Attribution of yield change for rice-wheat rotation system in China to climate change, cultivars and agronomic management in the past three decades

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Abstract Using the detailed field experiment data from 1981 to 2009 at four representative agro-meteorological experiment stations in China, along with the Agricultural Production System Simulator (APSIM) rice-wheat model, we evaluated the impact of sowing/transplanting date on phenology and yield of rice-wheat rotation system (RWRS). We also disentangled the contributions of climate change, modern cultivars, sowing/transplanting density and fertilization management, as well as changes in each climate variables, to yield change in RWRS, in the past three decades. We found that change in sowing/transplanting date did not significantly affect rice and wheat yield in RWRS, although alleviated the negative impact of climate change to some extent. From 1981 to 2009, climate change jointly caused rice and wheat yield change by -17.4 to 1.5 %, of which increase in temperature reduced yield by 0.0 – 5.8 % and decrease in solar radiation reduced it by 1.5 – 8.7 %. Cultivars renewal, modern sowing/transplanting density and fertilization management contributed to yield change by 14.4 – 27.2 , -4.7 – -0.1 and 2.3 – 22.2 %, respectively. Our findings highlight that modern cultivars and agronomic management compensated the negative impacts of climate change and played key roles in yield increase in the past three decades.

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1 Introduction

Rice and wheat are two vital cereal crops in China, accounting for 58.9 % (325.5 billion kg) of the total cereal production in 2013 (<http://www.stats.gov.cn>). However, the growth rates of rice and wheat yields have become stagnated in some major production areas of China since 2000 (Wei et al. 2015). The stagnation of crop yield has also documented in South Asia and Northern Europe (Timsina and Humphreys 2006; Wiesmeier et al. 2015). The slowdown in crop productivity growth has raised concerns on the long-term sustainability of intensive rice and wheat production system. The roles of genotype, agronomic management and climate change in the yield stagnation need to be investigated to seek the sustainable development pathway for the cropping system.

Several studies documented that increase in temperature since 1980s had reduced crop yields by shortening crop growth duration and aggravating heat/water stresses (Liu et al. 2012; Tao et al. 2012a; Lobell et al. 2013; Xiong et al. 2014). Decrease in solar radiation had reduced crop yield by reducing photosynthesis rate and biomass accumulation (Sheehy et al. 2006; Zhang et al. 2010). On the other hand, improvement in crop cultivars and agronomic management practices had alleviated the negative impacts of climate change and increased crop yields (Zhang et al. 2013; Xiao and Tao 2014). The interactions between genotype, agronomic management and climate change were quite complicated and differed substantially between regions and cropping systems (Tao et al. 2014). In order to accelerate understanding of climate change impacts and develop adaptation options, it is necessary to disentangle the contributions of climate change, cultivars renewal and modern agronomic management, as well as change in each climate variables, to change in crop yield.

Most of previous studies focus on the mono-cropping system, although crop rotation system dominates at some areas. The rice-wheat rotation system (RWRS) is one of major cropping systems in eastern China (Fig. 1). In this study, using the detailed field experiment data on RWRS from 1981 to 2009 at four representative stations, together with the Agricultural Production System Simulator (APSIM) rice-wheat model, we aim (1) to evaluate the impact of sowing/transplanting date on phenology and yield of rice and wheat in RWRS; (2) to disentangle the contributions of climate change, modern cultivars, sowing/transplanting density and fertilization management, (3) as well as change in each climate variable, to yield change of RWRS in the past three decades.

2 Materials and methods

2.1 Study sites, climate and crop data

The study region includes Jiangsu and Anhui provinces, which is one of the major agricultural production regions in China. RWRS is the dominant cropping system in the region. The four agro-meteorological experiment stations, including Hefei and Shouxian stations in Anhui province and Kunshan and Xuzhou stations in Jiangsu province, were selected in this study (Fig. 1).

Daily weather data at the four stations from 1980 to 2010, including minimum and maximum temperature, sunshine hours and precipitation, were obtained from the Chinese Meteorological Administration (CMA). The daily solar radiation was calculated from sunshine hours using the empirical Angstrom function (Prescott 1940).

Fig. 1 Location of the four agro-meteorological experiment stations in this study

Field experiment data for RWRS in the four agro-meteorological experiment stations during 1981–2009, including crop phenology, cultivar type, yield, yield components and management practices, were obtained from CMA. In the study region, continuous flood irrigation was applied to rice, although wheat was rain-fed. In order to evaluate the contributions of cultivars renewal and modern agronomic management practice to yield change, representative cultivars, sowing/transplanting density and fertilization management practices for the period of 1981–1989 (80s) and 2005–2009 (00s) were, respectively, selected at each station (Table 1), based on the long term field experiment data.

2.2 APSIM rice-wheat rotation system model

APSIM model simulates crop growth/development, yield, soil water and nutrient dynamic for single crop or crop rotations in response to changes in climate and management conditions (Keating et al. 2003). APSIM rice-wheat rotation system model consists of two sub-models: APSIM-oryza model and APSIM-wheat model, which can simulate flooding condition for rice growth and drought conditions for wheat growth. APSIM model has been widely applied to simulate agricultural system in different regions of the world, including China (e.g., Wang et al. 2012; Liu et al. 2013; Xiao and Tao 2014).

2.3 Modelling the impact of sowing/transplanting date on phenology and yield

Two groups of simulations were conducted from 1981 to 2009 to investigate the impact of sowing/transplanting date on phenology and yield of RWRS. The first group of simulations was conducted with the single cultivar-80s, the observed sowing and

Table 1 Details on cultivar, yield, yield components and management practice in RWRS for 1981–1989(80s) and 2005–2009(00s) at the four agro-meteorological experiment stations. The number after “±” is standard deviation (*STD*) of the respective variable

Station	Hefei			Shouxian			Kunshan			Xuzhou		
Crop	Rice			Rice			Rice			Rice		
Cultivar	80s			80s			80s			80s		
Name	Guiqing2	00s	Xianmuo	Xieyou63	00s	Zaodan8	Jia33	00s	Xudao1	00s	Xufu2	00s
Sowing year	1981–1983	2007–2009	1985–1987	2005–2007	2005–2007	1986–1989	2007–2009	2007–2009	1986–1989	2005–2008	1986–1989	2005–2008
TD (DOY)	138±0	163±4	167±1	167±2	167±2	173±2	179±1	179±1	174±5	164±1	174±5	164±1
AD (DOY)	212±2	231±3	225±6	229±1	229±1	250±2	249±2	249±2	235±2	237±4	235±2	237±4
MD (DOY)	237±3	262±1	254±13	263±0	263±0	296±2	295±2	295±2	277±4	277±4	277±4	277±4
GNPS	61.3±9.8	266.8±31.7	91.7±12.6	145.2±28.5	145.2±28.5	69.3±11.4	103.9±7.5	103.9±7.5	110.7±7.0	125.2±13.7	110.7±7.0	125.2±13.7
1-GW (g)	25.1±2.2	28.4±0.5	28.9±0.9	29.4±1.5	29.4±1.5	27.8±1.2	27.4±1.3	27.4±1.3	24±1.0	25.7±1.7	24±1.0	25.7±1.7
Harvest index	0.41±0.02	0.49±0.01	0.52±0.11	0.54±0.02	0.54±0.02	0.39±0.04	0.45±0.03	0.45±0.03	0.41±0.04	0.47±0.01	0.41±0.04	0.47±0.01
TDen (hills m ⁻²)	45	30	45	30	30	45	30	30	45	30	45	30
Fertilization (kg N ha ⁻¹)												
Base	30	180	80	150	150		50	50	50	80	50	80
Transplanting	80		120	180	180	35			50	80	50	80
Tillering stage	30	90				25	100	100				
Panicle differentiation						70	80	80				
Crop	Wheat			Wheat			Wheat			Wheat		
Cultivar	80s			80s			80s			80s		
Name	Ningmai73	00s	Boai74-22	Xumai27	00s	Yangmai4	Yangmai12	00s	Jinan13	00s	Xuzhou24	00s
Sowing year	1981–1983	2007–2009	1985–1987	2005–2007	2005–2007	1986–1989	2007–2009	2007–2009	1986–1989	2005–2008	1986–1989	2005–2008
SD (DOY)	300±2	299±2	303±16	294±4	294±4	307±4	309±4	309±4	280±1	290±5	280±1	290±5
AD (DOY)	119±2	104±1	124±1	110±2	110±2	119±5	110±4	110±4	124±1	124±9	124±1	124±9
MD (DOY)	152±1	137±3	150±1	144±2	144±2	153±3	144±2	144±2	157±0	153±1	157±0	153±1
GNPS	40.1±1.6	46.0±10.1	29.6±2.3	31.0±5.5	31.0±5.5	29.7±4.0	31.1±2.6	31.1±2.6	27.8±2.6	28.9±2.0	27.8±2.6	28.9±2.0
1-GW (g)	35.7±3.0	39.7±0.9	37.9±3.2	37.7±2.9	37.7±2.9	35.3±5.0	45.2±4.7	45.2±4.7	43.9±2.0	43.5±4.2	43.9±2.0	43.5±4.2

Table 1 (continued)

Station	Hefei	Shouxian	Kunshan	Xuzhou
Harvest index	0.41±0.02	0.48±0.01	0.53±0.01	0.34±0.07
PD (plant m ⁻²)	300	270	220	220
Fertilization (kg N ha ⁻¹)				
Base	120	180	160	160
Jointing stage	60	70	30	110

TD is transplanting date, SD is sowing date, AD is anthesis date, MD is maturity date, GNPS is grain number per spike, 1-GW is 1000-grain weight, TDen is Transplanting density, PD is planting density, N is nitrogen. 80s denotes 1981–1989 and 00s denotes 2005–2009

transplanting date for rice and observed sowing date for wheat in 1981 at each station. Because of cultivar and sowing/transplanting date were fixed in the simulations, the simulated changes in phenology and yield were affected only by climate change. The second group of simulations was conducted with the single cultivar-80s too, but with the observed sowing and transplanting date for rice and the observed sowing date for wheat in each year at each station. The impact of sowing/transplanting date change on phenology and yield of RWRS was investigated by comparing the results from the two groups of simulations.

2.4 Disentangling the impact of change in each climate variable on yield

At each station, to investigate the impacts of changes in all the climate variables including temperature, precipitation and solar radiation on yield of RWRS, the model was run with observed daily temperature, precipitation and solar radiation data from 1981 to 2009. Then, the impacts of changes in all the climate variables on yield were estimated by computing annual change of the simulated yields from 1981 to 2009. To disentangle the impact of change in temperature on crop yield, the model was firstly run from 1981 to 2009 with observed daily temperature data from 1981 to 2009 and the observed daily solar radiation and precipitation data in 1981. The process was repeated for 29 times by replacing the inputs for daily solar radiation and precipitation data using observed daily data in each individual year from 1982 to 2009, resulted in totally 29 years $\times$ 29 times = 841 simulations. Then, the impact of change in temperature on crop yield were estimated by computing annual change of simulated yields from 1981 to 2009, based on the total 841 simulated results. Likewise, the impact of change in solar radiation on crop yield was estimated. Because there was no significant trend in precipitation during the study period, the impact of change in precipitation on yield were not investigated.

2.5 Quantifying the contributions of crop cultivars, sowing/transplanting density and fertilization to yield change

To evaluate the contributions of cultivars, sowing/transplanting density and fertilization management to yield change in RWRS in the past three decades, five sets of modeling experiments (i.e., E1, E2, E3, E4 and E5) were designed (Table 2). The impacts of cultivars, sowing/transplanting density and fertilization management on crop yield were disentangled by comparing the results from different modeling experiments, using the following equations:

Table 2 Five modeling experiments (i.e., E1, E2, E3, E4 and E5) designed to investigate the individual contribution of cultivars renewal, modern sowing/transplanting density and new fertilization to yield change of RWRS. 80s and 00s denote the period of 1981–1989 and 2005–2009, respectively

Experiment	Cultivar	Sowing/transplanting density	Fertilization
E1	80s	80s	80s
E2	00s	80s	80s
E3	80s	00s	80s
E4	80s	80s	00s
E5	00s	00s	00s

$$C_{\text{Cul}} = \frac{Y_{\text{E2}} - Y_{\text{E1}}}{Y_{\text{E1}}} \times 100\% \quad (1)$$

$$C_{\text{Den}} = \frac{Y_{\text{E3}} - Y_{\text{E1}}}{Y_{\text{E1}}} \times 100\% \quad (2)$$

$$C_{\text{Fer}} = \frac{Y_{\text{E4}} - Y_{\text{E1}}}{Y_{\text{E1}}} \times 100\% \quad (3)$$

$$C_{\text{CDF}} = \frac{Y_{\text{E5}} - Y_{\text{E1}}}{Y_{\text{E1}}} \times 100\% \quad (4)$$

Where C_{Cul} , C_{Den} and C_{Fer} are the contributions of cultivars renewal, modern sowing/transplanting density management, modern fertilization management to yield change, respectively. C_{CDF} is the joint contributions of cultivars renewal, modern sowing/transplanting density and fertilization management to yield. Y_{E1} , Y_{E2} , Y_{E3} , Y_{E4} and Y_{E5} are the simulated yields by the modeling experiments E1, E2, E3, E4 and E5, respectively.

3 Results

3.1 Changes in crop cultivars, phenology and yield, and agronomic management, based on field experiment data from 1981 to 2009

According to the field experiment data from 1981 to 2009, for rice, the duration from transplanting to maturity of cultivar-00s was longer than that of cultivar-80s at all the stations except Kunshan (Table 1). And the duration from anthesis to maturity of cultivar-00s was longer than that of cultivar-80s at all the stations except Xuzhou. For wheat, the duration from sowing to maturity of cultivar-00s was shorter than that of cultivar-80s at all the stations except Shouxian. However, the duration from anthesis to maturity of cultivar-00s was longer than that of cultivar-80s at all the stations except Xuzhou. For both rice and wheat, the grain number per spike, HI and yields of cultivar-00s were larger than those of cultivar-80s at all the four stations (Table 1). In term of agronomic management, from 1981 to 2009, rice transplanting density became lower at all the four stations, and wheat sowing density became lower too at all the stations except Xuzhou. The fertilizer application rate increased substantially for both rice and wheat at all the four stations (Table 1).

3.2 Calibration and validation of APSIM rice-wheat model using observed experiment data

At each station, the APSIM rice-wheat model was calibrated and validated for cultivar-80s and cultivar-00s based on the field experiment data during 1981–1989 and during 2005–2009, respectively. The cultivar-specific parameters required to run APSIM-oryza model include development rates during juvenile phase, photoperiod-sensitive phase, panicle development

phase and reproductive phase, and photoperiod sensitivity. The cultivar-specific parameters required to run APSIM-wheat model include four parameters related to phenological development (i.e., *tt_end_of_juvenile*, *Startgf_to_mat*, *Vern_sens*, *Photop_sens*), and three parameters related to grain yield (i.e., *Potential_grain_filling_rate*, *Grains_per_gram_stem*, *Max_grain_size*).

The results showed that the simulated dates of anthesis and maturity were in good agreement with the observed dates for rice and wheat at all the four stations (Fig. 2). The difference between simulated and observed phenological dates for both crops was on average less than 5 days. The simulated yield also agreed well with observed yield for rice and wheat (Fig. 2). Compared with the observed yield, the relative error of the simulated yield was less than 15 %. Overall, APSIM rice-wheat model can simulate the phenological development and yield information in RWRS fairly well.

3.3 Impact of sowing/transplanting date on phenology and yield of RWRS

Due to climate warming, for rice, the simulated growth duration from sowing to anthesis decreased significantly by 1.0–1.6 days/decade at all the stations (Table 3), however the duration from anthesis to maturity had no significant change at all the stations except Kunshan. For wheat, the simulated growth duration from sowing to anthesis was shortened significantly by 4.0–5.5 days/decade, and the duration from anthesis to maturity had no significant change at all the stations.

During the study period, the observed rice sowing and transplanting dates were delayed significantly at Hefei and Kunshan (Table 3). As a result, rice growth duration from sowing to anthesis was slightly shortened, but growth duration from anthesis to maturity was slightly prolonged. The observed wheat sowing date was delayed significantly ($P < 0.01$) only at Xuzhou, which shortened slightly the growth duration from sowing to anthesis, and from anthesis to maturity.

As shown in Fig. 3, shifts in sowing/transplanting date had no significant impact on rice and wheat yield. Shifts in transplanting date increased rice yield slightly at all the stations. Late sowing of wheat reduced slightly wheat yield at Xuzhou.

3.4 Impacts of different climate variables on rice and wheat yield from 1981 to 2009

Trends in different climatic variables at the four stations from 1981 to 2009 were shown in Table 4. Annual mean maximum and minimum temperature increased significantly at all the four stations and annual mean solar radiation decreased significantly at Hefei, Shouxian and Xuzhou stations. During both rice and wheat growth period, mean maximum and minimum temperature increased significantly at all the stations. Mean solar radiation decreased significantly at Hefei, Shouxian and Xuzhou during rice growth period, however changed slightly during wheat growth period (Table 4).

In the past three decades, increase in temperature reduced the total yields of RWRS by 0.1–0.3 % per year at all stations for cultivar-80s, and reduced it at Kunshan and Xuzhou for cultivar-00s (Table 5). For both cultivar-80s and cultivar-00s, decrease in solar radiation reduced the total yield of RWRS by 0–0.5 % per year at Hefei, Shouxian and Xuzhou, and increase in solar radiation increased it significantly ($P < 0.01$) by 0.2–0.3 % per year at Kunshan. For cultivar-80s, changes in all the climatic variables jointly reduced the total yield of RWRS by 0.4–0.9 % per year at Hefei, Shouxian and Xuzhou, however increased it by

Fig. 2 Validation of the APSIM rice-wheat model simulations on anthesis date, maturity date and yield for RWRS at the study stations

0.1 % per year at Kunshan. For cultivar-00s, changes in all the climatic variables jointly reduced the total yield of RWRS by 0.0–0.3 % per year at Hefei, Kunshan and Xuzhou, however increased it by 0.2 % per year at Shouxian.

Increase in temperature reduced rice yield at all stations for cultivar-80s, however, had insignificant impact on yield for cultivar-00s. Decrease in solar radiation reduced rice yield for cultivar-80s significantly ($P < 0.05$) at Hefei, Shouxian and Xuzhou, and reduced it for cultivar-00s significantly only at Shouxian ($P < 0.05$). Increase in solar radiation increased rice yield

Table 3 Trends (days/decade) in observed and simulated durations of key development stages at each station

Crop	Station	SD	TD	SA1	SA2	AM1	AM2	SM1	SM2
Rice	Hefei	6.55**	5.39*	-1.55**	-2.41**	0	0.31	-1.54**	-2.1**
	Shouxian	0.96	-0.78	-1.35**	-2.02**	-0.18	-0.35	-1.53*	-2.37*
	Kunshan	5.33**	2.23	-1.24*	-2.98**	-4.02**	-1.64*	-5.26**	-4.62**
	Xuzhou	-1.98	-2.77	-1.03*	-1.10	-0.99	-1.49*	-2.02*	-2.59*
Wheat	Hefei	-1.13		-5.52**	-4.95**	0.35	0.53	-5.17**	-4.41**
	Shouxian	-1.80		-4.03**	-3.29	-0.07	0.32	-3.96**	-2.93
	Kunshan	-0.19		-3.93*	-4.20	-0.24	-0.14	-4.18**	-4.35*
	Xuzhou	6.15**		-4.89**	-6.3**	0.27	-0.42	-4.63**	-6.73**

*Significant at $P<0.05$ and ** significant at $P<0.01$. SD is sowing date. TD is transplanting date. SA, AM, SM are the duration from sowing to anthesis, anthesis to maturity and sowing to maturity, respectively. 1, 2 denote the simulated durations with sowing/transplanting date in 1981 and the simulated durations with recorded sowing/transplanting dates, respectively

slightly at Kunshan for both cultivar-80s and cultivar-00s. Changes in all the climatic variables jointly reduced rice yield for cultivar-80s significantly ($P<0.01$) by 0.8–1.0 % per year at Hefei, Shouxian and Xuzhou, and reduced it for cultivar-00s significantly only at Hefei by 0.4 % ($P<0.05$). Rice cultivar-00s was more resilient to high temperature and low solar radiation than cultivar-80s.

Increase in temperature reduced wheat yield at Hefei, Kunshan and Xuzhou stations with cultivar-80s, and reduced it at Kunshan and Xuzhou with cultivar-00s (Table 5). For both cultivar-80s and cultivar-00s, increase in solar radiation increased wheat yield significantly at Shouxian and Kunshan stations, however decrease in solar radiation reduced it slightly at Hefei and Xuzhou stations. Changes in all the climatic variables jointly reduced wheat yield by 0.4–0.7 % per year at Hefei and Xuzhou while increased it by 0.3–0.5 % per year at Shouxian and Kunshan, with cultivar-80s. By contrast, with cultivar-00s, changes in all the climatic variables jointly increased wheat yield at all stations except Xuzhou. Wheat cultivar-00s was more resilient to climate change in the past three decades than cultivar-80s.

Fig. 3 Impacts of sowing/transplanting date on yield of RWRS. Yield trends denote linear trends in the differences between the simulated yields with fixed sowing/transplanting date and observed sowing/transplanting date from 1981 to 2009. * denotes significant at $P<0.05$ and ** denotes significant at $P<0.01$

Table 4 Trends in maximum temperature (Tmax), minimum temperature (Tmin), solar radiation (Rad) and precipitation (Prec) during the year, during rice growth period (RGP) and during wheat growth period (WGP) at the four stations for 1981–2009

Station	Period	Tmax		Tmin		Rad		Prec	
		Mean (°C)	Trend (°C decade ⁻¹)	Mean (°C)	Trend (°C decade ⁻¹)	Mean (MJm ⁻²)	Trend (MJm ⁻² decade ⁻¹)	Mean (mm)	Trend (mm decade ⁻¹)
Hefei	Annual	21.8	0.63**	13.8	0.58**	11.9	-0.31**	995.5	-4.9
	RGP	28.7	0.60**	20.9	0.62**	13.6	-0.50**	557.8	-33.7
	WGP	14.9	0.67**	6.6	0.53**	10.3	-0.13	437.7	28.8
Shouxian	Annual	21.3	0.47**	12.3	0.46**	12.6	-0.21*	937.6	-17.3
	RGP	28.2	0.39**	19.9	0.38**	14.6	-0.50*	614.9	-32.5
	WGP	14.5	0.56**	4.7	0.53**	11.0	0.08	322.7	15.2
Kunshan	Annual	21.8	0.55**	14.9	0.84**	12.3	0.15	1196.3	-3.5
	RGP	28.5	0.55**	22.0	0.85**	14.2	0.10	700.3	-13.4
	WGP	15.0	0.56**	7.7	0.83**	10.4	0.20	496.0	9.9
Xuzhou	Annual	21.1	0.30**	11.8	0.65**	13.6	-0.39**	852.1	27.9
	RGP	28.2	0.24	19.4	0.64**	15.3	-0.66*	628.3	30.0
	WGP	13.9	0.36*	4.3	0.66**	11.9	-0.12	223.8	-1.7

*Significant at $P < 0.05$ and ** significant at $P < 0.01$

3.5 Contributions of crop cultivars, modern sowing/transplanting density and modern fertilization to yield change during 1981–2009

As shown in Table 6, from 1981 to 2009, cultivars renewal boosted the total yield of RWRS, rice yield and wheat yield by 14.4–27.2, 19.3–33.4 and 6.5–27.8 %, respectively. Modern sowing/transplanting density management changed the total yield of RWRS, rice yield and wheat yield by -4.7–0.1, -4.2–0.1 and -13.5–0.2 %, respectively. Modern fertilization management boosted the total yield of RWRS, rice yield and wheat yield by 2.3–22.2, 0.5–24.9 and 5.8–14.8 %, respectively. Cultivars renewal, modern sowing/transplanting density and fertilization management jointly increased the total yield of RWRS, rice yield and wheat yield by 34.3–61.7, 26.0–62.5 and 45.6–63.3 %, respectively.

4 Discussions

4.1 Impacts of sowing/transplanting date on phenology and yield of RWRS in the past three decades

Shift in sowing/transplanting date is an effective adaptation strategy for RWRS to deal with ongoing climate change condition (Tao et al. 2012b). Proper late sowing and late transplanting can extend slightly rice growth duration from anthesis to maturity and increase rice yield. However, late sowing of rice may result in delayed sowing of wheat, which may reduce wheat yield because the period from anthesis to maturity may be increasingly subjected to high temperature and wheat grain filling duration may be shortened.

For double cropping system, the total yield of the whole cropping system should be considered rather than the yield of individual crop. In the North China Plain, late sowing of

winter wheat and late harvesting of maize increased the total yield of the wheat-maize system by 4–6 % (Wang et al. 2012). In this study, at Xuzhou, slight advance in rice sowing and transplanting date increased rice yield, however significant delay in wheat sowing reduced the total yield of RWRS. Therefore, the phenological dynamic should be optimized to identify the optimal sowing/transplanting date for rice and wheat in RWRS.

4.2 Impacts of different climate variables on yield of RWRS in the past three decades

Due to the diverse climate conditions among stations, as well as the different sensitivity of crop yields to each climate variable, the impacts of each climate variable on yield of RWRS were also different (Fig. 4). In the past three decades, significant increase in temperature reduced both rice and wheat yield, in particular for cultivar-80s, mainly because it accelerated the crop development rate, reduced crop growth duration (Table 3) and biomass accumulation (Tao et al. 2012a). Modern cultivar had longer growth durations, consequently more resilient to climate warming. Decrease in solar radiation reduced rice yield at Hefei, Shouxian and Xuzhou and reduced wheat yield at Hefei and Xuzhou. By contrast, increase in solar radiation increased rice yield at Kunshan and wheat yield at Shouxian and Kunshan.

Table 5 Impacts of all climatic variables (C_{All}), temperature (C_{Temp}), and solar radiation (C_{Rad}) on yield trends ($\text{kg ha}^{-1} \text{ year}^{-1}$) for two cultivars during 1981–2009 at each station. The numbers in parenthesis are the corresponding values in percentage

		Hefei	Shouxian	Kunshan	Xuzhou
RWRS					
Cultivar-80s	C_{All}	-58.3** (-0.6 %)	-37.8* (-0.4 %)	6.0 (0.1 %)	-61.0** (-0.9 %)
	C_{Temp}	-16.8 (-0.2 %)	-7.6 (-0.1 %)	-7.9 (-0.1 %)	-22.3** (-0.3 %)
	C_{Rad}	-34.5* (-0.4 %)	-12.2 (-0.1 %)	11.2* (0.2 %)	-35.7** (-0.5 %)
Cultivar-00s	C_{All}	-24.7 (-0.2 %)	23.3 (0.2 %)	-2.3 (0 %)	-23.4 (-0.3 %)
	C_{Temp}	8.4 (0.1 %)	9.8 (0.1 %)	-26.2** (-0.3 %)	-1.1 (0 %)
	C_{Rad}	-26.4 (-0.2 %)	-3.3 (0 %)	23.9** (0.3 %)	-1.4 (0 %)
Rice					
Cultivar-80s	C_{All}	-44.0** (-0.8 %)	-57.2** (-0.9 %)	-0.5 (0 %)	-42.3** (-1.0 %)
	C_{Temp}	-6.5 (-0.1 %)	-8.3 (-0.1 %)	-2.1 (-0.1 %)	-14.0* (-0.4 %)
	C_{Rad}	-32.9* (-0.6 %)	-42.1* (-0.7 %)	2.1 (0.1 %)	-28.2** (-0.7 %)
Cultivar-00s	C_{All}	-27.4* (-0.4 %)	-27.8 (-0.4 %)	-3.7 (0 %)	7.4 (0.1 %)
	C_{Temp}	2.9 (0 %)	3.6 (0 %)	-5.7 (-0.1 %)	2.6 (0.1 %)
	C_{Rad}	-24.3 (-0.3 %)	-34.0* (-0.5 %)	2.3 (0.1 %)	1.8 (0 %)
Wheat					
Cultivar-80s	C_{All}	-14.3 (-0.4 %)	19.4* (0.5 %)	6.5 (0.3 %)	-18.7 (-0.7 %)
	C_{Temp}	-10.3* (-0.3 %)	0.7 (0 %)	-5.8 (-0.3 %)	-8.4** (-0.3 %)
	C_{Rad}	-1.6 (0 %)	29.9* (0.8 %)	9.1** (0.5 %)	-7.5** (-0.3 %)
Cultivar-00s	C_{All}	2.7 (0.1 %)	51.1** (1.2 %)	1.4 (0 %)	-30.8 (-0.9 %)
	C_{Temp}	5.5 (0.1 %)	6.2 (0.2 %)	-20.5* (-0.7 %)	-3.7 (-0.1 %)
	C_{Rad}	-2.1 (0 %)	30.7* (0.8 %)	21.6** (0.7 %)	-3.2 (-0.1 %)

*Significant at $P < 0.05$ and ** significant at $P < 0.01$

Table 6 Contributions (%) of cultivars renewal (C_{Cul}), modern sowing/transplanting density (C_{Den}), and modern fertilization (C_{Fer}) to yield change at each station during 1981–2009. C_{CDF} denote the joint contributions of cultivars and management to yield change. The number after “ $\pm$ ” is standard deviation (STD) of the corresponding values

Station	Hefei	Shouxian	Kunshan	Xuzhou
RWRS				
C_{Cul}	21.8 $\pm$ 10.6	14.4 $\pm$ 7.2	27.2 $\pm$ 12.2	26.5 $\pm$ 9.7
C_{Den}	-2.1 $\pm$ 1.3	-0.1 $\pm$ 0.4	-4.7 $\pm$ 2.2	-2.4 $\pm$ 1.5
C_{Fer}	6.2 $\pm$ 5.3	2.3 $\pm$ 3.0	22.2 $\pm$ 6.0	14.3 $\pm$ 8.3
C_{CDF}	49.9 $\pm$ 11.7	34.3 $\pm$ 8.2	49.2 $\pm$ 29.1	61.7 $\pm$ 14.7
Rice				
C_{Cul}	27.1 $\pm$ 16.0	19.3 $\pm$ 9.5	33.4 $\pm$ 14.6	25.6 $\pm$ 12.7
C_{Den}	-3.4 $\pm$ 1.4	0.1 $\pm$ 0.7	-1.3 $\pm$ 0.6	-4.2 $\pm$ 1.9
C_{Fer}	6.6 $\pm$ 3.8	0.5 $\pm$ 0.9	24.9 $\pm$ 2.6	15.4 $\pm$ 4.0
C_{CDF}	40.4 $\pm$ 18.6	26.0 $\pm$ 9.2	49.9 $\pm$ 19.7	62.5 $\pm$ 10.2
Wheat				
C_{Cul}	15.2 $\pm$ 13.6	6.5 $\pm$ 14.1	10.5 $\pm$ 16.5	27.8 $\pm$ 14.7
C_{Den}	-0.3 $\pm$ 2.2	-0.2 $\pm$ 0.8	-13.5 $\pm$ 8.4	0.2 $\pm$ 2.3
C_{Fer}	6.0 $\pm$ 8.6	5.8 $\pm$ 7.9	14.8 $\pm$ 18.0	11.5 $\pm$ 10.0
C_{CDF}	63.3 $\pm$ 18.9	49.3 $\pm$ 18.8	45.6 $\pm$ 21.8	58.5 $\pm$ 35.4

Significant increase in temperature, together with significant decrease in solar radiation, reduced rice yield significantly at Hefei, Shouxian and Xuzhou, as well as wheat yield at Hefei and Xuzhou. Significant increase in temperature, together with insignificant increase in solar radiation, increased rice yield at Kunshan, as well as wheat yield at Shouxian and Kunshan. The results implied that change in solar radiation played a more important role in affecting crop yield in comparison with other climate variables. The results are supported by some

Fig. 4 Mean contributions of cultivars renewal, sowing/transplanting density, and fertilization and climate variables to yield change of RWRS across the four stations during 1981–2009. C_{All} , C_{Temp} , C_{Rad} , C_{Cul} , C_{Den} , C_{Fer} denote the contribution of all climatic variables, temperature, and solar radiation, cultivars, sowing/transplanting density and fertilization to yield change, respectively. C_{CDF} denotes the combined contributions of cultivars and management to yield change

previous studies based on both long term field experiment data and census data (Peng et al. 2004; Zhang et al. 2013; Tao et al. 2012a; Tao et al. 2014). which indicated that crop yield was positively correlated with solar radiation in this region. However, Liu et al. (2013) showed that climate change had a negative impact on rice yield at Kunshan from 1980s to 2000s. The disparity may be due to the different methods and data used in evaluating the impact of climate change on crop yield.

4.3 Contributions of cultivars and management to yield of RWRS in the past three decades

In this study, we found that from 1981 to 2009 cultivars renewal, modern fertilization management contributed substantially to yield increase in RWRS in the past three decades (Fig. 4). Cultivars renewal increased rice yields by 26.4 % from 1981 to 2009. Compared with old cultivars, modern cultivars were characterized by longer duration from anthesis to maturity, large number of grains and high HI for both rice and wheat. Cultivars renewal markedly increased crop yield and became more resilient to warmer climatic conditions. The findings are supported by some previous studies based on both field experiment data and model simulations (Tao et al. 2012b; Liu et al. 2013; Xiao and Tao 2014). For example, Tao et al (2012b) found wheat cultivars were being renewed to adapt to climate change. Liu et al. (2013) showed that cultivars renewal contributed to rice yields by about 21.7 % in the Taihu region in Jiangsu province from 1980s to 2000s.

We found that impacts of modern sowing/transplanting density on yield of RWRS were small, and decrease in sowing/transplanting density reduced yield of RWRS. Improved fertilization management had contributed notably to crop yield increase over the past three decades in China. Chinese agriculture had intensified greatly inputs of chemical fertilizers since the early 1980s (Guo et al. 2010). but fertilization use efficiency decreased with application rate increasing (Peng et al. 2006). Consequently, the key to optimize trade-offs among yield, profit, and environmental protection is to achieve synchrony between fertilizer supply and crop demand without surplus or deficiency (Cassman et al. 2002). In addition, other improvements in agronomic management practices such as pest, disease and weed management, soil melioration and no-tillage contributed to yield increase too, which however were not accounted in this study. The results highlight that breeding new cultivars and optimizing agronomic management practices have a high potential to cope with future climate risk.

5 Conclusions

During the past three decades, modern cultivars and fertilization management contributed remarkably to yield increase in RWRS. Change in sowing/transplanting date did not significantly affect the total yield of RWRS, although shift in sowing/transplanting date alleviated the negative effect of climate change. Without adaptation measures, climate change, characterized by increase in temperature and decrease in solar radiation, could negatively affect the yield of RWRS during the study period.

To compensate the negative impacts of climate change, effective adaptation strategies should be developed, including breeding climate resilient crop cultivars and developing climate smart agronomic management. Climate resilient crop cultivars that have longer

duration from anthesis to maturity, large number of grains and high HI for both rice and wheat are promising. Climate smart agronomic management should be developed, including optimal sowing/transplanting date, optimal planting/transplanting density, efficient cultivations and fertilization management.

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