we did not change any parameters in the model over the years, Y_{est} can be considered as a yield attainable under the climatic and N input conditions with fixed technological factors. By comparing Y_{est} and regional statistical yield (Y_{obs}), we can quantify the changes in the other technological factors as

$$\alpha = Y_{\mathrm{obs}}/Y_{\mathrm{est}},$$

where α represents yield improvement corrected by changes in N input and climate changes.

Second, we ran the SACRA model with a combination of hypothetical forcing variables for the same period by changing [CO_2] and temperature:

Case 1	actual changes in N, temperature, and [CO_2]
Case 2	actual change in N and no change in temperature or [CO_2]
Case 3	actual change in [CO_2] and no change in N or temperature
Case 4	actual change in temperature and no change in N and [CO_2]
Control	no change in N input, temperature, or [CO_2] from 1961

For cases with no change in [CO_2] or N, we fixed the values of N or [CO_2] in 1961. Actual changes were used for N or [CO_2] under Cases 1–3. For the temperature data, we first calculated nine-year moving averages of the mean temperature from April to November, which roughly cover the growing seasons across different provinces, to determine the temperature trend for the whole period. In cases with no change in temperature (Cases 2, 3, and Control), differences between the moving average and April–November mean temperature of the year of interest were added to the daily temperature data in 1961. The effects of N, [CO_2], and temperature on changes in yield can be quantified by subtracting Y_{est} under Control from that under Cases 1, 3, or 4, respectively.

Results and discussion

Spatial variability of climate and management

The nine provinces studied differed largely in climatic conditions, cropping systems, levels of N input, and grain yield (Table 1). Average temperatures from April to November ranged from 10.9 °C in Heilongjiang to 25.2 °C in Guangdong. Increases in temperature during the period between 1961 and 2003 were significant in all provinces, except in Zhejiang, and the decadal rates of change ranged from 0.09 to 0.31 °C. Three provinces located in the northeastern part of the country, where current temperatures are low, showed higher rates of temperature increase. Daily solar radiation averaged for the same period was between 14.5 MJ m^{-2} in Zhejiang and 16.1 MJ m^{-2} in Liaoning. The proportion of double cropping increased as the average temperature increased above 20 °C (Table 1). Nitrogen fertilizer inputs, averaged for the period 1990–2003, differed by as much as fourfold among the provinces, ranging from 68 kg ha^{-1} in Heilongjiang to 269 kg ha^{-1} in Jiangsu. Increases in N fertilizer use between 1961 and 2003 also differed significantly among the provinces, indicating that the gap in N inputs among provinces widened during the period studied. It should be noted, however, that the national N fertilizer input levels increased dramatically for the 16-year period from 1961 to 1976, but the increase slowed in the mid-1980s, and plateaued in the mid-1990s (Fig. 1). Grain yield averaged

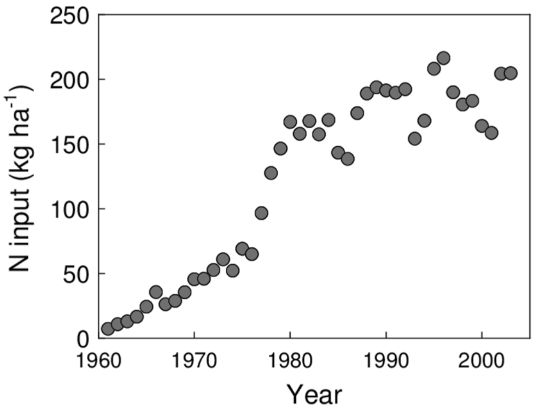


Fig. 1 Changes in N fertilizer input averaged over nine provinces

for the period 1990–2003 also ranged widely from 5.06 to 7.83 t ha^{-1}.

Spatial variation in provincial yield and partial factor productivity for N

Estimated grain yields for the period from 1990 to 2003 were slightly smaller than observed grain yields by 0.56 t ha^{-1} when averaged across the nine provinces (Fig. 2a), but spatial variation and ranking of provincial yields were similar between observed and estimated yields, with an root mean square error (RMSE) value of 0.82 t ha^{-1}, equivalent to 14 % of the observed average.

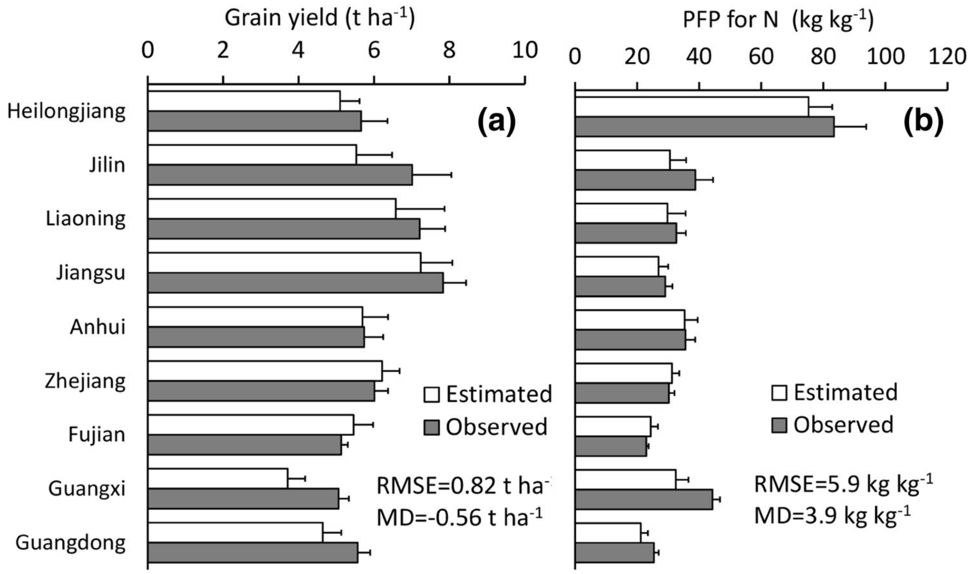
Partial factor productivity (PFP) for N, defined as the grain yield per unit N applied, also varied substantially from 23 to 83 kg kg^{-1}. Estimated PFP agreed well with the observed value with an RMSE of 5.9 kg kg^{-1}, equivalent to 15 % of the observed average (Fig. 2b). Because PFP for N is considered to be a representative measure of N fertilizer use efficiency (Peng et al. 1995), the model provides a good reflection of the spatial variation in N fertilizer use efficiency.

Estimated and observed changes in regional yields

Observed grain yields averaged over nine provinces have almost tripled since1961 (Fig. 3a). The rate of increase was pronounced until the 1980s, exceeding 5 % per year relative to the yield in 1961, but slowed in the 1990s. The value of α, representing yield improvement corrected by changes in N input and climate changes, remained unchanged until the late 1970s, but subsequently α increased sharply and the rate of increase was almost comparable to that in the observed yield. This result suggests that the estimated yield showed a similar trend to the observed yield during the period from 1960 to 1980 but that the subsequent increase was not accounted for by the model. For the entire 43-year study period, α averaged over nine provinces increased by as much as 71 %, which was about 35 % of the yield increase (Fig. 3a). Much of the increase occurred after 1980; the rate of increase in α amounted to 69 % of that in the observed yield in the 1980s and 90 % of that in the 1990s. Therefore, other technological factors lumped in α were indicated to be the major driver of yield enhancement during the 1980s and 1990s.

One of the major technological advancements for the period studied was cultivar improvement, and particularly development of hybrid rice cultivars, which show an approximately 10–20 % yield advantage over conventional inbred cultivars (Cheng et al. 2004). Areas planted to hybrid rice rose sharply from the late 1970s: 0.4 % in 1976,

Fig. 2 Comparison between estimated and measured rice yield (**a**) and partial factor productivity (PFP) for N (yield/N input) (**b**) in nine provinces in China averaged over the 1990–2003 period. *RMSE* root mean square error, *MD* mean difference between observed and estimated yields (or bias)



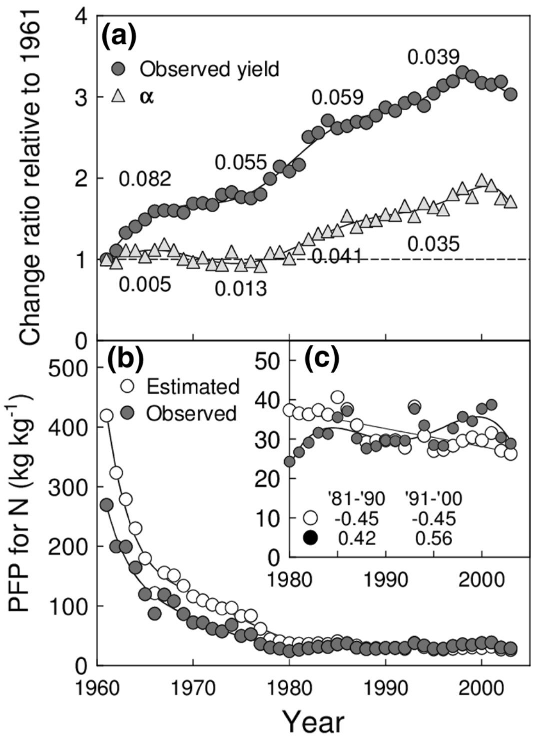


Fig. 3 Changes in observed yield and α (observed/estimated yield) relative to the values in 1961 (**a**) and in partial factor productivity (PFP) for N (yield/N input) (**b**) and (**c**) for the data averaged over nine provinces. Values specified in (**a**) and (**c**) are slopes (derivatives) of the polynomial fitted to the data at the mid-time point of each decade

17 % in 1982, 4 % in 1990, and 55 % in 2002 (Cheng et al. 2004). This corresponds to the period in which α increased substantially. In major C_3 cereals, genetic improvement in grain yield during the green revolution was realized through a large increase in HI (Evans 1993). For inbred *indica* cultivars, historical change in HI was summarized using the cultivars released by IRRI from 0.32 to 0.46 (Evans 1993) and from 0.28 to 0.55 in Peng et al. (2000). According to Song et al. (1990), the change in HI in the dominant cultivars planted in Zhejiang province was from 0.38 in native cultivars to 0.51 in new improved cultivars. The importance of genetic improvement since 1980 was also reported by Yu et al. (2012), who used the Agro-C model to analyze regional yields and associated factors.

On the other hand, PFP for N decreased substantially over the past 43 years (Fig. 3b). This was largely associated with the sharp increase in N input, particularly in the period between 1960 and 1980. The estimated PFP for N showed a similar change to the observed value, though the model overestimated PFP for N for the first 20 years (Fig. 3b). From 1980 onwards, PFP for N was relatively unchanged at about 30 kg kg^{-1}, lower than that reported for maize in the United States (57 kg kg^{-1}, Cassman et al. 2002). However, while the estimated PFP continued to decrease from 1980, the observed PFP increased consistently over the same period, overtaking the estimated value in the early 1990s. A slight but consistent increase in PFP indicated that some improvement in the fertilizer use efficiency has also contributed to the rise in α and regional yield, although overuse of N is still one of the key problems in rice production in China (Peng et al. 2009).

Large yield increases occurred in all nine provinces (Fig. 4). Trends in estimated yields agreed well with the observed yields in two northeastern provinces (Heilongjiang and Jilin), but in the other provinces estimated yields rose more sharply between 1961 and 1980 and plateaued earlier than did observed yields. In central and southern China, contribution of α to the yield increase was relatively more important than in the northeastern provinces. This finding is consistent with the fact that adoption of hybrid rice was much higher in the southern provinces, where *indica*-type cultivars are commonly planted.

Contributions of N input, temperature, and CO_2 to estimated yield changes

The combined effects of changes in N input, CO_2, and temperature on the simulated yield gains from 1961 to the 1990s were significant in all provinces ($P < 0.001$), with an average of about 3 t ha^{-1} (Table 2). Most of the increases occurred between 1961 and 1980 and plateaued thereafter, as evidenced by the significant quadratic relation between yield gains and year (Table 2, $P < 0.001$). The yield gains differed among provinces. In general, the yield gains were larger in northeastern and central provinces than in southern provinces; Heilongjiang and Liaoning recorded twofold increases compared with Guangxi and Guangdong (Table 2).

The largest sole contributor to these gains was N fertilizer input, which accounted for more than 90 % of the estimated yield gains averaged over nine provinces in the 1990s (Table 2, comparison between *N* vs *N*, CO_2, and *T*). Nearly 90 % of the increase during the whole period occurred in the first 20 years. Naturally, the yield gains with N input changes differed significantly among provinces, which reflected regional differences in the combined effects. Diminishing return on grain yield is apparent as N input exceeded the crop demand; this occurred relatively early (1960s–1980s), resulting in a drastic decrease in PFP for N (Fig. 3b) during this period. The regional differences in N effects are in part due to the level of N input, but the interpretation is not straightforward. The largest yield gain was observed in Heilongjiang where N input was smallest, followed by Jiangsu where N input and its increment was the largest.

Significant positive effects were observed for the effect of CO_2 in all provinces (Table 2, $P < 0.001$). This was

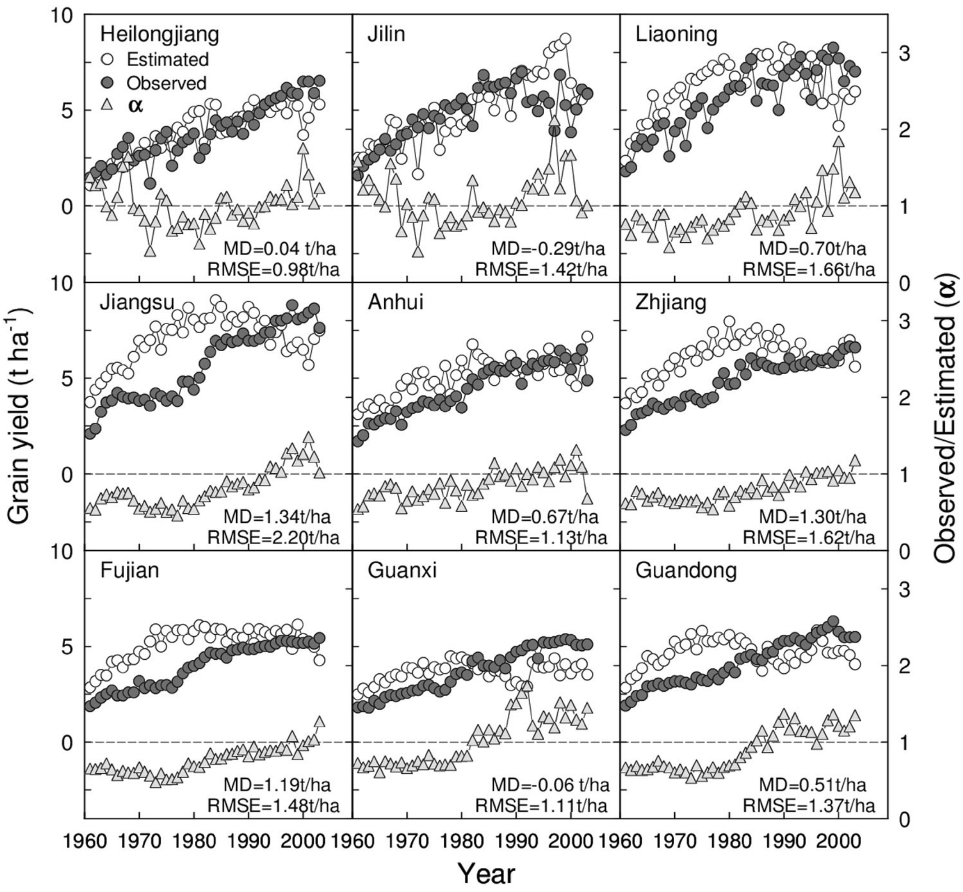


Fig. 4 Time course of observed yield, estimated yield, and α (observed/estimated yield) in nine provinces in China from 1961 to 2003. *RMSE* root mean square error, *MD* mean difference between observed and estimated yields (or bias)

because of the linear increase in [CO_2] during the period and near-linear increase in WUE in response to elevated [CO_2] in the range between 300 and 400 μmol mol^{-1}. The contribution of CO_2 fertilization to the estimated yield in the 1990s averaged 4.15 % relative to that in 1961 (Table 2). Xiong et al. (2012) estimated the contribution of the CO_2 fertilization effect during the period between 1961 and 2009 to be 8.7 % for rice, which was larger than that estimated in the current study. It is worth noting, however, that [CO_2] has risen substantially in the last 15 years, from 317 μmol mol^{-1} in 1960 to 360 μmol mol^{-1} in 1995 and 387 ppm in 2009. This suggests that these two studies showed a comparable contribution of CO_2 fertilization effect when corrected by the [CO_2] increase.

The yield gains with elevated [CO_2] differed significantly among provinces despite the assumption that changes in [CO_2] were uniform across provinces; they were smaller in the two northeastern provinces, Heilongjiang and Jilin. As a result, the relative contribution of elevated [CO_2] to regional yield was smaller in these provinces (less than 2 %) than in southern provinces, where yield gains with the combined factors were relatively small and the [CO_2] effect was relatively large (e.g., 5.5 % in Guangdong and 7.4 % in Guangxi). The northeastern provinces were apparently cooler and input N was relatively lower (Table 1) than those of the southern provinces. Ample experimental evidence indicates that N deficiency limits growth and yield responses to elevated [CO_2] (Makino et al. 1997; Kimball et al. 2002; Sakai et al. 2006; Yin 2013). The present model does not include a direct mechanism by which N deficiency limits the [CO_2] fertilization via photosynthesis or water use efficiency, but N conditions can affect [CO_2] response via growth enhancement by elevated [CO_2]. Enhancement of biomass increases crop demand for N, which promotes crop N uptake and leaf area growth, leading to a positive feedback on biomass production. Under scarce N conditions, crop N uptake is promoted by elevated [CO_2] initially but depletes N resources more rapidly than under ambient [CO_2]. This could limit the growth responses to elevated [CO_2] where a limited amount of N is applied.

Low temperature is another important factor that may limit [CO_2] fertilization. One physiological explanation for this phenomenon was provided by (Long 1991), where higher temperature generally increases photorespiration of C_3 plants, which reduces net photosynthesis. Elevated [CO_2] increases photosynthesis by increasing carboxylation and by decreasing photorespiration. In high

Table 2 Simulated yield increases (t ha^{-1}) from 1961 expressed as decadal averages in the nine major rice-producing provinces in China

Factors	Year	Heilongjiang	Jilin	Liaoning	Jiangsu	Anhui	Zhejiang	Fujian	Guangxi	Guangdong	Average[a]
Case 1:	1961–19870	0.896	1.154	1.793	1.422	0.706	1.410	0.997	0.693	1.134	1.092
N, CO_2, *T*	1971–1980	2.713	3.180	4.193	3.803	2.098	3.456	2.616	1.726	2.612	2.759
	1981–1990	3.574	4.413	4.770	4.718	3.038	4.117	3.057	1.653	2.319	3.178
	1991–2000	4.115a[b]	3.892abc	4.189a	4.009ab	3.135bcd	3.522abc	3.028cd	1.735e	2.461de	3.093
Slope[c] (kg ha^{-1} y^{-1})		100.2q***	88.4q***	71.7q***	79.7q***	77.6q***	66.4q***	61.5q***	29.5q***	34.9q***	41.6c***
Case 2:	1961–1970	0.912	1.068	1.669	1.398	0.816	1.414	1.083	0.698	1.162	1.115
N	1971–1980	2.694	2.767	3.828	3.496	1.855	3.208	2.577	1.656	2.589	2.605
	1981–1990	3.426	3.772	4.174	4.216	2.597	3.755	2.836	1.53	2.244	2.891
	1991–2000	4.010a	3.480ab	3.967a	3.547ab	2.753cd	3.166bc	2.782cd	1.574e	2.392d	2.834
Slope (kg ha^{-1} y^{-1})		96.2q***	79.0q***	69.0q***	65.2q***	62.1q***	54.5q***	50.0q***	23.7q***	31.4q***	25.0c***
Case 3:	1961–1970	0.004	0.006	0.011	0.015	0.012	0.015	0.014	0.012	0.013	0.013
CO_2	1971–1980	0.014	0.021	0.044	0.061	0.049	0.057	0.055	0.046	0.051	0.052
	1981–1990	0.028	0.043	0.087	0.114	0.090	0.107	0.105	0.094	0.095	0.097
	1991–2000	0.041f	0.061e	0.125d	0.155a	0.122d	0.147ab	0.147abc	0.129cd	0.135bcd	0.128
Slope (kg ha^{-1} y^{-1})		1.25***	1.88***	3.82***	4.70***	3.72***	4.49***	4.47***	4.00***	4.11***	3.88***
Case 4:	1961–1970	−0.012	0.021	−0.008	−0.03	−0.145	−0.015	−0.068	0.016	0.024	−0.021
T	1971–1980	0.017	0.107	0.027	−0.012	−0.064	0.036	−0.052	0.005	0.013	−0.004
	1981–1990	−0.011	0.020	−0.012	−0.072	−0.091	0.030	−0.070	−0.032	−0.051	−0.042
	1991–2000	0.022ab	0.054a	−0.093d	−0.039bcd	−0.093d	0.009abc	−0.064cd	−0.027bcd	−0.035bcd	−0.034
Slope (kg ha^{-1} y^{-1})		0.82ns	0.06ns	−3.34q***	−1.06ns	0.83ns	0.47ns	−0.11ns	−1.58***	−2.35***	−0.856ns
Relative contribution vis-a-vis the yield under Case 1 (%)											
N		97.4	89.4	94.7	88.5	87.8	89.9	91.9	90.7	97.2	91.7
CO_2		0.99	1.58	2.97	3.86	3.88	4.19	4.85	7.43	5.49	4.15
T		0.55	1.38	−2.23	−0.98	−2.97	0.26	−2.13	−1.55	−1.41	−1.11

Simulations were conducted using four different scenarios: simulated using (1) actual N input (*N*), CO_2 concentration (CO_2), and temperature (*T*) data; (2) actual *N* data but 1961 weather data; (3) actual CO_2 data but other factors unchanged from 1961; and (4) actual *T* data but other factors unchanged from 1961

[a] Average yield over nine provinces weighted by the planted area

[b] Analysis of variance was conducted on the data for 1991–2000 as cumulative changes over the 40 years. The effects of provinces were significant ($P < 0.001$) for all the scenarios. Values followed by the same letters are not significantly different between provinces at the 0.05 probability level based on Tukey's honestly significant difference

[c] Regression was conducted to determine if the year effect was significant. Individual data were regressed on year. Polynomials were also tested for significance. *** The regression is significant at 0.001. Slopes followed by 'q' or 'c' mean that the quadratic or cubic term was significant. The slope for the polynomial function is represented by the derivative at the mid-time point (1981). Those values not followed by a letter are the slope from simple linear regression. *Ns* not significant

temperature ranges, the latter effect becomes more pronounced, resulting in higher photosynthetic enhancement by elevated [CO_2]. However, in low temperature ranges, the effect of elevated [CO_2] on photorespiration is rather limited, resulting in a comparatively smaller photosynthetic enhancement under elevated [CO_2]. This mechanism, however, is not included in the present model, but an indirect effect may be involved; low temperature affects not just crop growth but also soil processes, including N mineralization as shown in Eqs. (2) and (3). The crop dependence on soil mineralization is large where N input is low. In the model, low N input and low temperature interactively limited the growth enhancement by elevated [CO_2] in the northern provinces.

The sole effect of temperature change was not significant on the estimated yield averaged over the nine provinces (Table 2). This was similar to the results reported by Xiong et al. (2012). The model accounts for various effects of increases in temperature, including positive effects on nitrogen supply, leaf area growth, crop water use, and negative effects on growth duration. The positive effects were likely counterbalanced by the negative effects in the average yield, but three provinces (Liaoning, Guanxi, and Guandong) showed significant negative effects ($P < 0.001$). In these provinces, negative effects on growth duration were estimated to have surpassed the positive effects. Statistical analyses previously conducted on the historical yield data showed that, in general, increases in temperature had significant positive effects on yield in northeastern provinces (Tao et al. 2008; Zhou et al. 2013) and nonsignificant effects in the central and southern parts of China (Tao et al. 2008; Zhang et al. 2010). The positive effects of increasing temperature observed in the census yield in the northeast could be a result of reduced occurrence of chilling injuries, an extended frost-free period, and improvements in countermeasures against chilling stresses (Zhou et al. 2013). None of these factors are accounted for by the model, which could be a reason for the nonsignificant temperature effects on the estimated yields in the northeastern provinces. These empirical studies also highlighted the importance of solar radiation, which could have overridden the effects of temperature changes. The present study, which aimed to identify the sole effect using a crop model, suggested increasing temperature has an ongoing negative effect in some provinces.

Summary and implications for the future

Simulated yields by crop models generally include large uncertainties due to various sources. For example, a recent model comparison study demonstrates that crop models even at a field level show large variation in responses to temperature and elevated [CO_2] (Li et al. 2014), which could be a large source of uncertainty in yield prediction under various climates. Regional yields vary spatially and temporally depending on a number of factors such as climate, soil, management practices, cultivars, and damages caused by pest and diseases, but models do not account for all the factors affecting the variations, which could be a source of gaps between observed and predicted yields. In this study, we intended to study long-term trends in provincial yields, but overlooked the year-to-year yield variability, which is often caused by environmental stresses such as extreme temperatures. We also assumed that water supply is not limited in irrigated rice fields which cover more than 90 % of the paddy area in China, but water availability is becoming a concern for the future rice production (GRiSP 2013). High-quality and high-resolution model input data are often difficult to obtain at large spatial scales, which reduces the precision of regional yield estimates. Despite these limitations, our quantitative comparison between observed and simulated yields and further analyses on the factors affecting yield trends have shown some important shift in the past yield records in China.

During the period between 1961 and 2003, dramatic increases in N input have made the largest contribution to the threefold increase in rice yield, but the effect has been saturated since the early 1980s (Fig. 1, 3; Table 2). Most of the continued increase in grain yield since 1980 is derived from factors other than climate and N input (represented by α), in which growth has also slowed in the twenty-first century (Fig. 3). Because the increased amounts of N application far exceed the crop needs, additional yield increase would not be expected by further increase in N input. As a penalty of heavy N fertilization, nitrogen use efficiency represented by PFP for N has declined dramatically to 30–40 kg kg^{-1} (Fig. 3b). Therefore, improvements in α will continue to play a pivotal role in the future.

An important driver among technological factors is cultivar improvement, which is suggested to be the major contributor to the yield increase since 1980 (Yu et al. 2012). Improvements in yield potential are the primary target of breeding, but efficient use of resources such as N and water is another important target. Efforts are ongoing, taking advantage of recent advances in molecular genetics (Zhang 2007). How these developments will impact field or regional-level productivity is of paramount importance. Quantitative analyses of the effects of these technological factors will be crucial in this regard.

The future course of cultivar development is also of strong relevance to the impacts of climate change. Tolerance to abiotic stresses such as heat or drought, which are predicted to occur more frequently in the future, is an important target for breeding. Another important aspect of breeding is to enhance productivity by utilizing an unexploited climate resource, namely elevated [CO_2]. This aspect has been overlooked, but recent experimental studies have shown substantial genotypic variation in the CO_2 fertilization effect (Hasegawa et al. 2013). Traits that perform better under the future climate could be a valuable breeding resource for improvement of resource use efficiency.

The impact of climate changes was much smaller compared with the effect of N input and technological factors in the past (Table 2), despite significant changes in climatic variables (Table 1). The yield change associated with the climate change was somewhat similar to those reported in recent model analyses (Xiong et al. 2012; Yu et al. 2012). Here, we showed that effects of $[CO_2]$ differed among provinces, which could be related to temperature and/or N levels as discussed earlier. Because the effects of projected climate change are expected to be more pronounced in the future (IPCC 2014), understanding the interaction between climate and crop management will become increasingly important. Models including these advances are needed to adequately evaluate climate, cultivar, and management interactions in the future.

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Competing interests The authors declare no potential competing interests.

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