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Impacts of climate changes, soil nutrients, variety types and management practices on rice yield in East China: A case study in the Taihu region

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ABSTRACT

Separation of the influencing factors (climate, soil, variety, management) affecting crop yield could provide valuable insight into how crop responds to climate change and how crop yield can be enhanced in the future. In this study, we reported the changes of climatic conditions, soil nutrients, variety types and management practices in the Taihu region (a typical rice growing zone) of east China in two periods (the 1980s and the 2000s), and simulated the changes of rice (*Oryza sativa* L.) yields under different scenarios by using the APSIM-Oryza model. The contributions of the influencing factors in rice growing system were also calculated. The results revealed that there was a warming trend in the rice growing period in the Taihu region. However, the precipitation and sunshine hours in the rice growing season showed a decreasing trend in the past 30 years. Compared with the soil nutrients in the 1980s, the mean concentrations of soil organic carbon, total nitrogen, available phosphorus and potassium in the 2000s in the Taihu region were increased by 15.85%, 79.55%, 124.55% and 10.37%, respectively. The rice varieties in the 1980s could be described as the 'panicle weight type', while in the 2000s as the 'panicle number type'. The differences in management practices between 1980s and 2000s were mainly attributed to the fertilization and irrigation methods. From the 1980s to 2000s, the average rice yield in the Taihu region increased by 46.3%. The individual contribution of the climate change, soil improvement, variety updating and management progress on rice productivity was estimated as −19.5%, 12.7%, 21.7% and 34.6%, respectively. In addition, the spatial variation of rice yields in the whole region was reduced from 13.7% to 7.4% with the soil fertility improvement. The results indicate that future adaptations to climate change for rice yields would require either enhanced tolerance to high temperatures in the existing rice varieties or change in the current management practices, while balancing the soil fertility is a continuing process.

1. Introduction

Rapid increases in population and economic development have enlarged the demand for food (Huang et al., 2002). Rice (*Oryza sativa* L.) is a major crop in the world after wheat, which is cultivated in at least 95 countries across the globe and provides a staple food for more than half of the world's current population (Ainsworth, 2008; Shimono, 2011). Peng et al. (2004) indicated that world rice production must increase by approximately 1% annually to meet the growing demand for food that will result from population growth and economic development. The issue of how to increase rice yield has been a key research question for agronomists for many years (Laza et al., 2003; Katsura et al., 2007; Krishnan et al., 2007; Yang et al., 2007; Peng et al., 2008).

Meanwhile, a global warming trend has been documented in most locations around the world during the last several decades, and this trend could shorten the crops development stages and reduce the yield (Southworth et al., 2000; Lobell and Asner, 2003; Tao et al., 2006; Yang et al., 2008; Liu et al., 2010, 2012; Shimono, 2011; Lobell et al., 2012). Sheehy et al. (2006) showed a 6% decline in rice yield with every 1 °C increase in average temperature in the Philippines. Lobell et al. (2011a,b) estimated that the changes of climate have decreased the global maize and wheat production by 3.8% and 5.5% since 1980. Chen et al. (2012) suggested that, the impacts of climatic conditions on maize yield were 0.67–22.5% from the 1950s to the 1970s, 2.6–27.0% from the 1970s to the 1990s, and

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9.1–51.1% from the 1990s to the 2000s. Since 1980, the length of rice development stages has extended (Liu et al., 2012) and the yield has increased nearly 3 fold (IRRI, 2007). The increases in the length of development stages and grain yield have resulted from the development of new varieties and the improved management practices (Peng et al., 1999; Anwar et al., 2007; Xiao et al., 2008; Chen et al., 2010). Peng et al. (2009) reported that the potential rice yield increased by about 30% due to the development of semi-dwarf varieties and an additional 15–20% increase was achieved by the use of heterosis. Liu et al. (2010) suggested that, for both wheat and maize, the varietal changes could help stabilize the length of pre-flowering period, extent the grain-filling stage, and increase the grain yield in the North China Plain. Chen et al. (2012) indicated that the contributions of variety to summer maize yield were 42.6–44.3% from the 1950s to the 1970s, 34.4–47.2% from the 1970s to the 1990s, and 21.0–37.6% from the 1990s to the 2000s. Chen et al. (2012) also indicated that irrigation and sowing date could make large contributions to the maize yield increases over the past 60 years. Since the influences of climate conditions, soil nutrients, variety types and management practices are often entangled with one another, it is often difficult to determine the decisive factor on yield increase (Chen et al., 2012). A detailed understanding of how to separate the influencing factors on crop yield could provide valuable insights into development of sustainable agricultural systems in the future. Yet most of the above studies are either based on statistical regression or simulation models for investigating the responses of crops to climate changes, and thus could not calculate the individual contributions of the changes in soil nutrients and management practices to crop yields.

Our main objectives were to (1) analyze the changes of climatic conditions, soil nutrients, variety types and management practices in rice production of the Taihu region in the 1980s and 2000s; (2) clarify the individual contribution of these four factors to rice yield in the Taihu region by combining the APSIM-Oryza model with the observed data in the 1980s and the 2000s.

2. Materials and methods

2.1. Study area

The Taihu region (30–31°N, 120–121°E) is located in the southeast of Jiangsu Province in China (Fig. 1). The region is one of the most ancient agricultural regions in China as well as one of the most economically developed areas (Li et al., 2003). It has a warm and moist climate, with annual mean air temperature of 15–16 °C, precipitation of 1000–1100 mm and frost-free period of 220–240 days (1954–2010). The double-cropping rotation of summer rice and winter wheat has been the dominant cropping system in the region. Since the 1980s, application of synthetic fertilizers has led to significantly increased input of nutrients into the soil (Ju et al., 2009). As a result, the total annual crop yield in Taihu region was increased by 34% and the average crop yield per unit area was increased by 58% from 1980 to 2010 (Jiangsu Province Statistic Bureau, 2010).

2.2. Data sources

The daily climate data collected in the 1980s (1980–1989) and the 2000s (2000–2009) in the 10 sites within the Taihu region (Fig. 1a) include the maximum and minimum temperatures (°C), sunshine hours (h) and precipitation (mm), which were obtained from Meteorological Bureau of Jiangsu Province, China. For the APSIM model, the solar radiation was needed instead of sunshine hours (see description below), so we converted the sunshine hours to solar radiation by referencing Pohlert (2004). In addition, it was assumed that the atmospheric CO_2 concentration in the world in 1980s and 2000s were representative of the Taihu region of China (ESRL, 2012). During the study period, the concentration of CO_2 has increased by 14.1%.

Soil nutrients data were obtained from the Soil and Fertilizer Station of Jiangsu Agricultural Department, China. The data were available from the same sites and collected using randomized samples in the 1980s and 2000s (Fig. 1b). The total depth of the

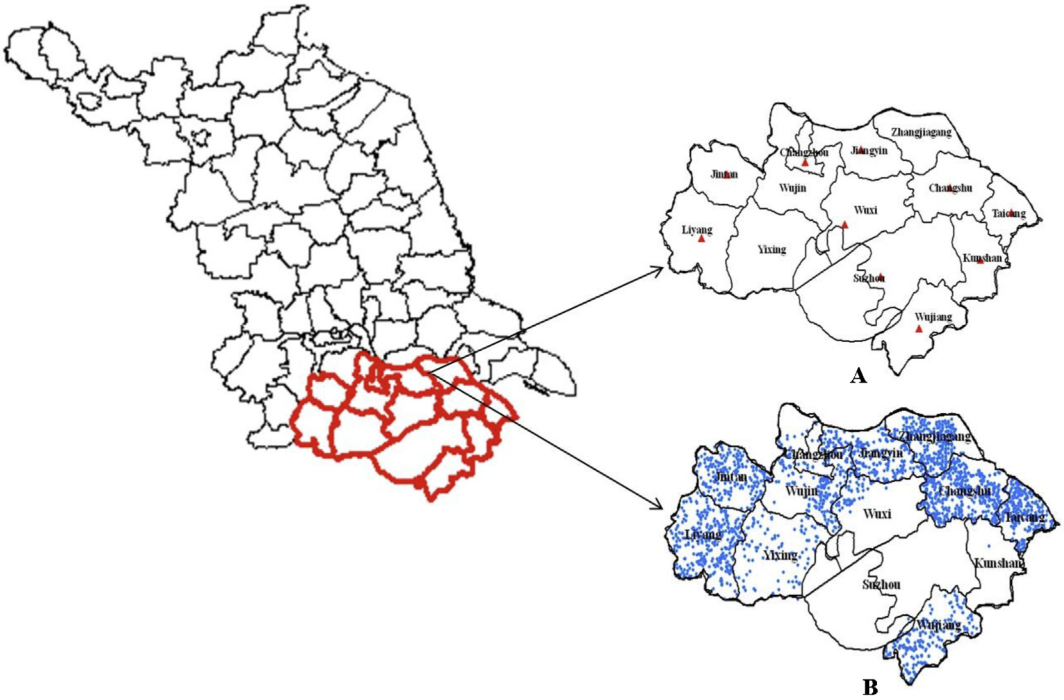

Fig. 1. Jiangsu Province and Taihu region ((A) distribution of the weather stations in the 1980s and 2000s and (B) distribution of the soil sample locations in the 1980s and 2000s).

Table 1
Varieties characteristics and management practices in the 1980s and 2000s of the Taihu region.

Varieties characteristics	1980s	2000s
Cultivars name	Yanjing2	Nanjing44
Maturity	Late	Early
Growing period (days)	140–145	155–158
Plant height (cm)	85	100
Spike number per m^2	405–450	285
Grain number per spike	70–80	130
1000-grain weight (g)	24.5–25.5	25.9
Seed setting rate (%)	86.9	89.7

Management practices	1980s			2000s			
Sowing date (dd/m)	25/5			20/5			
Sowing rate ($g\,m^{-2}$)	37.5			30.0			
Transplanting date (dd/m)	25/6			20/6			
Transplanting density (hills m^{-2})	45.0			24.0–27.0			
Fertilizing date (dd/m)	25/5	24/6	21/7	20/5	25/6	13/7	27/8
Fertilizer types	NH_4HCO_3	Pig manure	NH_4HCO_3	Urea	Urea	Urea	Urea
Fertilizer rate ($kg\,ha^{-1}$)	112.5	37,500	300	435	100	165	165
Irrigation method	Continuous flooding irrigation			Intermittent irrigation			

soil samples was 20 cm. Soil nutrients data from 20 cm to 100 cm decreased exponentially with soil depth (Jobbagy and Jackson, 2000; Ehleringer et al., 2000). There were 2157 soil samples in both 1980s and 2000s. The database of soil nutrients contained soil organic matter (SOM), total nitrogen (TN), available phosphorous (AP) and available potassium (AK). SOM content was measured using the dichromate oxidation (external heat applied) method; TN was determined by Kjeldahl digestion procedure; AP was extracted by 0.5 mol L^{-1} $NaHCO_3$ at pH 8.5 and then measured by an atomic absorption spectrometer; and AK was extracted with 1.0 mol L^{-1} NH_4Ac (ammonium acetate) at pH 7.0 and then measured by an atomic absorption spectrometer (Bao, 2005).

The rice varieties (Yanjing2 in the 1980s and Nanjing44 in the 2000s) and management practices (sowing date and rate, transplanting date and density, fertilizing date, rate and type, irrigation method) selected for the analysis were representative in the periods of the 1980s and 2000s in the Taihu region of Jiangsu Province, China (Table 1).

2.3. Data analysis

The interpolation method was used in this study to investigate the temporal and spatial distributions of climate conditions and soil nutrients across the study region. We used the inverse distance weighting (Thornton et al., 1997; Wang et al., 2010) and Kriging interpolation methods (Paz-González et al., 2000; Liu et al., 2006; Wang et al., 2009) to produce the distribution maps of climate factors and soil nutrient concentrations in the Taihu region. A cell size of 1 km × 1 km was chosen to divide the study area into a grid containing 170 rows and 260 columns.

In order to analyze the individual contribution of the changes in climate, soil nutrients, varieties and management practices to rice yield in the Taihu region, 6 different scenarios were designed (Table 2). The rice yields in different scenarios (*S1*–*S6*) were simulated with the APSIM-Oryza model by using the corresponding climate (including CO_2), soil nutrients, varieties and management data. Weeds, insects and diseases are not considered in this study. Also, extreme climate-related events such as flood or typhoon are not taken into account. Then, the individual contribution of climate, soil nutrients, variety types and management practices were calculated according to the following equations ((1)–(5)):

$$R_I = \frac{\bar{Y}_{2000s} - \bar{Y}_{1980s}}{\bar{Y}_{1980s}} \tag{1}$$

$$R_C = \frac{\bar{Y}_{2000s} - \bar{Y}_{C1980s}}{\bar{Y}_{C1980s}} \tag{2}$$

$$R_S = \frac{\bar{Y}_{2000s} - \bar{Y}_{S1980s}}{\bar{Y}_{S1980s}} \tag{3}$$

$$R_V = \frac{\bar{Y}_{2000s} - \bar{Y}_{V1980s}}{\bar{Y}_{V1980s}} \tag{4}$$

$$R_M = \frac{\bar{Y}_{2000s} - \bar{Y}_{M1980s}}{\bar{Y}_{M1980s}}, \tag{5}$$

where R_I, R_C, R_S, R_V and R_M are the contribution of all factors, climate conditions, soil nutrients, variety types and management practices, respectively. $\bar{Y}_{1980s}$ and $\bar{Y}_{2000s}$ represent the averages of simulated yields in the 1980s (*S1*) and 2000s (*S2*). $\bar{Y}_{C1980s}$, $\bar{Y}_{S1980s}$, $\bar{Y}_{V1980s}$ and $\bar{Y}_{M1980s}$ represent the averages of simulated yields in scenario *S3*, *S4*, *S5* and *S6*, respectively.

2.4. APSIM-Oryza model

The Agricultural Production System Simulator (APSIM) was used to simulate the rice yield as affected by the changes of climate conditions, soil nutrients, variety types and management practices. APSIM is a modular modeling framework developed in Australia. It runs at a daily time step and simulates crop growth and development, yield, soil water and nitrogen dynamics either for single crop or crop rotations in response to climatic and management changes (Keating et al., 2003). APSIM model has been extensively used to predict the wheat, maize, soybean and rice yield in many countries (Ludwig and Asseng, 2006; Suriadi et al., 2009; Chen et al., 2012; Wang et al., 2012).

APSIM-Oryza model was developed by incorporating the ORYZA2000 rice growth model (Bouman and van Laar, 2006) into the APSIM modeling framework (Keating et al., 2003; Gaydon et al., 2012a,b). The input data required to run the APSIM-Oryza include daily weather information (maximum and minimum temperature, precipitation and solar radiation), soil characterizing data (data by soil layers on extractable nitrogen, organic carbon, pH and soil water content, etc.), a set of variety-specific parameters (development rates during juvenile phase, photoperiod-sensitive phase, panicle development phase and reproductive phase, maximum optimum photoperiod and photoperiod sensitivity), and crop management information, such as number of plants direct-seeded in main field, seeded duration, number of plants per hill, number of hills, and fertilizer and irrigation schedules. Detailed descriptions of the model can be found in Keating et al. (2003). Fig. 2

Table 2
Production scenarios designed to analyze the individual contribution of climate, soil nutrients, variety types and management practices to rice yield in the Taihu region.

Scenario	Factor			
	Climate	Soil nutrient	Variety	Management
S1	1980–1989	1980–1989	1980–1989	1980–1989
S2	2000–2009	2000–2009	2000–2009	2000–2009
S3	**1980–1989**	2000–2009	2000–2009	2000–2009
S4	2000–2009	**1980–1989**	2000–2009	2000–2009
S5	2000–2009	2000–2009	**1980–1989**	2000–2009
S6	2000–2009	2000–2009	2000–2009	**1980–1989**

gives the simulated and observed phenological stages, biomass and yield of two rice cultivars (Yanjing2 in the 1980s and Nanjing44 in the 2000s) at Zhenjiang city in Taihu region under local practices. The results showed that APSIM-Oryza accurately reproduced the observed phonological stages with less than 10% error during the whole life cycle. The model could explain 81% of the variation in rice biomass and 85% of the variation in rice grain yield. Overall, APSIM-Oryza satisfactorily represents the dynamics of rice phenological development, biomass accumulation and yield formation.

3. Results

3.1. Changes of climate conditions in the Taihu region in the 1980s and 2000s

The spatial patterns of different climate factors in the rice growing seasons for the 1980s and 2000s and the changes of climate factors between the 1980s and 2000s are presented in Fig. 3. In the 1980s, the average temperature was lower than 24.6 °C in the whole Taihu region. The high value of total precipitation was found in the west of the Taihu region. However, the high value of total sunshine hours was found in the southeast (Fig. 3A). In the 2000s, the average temperature value was higher in southern part than in northern part. While the total sunshine hours value was higher in eastern part than in western part. In majority of the Taihu region, the total precipitation was lower than 670 mm (Fig. 3B). The temporal changes of average temperatures between 1980s and 2000s showed an increasing trend in the whole Taihu region, especially in the east. However, the total sunshine hours showed a decreasing trend in the whole study area. The most obvious declining occurred in the western region with the total sunshine hours reduced more than 20 h. Only the temporal change of total precipitation in the northeast showed an increasing trend. Meanwhile, the changes of precipitation in the Taihu region decreased from east to west (Fig. 3C).

From sowing to jointing, there was an increasing trend in average temperature, precipitation and sunshine hours in the Taihu region. From 1980s to 2000s, the average temperature, precipitation and sunshine hours were increased by 2.84%, 11.35% and 2.18%, respectively (Table 3). However, form jointing to heading, only the average temperature tended to increase with growth progress in the study area. The increasing rates of precipitation and sunshine hours were −18.43% and −44.75%, respectively. From heading to maturity, the average temperature and sunshine hours showed an increasing trend, with 12.48% and 37.62% increment rates, respectively, while the precipitation showed a decreasing trend and with 21.51% decreasing rate in this period. The results indicate that the declining of precipitation from jointing to heading and from heading to maturity led to the declining of total precipitation in the rice growing season. However, the declining of sunshine hours from jointing to heading was the reason for decrease in the total sunshine hours in the whole rice growing period.

3.2. Changes of soil nutrients in the Taihu region in the 1980s and 2000s

During the study period, the changes of soil nutrients in the Taihu region were different. The ranges of soil organic matter (SOM), total nitrogen (TN), available phosphorous (AP) and available potassium (AP) in the 1980s were 0.51–26.30 g kg^{-1}, 0.05–2.52 g kg^{-1}, 0.05–30.00 mg kg^{-1} and 5.20–184.00 mg kg^{-1}, respectively. However, the ranges of SOM, TN, AP and AK in the 2000s were 0.16–29.78 g kg^{-1}, 0.10–8.30 g kg^{-1}, 1.10–173.00 mg kg^{-1} and 22.00–397.90 mg kg^{-1}, respectively. As compared with the soil nutrients in the 1980s, the average concentrations of SOM, TN, AP and AK in the 2000s of the Taihu region were increased by 15.85%, 79.55%, 124.55% and 10.37%, respectively (Table 4).

Fig. 4 shows the temporal and spatial distribution of the soil nutrient concentrations in the Taihu region in 1980s and 2000s

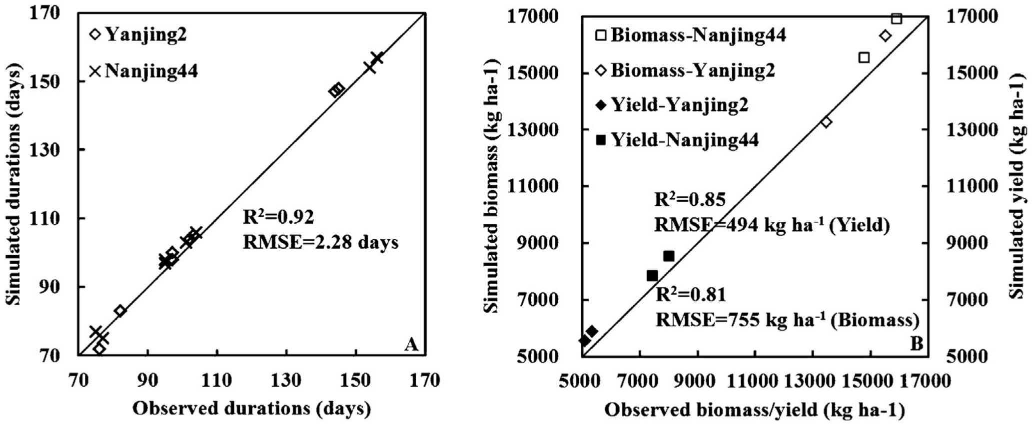

Fig. 2. Observed versus simulated rice phenological stages (A), biomass and yield (B) at Zhenjiang in Taihu region under local practices (Yanjing2 from 1984 to 1985, Nanjing44 from 2008 to 2009).

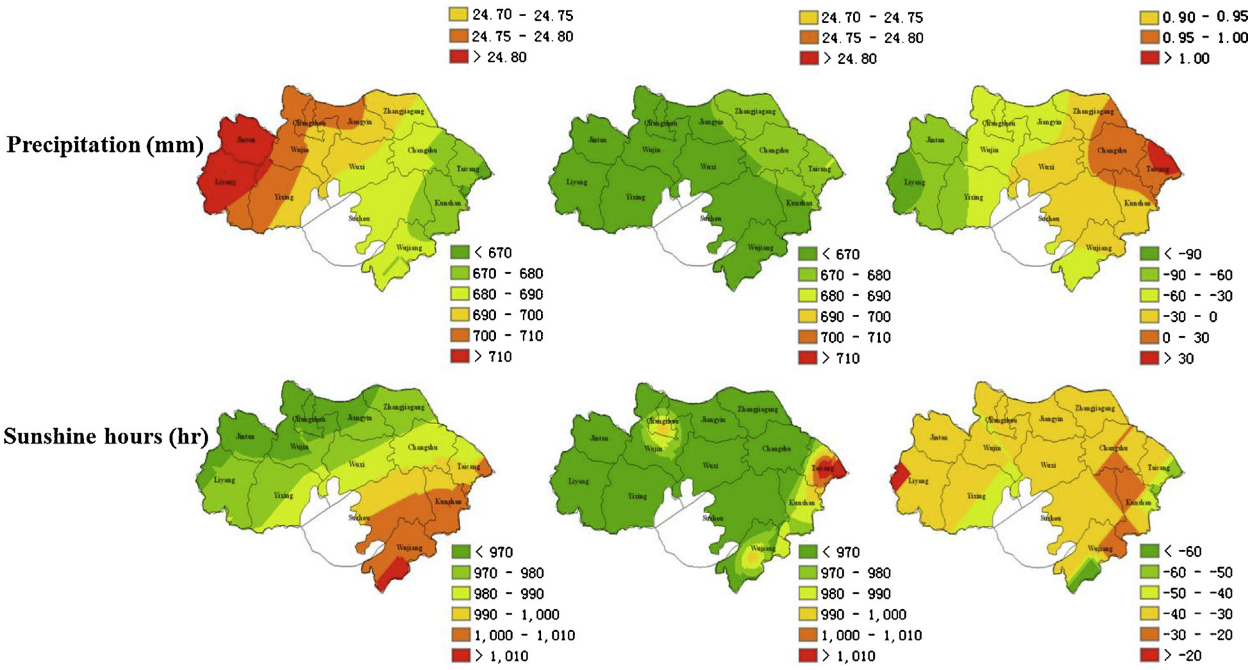

Fig. 3. Temporal and spatial distribution maps of average temperature, total precipitation and sunshine hours during the rice growing season in the Taihu region of Jiangsu Province in the 1980s and 2000s ((A) data for the 1980s; (B) data for the 2000s; (C) difference between 2000s and 1980s).

Table 3
Climate conditions in different growth periods in the 1980s and 2000s in the Taihu region.

Growth period	Age	Average temperature (°C)	Precipitation (mm)	Sunshine hours (h)
Sowing–jointing	1980s	25.67	355.0	421.8
	2000s	26.40	395.3	431.0
	Increasing rate	2.84%	11.35%	2.18%
Jointing–heading	1980s	26.12	163.3	285.6
	2000s	28.55	133.2	157.8
	Increasing rate	9.30%	−18.43%	−44.75%
Heading–maturity	1980s	20.59	145.5	227.8
	2000s	23.16	114.2	313.5
	Increasing rate	12.48%	−21.51%	37.62%

(Fig. 4A and B), as well as the temporal and spatial changes in soil nutrients between 1980s and 2000s (Fig. 4C). It can be seen that SOM, TN and AP increased in most of the study area. The areas with high levels covered about 74%, 82% and 89% of the region, respectively. The areas with declining levels mainly occurred in the northwest of the Taihu region. AK increased in more than 65% of the area, while about 35% of the area in the eastern part of the region exhibited a declining trend. These results indicate that in the past 30 years, the current agricultural and management systems have led to an addition and imbalance of N, P and K in the soil in the Taihu region.

3.3. Changes of variety types and management practices in the Taihu region in the 1980s and 2000s

The typical variety types and management practices in the 1980s and 2000s of the Taihu region were shown in Table 1. The late-maturing rice was planted in the 1980s, while the early-maturing rice was planted in the 2000s. From the 1980s to 2000s, the length of the rice growing period was extended for 3–18 days. In the 1980s, the dwarf variety was planted in the Taihu region, while the semi-dwarf variety was planted in the 2000s. From 1980s to 2000s, the plant height increased by 17.6%. Although the variety in the 1980s (Yanjing2) showed a significantly larger spike number per meter^2 than the variety in the 2000s (Nanjing44), Nanjing44 had a significantly larger grain number per spike than Yanjing2. Typically, Yanjing2 is described as the so-called ‘panicle weight type’ variety, while Nanjing44 is the ‘panicle number type’ variety. Compared with the 1980s, the 1000-grain weight and seed setting rate in the Taihu region were increased by 3.6% and 3.2% in the 2000s.

The management practices also changed markedly between 1980s and 2000s. Compared with the 1980s, the sowing and transplanting dates were earlier in the 2000s. The sowing rate and

Table 4
Soil nutrients in the 1980s and 2000s in the Taihu region.

	Organic carbon (g kg^{-1})	Total nitrogen (g kg^{-1})	Available-P (mg kg^{-1})	Available-K (mg kg^{-1})
1980s	21.13	0.88	8.31	88.17
2000s	24.48	1.58	18.66	97.31
Increasing rate (%)	15.85	79.55	124.55	10.37

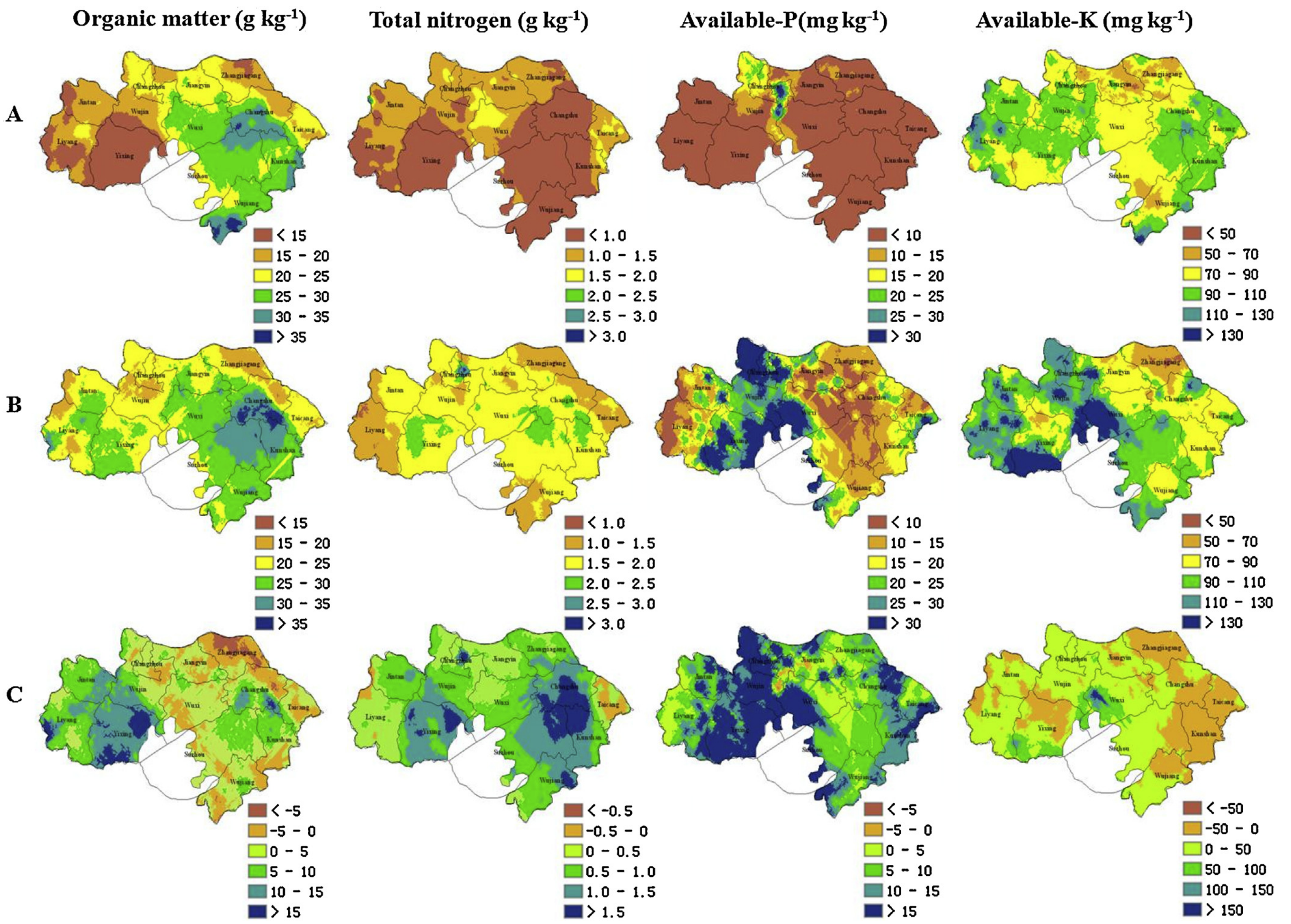

Fig. 4. Temporal and spatial distribution maps of organic matter, total nitrogen, available posphorous and aviable potassium in the Taihu region of Jiangsu Province in the 1980s and 2000s ((A) data for the 1980s; (B) data for the 2000s; (C) difference between 2000s and 1980s).

transplanting density were reduced in the past 30 years. In the 1980s, the type of nitrogen fertilizer in the Taihu region was mainly manure and NH_4HCO_3, while the nitrogen fertilizer type was mainly urea in the 2000s. The fertilizer application frequency in the Taihu region was increased with time. However, the amount of pure nitrogen application was reduced by 50.9% during the study period. The irrigation regime was the continuous flooding irrigation in the 1980s and intermittent irrigation in the 2000s. Generally, the rice varieties in the 2000s showed the characters of higher biomass and yield than the varieties in the 1980s. In addition, the management practices in the 2000s were more scientific and rational than those in the 1980s.

3.4. Individual contribution of climate change, soil nutrients, variety types and management practices to the rice yield in the Taihu region

Fig. 5 shows the spatial distribution of rice yield induced by climate change, soil improvement, variety updating and management progress. A decrease trend was simulated for the rice yields resulted from climate change between 1980s and 2000s in the whole Taihu region (Fig. 5A). This implies that the past climate change had a negative impact on rice yield in the study area. The most serious yield decrease occurred in the east of this region. However, the changes in soil improvement, variety renewal and management practices had positive impacts on rice yields in the past 30 years in the Taihu region (Fig. 5B–D). Yield induced by soil improvement was greater in the eastern part, while the opposite trend was found in the yield caused by variety updating. The highest yield induced by adopting management practices occurred in the center of the Taihu region, while the lower values were located at the edge of the region.

From 1980s to 2000s, the average grain yield increased by 46.3% in the Taihu region, which was caused by the interaction of climate, soil nutrients, varieties and management practices. The individual contribution of climate change, soil improvement, variety updating and management progress to rice yield differed with respected factors. Compared with the 1980s, the yield in the 2000s decreased by 19.5% from climate change, while the yield increased by 12.7%, 21.7% and 34.6% due to soil improvement, variety updating and management practices, respectively. In addition, the soil improvement also reduced the spatial variation of rice yields in the Taihu region. In the 1980s, the spatial variation of rice yields in the whole region was 13.7%, yet it was declined to 7.4% in the 2000s.

4. Discussion

Crops yield under climate change were determined by the interaction of variety traits, soil characteristics, management practices, and so on (Challinor et al., 2009). Therefore, studies on disentangling each influencing factor on crop yield should be helpful for exploring effective approach to increase crop production under climate change. Statistical analysis based evaluation of climate change impact on crop yield included not only the effect of climate change, but also the effects of improved crop varieties and management

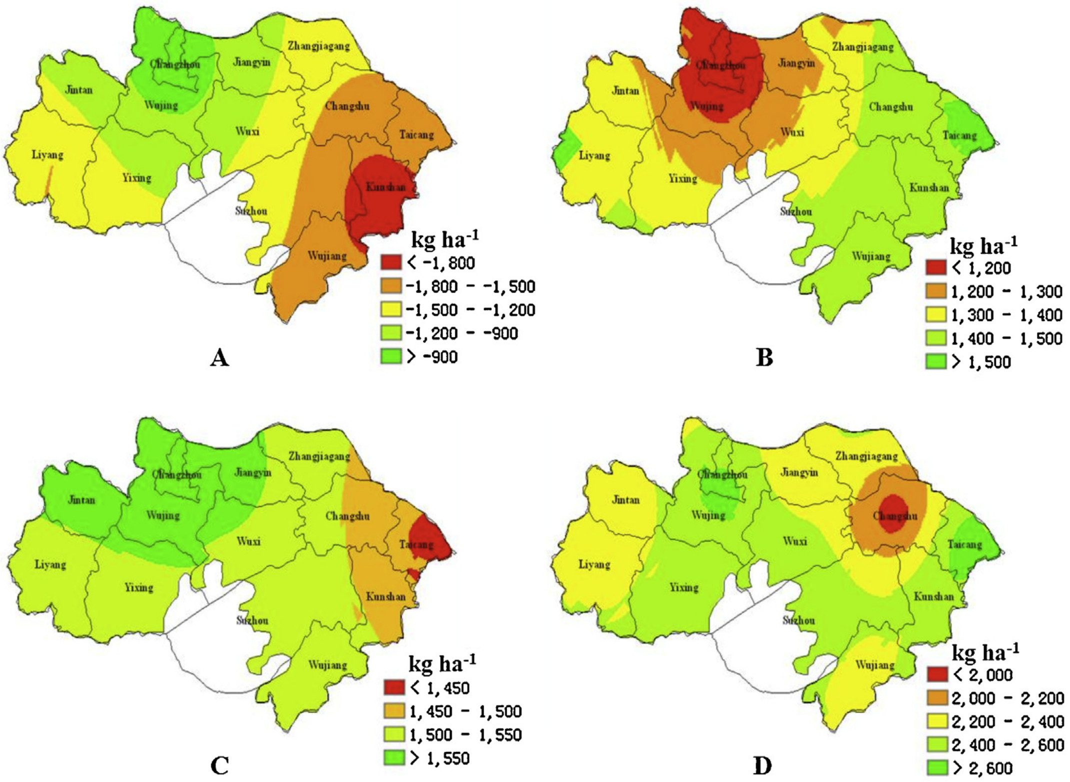

Fig. 5. Spatial distribution maps of rice yield ((A) the yield induced by climate change; (B) the yield induced by soil nutrients; (C) the yield induced by variety updating; (D) the yield induced by management practices).

practices (Lobell and Asner, 2003; Tao et al., 2006). Simulation model is a useful tool for disentangling different influencing factors on crop yield, but most of studies pay more attention to the evaluation of climate change impact on crop yield than that of crop variety updating, soil improvement or management progress (Xiong et al., 2007; Challinor et al., 2009; Asseng et al., 2011; Wang et al., 2011). Recently, modeling studies have shown that the variety updating and the improvement of management practices could have significant impact on simulated yield for a given climate change scenario (Liu et al., 2010, 2012). However, contributions of each factor to crop yield remains unclear. In this paper, the crop simulation model, GIS technology and scenario analysis method were combined together to investigate the impact of climate change, soil improvement, variety updating and management progress on rice productivity in the Taihu region. This method enables quantification of individual contribution of each factor to the yield changes of rice.

The results of this paper revealed that during the past 30 years, the average temperature showed an increasing trend, while the total precipitation and sunshine hours exhibited decreasing trends in the rice growing season in the Taihu region. We also found that the influence of climate change on rice production has been strengthened over years. In addition, considering the influence of climate conditions alone, we discovered that the rice yield in the 2000s in Taihu region was 19.5% lower than that in the 1980s. Similar negative impact of climate change on potential and rain-fed yields were also detected by Liu et al. (2012) in the single rice production region of China, but no quantified effect of climate change was analyzed.

Chinese agriculture has intensified greatly since the early 1980s on a limited land area with large inputs of chemical fertilizers and other resources (Guo et al., 2010). The amount of nitrogen and phosphorus inputs in China has significantly increased in the past decades, which resulted in the enhancement of soil nutrient contents (Ju et al., 2009; Liu and Diamond, 2005, 2008). Kong et al. (2006) presented that due to the increased fertilizer input, the soil nutrient contents were higher in 1999 than in 1980 in the North of China, and the increases of SOC, TN and AP were approximately 41%, 102% and 351%, respectively. In this paper, the results indicated that, from the 1980s to 2000s, the concentrations of soil SOC, TN, AP and AK in the Taihu region were increased by 15.85%, 79.55%, 124.55% and 10.37%, respectively. Our study further showed that the increased soil nutrients in Taihu region led to the increase of rice yield by 12.7%, without effects of climate change, variety updating and cultivation practices improvement. In addition, the spatial variation of rice yields in the whole region was reduced from 13.7% to 7.4% due to the soil improvement in the past 30 years.

The contribution of variety updating to yield increases under climate change has been studied in many crops by using statistical analysis or crop modeling (Peng et al., 2000; Kawano, 2003; Nersting et al., 2006; Liu et al., 2010, 2012). Most of the studies indicated that the adoption of new crop cultivars has been able to compensate the potential negative impact of global warming. These studies also showed that the increases of crop yields were attributed to the improvement in harvest index or biomass production, which is associated with plant height, spikelet and grain numbers (Tanien et al., 2008; Fischer, 2011). Based on analysis of the simulated data, the same results were detected in our present research. The rice varieties in the 1980s showed a significantly larger spike number per m^2, lower plant height, grain number per spike and 1000-grain weight than the varieties in the 2000s. Our study also indicated that without considering the changes in climate, soil nutrients and management practices, the variety updating in the past 30 years could explain 21.7% of the rice yield increment in the Taihu region.

Optimal management practice is a key factor that will shape the future severity of climate change impacts on food production

(Lobell et al., 2008). Chen et al. (2012) pointed out unless there is a major breakthrough in variety, improving cultivation measures will remain important for increasing future crop yield. Since the 1980s, China has experienced the changes in farming practices (Huang et al., 2007). During the past 4 decades, early sowing and transplanting dates, lower nitrogen application rate and higher fertilizer application frequency were observed in rice production area of China (Huang et al., 1998; Peng et al., 2010; Liu et al., 2012). Meanwhile, the type of nitrogen fertilizer was changed to chemical fertilizer from farm manure (Zhu and Chen, 2002; Tong et al., 2003). The same results were detected in Taihu region in our research. Our analysis also showed that from the 1980s to 2000s, the improvement of management practices made a contribution of 34.6% to rice yield enhancement in the Taihu region.

In summary, the impacts of climate change, soil nutrients, cultivars and management practices on rice production could be separated by combining scenarios analysis with crop simulation model as implemented in this study. Although the analysis results in this paper were encouraging, the performance of APSIM-Oryza is still needed to be evaluated in the near future under different management practices (sowing date, nitrogen application, water application, etc.) at more eco-sites. In addition, more detailed soil nutrients data under 20 cm depth is helpful to improve the model performance.

5. Conclusions

The negative influence of climate conditions on crop growth will increase in the future. Balancing and improving the regional soil fertility can reduce yield variation and enhance crop yield in the large scale on the long run. The application of optimized cultivation practices can also minimize potential impact of unfavorable climate changes on crop yield. Cultivation techniques such as changing the sowing date and harvest time for adapting to the changes in sunshine and temperature are desirable for maintaining high grain production. In addition, developing new varieties with increased heat tolerance, grain number per spike and grain filling percentage is another key approach to enhancing crop yield.

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