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Cost-Benefit Analysis for Single and Double Rice Cropping Systems under the Background of Global Warming

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Abstract: Global warming might expand crop growth areas for the prevailing single and double rice cropping systems in Southern China. Based on historical weather and crop data from 1981 to 2015, we evaluated the economic benefit and environmental cost for single and double rice cropping systems (SRCS and DRCS) in areas that are sensitive to climate variability in the middle and lower reaches of the Yangtze River. The five chosen indices were: net profit, agronomic nitrogen use efficiency (ANUE), water use efficiency (WUE), total amount, and global warming potential (GWP) of greenhouse gas (GHG). The goal of this study is to provide scientific evidence for local policymakers to use in selecting the most suitable rice cropping systems to maximize economic profits while adapting to climate change. The results showed that net profit was $171.4 per hectare higher for DRCS than for SRCS in the study region. In addition, output per unit nitrogen usage was $0.25 per kg N higher for DRCS than for SRCS. Net profit would increase if DRCS replaced SRCS, and the maximum amplitude of increase in net profit for this replacement occurred under the settings of 150 kg ha^{-1} nitrogen fertilizer level and continuous irrigation when the paddy water layer started to fade. On the other hand, annual variation in net profit for SRCS was consistently smaller than DRCS, regardless of changes in nitrogen fertilizer level and irrigation regime settings. SRCS showed better WUE than DRCS in both rainfed and irrigated situations, as well as lower seasonal CH_4 and N_2O emissions during the study period. Therefore, we conclude that SRCS is superior to DRCS for the sake of maximizing economic profit while maintaining sustainable agriculture in areas that are sensitive to climate variability in the middle and lower reaches of the Yangtze River.

Keywords: multiple cropping systems; net profit; ORYZA v3; agronomic nitrogen use efficiency; water use efficiency; global warming potential

1. Introduction

Under the background of global warming, increases in annual average temperatures ranged from 0.9 to 1.5 °C in China from 1909 to 2011 [1]. Temperature is the most important limiting factor for cropping systems [2]; such increases in temperature could potentially lengthen crop growing seasons [3–9]. In the middle and lower reaches of the Yangtze River, local warming led to a northward expansion of the northern limit for DRCS [10–12]. Compared with the period of 1961–1990, the northern limit of DRCS shifted northward by 300 km from 2000 to 2010 [13]. This northward shift in the northern limit of DRCS was projected to reach the Yellow River Basin in 2050 [14] and made it possible for DRCS to replace SRCS to achieve higher crop yields in the middle and lower reaches of the Yangtze River [10]. Before the 1980s, DRCS replaced SRCS in part of this region, mainly due to the advocacy of Chinese authorities to improve national food security and, ultimately, to promote social stability [15]. With the implementation of the reform and opening-up policy of China, rapid economic development has brought increasing employment opportunities and higher payment in the urban area. Many young farmers have moved to the urban area for employment, resulting in a decrease in the number of available farmers and the increasing costs of labor (i.e., economic costs) in the rural area. In addition, the rapid increasing price in fertilizer and insecticide further increased the economic costs from rice production, making marginal profit from DRCS [16,17]. Reports showed that total regional labor force for rice, wheat, and corn production decreased by 46, 53, and 40 percent, while the total inputs of machinery and fertilizer increased by 14, 2, and 6 times composite input of machinery and fertilizer for these three crops, respectively [18,19]. Take Zhejiang Province as an example; the planting area of DRCS decreased from 79.6 percent (37.3 for early rice and 42.3 percent for late rice) in 1998 to 41.9 percent (18.8 for early rice and 23.1 percent for late rice) in 2002. Meanwhile, the planting area of SRCS increased from 20.4 percent to 58.1 percent in Zhejiang province [20]. In addition, technological development has transformed the way modern farmers access information and practice fieldwork; more small-scale single-household farming is being replaced by medium- and large-scale commercial farming [21,22]. Since 2005, the decrease in planting area of DRCS paused, (Figure 1) thanks to governmental intervention strategies, such as increasing grain prices in the market to compensate the high cost of rice production, installing irrigation systems to help farmers save water cost, and building roads for farmers to transport rice grains. Though temperature increase has made it possible to replace SRCS with DRCS in the middle and lower reaches of the Yangtze River, other non-climatic factors (such as available labor force and cost of fertilizer) should also be considered during the decision-making process.

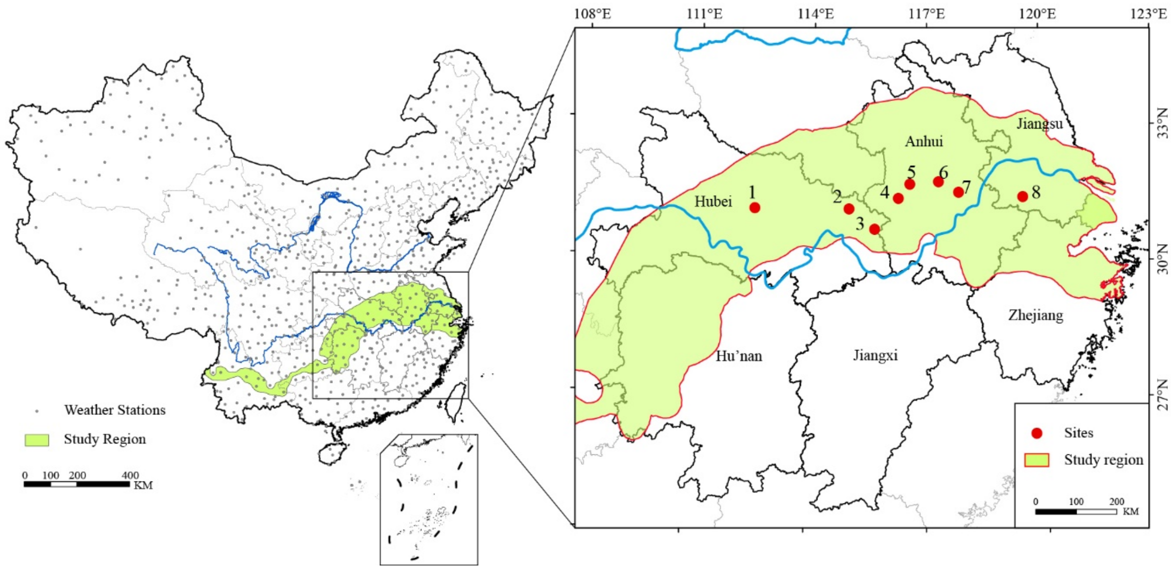

Figure 1. The study region, the selected 8 rice experimental sites (Red dots), and the locations of meteorological stations (black points) in the middle and lower reaches of the Yangtze River in China.

In sustainable agriculture, the cost of environmental degradation (such as pollution from fertilizers and pesticides) should also be considered in addition to the economic input of labor, fertilizers, pesticides, irrigation, machinery, and plant seeds [23]. In particular, rice cultivation is one of the major human-induced sources for GHG emissions like methane (CH_4) and Nitrous Oxide (N_2O) [24–27]. In 2000, records showed that CH_4 emission from rice paddy fields was 7.41×10^9 kg in China, accounting for 29% of the total amount worldwide [28]. In 2007, N_2O emission from rice paddy fields was 3.6×10^7 kg in China [29]. When a shortage of agricultural labor was concurrent with increasing weather extremes and worsening environmental pollution, it became inevitable that SRCS outperformed DRCS in the middle and lower reaches of the Yangtze River in Southern China. Therefore, it is important to conduct a comprehensive regional study on the pros and cons of SRCS and DRCS from three aspects: climatic safety, economic profit, and environmental benefit [30,31]. We used the ORYZA v3 model in this study to simulate the most commonly planted varieties for both SRCS and DRCS in the middle and lower reaches of the Yangtze River, including for indica rice, japonica rice, and hybrid rice [32–34]. The total rice planting area and grain production in this region account for 49% and 50% of the national totals, respectively [35].

The overall goal of this study was to comprehensively assess the advantages and disadvantages of SRCS and DRCS in the middle and lower reaches of the Yangtze River. We selected the study region as all areas where northern limits shifted from 1981 to 2015 (Figure 1). We used the ORYZA v3 model to simulate the two rice cropping systems in the study region. The chosen indices for this analysis included: agronomic nitrogen use efficiency, water use efficiency, irrigation water use efficiency, and emissions of CH_4 and N_2O [36,37].

2. Materials and Methods

2.1. Study Region

The study region is located in the middle and lower reaches of the Yangtze River of China, which has a subtropical climate (Figure 1). The study region includes five provinces, i.e., Hunan, Hubei, Henan, Anhui, Jiangsu, and Zhejiang. According to the method of Yang et al. [10], we used the spatial analysis tool in ArcGIS 10.2(Esri Inc., Redlands, CA, USA) to depict the two northern limits of DRCS for the coldest and warmest years in China [38]. The areas that were within these two specific boundaries are considered sensitive to climate variability for rice cropping. In the middle and lower reaches of the Yangtze River, all areas that are sensitive to climate variability for rice cropping.

2.2. Data Collection and Descriptions

China Meteorological Administration established experimental stations for rice (including both SRCS and DRCS) in 1983 [39] and provided complete field-level data beginning from 1991 (http://data.cma.cn/). Eight of the rice sites located in the study region were selected. The collected observational data from the 8 sites include phenology (i.e., emergence date, transplanting date, panicle initiation date, flowering date, and maturity date); rice grain yield (GY), and farming management practice information (i.e., amount of nitrogen fertilizer, irrigation time, and volume) (Table 1). These collected data were used to run, calibrate, and validate the crop model ORYZA v3.

Daily weather data during the period of 1981–2015 for 862 meteorological stations across the entire country were obtained from the China Meteorological Administration (http://data.cma.cn/) (Figure 1). The climate factors include maximum, minimum, and mean temperatures, average relative humidity, wind speed, precipitation, and sunshine duration. The 8 meteorological stations closest to the rice experimental sites were selected to represent climate conditions for these rice sites. These climate data were used to drive the ORYZA v3 model.

Table 1. Dates (day of the year, DOY) of phenology stages and the length of the growing season (LGS) for early rice, middle rice, and late rice at the selected 8 sites for rice in the study region.

No.	Sites	Early Rice					Middle Rice					Late Rice				
		ED *	PI	FD	MD	LGS	ED	PI	FD	MD	LGS	ED	PI	FD	MD	LGS
1	Zhongxiang	91	154	178	203	113	125	203	225	255	131	173	228	248	282	110
2	Macheng	90	153	177	203	114	125	203	226	256	132	173	229	249	281	109
3	Yingshan	90	154	178	204	115	125	204	227	258	134	174	230	250	283	110
4	Huoshan	94	158	183	209	116	130	209	233	265	136	179	235	257	299	121
5	Liuan	93	156	181	207	115	130	208	231	262	133	177	232	253	290	114
6	Hefei	94	157	181	206	113	130	208	230	261	132	176	231	251	285	110
7	Chaohu	94	157	181	207	114	130	208	231	261	132	177	232	252	286	110
8	Liyang	95	160	184	210	116	140	217	239	272	133	180	235	255	291	112
Average		93	156	180	206	114	129	207	230	261	133	176	232	252	287	112

* Note: ED: emergence date; PI: panicle initiation date; FD: flowering date; MD: maturity date.

Other agro-economic data were collected to calculate the profits of rice production. These data included the costs of nitrogen fertilizer, irrigation, plant seed, and labor, which were acquired from the Chinese yearly compilation book of cost and benefit of agricultural products (1981–2015) [40] and the National product cost survey network (http://www.npcs.gov.cn/).

2.3. Calculation Methods for Nitrogen and Water Use Efficiency, and Greenhouse Gas Emission

We selected agronomic nitrogen use efficiency (ANUE, kg grain kg^{-1} N), water use efficiency (WUE, kg grain m^{-3}), and irrigation water use efficiency (IWUE, kg grain m^{-3}) to compare the different effects from SRCS and DRCS. ANUE is defined as the increase in grain yield per unit of nitrogen applied [41]. WUE is defined as the output of grain yield per unit of water used by rice; IWUE is defined as the increase in grain yield per unit increase in applied irrigation water [42]. We used Equations (1)–(3) to calculate these three indices.

$$\text{ANUE} = \frac{GY_{+N} - GY_{N0}}{FN} \quad (1)$$

$$\text{WUE} = \begin{cases} \dfrac{IGY}{R+I}\ if\ irrigated \\ \dfrac{RGY}{R}\ if\ rainfed \end{cases} \quad (2)$$

$$\text{IWUE} = \frac{IGY - RGY}{I} \quad (3)$$

where GY_{+N} is the grain yield under different nitrogen levels (kg grain ha^{-1}); GY_{N0} is the grain yield with no nitrogen application (kg grain ha^{-1}); FN is the nitrogen level (kg N ha^{-1}); IGY is the irrigated grain yield (kg grain ha^{-1}); RGY is the rainfed grain yield (kg grain ha^{-1}); R is the rainfall amount (mm); I is the irrigation amount (mm).

Paddy rice production contributes to GHG emissions mainly by releasing methane (CH_4) and nitrous oxide (N_2O) [26,27,43]. According to the mechanisms developed in Olszyk et al. [43], we estimated the CH_4 emissions in rice paddy based on the ORYZA simulated rice biomass. The equations are

$$E_{CH4} = B_{tol} \times C_b \times 2.9\% \quad (4)$$

$$B_{tol} = B_a \times 1.17 \quad (5)$$

where E_{CH4} is the amount of methane emission for rice production (kg ha^{-1}); B_{tol} is the ORYZA simulated total biomass for rice (kg ha^{-1}); B_a is the simulated above-ground biomass for rice (kg ha^{-1}), and C_b is the carbon content of biomass (42.84% is used) [44].

Nitrogen fertilizer is the direct source for nitrous oxide emission [45], and precipitation plays a positive role in nitrous oxide emission [46]. We used Equation (6) to calculate the amount of N_2O emission [46]:

$$E_{N_2O} = 1.57 \times \mathrm{P} + 0.0164 \times \mathrm{P} \times \mathrm{F} \quad (6)$$

where E_{N_2O} is the amount of N_2O emission for paddy rice during the growing season (kg ha^{-1}); P is accumulated precipitation during a growing season (mm); and F is the nitrogen fertilizer level (kg ha^{-1}).

In addition, we assessed the global warming potential (GWP) of CH_4 and N_2O for a 100-year time horizon. GWP is defined as the time-integrated warming effect due to an instantaneous release of unit mass (1 kg) of given greenhouse gas in today's atmosphere, relative to that of carbon dioxide [47]. In this study, we converted methane and nitrous oxide into CO_2 equivalents (CO_2-eq) by taking into account the specific radiative forcing potential relative to CO_2 of 25 for CH_4 and 298 for N_2O for a 100-year time horizon [48]. The combination of total and mean GWP (kg CO_2-eq GY^{-1}) of GHG has been used previously to compare the greenhouse effects of SRCS and DRCS in other regions [49,50].

2.4. Model Description, Calibration, Validation, and Simulations

ORYZA is a process-based crop model; the initial version ORYZA 2000 simulates crop growth and development dynamics for rice (*Oryza sativa* L.) [37]. ORYZA 2000 has been widely used in studies on the effect of climate change on rice production [51–56]. In Asia, ORYZA 2000 has been tested, evaluated, and used to simulate rice production across rice planting regions [51,57]. In this study, we used ORYZA v3 [36,37], the successor of ORYZA 2000, to simulate rice growth for SRCS and DRCS in the study region.

Based on the climate data, phenological dates, and management practices (i.e., nitrogen fertilization and irrigation), we ran the ORYZZA v3 model to obtain total biomass, grain yield, and water demand under climate change, nitrogen fertilization, and irrigation for SRCS and DRCS. We set up ten levels of irrigation and fertilization application rates to calculate the ANUE, WUE, and IWUE. We compared the results for the alternate wetting and drying water management technique with the results for the non-irrigation method (i.e., rainfed). In ORYZA v3, the wet-dry-wet technique was fulfilled by applying irrigation on the 0, 3, 6, 9, 12, 15, 20, 25, and 30 days after soil surface water disappears. The ten levels of nitrogen fertilization application rates were 0, 25, 50, 100, 150, 200, 250, 300, 400, and 600 kg N ha^{-1}/y for SRCS. Accordingly, the fertilization rates for DRCS are doubled of these levels.

The model calibration for key parameters was based on one-year observational data at the 8 sites (Table 2). The calibrated parameters and values are listed in Table 3. The more detailed calibration processes and parameters of the ORYZA v3 crop model can be found in the papers of Li et al. [36,37] work. We selected a representative cultivar from each growing season to specify crop coefficients during the model calibration, and the specified cultivar coefficients were used in the subsequent modeling analysis. Some other years that were not used for calibration were selected to validate the model performance (Table 2). The statistical indices of the correlation coefficient (R^2), normalized root mean squared errors (NRMSE), and D value. R^2 and D values closer to 1 and lower NRMSE indicate good performance and low model bias between the observed and simulated variables [58]. The validation results were shown in Figure 2. The correlation coefficient (R^2) and D values between the observed and simulated dates of different growing stages and rice grain yield were closed to 1.0 for all validation sites and years. It indicates that the ORYZA v3 crop model can reliably simulate rice yield and phenology.

Table 2. Description of calibration and validation dataset for the ORYZA v3 crop model at 8 agrometeorological stations along the middle and lower reaches of the Yangtze River.

Season	Cultivar	Calibration Dataset	Validation Dataset
Early season	Jinyu402	Liyang (2006), Liuan (2002)	Liyang (2005), Liuan (2002–2003), Macheng (2003–2004), Huoshan (1992–1996), Hefei (2000–2002), Yinshan (1993), Chaohu (2001, 2003–2004), Zhongxiang (1996–1998）
Late season	Jinyu207	Liyang (2003) Liuan (2004)	Zhongxiang (1997–2001), Chaohu (2000–2005), Liyang (2006–2007), Macheng (2001–2005), Liuan (2007–2008), Yinshan (2004–2006)
Middle season	Shanyu63	Liyang (1993–1994)	Huoshan（1991–1998, Zhongxiang (1989–1993), Macheng (1993–1998), Yingshan（1990–1998), Chaohu（1991–1994), Hefei (1996–1998)

Table 3. Description and calibrated values of the selected parameters of the ORYZA v3 model.

Parameters	Description	Unit	Jinyu402	Jinyu207	Shanyu63
DVRJ	Development rate in the juvenile phase	°C d^{-1}	0.001474	0.001009	0.000593
DVRI	Development rate in photoperiod-sensitive phase	°C d^{-1}	0.000758	0.000758	0.000758
DVRP	Development rate in panicle development	°C d^{-1}	0.000877	0.001003	0.000858
DVRR	Development rate in the reproductive phase	°C d^{-1}	0.002225	0.002119	0.001968
SLA0.00	Specific leaf area at DVS = 0	ha kg^{-1}	0.0045	0.0045	0.0045
SLA0.16	Specific leaf area at DVS = 0.16	ha kg^{-1}	0.0045	0.0045	0.0045
SLA0.33	Specific leaf area at DVS = 0.33	ha kg^{-1}	0.0041	0.0037	0.0036
SLA0.65	Specific leaf area at DVS = 0.65	ha kg^{-1}	0.0033	0.0035	0.0029
SLA0.79	Specific leaf area at DVS = 0.79	ha kg^{-1}	0.0028	0.0029	0.0027
SLA1.50	Specific leaf area at DVS = 1.5	ha kg^{-1}	0.0023	0.0024	0.0022
SLA2.00	Specific leaf area at DVS = 2	ha kg^{-1}	0.0023	0.0024	0.0022
FLV0.00	Shoot dry matter $^{\text{partitioned}}$ to the leaves at DVS = 0	Fraction	0.55	0.55	0.55
FLV0.50	Shoot dry matter partitioned to the leaves at DVS = 0.5	Fraction	0.55	0.55	0.55
FLV0.75	Shoot dry matter partitioned to the leaves at DVS = 0.75	Fraction	0.35	0.35	0.25
FLV1.00	Shoot dry matter partitioned to the leaves at DVS = 1	Fraction	0.00	0.00	0.00
FST0.00	Shoot dry matter partitioned to the stems at DVS = 0	Fraction	0.45	0.45	0.45
FST0.50	Shoot dry matter partitioned to the stems at DVS = 0.5	Fraction	0.45	0.45	0.45
FST0.75	Shoot dry matter partitioned to the stems at DVS = 0.75	Fraction	0.65	0.65	0.65
FST1.00	Shoot dry matter partitioned to the stems at DVS = 1	Fraction	0.40	0.40	0.35
FSO0.75	Shoot dry matter partitioned to the panicles at DVS = 0.75	Fraction	0.00	0.00	0.10
FSO1.00	Shoot dry matter partitioned to the panicles at DVS = 1	Fraction	0.60	0.60	0.65
FSO1.20	Shoot dry matter partitioned to the panicles at DVS = 1.2	Fraction	1.00	1.00	1.00

This study aims to simulate the effects of climate change. Due to a lack of long-term data and to reduce uncertainties, the model simulations did not consider the changes of rice cultivars, agronomic techniques, and most agro-economic factors such as inflation of rice grain prices and change of labor costs. All these data were kept constant during the simulation period 1981–2015. Only climate, nitrogen fertilization rates, and irrigation rates were considered in the model simulations. The technology and management consisting of nitrogen, irrigation management, and planting density used in the ORYZA v3 model were the same in three rice growing seasons (early, late, and middle rice seasons) as below: (i) for nitrogen management, fertilizer N was applied in the form of urea with 40% as basal 2 days before transplanting, 20% at mid-tillering, 30% at panicle initiation and 10% at heading stage; (ii) for irrigation management, paddy water kept 5 cm from transplanting to end-tillering (the tiller number reaches 80% of the targeted panicle number), followed by mid-season drainage for 20 days to suppress excessive tillers, then kept 5 cm water depth during the whole heading stage, and finally shallow wetting irrigation after the heading stage; (iii) for planting density, rice plants were transplanted at 25–30 days after emerging at a spacing of about 0.24 m × 0.18 m, with two seedlings per hill. Three model simulation experiments were designed and conducted, including climate only (CLM), nitrogen fertilization only (NFER), and irrigation only (IRRI). The model results from these three experiments represented the effects of climate, nitrogen fertilization, and irrigation, respectively.

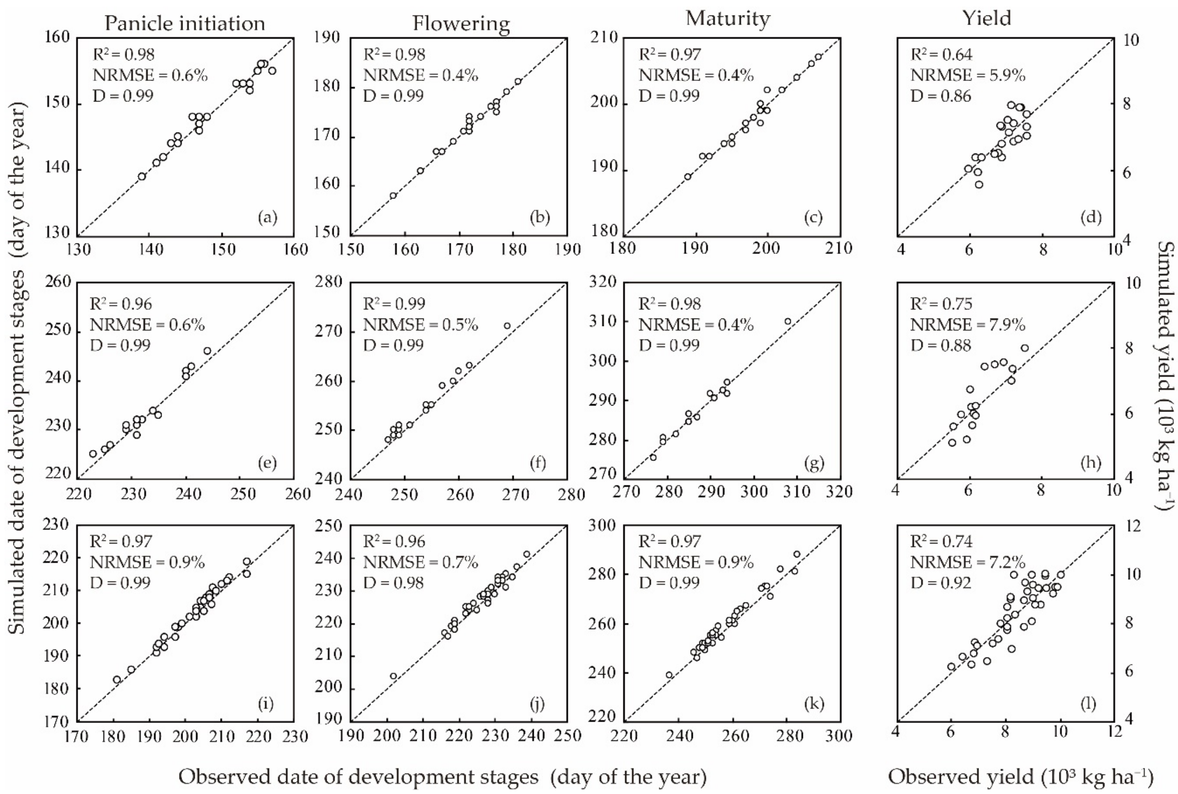

Figure 2. Comparison of the simulated and observed date of panicle initiation (**a**,**e**,**i**), flowering (**b**,**f**,**j**), physiological maturity (**c**,**g**,**k**), and grain yield (**d**,**h**,**l**) for early rice (**a**–**d**), late rice (**e**–**h**) and middle rice (**i**–**l**). The dashed line represents the 1:1 line.

2.5. Min–Max Normalization Method

In the rice production industry, the producers always seek the highest net profit as well as the highest ANUE. However, the net profit decreases after the ANUE reaches a certain level. In this study, we used the min-max normalization method [59] (Equation (8)) to calculate the nitrogen level for the optimal net profit and ANUE scenario in both SRCS and DRCS.

$$x_{norm} = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{1}$$

where x_{norm} is the normalization value of x_i; x_{min} is the minimum value of time-series x_i; x_{max} is the maximum value of time-series x_i.

3. Results

3.1. Rice Production Statistics

The main output of DRCS from 1978 to 2015 was \$2616.2 ha^{-1} y^{-1}, which was 60% higher than that of SRCS from 1981 to 2015. Meanwhile, the total cost of DRCS (\$2107 ha^{-1} y^{-1}) was almost twice as that of SRCS (\$1155.4 ha^{-1} y^{-1}). Since the 1980s, the output (total cost) per hectare increased by 96.9 (77.2) and \$166.9 (\$130.6) per year for SRCS and DRCS, respectively (Figure 3a,b). Overall, the net profit per hectare showed an increasing trend for both SRCS (\$15.8 per year) and DRCS (\$17.0 per year) during the study period. The net profit per hectare for DRCS was higher than that of SRCS during most of the study period, with the exceptions in years of 1997–2002 and 2005 (Figure 3c). Due to the gradually increasing cost of rice cultivation, the profit-cost ratio showed a decreasing trend for both SRCS and DRCS. Nevertheless, the average profit-cost ratio for SRCS (47%) was higher than that of DRCS (28%) (Figure 3d).

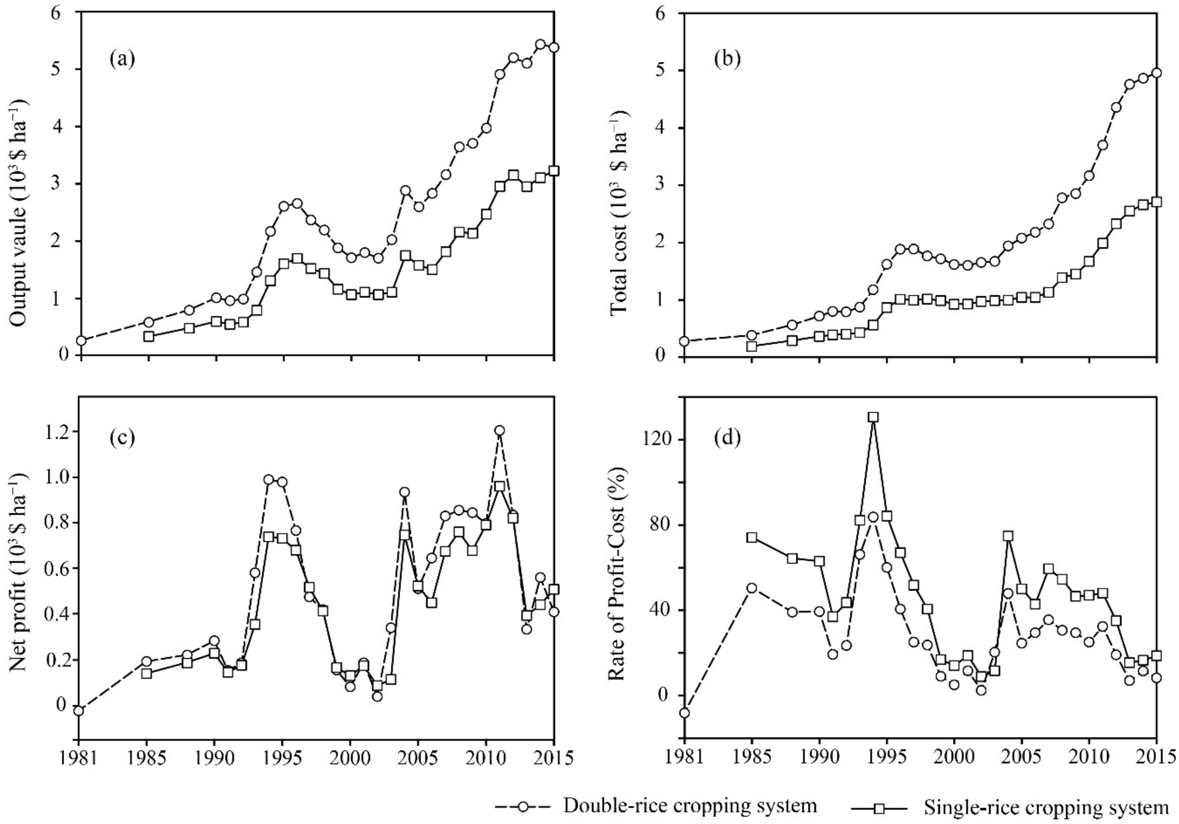

Figure 3. Rice production statistics for single rice cropping systems (SRCS) during the period of 1981–2015 and double rice cropping systems (DRCS) during the period of 1978–2015. (**a**) Output per unit area. (**b**) Total cost per unit area. (**c**) Net profit per unit area. (**d**) Profit-cost ratio.

Food security is about increasing food production to meet the demand of the growing population. Due to the limitation of the agricultural land area, multiple cropping systems could help to achieve this goal. Worldwide, multiple cropping systems accounted for 10% of agricultural land use but produced enough food to feed 22% of the total population [60]. In China, the domestic population is expected to increase quickly following the institution of the two-child policy (the single-child policy ended) in 2015. According to the most recent studies in the study region, air temperature increase made it possible to expand the planting area of DRCS, and total rice grain yield could increase by 4% if DRCS replaced SRCS [10,60]. However, expanding DRCS might not be economically feasible due to the relatively high profit-cost ratio.

3.2. Rice Grain Yield and Net Profit

From 1981 to 2015, the crop model simulation results indicated that the highest net profit occurred at a nitrogen fertilizer level of 200 and 300 kg ha^{-1} for DRCS and SRCS, respectively. When nitrogen fertilizer level was increased after 200 (300) kg ha^{-1} for DRCS (SRCS), the net profit decreased then held constant after the nitrogen fertilizer level of 600 kg ha^{-1} (Figure 4a). The cut-off point of nitrogen fertilizer level after which rice grain yield stopped increasing even with more nitrogen fertilizer application was 300, 200, and 400 kg ha^{-1} for early rice, late rice, and middle rice, respectively (Figure 4b). When the nitrogen fertilizer level was below 25 kg ha^{-1}, the net profit gap between DRCS and SRCS was negative (i.e., net profit for SRCS was higher than that for DRCS). The net profit gap between DRCS and SRCS reached the maximum when the nitrogen fertilizer level was between 100 to 150 kg ha^{-1} (Figure 4c). In other words, if DRCS replaced SRCS, the optimal nitrogen level for the highest net profit would be between 100–150 kg ha^{-1}. The rice grain yield gap between DRCS and SRCS increased with the increase in nitrogen fertilizer application and reached the maximum (7444 kg ha^{-1} y^{-1}) at the nitrogen fertilizer level of 150 kg ha^{-1} (Figure 4d).

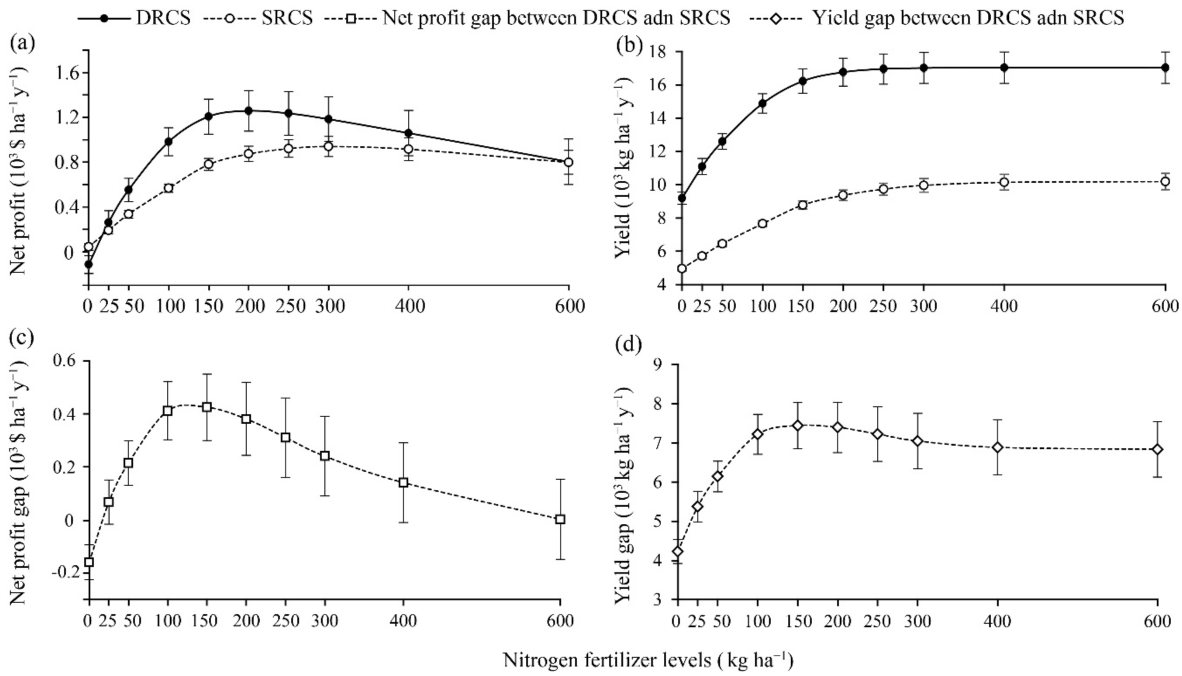

Figure 4. Net profit ($ ha^{-1} y^{-1}) (**a**) and rice grain yield (kg ha^{-1} y^{-1}) (**b**) for DRCS and SRCS at different nitrogen fertilizer levels during the growing season (kg ha^{-1}) from 1981 to 2015. Note: Error bars indicate the standard deviations. (**c**) Net profit gap between DRCS and SRCS. (**d**) Rice grain yield gap between DRCS and SRCS.

During the study period, both the net profit and rice grain yield showed a statistically significant ($p < 0.01$) decreasing trend in DRCS and SRCS (Tables 4 and 5); the decreasing trend was not sensitive to nitrogen fertilizer level or irrigation regime, indicating that fertilization rates did not significantly change the yield change rates.

Table 4. The temporal tendency in rice grain yield (kg ha^{-1} y^{-1}) and net profit ($ ha^{-1} y^{-1}) for DRCS and SRCS at different nitrogen fertilizer levels (kg ha^{-1}) during the growing season from 1981 to 2015.

Nitrogen Fertilizer Level	DRCS		SRCS	
	Yield	Net Profit	Yield	Net Profit
0	−21.54 **	−76.01 **	−10.89 **	−101.34 **
25	−39.29 **	−107.3 **	−10.89 **	−96.87 **
50	−34.92 **	−96.87 **	−12.5 **	−102.83 **
100	−40.37 **	−90.91 **	−12.33 **	−93.89 **
150	−52.64 **	−95.38 **	−20.78 **	−110.28 **
200	−61.07 **	−95.38 **	−27.96 **	−116.24 **
250	−65.35 **	−95.38 **	−30.99 **	−113.26 **
300	−66.78 **	−95.38 **	−34.99 **	−111.77 **
400	−67.47 **	−95.38 **	−39.96 **	−111.77 **
600	−67.5 **	−95.38 **	−41.39 **	−111.77 **

Note: ** indicates $p < 0.01$.

Table 5. The temporal tendency in rice grain yield (kg ha^{-1} y^{-1}) and net profit ($ ha^{-1} y^{-1}) for DRCS and SRCS at different irrigation regimes (days after water layer disappeared), including rainfed condition (values are set in italics), during the rice-growing season from 1981 to 2015.

Irrigation Regime	DRCS		SRCS	
	Yield	Net Profit	Yield	Net Profit
0	−54.0 **	−81.04 **	−24.5 **	−36.7 **
3	−58.8 **	−88.21 **	−23.6 **	−35.33 **
6	−69.2 **	−103.83 **	−23.6 *	−35.45 *
9	−79.2 **	−118.8 **	−25.9	−38.8
12	−92.2 **	−138.24 **	−25.5	−38.29
15	−97.6 **	−146.38 **	−26.5	−39.76
20	−99.7 **	−149.57 **	−29.3	−43.98
25	−117.2 **	−175.77 **	−27.0	−40.52
30	−110.8 **	−166.15 **	−28.0	−42.02
rainfed	−116.5 **	−174.69 **	−20.1	−30.2

Note: * indicates $p < 0.05$, and ** indicates $p < 0.01$.

For SRCS, rice grain yield ranged from 6285 to 8981 kg ha^{-1} y^{-1}; net profit ranged from $263.5 to $815.9 ha^{-1} y^{-1}. For DRCS, rice grain yield ranged from 10,794 to 16,275 kg ha^{-1} y^{-1}; net profit ranged from $245.5 to $1201.2 ha^{-1} y^{-1}. The longer it took for the paddy water layer to disappear after irrigation was applied, the lower the net profit was. When irrigation was applied right after the paddy water layer disappeared, both SRCS and DRCS reached a relatively high rice grain yield and net profit; the relatively high net profit of DRCS was $14.2 to $385.3 ha^{-1} y^{-1} more than that of SRCS.

From 1981 to 2015, a unanimous declining trend was detected in (a) rice grain yield for SRCS and DRCS, (b) net profit for SRCS and DRCS, (c) rice grain yield gap between DRCS and SRCS, and (d) net profit gap between DRCS and SRCS (Figure 5). The amplitude of this declining trend in (a) and (b) increased as irrigation was applied more days after the paddy water layer disappeared (Table 5). DRCS showed a greater declining amplitude in rice grain yield and net profit than SRCS. When irrigation was applied right after soil surface water disappeared, both (c) and (d) reached the highest value (7294 kg ha^{-1} y^{-1}, and $385.3 ha^{-1} y^{-1}, respectively). In other words, rice grain yield and net profit would theoretically increase by 7294 kg ha^{-1} y^{-1} and $385.3 ha^{-1} y^{-1}, respectively, if DRCS replaced SRCS when irrigation was applied right after the soil surface water was disappeared. When irrigation was applied 30 days after the paddy water layer disappeared, index (d) turned out to be zero. When no irrigation was applied (rainfed), index (d) showed a negative value. This indicated that a water deficit would occur during the growing season of rice when rainfed DRCS replaced rainfed SRCS; hence, the net profit would decrease by $167.8 ha^{-1} y^{-1}.

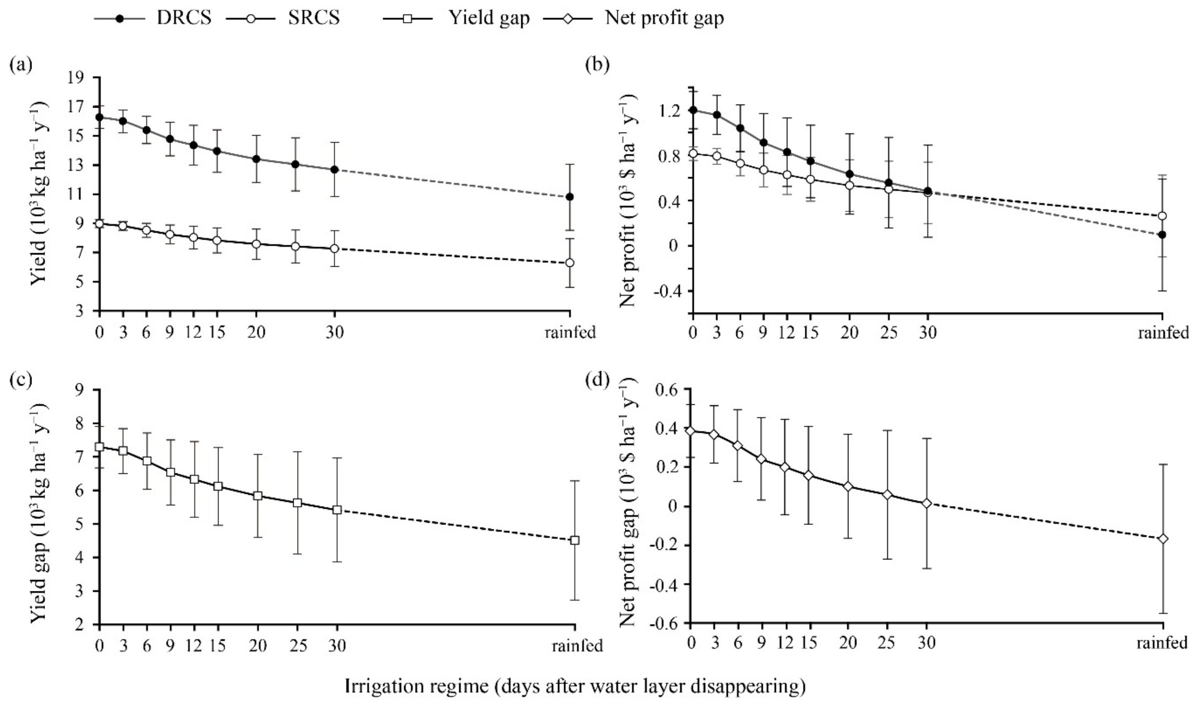

Figure 5. Rice grain yield (10^3 kg ha^{-1} y^{-1}) (**a**) and net profit (10^3 \$ ha^{-1} y^{-1}) (**b**) for DRCS and SRCS at different irrigation regimes, including rainfed condition (i.e., no irrigation), during the growing season from 1981 to 2015. Note: Error bars indicate the standard deviations. (**c**) Rice grain yield gap between DRCS and SRCS. (**d**) Net profit gap between DRCS and SRCS.

3.3. Agronomic Nitrogen Use Efficiency

Leaching of nitrogen fertilizer in paddy fields could contaminate both groundwater and surface water [61–63]. Greenhouse gas emissions such as CH_4 and N_2O would increase with the increase of nitrogen fertilizer in paddy fields [27].

When nitrogen fertilizer level was between 0 to 400 kg ha^{-1} (250 kg ha^{-1}) in SRCS (DRCS), rice grain yield increased with the increase in nitrogen fertilizer application (Figure 4b); but ANUE decreased with the increase in nitrogen fertilizer application (from 30.2 to 8.7 kg grain kg^{-1} N in SRCS, and from 38 to 6.5 kg grain kg^{-1} N in DRCS). The declining amplitude of ANUE varied among different rice grain yield levels; the declining amplitude of ANUE for DRCS was greater than that for SRCS (Figure 6). For SRCS, ANUE decreased by 1.7 kg grain kg^{-1} N per 1000 kg ha^{-1} y^{-1} increase in yield when rice grain yield was between 5000–9000 kg ha^{-1} y^{-1}, and by 14.2 kg grain kg^{-1} N per 1000 kg ha^{-1} y^{-1} increase in yield when rice grain yield was above 9000 kg ha^{-1} y^{-1}. For DRCS, ANUE decreased by 2.8 kg grain kg^{-1} N per 1000 kg ha^{-1} y^{-1}increase in yield when rice grain yield was between 11,000–16,000 kg ha^{-1}, and by 35.8 kg grain kg^{-1} N per 1000 kg ha^{-1} y^{-1} increase in yield when rice grain yield was above 16,000 kg ha^{-1} y^{-1}.

For both SRCS and DRCS, the highest ANUE occurred at the nitrogen fertilizer level of 25 kg ha^{-1}, which could be interpreted as the minimal nitrogen pollution level to the environment but also the lowest rice grain yield (the opposite of achieving the food security goal). When more nitrogen fertilizer was applied after the initial 25 kg ha^{-1}, both rice grain yield and net profit increased but ANUE decreased. To maintain a high level of rice grain yield while making a sustainable agriculture environment (producing as little nitrogen pollution as possible), we used the normalization method to find the optimal nitrogen fertilizer level for the highest ANUE as well as the highest net profit. The results showed that the nitrogen fertilizer level of 150 kg ha^{-1} was the best for both SRCS and DRCS to achieve high ANUE and net profit at the same time (Figure 6). At this optimal nitrogen fertilizer level, rice grain yield (net profit) for DRCS was 7443 kg ha^{-1} y^{-1} (\$428.3 ha^{-1} y^{-1}) higher than that for SRCS. This indicated that DRCS was superior to SRCS in the study region when the goal was to achieve high ANUE and net profit.

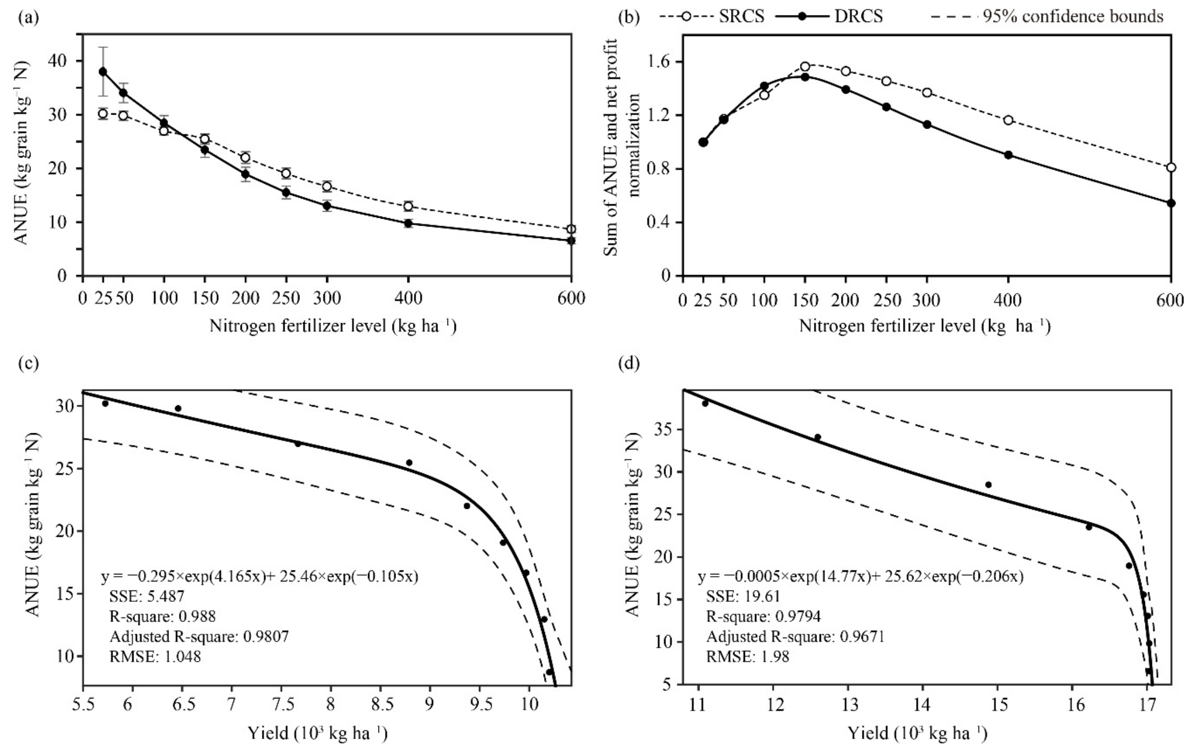

Figure 6. Relationships between agronomic nitrogen use efficiency (ANUE) and nitrogen fertilizer levels, rice grain yield, and net profitfor SRCS and DRCS in the study region. Note: Dotted lines are the 95% confidence bounds. (**a**) ANUE vs. nitrogen fertilizer level for SRCS and DRCS. (**b**) Sum of ANUE and net profit normalization vs. nitrogen fertilizer level for SRCS and DRCS. (**c**) ANUE vs. rice grain yield for SRCS. (**d**) ANUE vs. rice grain yield for DRCS.

3.4. Water Use Efficiency

Nitrogen fertilizer level could affect both water use efficiency and irrigation water use efficiency for paddy rice [64,65]. In this study, we selected the average nitrogen fertilizer level (170 kg ha^{-1}) and critical nitrogen fertilizer level (300 kg ha^{-1} for early rice, 200 kg ha^{-1} for middle rice, and 400 kg ha^{-1} for late rice) in ORYZA v3 to analyze WUE and IWUE for SRCS and DRCS in the study region.

At the average nitrogen fertilizer level, rice grain yield ranged from 10,795 to 16,275 kg ha^{-1} y^{-1} (from 4510 to 7294 kg ha^{-1} y^{-1}) for SRCS (DRCS) from 1981 to 2015. When comparing the composite values among the three rice varieties, early rice had the lowest rice grain yield, WUE, and IWUE; late rice had the highest amount of irrigation application, WUE, and IWUE; middle rice had the highest amount of rainfall during the growing season, the least amount of irrigation applied, and the highest rice grain yield (Table 6). Overall, SRCS was superior to DRCS in the study region when the goal was to achieve high WUE and IWUE while maintaining a high level of rice grain yield at the average nitrogen fertilizer level.

Table 6. Rainfall amount (mm), irrigation regime (amount of irrigation application for certain days after the paddy water layer disappeared, mm), rice grain yield (kg ha^{-1} y^{-1}), WUE (kg grain m^{-3}), and IWUE (kg grain m^{-3}) at 170 kg ha^{-1} nitrogen fertilizer level for early rice, late rice, and middle rice during the period of 1981–2015 in the study region.

Variety		Irrigation Regime										Average
		0	3	6	9	12	15	20	25	30	rainfed	
Early rice	Rainfall	448.7	448.7	448.7	448.7	448.7	448.7	448.7	448.7	448.7	448.7	448.7
	Irrigation	300.0	235.9	189.1	160.0	135.3	119.7	101.3	94.1	88.4	--	158.2
	Yield	7580	7407	7069	6744	6547	6316	6119	5943	5772	5014	6451
	WUE	10.41	11.20	11.52	11.58	11.76	11.63	11.68	11.46	11.17	11.72	11.4
	IWUE	7.39	8.86	9.55	9.80	10.43	10.19	10.73	9.88	8.49	--	9.5
Late rice	Rainfall	267.1	267.1	267.1	267.1	267.1	267.1	267.1	267.1	267.1	267.1	267.1
	Irrigation	304.4	245.3	202.2	177.2	150.9	130.9	113.1	98.1	81.3	--	167.0
	Yield	8695	8598	8329	8033	7811	7639	7297	7104	6916	5781	7620
	WUE	15.32	16.92	17.95	18.33	18.98	19.51	19.47	19.79	20.49	22.52	18.9
	IWUE	8.17	9.86	10.90	11.07	11.90	12.54	12.10	12.40	12.60	--	11.3
Middle rice	Rainfall	493.7	493.7	493.7	493.7	493.7	493.7	493.7	493.7	493.7	493.7	493.7
	Irrigation	285.9	223.1	182.8	154.4	131.6	116.3	100.0	90.6	81.6	--	151.8
	Yield	8981	8831	8523	8241	8032	7838	7578	7417	7274	6285	7900
	WUE	11.71	12.57	12.89	13.03	13.21	13.21	13.10	13.02	12.95	12.95	12.9
	IWUE	7.23	8.74	9.52	9.83	10.67	10.64	10.28	10.03	9.94	--	9.7

At the critical nitrogen fertilizer level, middle rice showed the highest IWUE when irrigation was applied between zero to 12 days after the paddy water layer disappeared; late rice showed the highest IWUE when irrigation was applied between 15 to 30 days after the paddy water layer disappeared. Among the three rice varieties, early rice showed the lowest IWUE under all the irrigation regimes (Table 7). Overall, SRCS was superior to DRCS in the study region when the goal was to achieve high IWUE.

Table 7. Water use efficiency (WUE) (kg grain m^{-3}) and irrigation water use efficiency (IWUE) (kg grain m^{-3}) under different irrigation regimes (irrigation was applied on different days after the paddy water layer disappeared) and rainfed condition at critical nitrogen fertilizer level for early rice, late rice, and middle rice during the period of 1981–2015 in the study region.

Variety	Index	Irrigation Regime										Average
		0	3	6	9	12	15	20	25	30	Rainfed	
Early rice	WUE	10.87	11.65	11.91	11.91	12.07	11.90	11.93	11.70	11.40	11.88	11.72
	IWUE	8.20	9.75	10.41	10.62	11.26	10.92	11.48	10.58	9.16	-	10.26
Late rice	WUE	15.51	17.11	18.13	18.48	19.12	19.64	19.58	19.90	20.56	22.59	19.06
	IWUE	8.43	10.14	11.17	11.33	12.16	12.77	12.27	12.58	12.82	-	11.52
Middle rice	WUE	13.09	14.01	14.28	14.38	14.52	14.47	14.32	14.21	14.11	13.92	14.13
	IWUE	8.72	10.50	11.36	11.73	12.61	12.49	11.98	11.73	11.54	-	11.41

3.5. CH_4/N_2O Emissions and Global Warming Potential

From 1981 to 2015, emissions of CH_4 and N_2O during the growing season of rice increased with the input of nitrogen fertilizer. Total GWP of CH_4 and N_2O for DRCS was 7757.8 to 15,456.3 kg CO_2-eq ha^{-1} y^{-1} higher than that for SRCS under various nitrogen fertilization rates; mean GWP for DRCS was 0.39 kg CO_2-eq GY^{-1} higher than that for SRCS (Table 8). When nitrogen fertilization rates ranged between 0–300 kg ha^{-1} y^{-1}, overall GWP for the early rice increased by 356 kg CO_2-eq per 10% increase in rice grain yield. When nitrogen fertilization rates ranged from 0–250 kg ha^{-1} y^{-1}, the overall GWP of the late rice increased by 875 kg CO_2-eq per 10% increases in rice grain yield. When nitrogen fertilization rates ranged from 0–400 kg ha^{-1} y^{-1}, overall GWP during the growing season of middle rice increased by 385 kg CO_2-eq GY^{-1} per 10% increase in rice grain yield.

Table 8. Emissions of CH_4 and N_2O (kg ha^{-1} y^{-1}), total GWP (kg CO_2-eq ha^{-1} y^{-1}), and mean GWP (kg CO_2-eq GY^{-1}) at different nitrogen fertilization rates (kg ha^{-1} y^{-1}) for SRCS and DRCS during 1981–2015.

Nitrogen Fertilizer Level	SRCS				DRCS			
	CH_4	N_2O	Total GWP	Mean GWP	CH_4	N_2O	Total GWP	Mean GWP
0	154.2	0.78	4085.4	0.82	460.3	1.12	11,843.2	1.29
25	179.5	0.98	4779.6	0.84	536.0	1.42	13,823.0	1.25
50	198.8	1.18	5321.0	0.82	593.5	1.71	15,346.9	1.22
100	234.2	1.58	6326.1	0.83	699.1	2.30	18,162.7	1.22
150	257.6	1.99	7033.8	0.80	769.2	2.88	20,090.6	1.24
200	271.2	2.39	7493.6	0.80	809.7	3.47	21,278.0	1.27
250	280.2	2.80	7838.0	0.81	836.5	4.06	22,121.0	1.30
300	286.3	3.20	8112.6	0.81	854.8	4.65	22,755.5	1.34
400	292.7	4.01	8512.8	0.84	873.8	5.82	23,579.9	1.38
600	296.1	5.63	9081.9	0.89	884.2	8.17	24,538.2	1.44

CH_4 emission during the rice-growing season for DRCS was 401.5 to 517.1 kg ha^{-1} y^{-1} higher than that for SRCS. When irrigation was applied on more days after the paddy water layer disappeared, CH_4 emission during the rice-growing season decreased for both SRCS and DRCS (Table 9). Under all the irrigation regimes, total GHG for DRCS was 10,327 to 13,215 kg CO_2-eq ha^{-1} y^{-1} higher than that for SRCS; mean GWP for DRCS was 0.46 to 0.58 kg CO_2-eq GY^{-1} higher than that for SRCS.

Table 9. CH_4 and N_2O emissions (kg ha^{-1} y^{-1}), total GWP (kg CO_2-eq ha^{-1} y^{-1}), and mean GWP (kg CO_2-eq GY^{-1}) under different irrigation regimes and rainfed condition for SRCS and DRCS during 1981–2015.

Irrigation	SRCS				DRCS			
Regime	CH_4	N_2O	Total GHG	GWP	CH_4	N_2O	Total GHG	GWP
0	260.4	2.15	7151.0	0.80	777.5	3.12	20,366.4	1.25
3	256.0	2.15	7041.9	0.80	764.4	3.12	20,040.5	1.25
6	249.4	2.15	6876.3	0.81	744.7	3.12	19,546.1	1.27
9	243.6	2.15	6731.5	0.82	727.4	3.12	19,113.7	1.29
12	238.3	2.15	6597.6	0.82	711.4	3.12	18,713.8	1.30
15	234.1	2.15	6494.5	0.83	699.1	3.12	18,406.2	1.32
20	229.8	2.15	6386.2	0.84	686.1	3.12	18,082.7	1.35
25	226.5	2.15	6302.8	0.85	676.2	3.12	17,833.7	1.37
30	224.7	2.15	6257.7	0.86	670.8	3.12	17,699.1	1.39
Rainfed	202.2	2.15	5696.5	0.91	603.8	3.12	16,023.6	1.48

When both nitrogen fertilization and irrigation (irrigation was applied between 0–30 days after surface water disappeared) were considered, CH_4 (N_2O) emissions for DRCS ranged from 306.2 to 588.0 kg ha^{-1} y^{-1} (0.35 to 2.53 kg ha^{-1} y^{-1}) higher than that for SRCS from 1981 to 2015 in the study region. This means that CH_4 and N2O emissions would be reduced by two-thirds and one-third, respectively if SRCS replaced DRCS. From the perspective of lower environmental pollution, SRCS is superior to DRCS in the study region, no matter the nitrogen fertilizer level or irrigation regime.

4. Discussion

Our results indicated that the net profit of rice grain yield first increased with nitrogen fertilization rates and then slightly declined for DRCS, with the tipping point for nitrogen fertilization rate at 150–200 kg N ha^{-1} per growing season (300–400 kg N ha^{-1} y^{-1}). However, for SRCS, the net profit rapidly increased with nitrogen fertilization rate before 200–250 kg N ha^{-1} per growing season, and then leveled off. Many previous studies have also proved that the over-dose nitrogen fertilization rate can significantly reduce the grain yield of rice and other crop types. This can be explained by that over-dose nitrogen input will stimulate a more vegetative growth phase than that of the reproductive growth phase, resulting in a greater proportion of biomass allocated in other organs (such as leaf, stem, and root) and thus less grain yield [66,67]. The different response curves for SRCS and DRCS were caused by the fact that the extra fertilized nitrogen that cannot be absorbed by the early rice was continuously transferred to the late rice for the DRCS, which resulted in doubled nitrogen input effects for the late rice. For the SRCS, the extra fertilized nitrogen that cannot be absorbed will be leached to the aquatic systems and would not affect the grain yield anymore. From the perspective of net profit, we recommend a nitrogen fertilization rate of 200–250 kg N ha^{-1} per growing season for the SRCS and 150–200 kg N ha^{-1} per growing season for the DRCS in the study region.

Inevitably, this study has some limitations. We referred to the air-temperature-defined (including indices of annual accumulated temperature above 0 °C, extreme minimum temperature, a period of 20 °C termination) northern limit of DRCS in China [10,68] to locate the study region. However, the northern limit of DRCS was also affected by other non-weather factors, such as government intervention in the rice grain market, availability of agricultural labor force, access to advanced cultivation techniques (i.e., prevention of agro-meteorological disasters for rice production), and so on. As a result, our chosen study region may not accurately represent all the areas that are sensitive to climate variability in the middle and lower reaches of the Yangtze River. We obtained the rice grain price data from the Chinese Yearly Compilation Book of Cost and Benefit of Agricultural Products from 1981 to 2015, which was a commonly used source for other studies on the economic evaluation of rice planting [69]. To minimize the effect of socio-economic factors (such as rice price, cultivation, techniques, agricultural labor force, etc.), we used the price records for the most recent five years to quantify the economic net profit for SRCS and DRCS. Therefore, the results would only reflect the rice market situation during the end of the study period instead of the entire period. We used ORYZA v3 to simulate different irrigation regimes during the growing season of rice by changing the setting of irrigation application on days after the paddy water layer disappeared. This was a decent improvement compared to the old crop model that only allowed setting a fixed-time and fixed-amount irrigation application, but without considering precipitation as a water source for rice plants. However, actual rice plants have different water demands and sensitivity levels during different growth stages [70,71]. For example, during the tillering stage (i.e., the critical stage for vegetative growth) and the booting stage (i.e., the sensitive stage for water demand), the ideal irrigation regime would be keeping the water layer in the paddy field all the time [72]. Paddy soil only stays wet during the heading-to-flowering stage and grouting-to-milking-maturity stage. Therefore, only irrigating on a certain number of days after the paddy water layer disappears may not provide the best water condition for rice plants. Due to the internal limitation of the crop model ORYZA v3, only one fixed irrigation regime could be set during the entire growing season of rice. Nevertheless, this would not undermine the usefulness of our study results for comparing the grain yield productivity of SRCS and DRCS. We adopted the method that was recommended by [43,46,73] to compute the CH_4 and N_2O emissions for SRCS and DRCS in the study region. The concern about this method was that it did not fully consider the possible effects of irrigation and cultivation techniques (e.g., straw return, no-tillage) on CH_4 and N_2O emissions. It was reported that soil moisture plays an important role in CH_4 and N_2O emissions [74,75]; CH_4 emission from paddy fields that have an alternate dry-wet pattern is only 53 percent of that from paddy fields that are flooded throughout the rice-growing season [76]; N_2O emission from paddy fields that have an alternate dry-wet pattern is 13.4 percent higher than that from paddy fields that are flooded throughout the rice-growing season [77]. In addition, the straw return technique can increase CH_4 emission but decrease N_2O emission for flooded paddies [78]. Hence, we suggest conducting future studies to acquire detailed soil moisture data during the rice-growing season to further evaluate the paddy CH_4 and N_2O emissions for SRCS and DRCS in the areas that are sensitive to climate variability for rice production in the middle and lower reaches of Yangtze River.

Compare to the crop model, the experimental data for grain yield cannot separate the effects from a single factor such as climate, nitrogen fertilization, and irrigation. The results of experiments can only reflect the overall changes in grain yield and the effects of all environmental and socio-economic factors. In addition, there are many missing data (especially for the greenhouse gas emission data) for the period 1981–2015 in the field experiments, making the results incomparable in some stages of the study period. Therefore, we cannot directly use the field experimental data to address the impacts of individual effects from climate change, nitrogen fertilization, and irrigation. In contrast, the calibrated and validated model using field-based data can consistently and accurately monitor the dynamics of grain yield, greenhouse gas emissions, and other variables. There are still some uncertainties in the application of the model, data processing, and other aspects. To make a better interpretation of the evaluation results, it is necessary to analyze these uncertainties: (i) although the ORYZA v3 model has been widely used in the validation, assessment, and recognition in the world, its many crops in the process of machine most rational description or half empirical (such as the dynamic development of leaf area, leaf aging process, and dry goods and materials distribution, etc.), many quantitative relations are derived and based on historical climate conditions. Therefore, it is difficult to carry out accurate verification at present. (ii) crop yield is affected by many factors, such as weather, soil, and management measures, but also by diseases, insects, and grasses. The occurrence and development of diseases and insect pests will be aggravated under the condition of climate warming and high temperature and humidity. At the same time, under the condition of warm winter, the sources of pests and diseases will increase over winter, which will affect the yield of rice to different degrees. In addition, besides nitrogen fertilizer, the application amount of phosphorus fertilizer and potash fertilizer, as well as economic and cultural factors on rice production cannot be ignored, which are not covered in the model. The model needs to be improved and perfected in the future. (iii) the simulation effect of the model on the influence of temperature change is good, but the simulation of extreme weather events such as hail, typhoon, rainstorm, and flood need to be improved, and extreme weather events have the greatest influence on the yield. (iv) since the model is designed based on a single point of test, it is assumed that all the influencing factors have spatial consistency when it is applied to regional simulation. At the same time, this study spans 35 years. In such a long-time span, the management level, planting technology, and varieties of agricultural production will change significantly, which are not considered in this study due to the design of the model and technical factors. (v) this research according to the middle and lower reaches of the Yangtze River region in the same variety of experimental data obtained under different management techniques of double season rice and double season rice and late rice genetic parameters, but as a result of the test data are different years, different sites and different observation personnel access, data differences tend to affect the determination of genetic parameters. The simulation results based on this genetic parameter may have some deviations. Therefore, the uncertainty of space and time will increase the uncertainty of the results of this study.

5. Conclusions

From 1981 to 2015 in the study region, the maximum net profit (based on the most recent five-year price data for rice grain; this same note applies to the rest of the conclusions) was reached at the nitrogen fertilizer level of 250, 300, and 200 kg ha^{-1} for early, middle, and late rice, respectively. If DRCS replaced SRCS in the areas that are sensitive to climate variability for rice production in the middle and lower reaches of the Yangtze River, the highest net profit gain would occur at the 150 kg ha^{-1} nitrogen fertilizer level and the immediate irrigation regime (irrigation at the day right after the surface water is disappeared). Annual variation of net profit for SRCS was less than that for DRCS no matter the nitrogen fertilizer level or irrigation regime. At nitrogen levels that are below 150 kg ha^{-1}, late rice showed a higher ANUE than both early rice and middle rice. At nitrogen levels that are above 150 kg ha^{-1}, middle rice showed the highest ANUE, followed by late rice, and early rice. When the nitrogen fertilizer level was at 130, 118, and 221 kg ha^{-1}, respectively, for early rice, middle rice, and late rice, optimal net profit was achieved while maintaining a relatively high level of ANUE; net profit (output per kg N) of DRCS was \$171.4 ha^{-1} (\$0.25 kg N^{-1}) higher than that of SRCS. Nevertheless, DRCS showed a lower WUE and IWUE than SRCS under rainfed conditions and all nine study irrigation regimes. In addition, DRCS had higher CH_4 and N_2O emissions, total GHG, and GWP during the growing season than SRCS from 1981 to 2015. In conclusion, our historical-data-based analysis indicated that SRCS was superior to DRCS in the areas that are sensitive to climate variability for rice production in the middle and lower reaches of the Yangtze River. Compared to the DRCS, SRCS had lower GHG emissions, lower global warming potential, higher water use efficiency, higher irrigation water use efficiency, and higher profit-cost ratio.

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Abbreviations

ANUE	agronomic nitrogen use efficiency
DRCS	double rice cropping system
GHG	greenhouse gas
GWP	global warming potential
GY	grain yield
IWUE	irrigation water use efficiency
SRCS	single rice cropping system
WUE	water use efficiency

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