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RESEARCH ARTICLE

Contributions of climate, varieties, and agronomic management to rice yield change in the past three decades in China

He ZHANG[1,2], Fulu TAO (✉)[1], Dengpan XIAO[3], Wenjiao SHI[1], Fengshan LIU[4], Shuai ZHANG[1], Yujie LIU[1], Meng WANG[5], Huizi BAI[1,2]

1 Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
2 University of Chinese Academy of Sciences, Beijing 100049, China
3 Institute of Geographical Sciences, Hebei Academy of Sciences, Shijiazhuang 050011, China
4 Juncao Research Institute, Fujian Agriculture and Forestry University, Fuzhou 350002, China
5 Qufu Normal University, Rizhao 276826, China

Abstract The long-term field experiment data at four representative agro-meteorological stations, together with a crop simulation model, were used to disentangle the contributions of climate change, variety renewal, and fertilization management to rice yield change in the past three decades. We found that during 1981–2009 varieties renewal increased rice yield by 16%–52%, management improvement increased yield by 0–16%, and the contributions of climate change to rice yield varied from – 16% to 10%. Varieties renewal and management improvement offset the negative impacts of climate change on rice production. Among the major climate variables, decreases in solar radiation reduced rice yield on average by 0.1% per year. The impact of temperature change had an explicit spatial pattern. It increased yield by 0.04%–0.4% per year for single rice at Xinbin and Ganyu station and for late rice at Tongcheng station, by contrast reduced yield by 0.2%–0.4% per year for single rice at Mianyang station and early rice at Tongcheng station. During 1981–2009, rice varieties renewal was characterized by increases in thermal requirements, grain number per spike and harvest index. The new varieties were less sensitive to climate change than old ones. The development of high thermal requirements, high yield potential and heat tolerant rice varieties, together with improvement of agronomic management, should be encouraged to meet the challenges of climate change and increasing food demand in future.

Keywords adaptation, climate change, food security, impact, cultivar, management

1 Introduction

Crop growth and yield are subjected to the complex interactions among genotype, environment, and management (Lobell and Asner, 2003). Climate change has been documented in affecting crop growth and yield over many countries and continents in the past few decades (Tao et al., 2006; Lobell and Field, 2007; Kucharik and Serbin, 2008; Tao et al., 2008; Deng et al., 2010; Tao et al., 2012, 2014; Xiao et al., 2013a; Shi and Tao, 2014a, b; Zhang et al., 2014). Previous studies, using process-based crop models and/or statistical models, have documented that changes in climate variables such as solar radiation, temperature, precipitation, and CO_2 concentration had major impacts on crop growth and yield (Lin et al., 2005; Tao et al., 2006; Liu and Tao, 2012; Xiong et al., 2012; Shi et al., 2013; Xiao et al., 2013b). At the same time, the development of new varieties such as semi-dwarf varieties in the 1950s and hybrid rice varieties in the 1970s, as well as the improved crop management practices such as nitrogen fertilization and irrigation applications, contributed substantially to yield increase (Chen and Chen, 2007; Peng et al., 2009; Yu et al., 2012; Xiao et al., 2013b; Bryan et al., 2014; Nendel et al., 2014).

To accelerate understanding climate impacts and develop effective climate change adaptation options, we need to disentangle the roles of varieties, agronomic management and climate change in affecting crop yield.

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E-mail: taofl@igsnrr.ac.cn

In this study, we use a crop simulation model, together with the experimental data at four representative agro-meteorological experiment stations from 1981 to 2009, to (i) disentangle the contributions of climate change, varieties renewal and fertilization management improvement to rice yield; (ii) disentangle the impact of different climate variables (e.g., temperature, solar radiation) on rice yield in the past three decades.

2 Materials and methods

2.1 Study stations

Based on climate conditions, cropping systems, and geographic features, we selected four representative stations from two major rice production areas in China, which are located in the Northeastern China Plain (NECP) and the middle and lower reaches of the Yangtze River (MLRYR) (Fig. 1). The Xinbin station is located in the low mountainous area of Liaoning Province in the NECP with a north temperate continental monsoon climate. The climate is characterized by high temperature, long sunshine hours, abundant rainfall in summer, and a large temperature difference between day and night in autumn. Single rice cultivation is the main cropping system. The Ganyu station is located in Jiangsu Province in northern China. The climate belongs to a warm temperate monsoon humid climate. It is hot and rainy in summer while cold and dry in winter. The dominant cropping system is a rotation between wheat and rice. The Mianyang station is located in Sichuan Basin, with the least sunshine and solar radiation in China. It belongs to a subtropical monsoon humid climate, with a moist and humid atmosphere throughout the year. The dominant cropping system is rotation between wheat and rice. The Tongcheng station is located in Anhui province in the MLRYR, with a subtropical monsoon climate. It has a mild climate, well-marked seasons, abundant rainfall and sunshine. The dominant cropping system is double rice cultivation. The information on climate, soils, and agronomic managements in the four stations is shown in Table 1.

2.2 Data

Daily maximum temperature (T_{max}), minimum temperature (T_{min}), precipitation (Prec), and sunshine hours at the four stations from 1981 to 2009 were obtained from the Chinese Meteorological Administration (CMA). Solar radiation (SRD) was calculated by the Angstrom-Prescott equation (Angstrom, 1924; Prescott, 1940) using sunshine hours data.

Rice growth and yield observation data including cultivars, phenology, yield, and management were from the four corresponding agro-meteorological experiment stations in CMA. Phenology data included transplanting

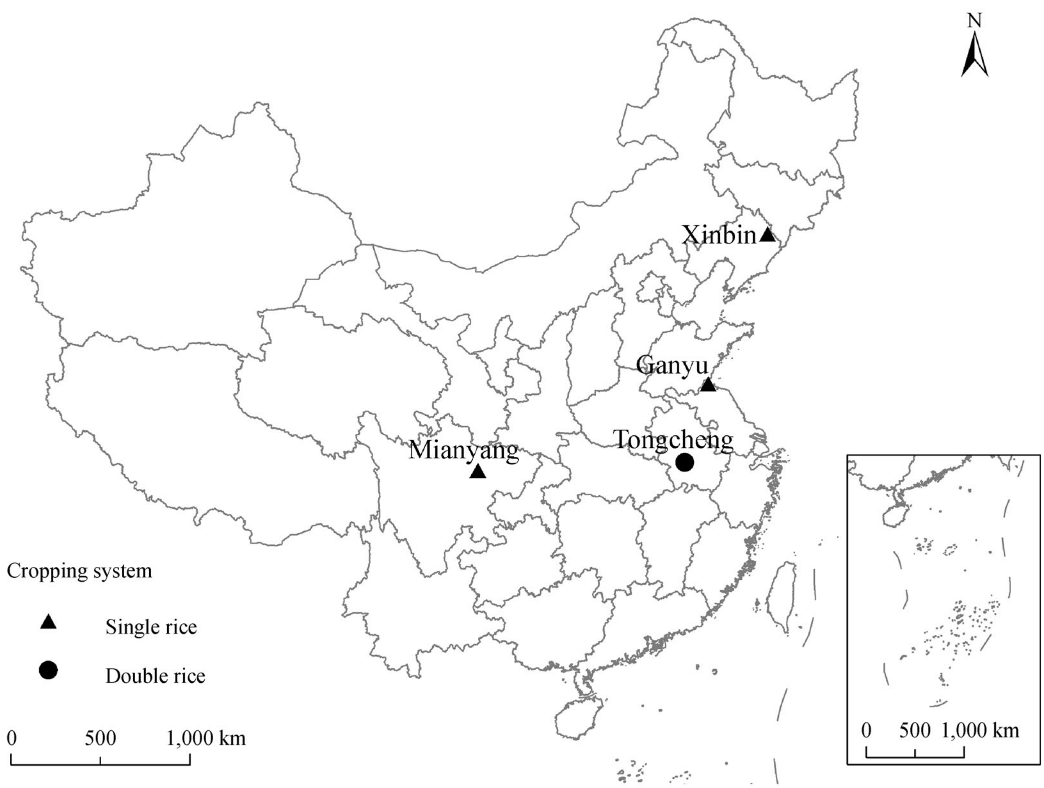

Fig. 1 Locations of the agrometeorological experiment stations used in this study.

Table 1 The information on climate, soils, and managements of the four representative stations

Stations	Xinbin	Ganyu	Mianyang	Tongcheng
Latitude/(°N)	41.73	34.83	31.45	31.07
Longitude/(°E)	125.05	119.12	104.73	116.95
Altitude/m	328	3	523	85
Cropping system	Single rice	Wheat–rice	Wheat–rice	Double rice
Region	Northeast China	North China	Central China	Central China
Period of rice data	1981–2009	1982–2009	1981–2009	1982–2009
Soil texture	Loam	Clay	Silty loam	Silty loam
Organic matter/%	1.82	2.15	2.33	2.15
Total N/%	0.089	0.132	0.135	0.131
Annual mean temperature/°C	4.8	13.2	16.0	16.0
Annual mean solar radiation/($MJ \cdot m^{-2}$)	12.99	14.07	9.73	11.4
Annual total precipitation/mm	766.6	915	858	133.9
Irrigation	Groundwater	Groundwater	Groundwater	Groundwater
Fertilizer	Chemical fertilizer (N,P,K)	Chemical fertilizer (N,P,K)	Chemical fertilizer (N,P,K)	Chemical fertilizer (N,P,K)

N: nitrogen fertilizer; P: phosphorous fertilizer; K: potassium fertilizer.

date, heading date, and maturity date. Yield data included grain yield, grain number per spike (GNS), and 1000-grain weight (1-GW). Management data included the amount of nitrogen fertilizer applied.

2.3 CERES-Rice model

The CERES-Rice model used in this research included in DSSAT (Decision Support System for Agro-technology Transfer) 4.5 version, is one of the most widely used crop simulation models in the world. The CERES-Rice model considers weather, genetic features, management, and soil, and can be used to simulate the growth, development and yield of rice. The model has eight genetic parameters: the time period in growing degree days (GDD) for basic vegetative phase (P1), photoperiod sensitivity parameter (P2R), critical photoperiod (P2O), the time period in growing degree days for grain filling phase (P5), potential spikelet number coefficient (G1), potential single grain weight (G2), tillering coefficient (G3), and temperature tolerance coefficient (G4). These were used to describe phenology and yield characteristics of the specific genotypes. The model assumes varieties, soil water, and management are the key factors of rice productivity (Bachelet and Gay, 1993), and has been widely used to assess the relationship between rice growth and the environment (Pinnschmidt et al., 1995; Cheyglinted et al., 2001; Timsina and Humphreys, 2006).

2.4 Disentangle the contributions of different climate variables to rice yield change

Three model simulation experiments were designed in order to disentangle the contributions of different climatic variables to rice yield change in the past three decades (Table 2). To disentangle the contribution of temperature change to rice yield, we keep the radiation and precipitation unchanged, and run the model using the observed temperature (maximum and minimum temperature). We firstly ran the model using the 29-year time series of observed temperature and the observed radiation and precipitation data of each single year from 1981–2009, then we computed the average of simulated yields for each year, and the contribution of temperature change to rice yield was investigated by analyzing the trend in the resultant yield series. Likewise, we disentangled the contribution of radiation change to rice yield.

2.5 Disentangle the contributions of varieties renewal and management improvement to rice yield change

Based on the analysis of the long-term trial data, we

Table 2 Simulation experiments and the input data used to disentangle the contributions of different climate variables to rice yield change

Climate variable	Temperature	Radiation	Precipitation
DN_all	1981–2009	1981–2009	1981–2009
DN_temp	1981–2009	Repeat of single year	Repeat of single year
DN_rad	Repeat of single year	1981–2009	Repeat of single year

DN_all, DN_temp, and DN_rad represent the modeling experiment about the impacts of all climate variables, temperature, and solar radiation on rice yield.

Table 3 Typical cultivars and fertilization managements in the 1980s and 2000s at the four stations

Stations	XB_S		GY_S		MY_S		TC_E		TC_L	
Sowing period	1980s	2000s	1980s	2000s	1980s	2000s	1980s	2000s	1980s	2000s
Cultivar	QG	TF8	NJ35	XD3	SY2	GY725	ZX26	XZX22	NH6	WYJ7
Base fertilizer	70	100	70	150	50	120	55	80	60	140
Topdressing	30	60	50		50		55	50	60	
Total fertilizer	100	160	120	150	100	120	110	130	120	140

XB_S; single rice in Xinbin; GY_S: single rice in Ganyu; MY_S: single rice in Mianyang; TC_E: early rice in Tongcheng; TC_L: late rice in Tongcheng. Fertilizer unit: $kg \cdot N \cdot ha^{-1}$.

Table 4 The simulation experiments used to evaluate the contributions of cultivar and management to rice growth and yield components

Experiment	Climate	Cultivar	Management
M1	1981–2009	1980s	1980s
M2	1981–2009	2000s	1980s
M3	1981–2009	2000s	2000s

summarized the characteristics of the typical cultivars and fertilization managements in the 1980s and 2000s, respectively (Table 3). Then we designed three different simulation experiments (i.e., M1, M2, and M3) to disentangle the contributions of varieties renewal and managements improvement to yields and the yield components including 1000-grain weight (1-GW) and harvest index (HI) during 1981–2009 (Table 4). In the simulation experiments M1 and M2, the same management and climate were used, but the cultivars were different; therefore, the difference between them is the contribution of cultivar renewal to rice yield change. The contribution of agronomic management to rice yield change during 1981–2009 was estimated similarly using the simulation experiments M2 and M3.

2.6 Analyses on sensitivity of old and new varieties to climate variables

We firstly ran the CERES-Rice model to obtain a baseline simulation using the observed meteorological data. Then, in order to investigate the sensitivity of the rice varieties to CO_2 concentration, CO_2 concentration was replaced by $(450, 540, \text{and } 630)\times10^6$, respectively, with radiation, temperature, and precipitation values unchanged. In order to investigate the sensitivity of different rice varieties to solar radiation, solar radiation was decreased by 10%, 20%, 30%, respectively, with CO_2 concentration, temperature, and precipitation unchanged. In order to investigate the sensitivity of different rice varieties to temperature, the T_{max} and T_{min} were increased by 1°C, 2°C and 3°C, with CO_2 concentration, solar radiation, and precipitation unchanged. Finally, the corresponding simulations were compared with the baseline simulation, resulting in the sensitivity of rice varieties to each climate variable.

3 Results

3.1 Observed changes in climate, rice phenology, yield, and yield components in the past three decades

3.1.1 Climate change during rice growth period

Climate during rice growth period had an obvious trend in the past three decades (Table 5). Solar radiation decreased at all four stations. T_{max} increased generally at the stations except Ganyu station. T_{min} increased at all four stations. From 1981 to 2009, precipitation during the rice growing period decreased generally at all stations except Ganyu station.

Table 5 Trends in Rad, T_{max}, T_{min} and Prec during rice growth period at the four stations during 1981–2009

Stations	Rad		T_{max}		T_{min}		Prec	
	Mean /$(MJ \cdot m^{-2})$	Trend /$(MJ \cdot m^{-2} \cdot 10\ yr^{-1})$	Mean /°C	Trend /$(°C \cdot 10\ yr^{-1})$	Mean /°C	Trend /$(°C \cdot 10\ yr^{-1})$	Mean /mm	Trend /$(mm \cdot 10\ yr^{-1})$
XB_S	16.59	−0.34	27.09	0.26	15.48	0.11	536.41	−22.52
GY_S	16.52	-0.92^{**}	28.28	−0.06	21.32	0.40^{*}	596.14	82.67
MY_S	13.39	−0.59	29.63	0.47^{*}	21.76	0.35^{**}	525.86	−69.67
TC_E	14.65	−0.11	29.25	0.41	22.27	0.25	570.73	−37.36
TC_L	13.33	−0.11	27.91	1.21^{**}	21.15	1.22^{**}	310.24	-44.52^{*}

XB_S: single rice in Xinbin; GY_S: single rice in Ganyu; MY_S: single rice in Mianyang; TC_E: early rice in Tongcheng; TC_L: late rice in Tongcheng. *Significant at $p < 0.05$; **Significant at $p < 0.01$.

Table 6 Trends in rice transplanting, heading and maturity dates, VGP, RGP, and WGP during 1981–2009 at the four stations

Stations	XB_S	GY_S	MY_S	TC_E	TC_L
TD	0.6	−0.2	−1.9	−5.2**	−3.5**
HD	0.7	1.1	1.6*	−1.4	−0.5
MD	3.3**	1.6	4.8**	−2.0*	−5.0**
VGP	0.1	1.3	3.5**	3.7**	3.1**
RGP	2.6**	0.5	3.2**	−0.5	−4.5**
GP	2.6*	1.8	6.7**	3.2**	−1.4

TD: transplanting date; HD: heading date; MD: maturity date; VGP: vegetative growth period, from transplanting date to heading date; RGP: reproductive growth period, from heading date to maturity date; GP: whole growth period, from transplanting date to maturity date. XB_S: single rice in Xinbin; GY_S: single rice in Ganyu; MY_S: single rice in Mianyang; TC_E: early rice in Tongcheng; TC_L: late rice in Tongcheng. *Significant at $p < 0.05$; **Significant at $p < 0.01$.

3.1.2 Observed changes in rice phenology

Based on the trial data during 1981–2009, we found that for single rice at Mianyang and Ganyu stations, as well as early rice and late rice at Tongcheng station, transplant dates were advanced, although transplant date was delayed slightly for single rice at Xinbin station in Northeast China Plain (Table 6). For single rice in Xinbin, Mianyang, and Ganyu stations, heading dates were delayed; by contrast, the heading date was advanced for early rice and late rice at Tongcheng station. For single rice in Xinbin, Mianyang, and Ganyu, maturity dates were delayed and advanced for early rice and late rice at Tongcheng station.

The length of vegetative growth period (VGP, from transplanting date to heading date) was generally prolonged. The length of reproductive growth period (RGP, from heading date to maturity date) was prolonged for single rice, although shortened for early rice and late rice. Rice growth period (GP, from transplanting date to maturity date) was prolonged generally, although shortened for late rice at Tongcheng station.

Transplanting dates, heading dates, and maturity dates were delayed for single rice at Xinbin station in the Northeast China Plain. The lengths of VGP and RGP were both prolonged, and as a result, the length of GP was prolonged significantly. For single rice at Ganyu and Mianyang stations, transplanting dates were advanced, heading dates and maturity dates were delayed, and the lengths of VGP, RGP, and WGP were prolonged. For both early rice and late rice at Tongcheng station, the transplanting dates, heading dates, and maturity dates were all advanced. For early rice at Tongcheng station, the length of VGP was prolonged significantly, the length of GP was prolonged; however, the length of RGP was shortened. For late rice at Tongcheng station, the length of VGP was prolonged; by contrast the lengths of RGP and WGP were shortened.

3.1.3 Changes of accumulated thermal time during rice growth period in the past three decades

During 1981 to 2009, for both single rice and double rice, the accumulated thermal time during VGP increased (Fig. 2). The accumulated thermal time also increased during RGP but less than during VGP. As a result, the accumulated thermal time increased during GP.

The increasing heat requirement was an important aspect of varieties renewal. For both single rice and double rice, the thermal time requirements of varieties in the 2000s during VGP and RGP were more than those of cultivars in the 1980s.

3.1.4 Observed changes in rice yield and yield components

The changes of rice yield and yield components (grain number per spike, 1000-grain weight, and harvest index) at four stations in the past three decades are shown in Fig. 3. In the past three decades, the rice yields at all the stations increased, although yields increased less at Mianyang than at other stations. At all the stations, the rice grain number per spike in the past three decades had a clear increasing trend. The 1000-grain weights for late rice at Tongcheng increased significantly but not significantly at the other stations. At all stations, harvest index had an increasing trend. Since the 1000-grain weights changed slightly, yield increase was mainly ascribed to increase in grain number per spike.

In general, the grain number per spike in the 2000s was more than that in the 1980s. The 1000-grain weight in the 2000s was less than that in the 1980s, although for double rice at Tongcheng it was higher in the 2000s than that in the 1980s. The HI was significantly higher in the 2000s than in the 1980s.

3.2 Calibration and validation of CERES-Rice model

Based on the analysis of the observed data, we summarized the characteristics of the typical cultivars and fertilization managements in the 1980s and 2000s, respectively. Cultivar parameters are summarized in Table 7. The rice at all four stations are paddy rice; we used automatic irrigation when required in the simulations. We used the observed heading dates, maturity dates, and yields at all the four stations to calibrate and validate the CERES-Rice

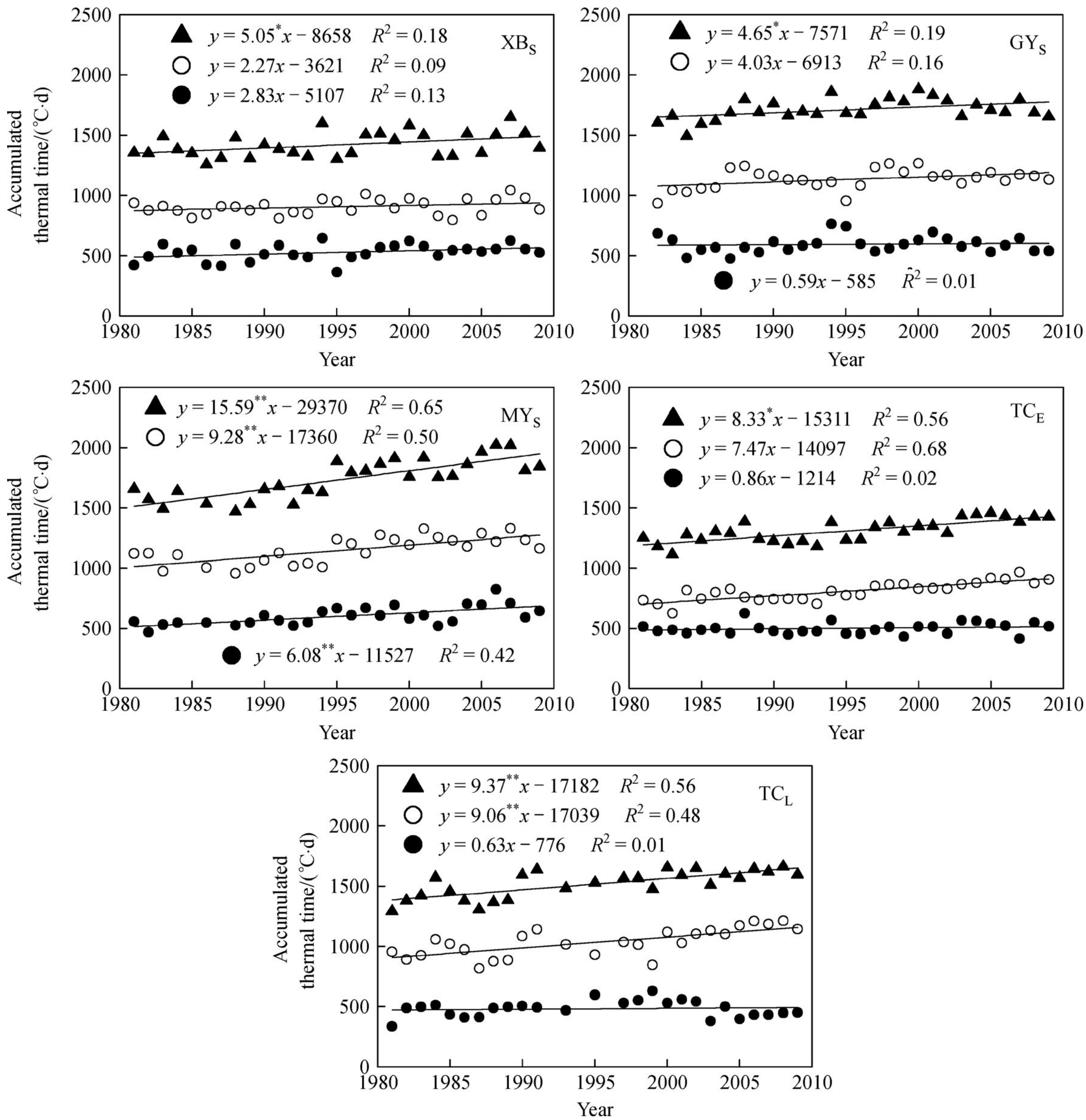

Fig. 2 Time series of accumulated thermal time during growth period (▲), vegetative growth period (○) and reproductive growth period (●) of rice at the four stations from 1981–2009. XB$_S$: single rice at Xinbin; GY$_S$: single rice at Ganyu; MY$_S$: single rice at Mianyang; TC$_E$: early rice at Tongcheng; TC$_L$: late rice at Tongcheng.

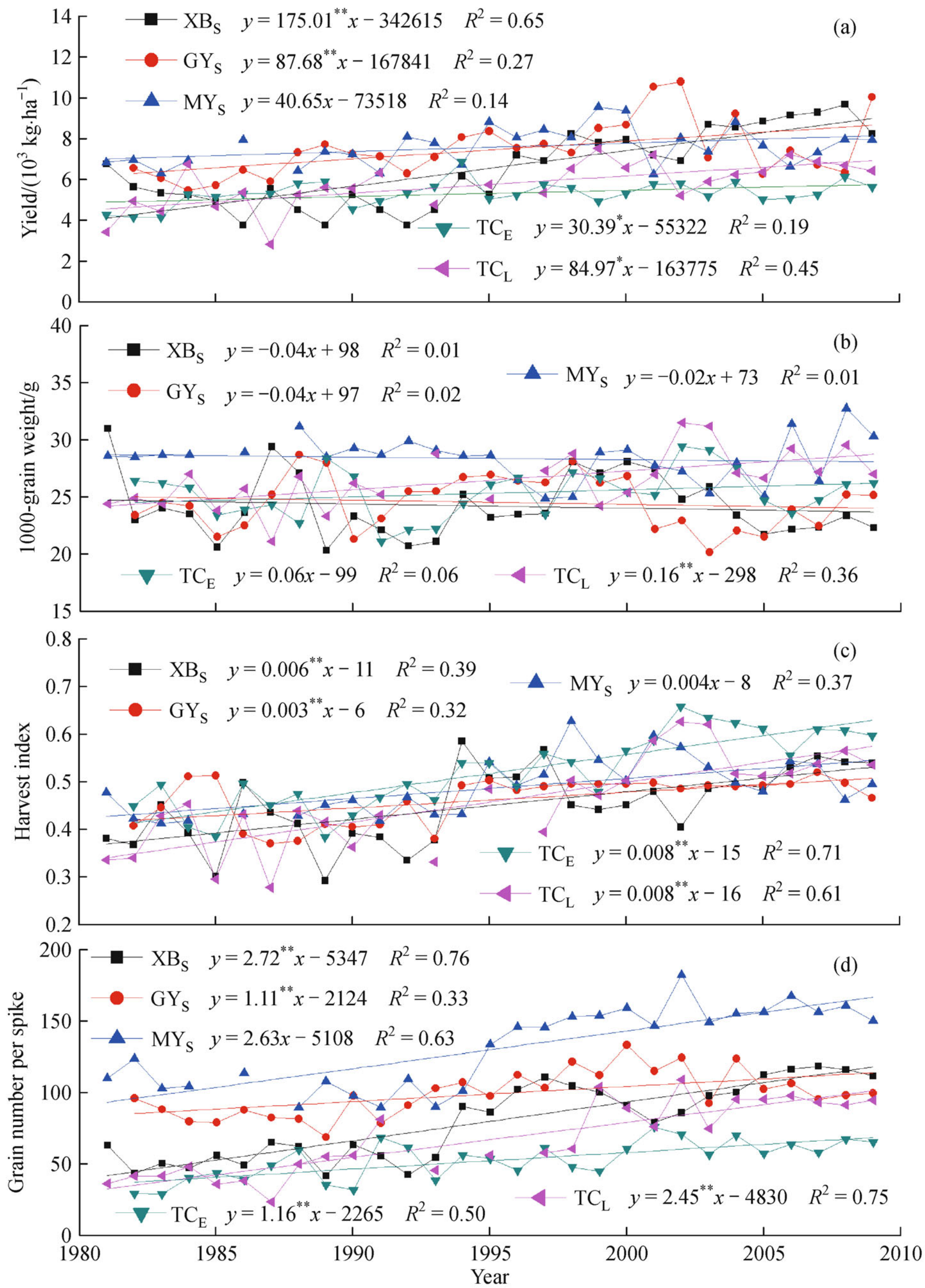

Fig. 3 Trends in yield (a), 1000–grain weight (b), harvest index (c), grain number per spike (d) at the four stations (1981–2009). *Significant at $p < 0.05$; **Significant at $p < 0.01$.

Table 7 Parameter values of the two representative crop cultivars used in the DSSAT model simulation

Parameter	XB_S		GY_S		MY_S		TC_E		TC_L	
	1980s	2000s	1980s	2000s	1980s	2000s	1980s	2000s	1980s	2000s
P1	208.5	270.5	349	414.5	424.3	590.9	284.8	426.5	233.9	369.4
P2R	57.5	54.9	108.8	105.3	71.2	68.5	42.9	40.8	169.2	163.2
P5	455.3	480.3	448.5	452.9	387.3	505.3	351.3	353.3	370.7	300.7
P2O	12.8	12.9	12.2	12.3	11.6	11.7	11.7	11.8	12.0	12.0
G1	58.3	89.9	57.5	65.7	47.2	49.9	47.9	55.9	50.6	54.8
G2	0.024	0.022	0.025	0.025	0.029	0.031	0.026	0.026	0.027	0.03
G3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
G4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

XB_S: single rice in Xinbin; GY_S: single rice in Ganyu; MY_S: single rice in Mianyang; TC_E: early rice in Tongcheng; TC_L: late rice in Tongcheng.

model; the errors of simulated heading date and maturity date were within 5% (Fig. 4), and the errors of simulated yields and observed yields were within 15% (Fig. 4). The results suggested that the validated CERES-Rice model can be accepted for the purpose of this study.

3.3 Contributions of changes in climate and each climate variable to rice yields

Rice yields increased significantly at all four stations during 1981–2009. As shown in Table 8 and Fig. 5, in the

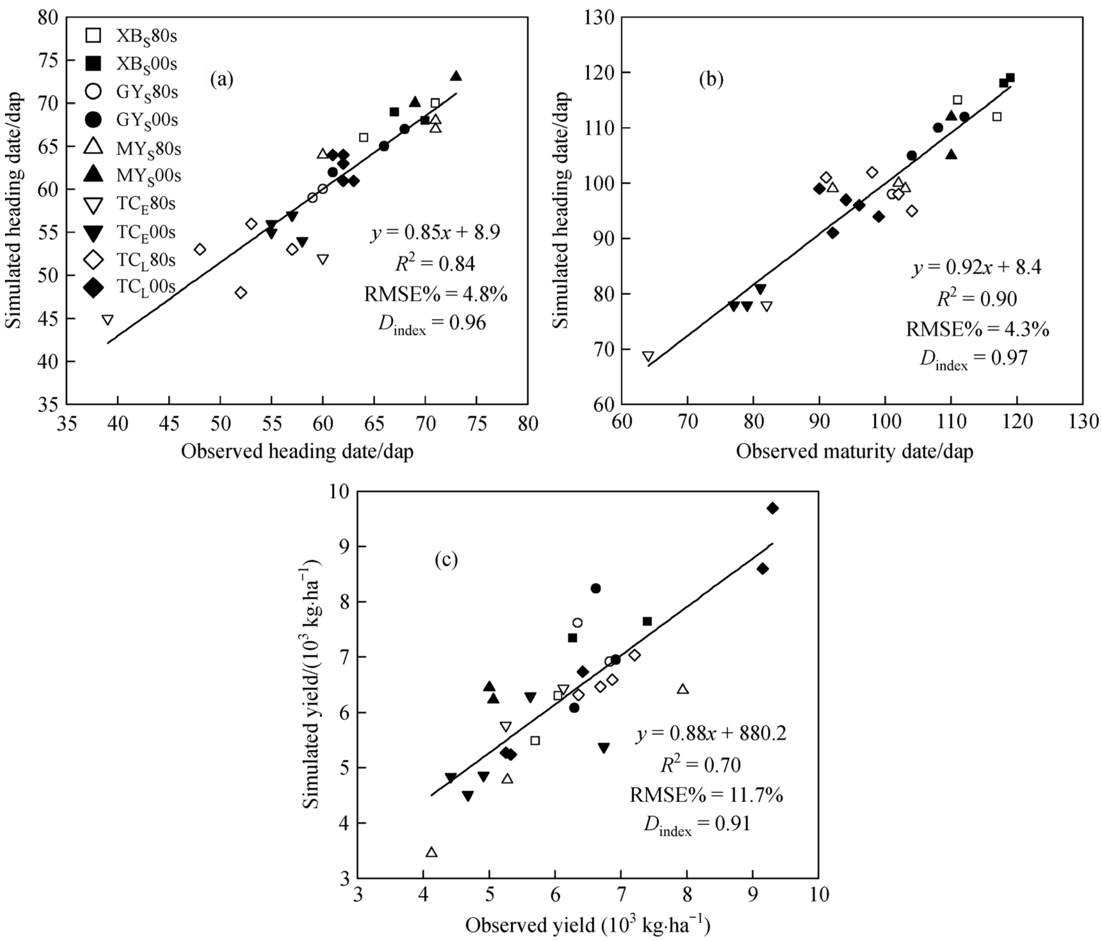

Fig. 4 Comparisons between CERES-Rice model simulated with field-observed heading date (a), maturity date (b), and grain yield (c) at the four stations.

Table 8 Contributions of changes in all climatic variables, temperature, and solar radiation to yields in $kg \cdot ha^{-1} \cdot yr^{-1}$ (%) of two rice cultivars (1981–2009)

Years	Variable	XB_S	GY_S	MY_S	TC_E	TC_L	Average
1980s	DN_all	9.4 (0.2%)	−13.5 (−0.2%)	−31.3 (−0.5%)	−22.6 (−0.5%)	−13.5 (−0.3%)	−14.3 (−0.3%)
	DN_rad	−4.0 (−0.1%)	−9.1 (−0.1%)	3.4 (0.1%)	−2.6 (0.0%)	−12.8 (−0.3%)	−5.0 (−0.1%)
	DN_temp	11.6 (0.2%)	2.4 (0.0%)	−24.6 (−0.4%)	−16.4 (−0.4%)	4.3 (0.1%)	−4.5 (−0.1%)
2000s	DN_all	29.4 (0.3%)	−12.1 (−0.2%)	−39.3 (−0.5%)	−11.8 (−0.2%)	1.3 (0.0%)	−6.5 (−0.1%)
	DN_rad	−9.1 (−0.1%)	−12.7 (−0.2%)	−1.9 (0.0%)	3.6 (0.1%)	−12.9 (−0.2%)	−6.6 (−0.1%)
	DN_temp	32.1 (0.4%)	6.3 (0.1%)	−22.4 (−0.3%)	−13.2 (−0.2%)	23.4 (0.3%)	5.2 (0.1%)

XB_S: single rice in Xinbin; GY_S: single rice in Ganyu; MY_S: single rice in Mianyang; TC_E: early rice in Tongcheng; TC_L: late rice in Tongcheng.

past three decades the contributions of climate change to rice yield were from −16.1% to 10.0%. Climate change increased yield by 0.2%–0.3% per year for single rice at Xinbin station, but reduced yield by 0.2%–0.5% per year at the other three stations. Changes in solar radiation reduced yield by about 0.1% per year. Changes in temperature increased yield by 0.04%–0.4% per year for single rice at Xinbin and Ganyu station and late rice at Tongcheng station; however, yield was reduced by 0.2%–0.4% per year for single rice at Mianyang station and early rice at Tongcheng station.

3.4 Contribution of varieties renewal and management improvement to rice yield during 1981–2009

In the past three decades, varieties renewal and management improvement greatly increased the rice yield, the 1000-grain weight, and the harvest index (Table 9). The

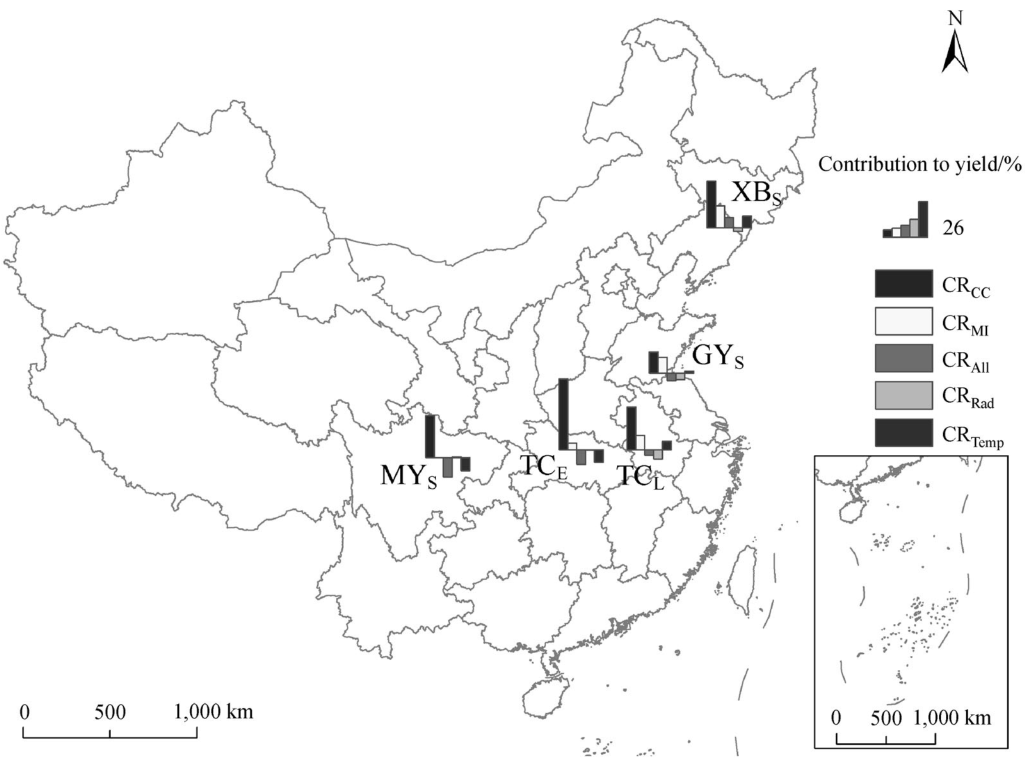

Fig. 5 Contributions of cultivar renewal (CR_{CC}), new fertilization management (CR_{MI}), all climatic variables (CR_{All}), solar radiation (CR_{Rad}) and temperature (CR_{Temp}) to rice yield at different stations during 1981–2009. XB_S: single rice at Xinbin; GY_S: single rice at Ganyu; MY_S: single rice at Mianyang; TC_E: early rice at Tongcheng; TC_L: late rice at Tongcheng.

Table 9 Contributions of cultivar renewal and new fertilization management (%) to rice yield (Yd), 1000-grain weight (1-GW) and harvest index (HI) during 1981–2009

Stations	XB_S	GY_S	MY_S	TC_E	TC_L	Average
CR_{CCMI} (Yd)	55.9±11.9	29.0±3.3	30.8±4.7	59.8±14.4	45.2±9.7	44.1±4.4
CR_{CC} (Yd)	34.4±7.1	15.6±3.2	30.9±6.4	52.0±12.3	31.6±11.9	32.9±5.0
CR_{MI} (Yd)	16.0±7.2	11.7±1.3	0.0±3.6	5.1±5.0	10.8±7.0	8.7±2.2
CR_{CCMI} (1-GW)	−4.1±6.5	0.0±0.0	6.9±0.0	0.0±0.0	11.9±3.0	2.9±1.6
CR_{CC} (1-GW)	−5.8±4.8	0.0±0.0	6.9±0.0	0.0±0.0	15.7±6.9	3.3±2.1
CR_{MI} (1-GW)	1.9±4.3	0.0±0.0	0.0±0.0	0.0±0.0	−3.0±4.8	−0.2±1.4
CR_{CCMI} (HI)	16.9±7.7	11.0±3.0	9.0±4.1	16.1±5.3	19.0±5.9	14.4±2.8
CR_{CC} (HI)	26.8±8.5	12.3±3.1	10.0±5.3	18.9±6.1	6.2±8.7	14.8±3.4
CR_{MI} (HI)	−7.7±4.3	−1.1±1.1	−0.8±3.1	−2.3±2.8	12.5±8.3	0.1±2.6

XB_S: single rice in Xinbin; GY_S: single rice in Ganyu; MY_S: single rice in Mianyang; TC_E: early rice in Tongcheng; TC_L: late rice in Tongcheng.

combined contributions of varieties renewal and management improvement to yield were about 44%. The contribution of varieties renewal to rice yield was about 32.9%, and the contribution of management improvement to the rice yield was about 8.7%. The impacts were different at different stations (Fig. 5).

The contributions of varieties renewal and management improvement to 1-GW were about 2.9%. For single rice at Xinbin station, varieties renewal reduced 1-GW and management improvement improved 1-GW, and 1-GW decreased under their combined effects. For the single rice at Ganyu station and early rice at Tongcheng station, varieties renewal and management improvement did not affect 1-GW much. For the single rice at Mianyang station and late rice at Tongcheng station, varieties renewal increased 1-GW, management improvement did not improve 1-GW for single rice, but reduced 1-GW for late rice.

Varieties renewal increased HI. The contribution of varieties renewal to HI was about 6.2%–26.8%. Management improvement had a positive impact on HI for late rice at Tongcheng, but had a negative impact on it for single rice at Xinbin, Ganyu and Mianyang stations, as well as for early rice at Tongcheng station. In summary, varieties renewal and management improvement were the main reasons for rice yield increase in the past three decades. The contributions of varieties renewal were greater than those of management improvement to rice yield change.

3.5 Sensitivity of rice cultivars to climate variables

Figure 6 shows the sensitivity of different rice cultivars to climate variables including SRD, temperature, and CO_2 concentration. We found that increase in CO_2 concentration increased rice yield significantly. Decrease in solar radiation and increasing in temperature reduced yield significantly. The new varieties were less sensitive to climate change than the old ones.

With SRD decreasing by 10%, 20%, and 30%, yield of cultivar-1980 decreased by about 6.4%, 13.4%, and 21.7%, and yield of cultivar-2000 decreased by about 5.2%, 11.1% and 18.0%, respectively. When temperature increased by 1°C, 2°C, and 3°C, yield of cultivar-1980 decreased by 4.4%, 10.0%, and 16.1%, and yield of cultivar-2000 decreased by 1.2%, 5.3%, and 10.5%, respectively. Cultivar-1980 was more sensitive to tem-

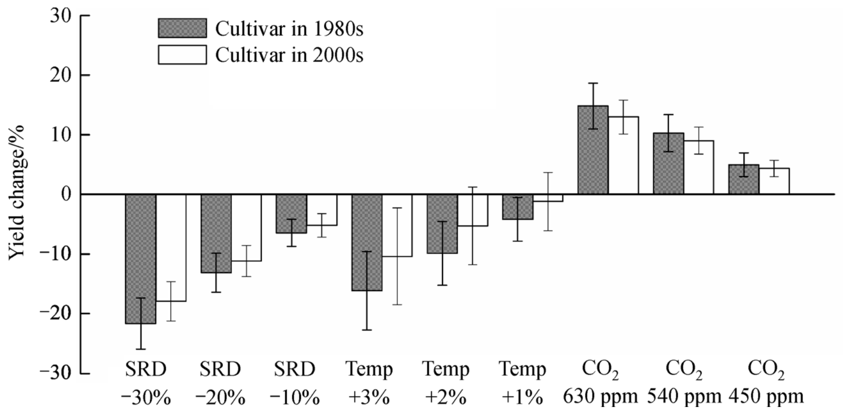

Fig. 6 Sensitivities of two representative rice cultivars to changes in solar radiation (SRD), temperature (Temp) and CO_2 concentration at the four stations.

perature increase than cultivar-2000. With CO_2 concentration reaching to 450 ppm, 540 ppm, and 630 ppm, yield of cultivar-1980 increased by 5.2%, 10.7%, and 15.2%, and yield of cultivar-2000 increased by 4.1%, 8.7%, and 12.5%, respectively.

4 Discussion

In this study, across the four representative stations, we found that varieties renewal increased rice yield by 16%–52% during 1981–2009. Management improvement increased rice yield by 0–16%. The impact of climate change on rice yield was from −16% to 10% (Fig. 7). Climate change had a negative impact on rice yield, which is consistent with previous studies (Peng et al., 2004; Tao et al., 2008). Varieties renewal and management improvement offset the negative effects of climate change on rice production, maintained or increased rice yield steadily. In the past three decades, rice varieties were renewed frequently. Varieties renewal was characterized by increase in varieties thermal requirements, longer growth period, increase in grain number per spike, and harvest index. Our study indicated that among the factors, varieties renewal played an important role in rice yield increase in the past three decades. Agronomic managements mainly include irrigation, fertilization, and so on. Here we focused on the nitrogen fertilizer application rates, and found that the application levels of nitrogen fertilizer in the paddy field increased, which had an important effect on rice yield increase.

Our results are supported by previous studies. For example, Yu et al. (2012), using Agro-C model and observation data, showed that varieties renewal was the main factor for rice yield increase in the past three decades, contributing to yield increase by 74%. Liu et al. (2013), using the APSIM-Oryza model, showed that increased thermal requirements stabilized or increased the aboveground biomass, and offset the negative impact of climate warming in reducing growth duration. Peng et al. (1999) also showed that varieties renewal and management improvement are the main reason for rice yield increase. Here, using a different model, methods, and long-term experimental data, we thoroughly disentangled the impacts of climate change, varieties renewal, and management improvement on yield.

For different climate regions, increase in temperature had different impacts on rice yield. Mean T_{max} during rice growth period was as high as 29.63°C at Mianyang station, moreover it increased significantly in the past three decades, which can reduce rice growth period and have heat stress at rice flowering stage. Mean T_{max} during rice growth period was as high as 28.28°C at Ganyu station where rice yield was positive related to temperature. However, temperature had a slightly decreasing trend in the past three decades at this station, which increased rice yield. The estimated impact of temperature change on rice yields are consistent with previous studies based on long-term experimental data (Tao et al., 2013). Decrease in solar radiation had a negative impact on rice yield at all the stations (Fig. 6). Decrease in solar radiation can directly reduce crop photosynthesis rate and biomass accumulation; moreover, the magnitude of solar radiation decrease was quite large in the past three decades, which reduced yield more than temperature change. These results are also supported by previous studies (e.g., Zhang and Tao, 2013; Xiao and Tao, 2014).

5 Conclusions

In this study, the long-term field experiment data at four

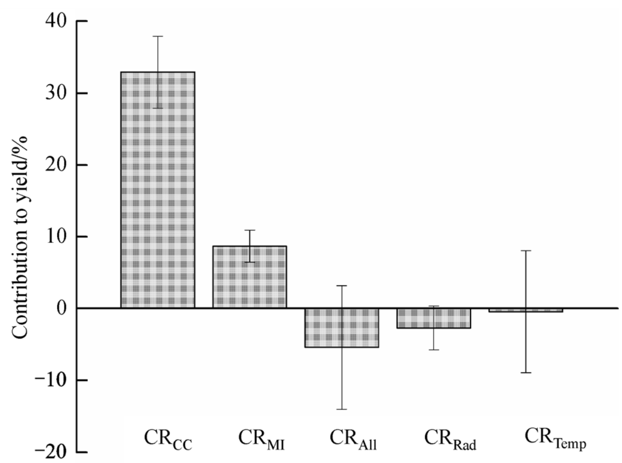

Fig. 7 Mean contributions of varieties, fertilization management and climate to rice yield across the four stations during 1981–2009. The error bars represent stand deviation. CR_{CC}: cultivar renewal; CR_{MI}: fertilization management improvement; CR_{All}: all climatic variables, CR_{Rad}: solar radiation; CR_{Temp}: temperature.

representative agro-meteorological stations, together with a crop simulation model, were applied to disentangle the contributions of climate change, variety renewal, and fertilization management improvement, as well as the contributions of different climate variables, to rice yield in the past three decades.

We found that the contribution of climate change to rice yield change was from −16% to 10% in the past three decades, but varieties renewal and fertilization management improvement offset the negative impacts of climate change on rice yield. During 1981–2009, varieties renewal increased rice yield by 16%–52%, and management improvement increased rice yield by 0–16%. Varieties renewal was the main factor for yield increase, in particular, through increasing varieties thermal requirements, grain number per spike, and harvest index. Increases in temperature had different impacts on rice yield in different climate regions, although decreases in SRD significantly reduced rice yield for almost all the stations.

The negative impacts of extreme high temperature are projected to increase with climate warming. Therefore, the development of high thermal requirements, high yield potential and heat tolerant rice varieties, together with improving agronomic management, should be encouraged to meet the challenges of climate change and increasing food demand in future.

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