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Study on the Nutrient Optimal Management Strategy of High and Stable Annual Yield in the Rice–Wheat System: A 10-Year Term Experiment

Guofa Zhang [1,2,†], Jianwei Zhang [1,3,†], Lei Xu [1], Yan Zhou [1], Pengfu Hou [3], Fei Yang [1], Weiwei Li [1], Zhenghui Liu [1], Yanfeng Ding [1] and Ganghua Li [1,*]

1 National Engineering and Technology Center for Information Agriculture, Key Laboratory of Crop Physiology and Ecology in Southern China, Jiangsu Collaborative Innovation Center for Modern Crop Production, Nanjing Agricultural University, Nanjing 210095, China; 2007201008@stu.njau.edu.cn (G.Z.); 2017201024@njau.edu.cn (J.Z.); 2021201015@stu.njau.edu.cn (L.X.); 2018201013@njau.edu.cn (Y.Z.); 2019101029@stu.njau.edu.cn (F.Y.); li1990@njau.edu.cn (W.L.); liuzh@njau.edu.cn (Z.L.); dingyf@njau.edu.cn (Y.D.)
2 Teaching Affairs Office, Daqing Normal University, Daqing 163712, China
3 Institute of Agricultural Resources and Environment, Jiangsu Academy of Agricultural Sciences, Nanjing 210014, China; houpengfu@jaas.ac.cn
* Correspondence: lgh@njau.edu.cn; Tel.: +86-25-8439-6475; Fax: +86-25-8439-6302
† These authors contributed equally to this work.

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Abstract: What strategy of nutrient management can maintain the high and stable annual yield in rice–wheat systems under climate change? A 10-year term experiment was conducted in the rice–wheat system to investigate the effect of optimal nutrient management on crop yield and meteorological drivers of year-to-year fluctuations in rice and wheat yield. Treatments were as follows: conventional fertilization (CF, as control), fertilizer postponing (FP, with the same amount fertilization as CF and increasing rate and times of panicle fertilizer) with/without straw incorporation (including only straw returned in rice (W) or wheat (R) season, and both straw incorporation (WS), RFP (reducing amount based on FP) with/without organic fertilizer. Results showed that FP with/without straw incorporation increased 10-year average yields of rice, wheat, and annual by 4.5~6.5%, 3.8~7.2%, and 4.8~6.8%, respectively, while RFP with/without organic fertilizer did not markedly reduce wheat yield, compared with CF. Effect of optimal treatments on wheat and rice yield stability was different; among the annual yield stability in FP + WRS was the greatest due to increasing and a stable number of spikelets and dry matter accumulation (DMA) after heading. Furthermore, the coefficient of variation (CV) of DMA during rice jointing-heading (21.6~30.0%) and heading-maturity stage (20.1~27.9%) was higher than before jointing (13.9~16.7%), which were affected by day photosynthetically active radiation (explain: 26%) and the number of rainy days (explain: 34%), respectively, using Stepwise regression; in contrast, in wheat season, the fluctuation of DMA before jointing was the highest (CV: 83.8~109.9% (before jointing) vs. 61.1~97.4% (heading-mature stage) vs. 33.7~46.3% (jointing-heading period), 55% of its variations was impacted by day-night temperature differences, the number of rainy days and photosynthetically active radiation accumulation. Our finding suggested that nutrient management to increase and stable the DMA after rice jointing and before wheat jointing could maintain the high and stable annual yield in rice–wheat systems.

Keywords: rice–wheat system; optimized nutrient management; yield; stability

1. Introduction

Rice and wheat are important food crops in China, accounting for 51.6% of China's total grain yield [1]. The middle and lower reaches of the Yangtze River is an important rice–wheat rotation region in China, with an area of about 3.4 million hm^2 and an average annual grain yield of 8 t hm^{-2} rice and 5.5 t hm^{-2} wheat [2]. However, high production in this region is achieved by high nitrogen (N) fertilization levels (average N fertilizer rate 209 kg N hm^{-2} for rice and 210 kg N hm^{-2} for wheat) [3,4]. In addition, unreasonable nutrient management, such as applying over 75% of fertilizer rate at the early-growth stage straw burning, remains in this region's conventional fertilization mode [5,6], which may weaken the adaptability of crops to unfavorable weather. Specifically, the intensity and frequency of unfavorable weather may be increased in the future due to climate change, crop yields stability being further threatened [7–9]. Therefore, the selection strategy of high and stable yield in rice–wheat rotation systems is of great significance for ensuring future food security under climate change.

Reasonable nutrient management is common to increase crop production [3,10,11]. Over the past 20 years, optimized nutrient management (i.g. N fertilizer precise quantitative management, real-time field nutrient management, straw returning, and partial replacement of chemical fertilizer with organic fertilizer) was proposed, which achieved high wheat and rice yield and high nutrient use efficiency in the season [3,4,6,12–15]. It was due to coordination with the law of fertilizer demands of rice and wheat, namely reducing the amount of fertilizer at the early growth stage and increasing nutrient supply at the late growth stage. Some studies reported that increasing the spikelets number of wheat and rice and promoting biomass accumulation after heading based on guaranteeing the full number of productive tillers was key in the nutrient management of high and stable yield [6,11,16–19]. However, many studies only focus on a single-season crop in rice–wheat rotation systems, lack of assessment annual yield, especially yield stability evaluation.

The long-term experiment is an essential means for evaluating the sustainability of nutrient management [20–24]. The 34-year term experiment found that the combined application of manure and chemistry fertilizer significantly increased the stability of rice yield under a double rice cropping system [23]. The 11-year term experiment found that long-term straw management could stable wheat and maize yield in the Northern China Plain [24]. However, to the best of our knowledge, no long-term experiments have so far assessed the effect of integrated nutrient management on crop stability in the rice–wheat system.

Weather change is a major factor affecting the year-to-year fluctuations of crop yield [8,9]. Climate variation explained one-third of crop yield variability globally [8]. 35% of rice yield fluctuations came from weather changes in China due to solar radiation changes [9]. Yield losses caused by nighttime warming were higher than daytime owing to enhance respiration to consume carbohydrates [25]. Stepwise regression showed that minimum temperature explained 44% of the variability in wheat yield, respectively, in northwear India [26]. However, previous reports showed that the sensitivity of crops to weather changes at different growth stages was different and more than seasonal changes [27–29]. Therefore, it was necessary to determine the effect of meteorological drivers at different growth stages on the year-to-year fluctuations of wheat and rice productivity. Moreover, Zhang et al. observed that straw incorporation significantly increased rice yield in the low light-years [20]. Winter wheat yield-increasing effects of fertilizers were greater in wet years than in dry years in arid and semiarid regions [21,22]. These implied that reduce the negative effects of extreme weather events by formulating reasonable management measures to stabilize yields.

Thus, we conducted a 10-year field experiment to investigate the effect of selection and integration of nutrient management on crop yield in rice–wheat systems in the middle and lower reaches of the Yangtze River. We also assessed the main meteorological factors driving yield fluctuation. The research results can provide a reference for the selection of nutrient-optimized management strategies for sustainable rice–wheat annual production under climate change.

2. Materials and Methods

2.1. Experimental Site and Design

The experimental site (119°28′ E, 31°54′ N) was located in Danyang experiment station, Jiangsu Province, China. This region is a typical rice–wheat cropping area in the middle and lower reaches of the Yangtze River. A long-term experiment of nutrient management modes was conducted from the 2009 wheat season to the 2019 rice season. The basic properties of the soil at the beginning of the field experiment were organic matter 17.15 g kg^{-1}, total N 0.97 g kg^{-1}, total P 0.5 g kg^{-1}, total K 11 g kg^{-1}, available P 13.6 mg kg^{-1}, available K 93.5 mg kg^{-1}.

2.2. Field Experiment

The experiment was arranged in a randomized completely block design, including seven treatments with three replicates: CF (conventional fertilization, as control), FP (fertilizer postponing with the same amount of fertilization as CF), FP + RS (FP with rice straw incorporation), FP + WS (FP with wheat straw incorporation), FP + RWS (FP with rice and wheat straw incorporation); RFP (reducing amount based on FP), RFP + O (RFP + organic fertilizer). Table 1 shows the times and rate of fertilizer among treatments at rice and wheat season, respectively.

Table 1. Fertilizer rates for each treatment at different stages of rice and wheat (kg hm^{-2}).

	CF	**FP**	**FP + RS**	**FP + WS**	**FP + RWS**	**RFP**	**RFP + O**
Total nitrogen	300–225 *	300–225	300–225	300–225	300–225	198–180	198–180
Basal	150–125	120–90	120–90	120–90	120–90	79.2–72	79.2–72
Tilling	75–0	60–45	60–45	60–45	60–45	39.6–36	39.6–36
Spikelets-promoting	75–100	60–45	60–45	60–45	60–45	39.6–36	39.6–36
Spikelets-protecting	-	60–45	60–45	60–45	60–45	39.6–36	39.6–36
Total phosphorous (P_2O_5)	150–105	150–105	150–105	150–105	150–105	120–90	120–90
Basal	150–105	75–60	75–60	75–60	75–60	60–45	60–45
Jointing	-	75–45	75–45	75–45	75–45	60–45	60–45
Total potassium (K_2O)	240–105	240–105	240–105	240–105	240–105	180–90	180–90
Basal	240–105	120–60	120–60	120–60	120–60	90–45	90–45
Jointing	-	120–45	120–45	120–45	120–45	90–45	90–45
Straw #			0–9750	6000–0	6000–9750	-	-
Organic fertilizer ##	-	-	-	-	-	-	1800–3000

Note: *: fertilizers rate of rice and wheat. #: The N, P, and K contents of rice straw are approximately 0.91%, 0.31%, and 3.20%, respectively; the N, P, and K content of wheat straw is approximately 0.45%, 0.04%, and 2.67%, respectively. ##: Organic fertilizer is a commercial organic fertilizer, and its organic matter, N, P, and K content are about 45%, 3.45%, 2.12%, and 1.02%, respectively. The same as below.

In each year, the rice cultivar Wuyunjing 23 (*Oryza sativa* L.) was transplanted by hand in mid-June with a plant spacing of 30 cm × 13.3 cm and transplanting density of 2–3 seeding per hole. Winter wheat (Yangmai 16 (2009–2013) and Yangmai 20 (2014–2018), *Triticum aestivum* L.) was sown in mid-November at a seed rate of 225 kg hm^{-2}. Other crop management was the same with local farmer practices.

2.3. Measurements and Data Analysis

2.3.1. Meteorological Data

The meteorological data were measured by weather station (WatchDog 2900ET, USA/SPECTRUM), including photosynthetically active radiation (PAR), accumulation of photosynthetic active radiation (PARA), daily mean temperature (mean), daily average maximum temperature (TMax), daily average minimum temperature (TMin), temperature difference (TD), precipitation (P) number of rainy days (DR) and rainfall intensity (RI). The meteorological parameters of each growth stage at the wheat and rice seasons are shown in Figure 1.

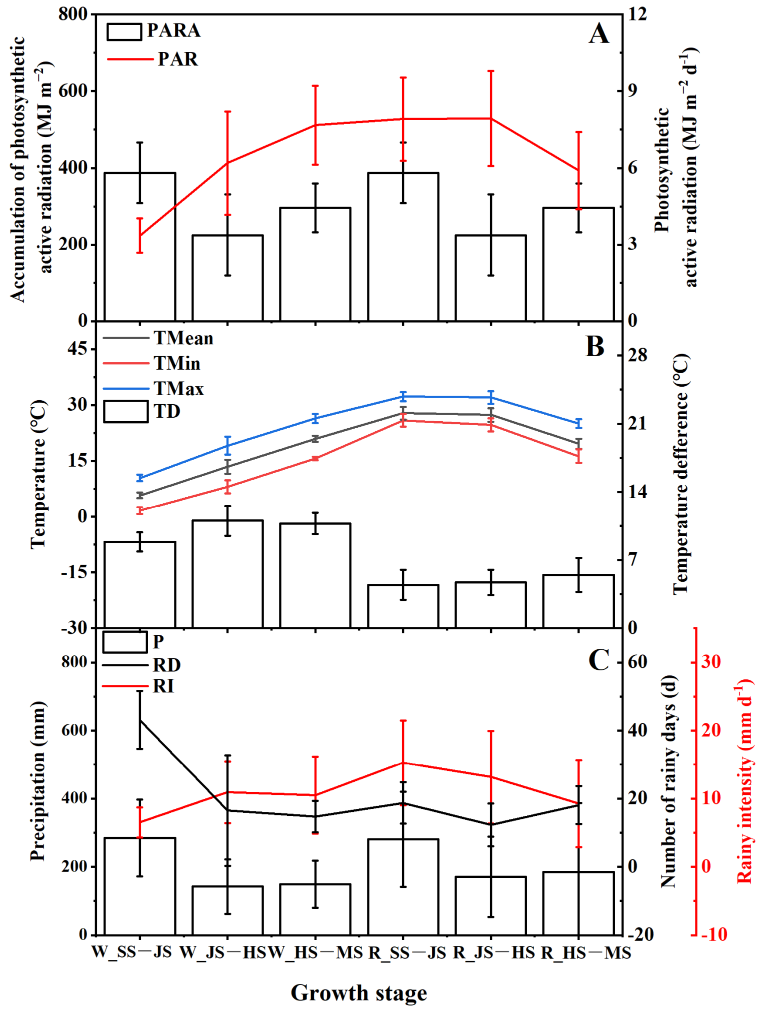

Figure 1. Meteorological condition. Note: (**A**) PAR and PARA at wheat and rice season; (**B**) TMean, TMin, TMax and TD at wheat and rice season; (**C**) P, RD and RI at wheat and rice season. W: wheat season; R: rice season; SS: sowing stage; JS: jointing stage; HS: heading stage; MS: maturity stage; PAR: photosynthetically active radiation; PARA: accumulation of photosynthetic active radiation; TMean: daily mean temperature; TMax: daily average maximum temperature; TMin: daily average minimum temperature; TD: temperature difference; P: precipitation; RD: number of rainy days; RI: rainfall intensity. Data were the 10 years average at the different growth stages. The same as below.

2.3.2. Yields and Their Components

At harvest, 5 m^2 areas were harvested manually to determine grain yields. The standard yield was converted according to 13.5% and 14% moisture content. Panicle numbers of rice and wheat were counted in 60 hills and 1 m^2 areas, respectively. Three hills representative rice plants and thirty wheat plants in each treatment were divided into above-ground parts to determine total biomass and yield formations. Moreover, wheat yields were culled in 2014–2015 and 2018–2019 due to large-scale disease and weeds. All plants sample were oven-dried at 105 °C for 1 h, and then at 80 °C to achieve a constant weight then weighting.

2.3.3. Data Analysis

Yield stability was evaluated by comparing treatments' sustainable yield index (SYI). Equations as follows [22,28,29]:

$$SYI(\%) = (Y_{mean} - Y_{sd})/Y_{max} \times 100 \quad (1)$$

where mean is the mean of rice yield during 2010–2018 for treatment. Y_{sd} is the yield standard deviation. Y_{max} is the maximum rice yield over 2010–2018 for each treatment.

To accurately grasp the impact of weather changes on crop yields, this study used the H-P filtering method in Eview 10 software for separating rice yield into trend yield (Y_t) and meteorological yield (Y_w):

$$Y = Y_t + Y_w \quad (2)$$

The H-P filtering made the sum of squares of deviations between the trend yield and the actual yield sequence of the rice yield sequence on a long-time scale reach the minimum. Y_t is the solution to the minimization problem in the following formula.

$$min\left\{\left\{ \sum_{t=1}^{n}(Y - Y_t)^2 \quad + \lambda \sum_{t=1}^{n}[(Y_{t-1} - Y) - (Y_t - Y_{t-1})]^2 \right\}\right. \quad (3)$$

where λ is the HP filter parameter, and the data in this study are annual, the reference value of the parameter λ is selected as 100. t is years since the start of this experiment.

We analyzed data on averaged yields, SYI, yield formations by variance (ANOVA) using SPSS 22.0 software. Differences between treatments were compared based on the least significant difference test at $p < 0.05$. Correlation of biomass and meteorological factors and stepwise regression using SPSS 22.0 software.

3. Results

3.1. Yield and Yield Stability

3.1.1. Annual

The 10-year average annual yield was 16.8 t hm^{-2}~18.0 t hm^{-2}, which was significantly affected by the nutrient management (Figure 2A). Compared with CF (16.9 t hm^{-2}), FP with/without straw incorporation (FP, FP + RS, FP + WS, FP + WRS) increased the average of annual yield by 0.8 t hm^{-2}~1.1 t hm^{-2}, with an increased rate of 4.8%~6.8%, the yield of FP + WS (18.0 t hm^{-2}) being the best. However, the 10-year average annual yield of RFP (16.5 t hm^{-2}) was slightly reduced, combined with organic fertilizer (RFP + O, 17.0 t hm^{-2}), which showed a trend of increasing yield but was still lower than FP (17.7 t hm^{-2}).

Nutrient management significantly affected the stability of annual yield, but there was no difference between optimized treatments and CF. Among optimized treatment, SYI of FP + WRS (84.5%) was the highest, whereas RFP + O was the lowest (74.5%) (Figure 1B). The fluctuation range of annual meteorological yield in the treatment of CF, FP, FP + RS, FP + WS, FP + WRS, RFP, and RFP + O during 10 years was −1.5 t hm^{-2} ~1.9 t hm^{-2}, −2.3 t hm^{-2}~2.8 t hm^{-2}, −2.3 t hm^{-2}~2.4 t hm^{-2}, −2.4 t hm^{-2}~2.7 t hm^{-2}, −1.9 t hm^{-2}~1.2 t hm^{-2}, −1.7 t hm^{-2}~1.8 t hm^{-2}, and −2.2 t hm^{-2}~3.2 t hm^{-2}, respectively (Figure 1C–I), of which the yield fluctuation of FP + WRS was the smallest.

3.1.2. Rice

The 10-year average rice yield of each treatment was over 11 t hm^{-2}. Compared with CF (11.1 t hm^{-2}), FP increased averaged rice yield by 0.5 t hm^{-2}, combined with straw incorporation remarkably enhanced yield level, with the increased rate being 6.0%, 6.5%, and 7.1% in treatments of FP + RS, FP + WS, and FP + WRS, respectively (Figure 3A). There was no significant difference in rice yield between the treatment of reduction fertilizer rate (RFP, RFP + O) and CF.

Except for RFP + O, SYI of rice in other treatments was above 75%, and the effect of different optimized treatments on the stability of rice yield was different (Figure 2B). Compared with CF, FP, FP + WS, FP + WRS, and RFP increased SYI of rice by 5.7%, 0.1%, 12.0%, and 2.1%, respectively, while FP + RS and RFP + O reduced by 0.6% and 3.1%, respectively. The fluctuation range of meteorological yield among treatments was opposite to that of SYI (Figure 3C–I).

3.1.3. Wheat

The average wheat yield was 5.6 t hm^{-2}~6.3 t hm^{-2}, significantly affected by nutrient management. Compared with CF, all optimized treatments had no significant impact on wheat yield (Figure 4A). Among them, FP with/without straw incorporation (FP, FP + RS, FP + WS, FP + WRS) showed a trend of increasing yield, with an average increase wheat yield of 0.2 t hm^{-2}~0.4 t hm^{-2}, while the treatment of reduction fertilizer rate (RFP, RFP + O) was a trend of decreasing yield, with the reduction rate of 2.5%~4.7%.

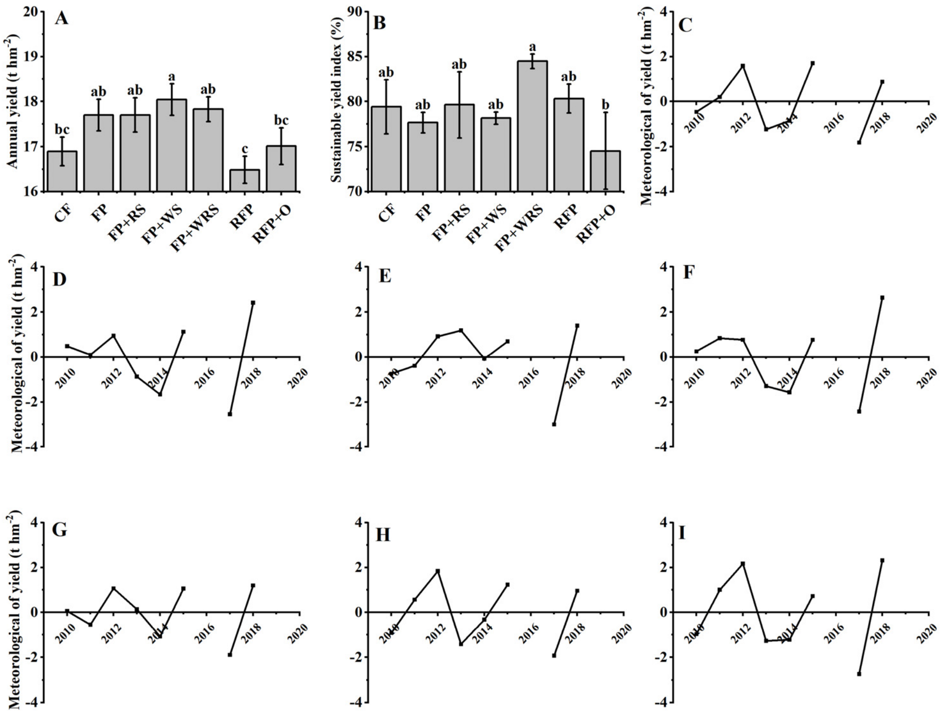

Figure 2. Effect of nutrient management modes on the annual yield of rice and wheat and its stability. Note: CF: convention fertilizer mode; FP: fertilizer postponing; FP + RS: fertilizer postponing + rice straw incorporation; FP + WS: fertilizer postponing + wheat straw incorporation; FP + WRS: fertilizer postponing + rice and wheat straw incorporation; RFP: fertilizer postponing and reducing amount; RFP + O: fertilizer postponing and reducing amount +organic fertilizer. (**A**) average annual yield of rice and wheat; (**B**) annual sustainable yield index of rice and wheat; (**C**–**I**) annual yield anomalies of CF, FP, FP + RS, FP + WS, FP + WRS, RFP, and RFP + O, respectively. Different lowercase letters indicate the difference between treatments at the $p < 0.05$ level.

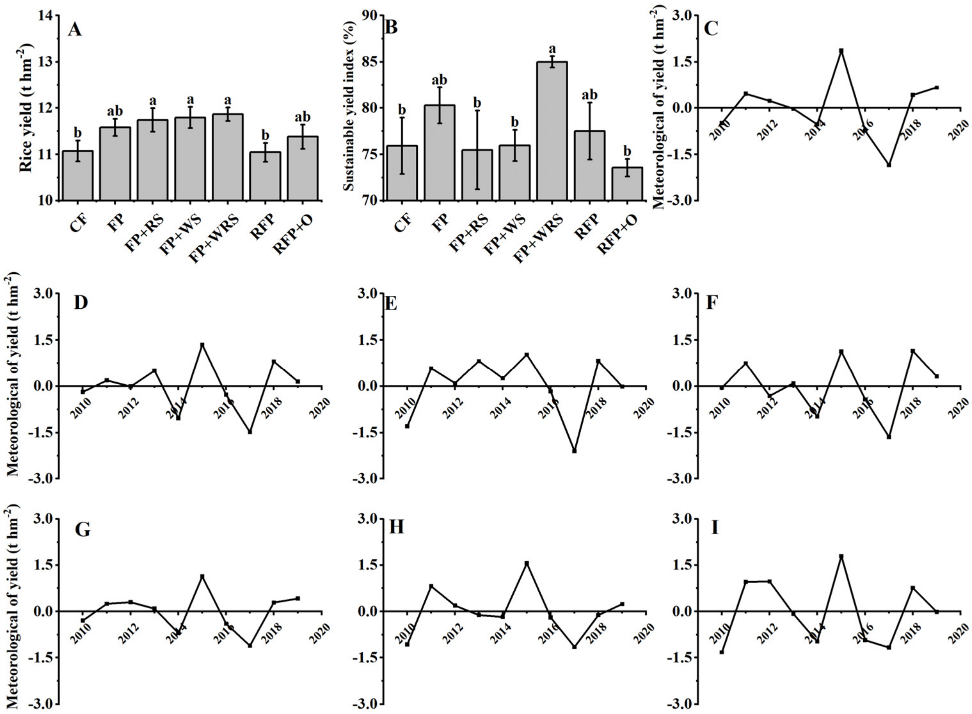

Figure 3. Effect of nutrient management modes on the yield of rice and its stability. Note: (**A**) average yield of rice; (**B**) sustainable yield index of rice; (**C**–**I**) rice meteorological yield of CF, FP, FP + RS, FP + WS, FP + WRS, RFP, and RFP + O, respectively. Different lowercase letters indicate the difference between treatments at the $p < 0.05$ level.

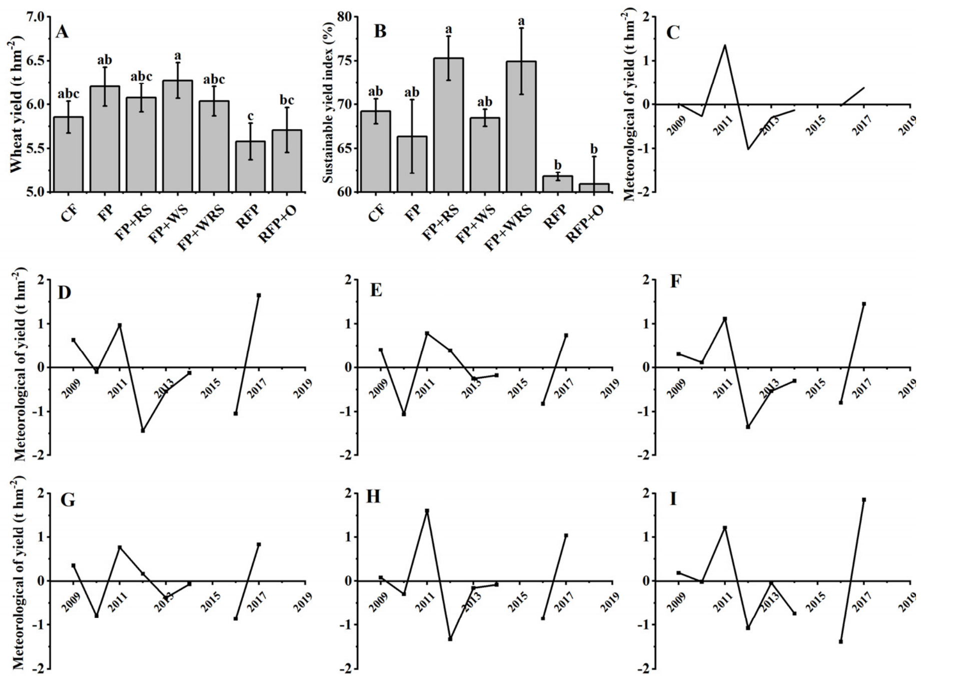

Figure 4. Effect of nutrient management modes on the yield of wheat and its stability. Note: (**A**) average yield of wheat; (**B**) sustainable yield index of wheat; (**C**–**I**) meteorological wheat yield of CF, FP, FP + RS, FP + WS, FP + WRS, RFP, and RFP + O, respectively. Different lowercase letters indicate the difference between treatments at the $p < 0.05$ level.

SYI of wheat in each treatment was below 75%. Compared with CF (69.6%), The SYI of FP + RS and FP + WRS were increased by 8.8% and 8.3%, but FP, FP + WS, RFP, and RFP + O were declined by 4.1%, 1.1%, 10.7%, and 12.0%, respectively (Figure 4B). Furthermore, the fluctuation range of the 10-year meteorological yield in CF, FP, FP + RS, FP + WS, FP + WRS, RFP, and RFP + O was -1.1 t hm^{-2}~1.3 t hm^{-2}, −1.5 t hm^{-2}~1.4 t hm^{-2}, −1.1t hm^{-2}~0.8 t hm^{-2}, −1.4 t hm^{-2}~1.4 t hm^{-2}, −1.0 t hm^{-2}~0.9 t hm^{-2}, −1.3 t hm^{-2}~1.7 t $hm^{-2,}$ and −1.8 t hm^{-2}~1.4 t hm^{-2}, respectively (Figure 4C–I), FP + RS and FP + WRS showed the most stable.

3.2. Yield Components

3.2.1. Rice

The yield components of rice (panicles, spikelets per panicle, seeding rate, and grain weight) were significantly affected by nutrient management (Table 2). The 10-year average number of panicles in the treatment of FP, FP + RS, FP + WS, FP + WRS increased by 5.0%, 5.7%, 5.7%, and 2.8%, respectively, but RFP and RFP + O were reduced by 6.3% and 2.8%, respectively, compared with CF. All optimized treatments (FP, FP + RS, FP + WS, FP + WRS, RFP, and RFP + O) had a higher 10-year average spikelets per panicle than that of CF (125), showing FP + WRS (140) > FP + RS (135), FP + RS (134) > FP (133), RFP + O (130) > RFP (129). In contrast, the seeding rate in all optimized treatments showed trends of reduction, with a decrease of 5.7% (FP), 4.8% (FP + RS), 5.3% (FP + WS), 5.8% (FP + WRS), 1.0% (RFP), and 1.3% (RFP + O), respectively. There were no statistical differences in grain weight between FP with/without straw incorporation (FP, FP + RS, FP + WS, FP + WRS) and CF. 10-year average grain weight of PRF (31.5 mg) was remarkably higher than that of CF (30.6 mg) and FP with/without straw incorporation (FP, FP + RS, FP + WS, FP + WRS), while combined with organic fertilizer (FPR + O, 31.2 mg) was slightly reduced.

Table 2. Effect of nutrient management modes on rice and wheat yield components and coefficient of variation. Different lowercase letters indicate the difference between treatments at the $p < 0.05$ level.

	Rice				Wheat		
	Panicles (m^{-2})	**Spikelets per Panicle**	**Seeding Rate (%)**	**Grain Weight (mg)**	**Spikes (m^{-2})**	**Spikelets per Spike**	**Grain Weight (mg)**
Mean							
CF	327 ab	125 c	90.5 a	30.6 b	391 a	36.9 ab	41.9 a
FP	343 a	133 bc	85.3 c	30.5 b	406 a	37.1 ab	42.4 a
FP + RS	345 a	135 b	86.2 bc	30.6 b	400 a	39.6 a	41.2 a
FP + WS	346 a	134 b	85.7 c	30.5 b	415 a	40.5 a	40.3 a
FP + WRS	336 a	140 a	85.2 c	30.5 b	387 a	38.4 ab	42.0 a
RFP	306 c	129 c	89.6 a	31.5 a	388 a	35.4 b	42.0 a
RFP + O	318 bc	130 bc	89.3 ab	31.2 ab	386 a	35.5 b	42.6 a
CF	11.6	9.9	5.7	4.1	27.0	18.4	10.6
FP	9.8	7.8	7.6	5.9	19.9	17.4	12.4
FP + RS	9.2	8.0	8.6	5.0	17.5	19.0	9.7
FP + WS	9.4	7.1	9.1	5.4	18.8	17.9	12.4
FP + WRS	11.0	5.3	9.2	5.7	17.0	16.1	10.9
RFP	9.2	6.2	6.6	6.2	24.0	18.6	9.7
RFP + O	9.7	8.2	6.7	5.8	18.8	20.9	10.6

The coefficient of variation (CV) of rice yield components showed the number of panicle (9.2%~11.1%) > spikelets per panicle (5.3%~9.9%), seeding rate (5.7%~9.2%) > grain weight (4.1%~6.2%) (Table 2). Compared with CF, each optimized treatment declined the CV of the number of panicle (15.8%, 20.8%, 19.0%, 4.9%, 20.4%, and 16.2% in the treatment of FP, FP + RS, FP + WS, FP + WRS, RFP and RFP + O, respectively) and spikelets per panicle (21.1%, 19.2%, 27.7%, 46.3, 37.5, 17.4% in the treatment of FP, FP + RS, FP + WS, FP + WRS, RFP and RFP + O, respectively), but intensified the inter-annual fluctuations of seeding rate (34.0%, 51.5%, 60.1%, 61.6%, 15.7% and 18.7% in the treatment of FP, FP + RS, FP + WS, FP + WRS, RFP and RFP + O, respectively) and grain weight (42.6%, 23.2%, 32.2%, 38.6%, 52.8% and 42.5%, in the treatment of FP, FP + RS, FP + WS, FP + WRS, RFP and RFP + O, respectively).

3.2.2. Wheat

Nutrient management significantly impacted spikelets per spike but did not affect other components factors (panicles and grain weight) (Table 2). Compared with CF, spikelets per spike in the treatment of FP with/without straw incorporation showed an increasing trend, with an increased rate of 0.3% (FP), 7.1% (FP + RS), 9.6% (FP + WS), and 4.0% (FP + WRS), respectively, while RFP with/without organic fertilizer showed a downward trend, with a decrease of 4.2% (RFP) and 3.9% (RFP + O), respectively.

The CV of wheat yield components showed as follows: the number of spikes (17.0%~27.0%) > spikelets per spike (16.1%~20.9%) > grain weight (9.7%~10.9%) (Table 2). Compared with CF, all optimized treatments reduced the CV of the number of spikes, showing FP + WRS > FP + RS > RFP + O > FP + WS > FP > RFP. The effect of nutrient management on the CV of spikelets per spike and grain weight did not show obvious regularity.

3.3. Source and Sink

3.3.1. Rice

The nutrient management significantly affected the total number of spikelets, LAI, and the spikelet-leaf ratio (Figure 5A,C,E). Compared with CF, FP with/without straw incorporation (FP, FP + RS, FP + WS, FP + WRS) significantly increased the total number of spikelets, with rising rates of 11.1% (FP), 14.1% (FP + RS), 14.1% (FP + WS), and 15.5%RFP+O (FP + WRS), respectively, but did not affect LAI, making high spikelet-leaf ratio. In contrast, RFP and RFP + O had no statistical difference in the total number of spikelets but significantly reduced LAI, increasing the spikelet-leaf ratio.

The CV of LAI was 13.0%~19.4%, which was higher than that of the spikelet-leaf ratio (11.8%~16.8%) and the total number of spikelets (9.1%~13.2%) (Figure 5B,D,F). However, the effect of optimized treatment on the CV of each rice sink and source did not show apparent regularity.

3.3.2. Wheat

In this experiment, the total number of spikelets, LAI, and the spikelet-leaf ratio in the wheat season were 1.3×10^3 spikelets m^{-2} ~1.7×10^3 spikelets m^{-2} (Figure 6A), 2.6–3.1 (Figure 6C), and 0.4~0.7 (Figure 6E). Compared with CF, the total spikelets of wheat in the treatments of FP, FP + RS, FP + WS, FP + WRS increased by 5.3%, 10.0%, 17.8%, 4.5%, respectively (Figure 5A); RFP and RFP + O showed a decreasing trend. In addition, optimized treatments had no difference in LAI and spikelet-leaf ratio compared with CF. However, FP + WS had the highest spikelet-leaf ratio among optimized treatments, and FP was the lowest.

In the wheat season, CV of LAI was 34.8%~45.2% (Figure 6B), which was higher than that of the spikelet-leaf ratio (24.1%~32.7%) (Figure 6D) and total spikelets (14.4%~23.6%) (Figure 6F). FP with/without straw incorporation (FP, FP + RS, FP + WS, FP + WRS) reduced the CV of total spikelets, while RFP and RFP + O increased by 7.8% and 5.4%, respectively. There was no obvious trend on the effects of optimized treatments on the CV of LAI and spikelet-leaf ratio.

3.4. Dry Matter Accumulation

3.4.1. Annual

Optimized nutrient management significantly affected the annual dry matter accumulation (Figure 7A). The FP, FP + RS, FP + WS, FP + WRS remarkedly increased the annual dry matter accumulation by 5.3%, 10.0%, 17.8%, 4.5%, respectively, while RFP and RFP + O decreased by 4.3% and 3.9%, respectively, compared with CF. All optimized treatments alleviated the fluctuations of annual dry matter accumulation, with decrease rates of 54.4% (FP), 22.0% (FP + RS), 14.4% (FP + WS), 43.1% (FP + WRS), 26.8% (RFP), and 6.6% (RFP + O).

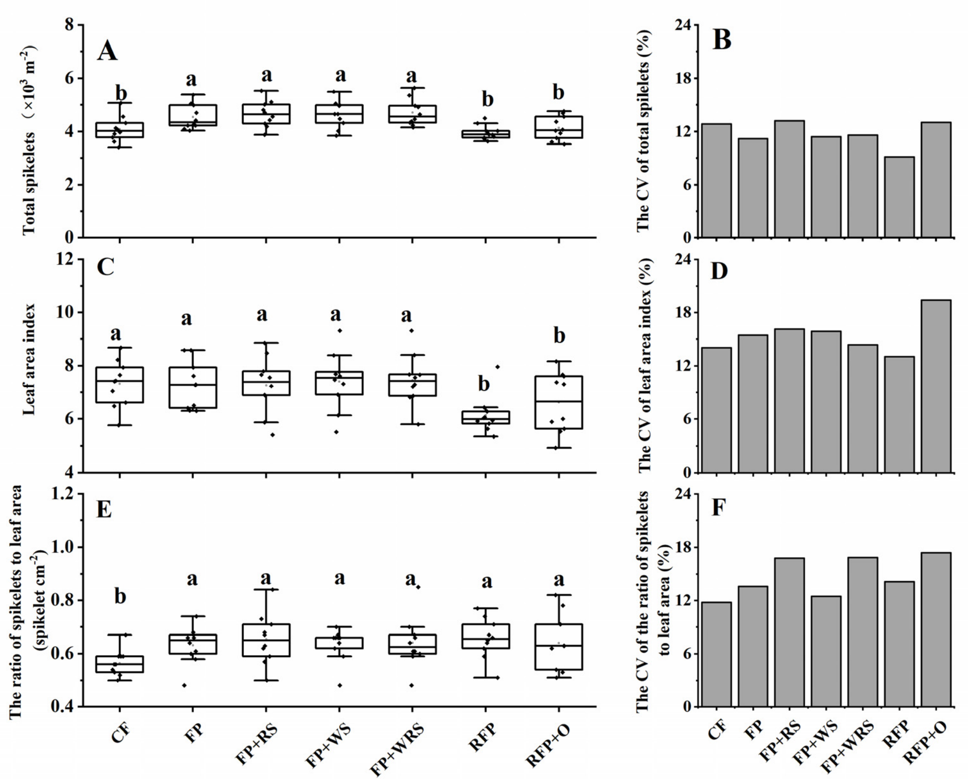

Figure 5. Effect of nutrient management modes on the total number of spikelets, leaf area index, and spikelets to leaf area ratio of rice and those coefficients of variation. Note: (**A**,**B**) total spikelets and their coefficient of variation; (**C**,**D**) leaf area index and its coefficient of variation; (**E**,**F**) the ratio of spikelets to leaf area and its coefficient of variation. Different lowercase letters indicate the difference between treatments at the $p < 0.05$ level.

3.4.2. Rice

The total dry matter accumulation of rice mainly came from the heading-maturity stage (10.9 t hm^{-2}~11.7 t hm^{-2}), and then the jointing-heading stage (5.8 t hm^{-2}~6.5 t hm^{-2}) and jointing stage (5.0 t hm^{-2}~5.4 t hm^{-2}) (Figure 7B). Nutrient management significantly affected the dry matter accumulation at the jointing and heading-maturity stages. RFP + O had the highest dry matter accumulation at the jointing stage, but RFP was the lowest. Compared with CF, FP with/without straw incorporation increased dry matter accumulation at the heading-maturity stage, of which FP + WRS was the highest; in contrast, RFP and RFP + O showed a decreased trend. The effect of nutrient management on total dry matter accumulation was similar to that of the heading-maturity stage.

The CV of dry matter accumulation at different growth stages from large to small were as follows: jointing-heading stage (21.6%~30.0%) > heading-maturity stage (20.1%~27.9%) > jointing stage (13.9%~16.7%) (Figure 7B). All optimized treatments had a higher CV of dry matter accumulation at the jointing-heading stage than CF, while an opposed trend at the heading-maturity and maturity stages was observed.

3.4.3. Wheat

As shown in Figure 7C, dry matter accumulation of wheat at the jointing-heading stage was 5.6 t hm^{-2}~6.4 t hm^{-2}, which was higher than that of the joining stage (2.1 t hm^{-2}~2.7 t hm^{-2}) and heading-maturity stage (2.7 t hm^{-2}~3.7 t hm^{-2}). Nutrient management only significantly affected dry matter accumulation at the heading maturity and maturity stages. Compared with CF, FP with/without straw incorporation (FP, FP + RS, FP + WS, FP + WRS) increased dry matter accumulation at heading-maturity by 2.2%~36.0%; RFP and RFP + O decreased by 14.4% and 5.9%, respectively. Total dry matter accumulation showed as follows: FP + RS > FP + WS > FP >FP + WRS > CF > RFP + O > RFP.

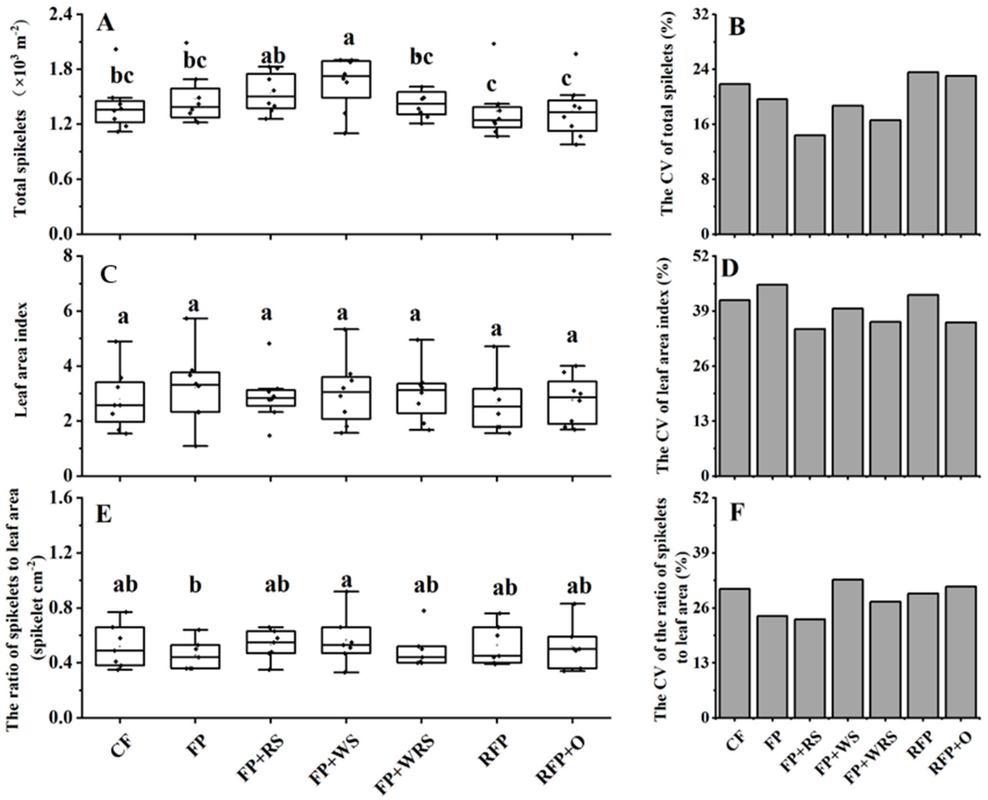

Figure 6. Effect of nutrient management modes on the total number of spikelets, leaf area index, and spikelets to leaf area ratio of wheat and those coefficients of variation. Note: (**A**,**B**) total spikelets and their coefficient of variation; (**C**,**D**) leaf area index and its coefficient of variation; (**E**,**F**) the ratio of spikelets to leaf area and its coefficient of variation. Different lowercase letters indicate the difference between treatments at the $p < 0.05$ level.

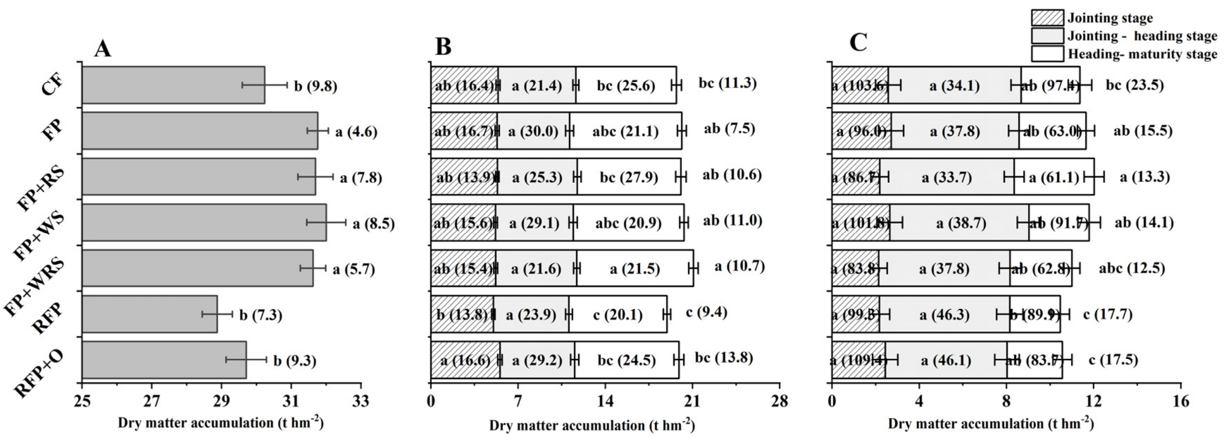

Figure 7. Effect of nutrient management modes on the dry matter accumulation of annual (**A**), rice (**B**), wheat (**C**), and those coefficients of variation**.** Note: Different lowercase letters indicate differences between treatments at the same growth stage. The coefficient of variation of dry matter was shown in brackets. Different lowercase letters indicate the difference between treatments at the $p < 0.05$ level.

In terms of stability of dry matter accumulation, the seeding-jointing period (83.8%~109.9%) > heading-maturity period (61.1%~97.4%) > jointing-heading period (33.7%~46.3%) was shown (Figure 7C). All optimized treatments decreased the CV of dry matter accumulation at the jointing stage (except for RFP + O) and heading-maturation stage. Among them, FP+WRS had the lowest decline.

3.5. The Relationship between Material Accumulation and Meteorological Factors

We selected meteorological factors that were significantly correlated with dry matter accumulation (Figure S1) and performed stepwise regression analysis and collinearity test (Table 3). As shown in Table 3, dry matter accumulation of rice at transplanting-jointing stage and jointing stage-heading stage and heading-maturation stage had a significant one-dimensional linear relationship with PARA (partial regression coefficient was 0.49 **, R^2 = 0.22 **), PAR (partial regression coefficient was 0.52 **, R^2 = 0.26 **) and DA (partial regression coefficient was −0.60 **, R^2 = 0.34 **), respectively. Dry matter accumulation at the seeding-jointing stage at the wheat season had a positive multivariate linear relationship with PARA, RD, and TD (R^2 = 0.77 **) in this period. At the jointing-heading stage, there was a one-dimensional linear between dry matter accumulation and TMin (R^2 = 0.40*). Dry matter accumulation at the heading-maturation stage showed a negative binary linear relation with TMin and RD (R^2 = 0.34 **).

Table 3. Stepwise regression analysis between dry matter accumulation and meteorological parameters in the different growth stages of rice and wheat. (*: $p < 0.05$; **: $p < 0.01$)

Rice			Wheat		
Meteorological Parameters	**Partial Regression Coefficient**	R^2	**Meteorological Parameters**	**Partial Regression Coefficient**	R^2
TS-JS			SS-JS		
PARA	0.49 **	0.22 **	PARA	0.45 **	
			RD	0.49 **	0.77 **
			TD	0.56 **	
JS-HS			JS-HS		
PAR	0.52 **	0.260 **	TMin	−0.65 **	0.40 *
HS-MS			HS-MS		
RD	−0.60 **	0.344 **	TMin	−0.65 **	0.55 *
			RD	−0.23 **	

4. Discussion

4.1. Optimized Nutrient Strategy and High Annual Yield in Rice–Wheat System

With population growth and urbanization development, producing the highest crop yield on limited arable land is essential for meeting future food demand [4,30]. In this study, a 10-year term experiment showed that FP with/without straw incorporation and RPF + O contributed to increasing annual yield, in agreement with previous studies [6,11,12]. It suggests that scientific and reasonable nutrient optimization can stimulate crop production potential, shrinking the yield gap [4,30].

On the one hand, reducing the nitrogen fertilizer rate in the early growth stage was beneficial to control ineffective tillers, forming a healthy population with good ventilation due to the low nutrient absorption of rice and wheat in this period [7,11,12]. Providing sufficient nutrients during the middle and later growth stage could promote the differentiation of spikelets, reduce the amount of degradation, form a greater number of spikelets and the higher spikelets-leaf ratio [6,11,17,18]; simultaneously, high-efficiency leaves could maintain strong photosynthetic potential and long photosynthetic duration after heading, providing sufficient carbohydrates for yield formation [11,12,18,19,31]. On the other hand, organic amendment application (straw and organic fertilizer) could remarkably improve soil quality and strong ability for immobilization fertilizer-nutrient of fore-crop and current season [13,15,32,33]. More root exudates during the high nutrient demand of stage were released, stimulated the growth of soil microorganisms and the activity of soil enzymes to mineralization and release of nutrient (including the soil itself, organic amendment, and immobilization fertilizer-nutrient) in soil [34], enhancing nutrient content of leaf and panicle, and strengthening photosynthesis and promoting the differentiation of spikelets [19]. However, the high number of spikelets negatively affected grain filling [6] due to intensified competition for nutrients, carbohydrates, space, and other resources among spikelets. Therefore, in our research, highlighting the decisive role of expanding sink capacity in high production strategy suggested that further study needed to focus on grain filling and promote assimilation accumulation and transport (source) after heading based on ensuring high spikelets (sink) for achieving high annual yield.

However, it was worth noting that the increased yield effect of wheat in PF was not significant. It was due to the fact that LAI at the wheat heading stage in this study (2.6~3.1) was lower than optimal LAI (4.7~6.3) [35], implying that insufficient populations at the heading stage could not highlight the advantage of PF with high photosynthetic productivity after heading. Under the condition of PF, the wheat yield of straw incorporation was lower than without straw incorporation, indicating that straw incorporation had a negative effect on wheat yield formation due to a low germination rate [32]. Therefore, ensuring the emergence of wheat and increasing the effective photosynthetic population played a key role in wheat production in the rice–wheat system.

Moreover, in our experiment, reducing the 25% nitrogen fertilizer rate (225 kg N hm^{-2}) can maintain rice yield due to high soil productivity (no fertilizer application with about 6 t hm^{-2} during 10 years in our study) [5], in agreement with this region studies [2,36]. However, RFP reduced wheat yield, which might be because N fertilizer application (180 kg N hm^{-2}) in this study lower than the optimum fertilizer rate (210–225 kg N hm^{-2}) in this region [2,36]. Therefore, for winter wheat in this region, under suitable N fertilizer rate, further reduction of fertilizer rate combined with fertilizer postponing was limited room.

The yields of wheat and rice with organic fertilizers replacing chemical fertilizers were lower than that of FP, which was inconsistent with previous research [37,38]. Fu et al. (2020) observed that organic fertilizer application under reducing chemical fertilizer by 20–30% could not cause rice yield loss [37]. A meta-analysis showed that the replacement of a low proportion of chemical (<40%) fertilizers with organic fertilizers could significantly improve dryland crop yields in China [14]. Different results might be attributed to soil type, climatic conditions, and organic fertilizer type [14,38].

4.2. Optimized Nutrient Strategy and Stability of Annual Yield in Rice–Wheat System

The variability of future weather and the frequency of extreme weather events will intensify under climate change, directly or indirectly harming agricultural production [7,8]. SYI is important for evaluating crop yield stability [23,39]. In this study, the SYI of wheat was lower than that of rice, suggesting that wheat production was more vulnerable to year-to-year weather changes. Therefore, formulated reasonable nutrient management based on breeding highly resistant varieties for mitigating the negative effects of climate change.

Differences in biomass accumulation directly reflect yield formation [11,12,18,19,40]. In our study, at rice season, the year-to-year fluctuations of dry matter accumulation at the jointing-heading stage and after heading were higher than before jointing. It is well known that the jointing-heading stage is a critical period for rice spikelet differentiation and switch on grain filling; photosynthetic production after heading contributes more than 60% to rice grain yield [6,11,12]. Stepwise regression analysis found that dry matter accumulation during the jointing-heading stage was significantly positively correlated with PAR, while RD was mainly affected after heading. Therefore, paying more attention to the weather after jointing in rice planting is necessary for mitigating the loss of carbohydrates in yield formation.

Unlike rice, the CV of wheat spike number was higher than that of spikelets per spike and grain weight; the volatility of dry matter accumulation before jointing was higher than the jointing-heading and heading-maturity stage. It implied that the source of wheat yield fluctuation more came from before jointing, attributable to the climatic characteristics of growth region and water management in wheat [21,22,26]. On the one hand, due to the high frequency of precipitation and the high groundwater level in the lower reaches of the Yangtze River, water management in wheat production was mainly based on drainage and waterlogging reduction [41]. On the other hand, because this region belongs to the subtropical monsoon climate zone, different from the relatively concentrated precipitation at rice season, the rainfall at wheat season was more random. Yan et al. (2020) combined rainfall analysis and literature statistical research and found that the wheat seedling period (December) was the peak runoff period for wheat fields in the region of this study [42]. This suggested that the wheat tillering period was more prone to waterlogging and affected the emergence of wheat. Unlike rice which depended on tillering, wheat production more relied on high seeding rates in the rice–wheat system [11,23,43]. Thus, the uncertainty of weather conditions before jointing weakened wheat yield stability.

Moreover, in the rice–wheat system, to ensure the safe maturity of rice, late sowing of wheat was often occurred, which further reduced the ability of wheat seeding to defend against extreme weather [27,44]. In our study, TD, RD and PARA were the main meteorological factors affecting assimilation accumulation before jointing, which was different from the previous study that low temperature and freezing stress was the main reason for reducing wheat yield [40]. The different reasons might be that extreme weather low temperature rarely occurred in wheat season in our experimental area. Bao et al. (2012) divided the area of this study (Danyang City, Jiangsu Province) into low-risk areas in the regional division of winter wheat frost damage in Jiangsu Province [44]. Therefore, formulating agricultural measures with prevention and mitigation of disaster is important to improve the adaptability of crops to climate change.

In our study, SYI of rice in the treatment of FP, FP + RS, FP + WS, FP + WRS, and RFR was higher than that of CF, with an increased rate of 2.3%~11.6%, of which FP + WRS was best due to the increased stability of rice spikelets and dry matter accumulation after heading. Pan et al. (2014) showed that more stem and sheath carbohydrates could be provided for grains filling under rice’s lower photosynthetic capacity condition to reduce the yield loss caused by abiotic stress and stabilize yield [40]. This indicated that the stability of photosynthetic product synthesis during the jointing-heading stage and after heading had a synergistic effect of jointly coping with unfavorable weather. It was worth noting that optimized nutrient management with high stability of rice yield increased the fluctuations of seeding rate and grain weight due to increased competition for carbohydrates by spikelets under unfavorable weather conditions. In addition, this study found that the stability of rice yield in RFP + O was declined, in disagreement with previous studies that organic fertilizer combined with chemical fertilizer was beneficial to stable yield [28,39]. It may be different in duration time, planting areas, and soil type [14].

Our study showed that optimized treatments (except for RFP + O) could stabilize dry matter accumulation fluctuations before jointing and after heading, attributed to the optimal rate and time of fertilizer application. Reducing the fertilizer rate before jointing could decline weak productive tiller formation, enhancing adaptability to extreme weather [27,36,43]. Increasing jointing fertilizer rate could improve productive tiller rate and provide more nutrients for the differentiation of spikelets and the synthesis of carbohydrates after heading, stabilizing yield. Specifically, returned wheat straw nutrient was slow-released at rice season, which was provided for the growth of succeeding wheat seedlings [33,45].

In China, labor costs account for 42.3% and 37.0% of rice and wheat production costs [46], respectively, especially conventional split fertilizer application. One-time controlled-release nitrogen fertilizer had lower labor/time costs and fertilizer rate and increased yield and fertilizer use efficiency [47]. The FP treatment with the high and stable yield of rice and wheat in this study could provide the reference for the development of slow-release fertilizers suitable for the nutrient demand law of rice and wheat.

In China, straw yield reaches 718 million tons, of which rice and wheat straw accounts for 57.6% [10,48]. In rice–wheat rotation, straw burning is a method popular with farmers due to the short time for rice harvesting and wheat sowing [6], which was not conducive to realizing carbon peaks and carbon neutrality. The direct straw incorporation can expand soil carbon capacity and increase and stabilize the annual yield [13,15], but rice straw returned to the wheat field needs to be combined with machines to improve the quality of straw incorporation. Because global warming often increases the frequency and intensity of rainfall, PAR is projected to decline [7]. The solar radiation over China decreased by 1.5–8.7% between 1981 and 2009 in the middle and lower Yangtze River Region [49]. Our study and Franziska et al. (2019) [9] showed that light was a main meteorological factor affecting the year-to-year fluctuations of photosynthate accumulation at the key growth stage of rice and wheat, suggesting that it was necessary to breed shade-tolerant varieties and cultivation measures with strong crop adaptability to low light.

5. Conclusions

Our findings demonstrated differences in annual yield in the rice–wheat system among the different optimized nutrient management. FP with/without straw incorporation was conducted to achieve high annual yields, of which FP + WS was the greatest; in contrast, RFP had a negative effect on wheat productivity, alleviated by combination with organic fertilizer. Furthermore, the year-to-year fluctuation of annual yield in the rice–wheat system mainly came from wheat. The main sources of rice and wheat yield fluctuation were before jointing and after jointing, respectively. Optimization of nutrient management by increasing and stabilizing the number of rice and wheat spikelets and the accumulation of post-heading substances to stabilize annual yield, FP + WRS was the best. Stepwise regression analysis found that the biomass accumulation of rice during the jointing-heading and heading-maturity stage was significantly correlated with PAR and RD, respectively; at the wheat season, TD, RD, and PARA were mainly factored driving fluctuation of biomass accumulation before jointing.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12030698/s1, Figure S1: Correlation analysis between dry matter accumulation and meteorological parameters in the different growth stages of rice and wheat.

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