agronomy

Article

Matter Production Characteristics and Nitrogen Use Efficiency under Different Nitrogen Application Patterns in Chinese Double-Cropping Rice Systems

Wentao Zhou, Wenfei Long, Hongrui Wang, Pan Long, Ying Xu and Zhiqiang Fu *

Key Laboratory of Crop Physiology and Molecular Biology Ministry of Education of the People's Republic of China, College of Agronomy, Hunan Agricultural University, Changsha 410128, China; wentaozhou@stu.hunau.edu.cn (W.Z.); longwenfly@126.com (W.L.); whongrui94@stu.hunau.edu.cn (H.W.); longpan_lp@126.com (P.L.); yingxu@hunau.edu.cn (Y.X.)
* Correspondence: zqf_cis@126.com

Abstract: Panicle-stage nitrogen fertilizer is popular in parts of China due to its higher nitrogen recovery efficiency compared to basal and tiller nitrogen. However, the effect of conversion from basal to panicle-stage nitrogen on matter production, grain yield, and nitrogen use efficiencies (NUE) in Chinese double-cropping rice systems remains largely unknown. Here, we elucidate the effect by using two types of one-time basal nitrogen patterns (A and B), three panicle-N allocation patterns (C, D, and E), and the local conventional patterns (CK). The two-year experiment demonstrates that E (basal/tiller/spikelet-promoting /spikelet-developing nitrogen = 0:4:3:3) produced the greatest annual grain yield, nitrogen agronomic efficiency, and nitrogen partial productivity. The annual dry matter weight and nitrogen increment of panicle, nitrogen transportation of stems contributes the most to annual yield and NUE. Furthermore, the yield increase could be attributed to the higher effective panicles, plant dry matter weight at tillering, and net photosynthesis rate at heading. Moreover, years and varieties affect the yield in different N treatments. The improvement in the net photosynthesis rate at the milk stage also significantly increases nitrogen recovery efficiency. These findings suggest that it is worth paying attention to the rational ratio of tillering to panicle fertilizer without applying a base fertilizer, to synchronously increase the grain yield, NUE in Chinese double-cropping rice systems.

Keywords: rice (*Oryza sativa* L.); nitrogen; dry matter; photosynthetic; leaf area index

Citation: Zhou, W.; Long, W.; Wang, H.; Long, P.; Xu, Y.; Fu, Z. Matter Production Characteristics and Nitrogen Use Efficiency under Different Nitrogen Application Patterns in Chinese Double-Cropping Rice Systems. *Agronomy* **2022**, *12*, 1165. https://doi.org/10.3390/agronomy12051165

Academic Editor: Zina Flagella

Received: 19 April 2022
Accepted: 9 May 2022
Published: 11 May 2022

1. Introduction

As one of the three main grain crops, rice accounts for 25% of the total planting area in China, and 37% of its national grain output [1,2]. The double-cropping rice system includes two seasons of early rice and late rice, and the late rice is planted immediately after the early rice is harvested. It takes full advantage of light, heat, water, and other climatic resources in the growing area. The cultivation of double-cropping rice has provided an important contribution to increasing grain production and ensuring food security. With the promotion and popularization of modern high-yield rice cultivars, nitrogen fertilizer has become the main factor affecting rice yield [3]. The rational application of nitrogen fertilizer can promote the growth of rice; thus, improving the yield and promoting the absorption and utilization of nitrogen [4]. However, the improper timing of fertilization decreases grain yield and nitrogen uptake, and it also wastes resources and causes environmental pollution [5–7]. Current research shows that there are many methods for improving nitrogen management, such as determining the optimal application position of the nitrogen fertilizer, the deep application of nitrogen, precise quantitative cultivation technology, a complete set of soil crop system management, etc., although these depend on what technology is accepted by farmers [8–11]. With the renewal of rice cultivars and the improvement in basic production conditions, it is a relatively simple and efficient method to reasonably regulate the nitrogen application time based on traditional nitrogen application rates to match the peak rice nitrogen demand with the nitrogen application time. It is also important to consider the crop yield, increased economic benefits, improved nitrogen utilization efficiency, and control of agricultural non-point source pollution [12].

Panicle-stage nitrogen fertilizer has a higher nitrogen recovery efficiency than basal and tiller fertilizer, with the technique of topdressing to panicle nitrogen being popular in parts of China [13–15]. The optimization of nitrogen fertilizer management usually begins with the optimization of the nitrogen fertilizer distribution ratio. Some studies have shown that the contribution of base fertilizer, tiller fertilizer, and panicle fertilizer to nitrogen absorbed and that accumulated by rice in its lifetime is approximately 6.9%, 7.5%, and 26.02%, and the rest comes from soil nitrogen [5]. Panicle-N has a higher nitrogen recovery efficiency. Although a large amount of fertilization at the booting stage has adverse effects on food quality, it is considered an effective measure for increasing yield [16]. Many studies have confirmed that late and repeated nitrogen fertilization can improve rice yield and nitrogen use efficiency [17–21]. However, there is still a lack of research on the matter production characteristics of increasing yield and use efficiency under an increasing panicle-N ratio in double-cropping rice systems.

Photosynthesis is the basis of rice yield formation and the key to dry matter accumulation and transport. The higher the nitrogen absorption and utilization efficiency, the stronger the rice photosynthesis; thus, photosynthetic product distribution and utilization are favored [22,23]. To obtain a high yield, the biomass of rice should not be too large in the early stage, which should provide space for vigorous growth from the jointing to the heading stage. Studies have shown that under the condition of constant total nitrogen application rates, increasing the proportion of nitrogen fertilizer in the middle and late periods can improve the net assimilation rate and photosynthetic efficiency, and promote an increase in filled grain percentage and 1000-grain weight [24,25]. The nitrogen recovery rate of base fertilizer is low, and multi-split applications of nitrogen fertilizer could improve the nitrogen use efficiency of crops [26]. Applying more nitrogen fertilizer at the panicle initiation stage can promote the accumulation of biomass after the heading stage; thus, increasing crop yield [11]. Photosynthesis is the key to high yields in rice. The increase in photosynthetic products may be affected by the leaf area index. Reasonable development dynamics of leaf area are the basis for high photosynthesis in rice. The green leaf area of rice is maintained for a long time, the degradation rate of leaf area after the flowering stage is slow, and the photosynthetic potential is high, which is conducive to rice photosynthesis [27]. At the same time, nitrogen absorption by plants is mainly transmitted upward through roots, which affects the nitrogen absorption and utilization efficiency by maintaining root morphology and physiological activity; thus, affecting the chlorophyll content and net photosynthetic rate of rice leaves [28–30]. On the one hand, in the middle and early stages of rice growth, this increases the proportion of effective leaf area and efficient leaf area, and can achieve an appropriate leaf area index value for the population in a more timely manner. On the other hand, in the middle and late growth stages of rice, this could promote the material distribution of a single stem to tilt to the stem sheath, form a strong stem and large panicle, improve the permeability of the population and the grain leaf ratio, slow down the decline rate of leaf area from heading to maturity, improve the photosynthetic production capacity of rice in the later growth stage, and promote the filling of rice grains, improve the harvest index, and obtain seedlings, plants, panicles, a high yield, and a healthy population with reasonable grain development.

Most prior studies focused on optimizing nitrogen management to increase yield and NUE under single-season rice [15,16]. Studies on different nitrogen application patterns in Chinese double-cropping rice systems are limited, particularly concerning the effects of topdressing panicle-N ratio on matter production, grain yield, and NUE. The purposes are to (1) evaluate the effects of different nitrogen application patterns on the yield and NUE compared to the traditional nitrogen application model, and (2) to determine the matter production characteristics of these nitrogen application patterns in double-cropping rice systems in China.

2. Materials and Methods

2.1. Experimental Conditions

The field experiment was conducted at an experimental farm of Hunan Agricultural University, Yanxi Town (28°30′ N, 113°83′ E, elevation of 100 m), Liuyang City, Hunan Province, China, from March 2015 to October 2016. The area has a humid, subtropical monsoon climate with fertile land and four seasons. The average temperature was approximately 22.69 °C and the total precipitation was approximately 1840.3 mm from March to October in 2015; the average temperature was approximately 23.28 °C and the total precipitation was approximately 1573.5 mm from March to October in 2016; these data represent a typical double-cropping rice production area in China (Table 1). The soil type twos loam, and the chemical properties are listed in Table 2. Each treatment of the two-year trial was performed in the same location.

Table 1. The average air temperature and total precipitation from March to October.

Month	Average Air Temperature (°C)		Total Precipitation (mm)	
	2015	2016	2015	2016
March	13.10	13.33	289.40	115.30
April	17.95	19.77	116.70	233.70
May	23.30	21.64	147.20	282.00
June	26.95	27.15	713.10	237.10
July	26.75	29.27	287.00	492.30
August	27.65	29.10	155.10	29.70
September	25.35	25.04	108.10	162.60
October	20.45	20.95	23.70	20.80

Table 2. The chemical properties of soil on the site.

Years	Organic Matter ($g\cdot kg^{-1}$)	Effective N ($mg\cdot kg^{-1}$)	Effective P ($mg\cdot kg^{-1}$)	Effective K ($mg\cdot kg^{-1}$)	Total N ($g\cdot kg^{-1}$)	Total P ($mg\cdot kg^{-1}$)	Total K ($g\cdot kg^{-1}$)
2015	35.29	142.49	53.77	98.02	2.57	534	6.11
2016	34.81	138.27	53.95	98.06	1.87	538	5.93
Means	35.05	140.38	53.86	98.04	2.22	536	6.02

2.2. Experimental Design

The experiment was laid out in a completely randomized block design. Each experiment was performed in three replicates with a plot area of 50 m^2 (10 m × 5 m). Nitrogen fertilizer was applied at 120 $kg\cdot ha^{-1}$ for the early season and 150 $kg\cdot ha^{-1}$ for the late season. Treatments consisted of six N managements. Panicle fertilizer usually consisted of spikelet-promoting fertilizer and spikelet-developing fertilizer. These specific nitrogen fertilizer application patterns are shown in Table 3. No nitrogen fertilizer (F) was added in the 2016 trial, and the other treatments were the same in the two-year trial. No nitrogen fertilizer was added in this experiment. The purpose was to calculate the nitrogen use efficiency of other nitrogen treatments.

P and K fertilizers were the same under the above treatments. Early- and late-season N/P (P_2O_5)/K(K_2O) fertilizer was in a ratio of 1:0.5:1, and P fertilizer and K fertilizer were applied as tiller fertilizer in a one-time application, to ensure that the total fertilizer application to each plot was consistent. N, P, and K fertilizers were urea (N 46%), superphosphate (P_2O_5 12%), and potassium chloride (K_2O 60%), respectively. The compound fertilizer was a long brand ($N/P_2O_5/K_2O$ = 5:3:2), and the slow-release nitrogen fertilizer was resin-coated slow-release fertilizer (100% coated), which was provided by the Institute of

Agroecology and Environment of Hunan Academy of Agricultural Sciences. Basal fertilizer was applied at 2 d before transplanting; tiller fertilizer, spikelet-promoting fertilizer, and spikelet-developing fertilizer were applied at 5 d, 25 d, and 40 days after transplanting, respectively. At 35 d after transplanting, the field was left to dry in the sun for 5 days.

Table 3. Different nitrogen application patterns on the site.

Season	Treatment	Proportion	N Application Rate (kg·ha^{-1})				
			Total	Basal N	Tiller N	Spikelet-Promoting N	Spikelet-Developing N
Early rice	A	10:0:0:0	120	120	0	0	0
	B	10:0:0:0	120	120	0	0	0
	C	0:6:3:1	120	0	72	36	12
	D	0:5:3:2	120	0	60	36	24
	E	0:4:3:3	120	0	48	36	36
	CK	5:2:3:0	120	60	24	36	0
Late rice	A	10:0:0:0	150	150	0	0	0
	B	10:0:0:0	150	150	0	0	0
	C	0:6:3:1	150	0	90	45	15
	D	0:5:3:2	150	0	75	45	30
	E	0:4:3:3	150	0	60	45	45
	CK	5:2:3:0	150	75	30	45	0

A: a single basal application of compound fertilizer; B: a single basal application of slow-release fertilizer; other treatments used urea as N fertilizer.

2.3. Field Management

The field experiment involved a type of cropping system: double-season rice (DR) system comprising early-season rice (ER) and late-season rice (LR). The early-season variety was Luliangyou 996 (LLY996) from Hunan Golden Nonghua Seed Technology Limited Company, and the late-season variety was Yuzhenxiang (YZX) from Hunan Golden Nongfeng Seed Industry Limited Company in 2015. In 2016, an early-season variety Zhongzao39 (ZZ39) from Hunan Golden Nongfeng Seed Industry Limited Company, and a late-season variety Fengyuanyou 299 (FYY299) from Hunan Provincial Hybrid Rice Research Center were added to the experiment. The plot area of two cultivars was 50 m^2. Late-season rice variety YZX was continued to the plot of early-season variety LLY996, and FYY299 was continued to the plot of ZZ39. Due to the increase in varieties, two parallel cropping systems were established in the experiment, including (1) DR1, LLY996 + YZX; (2) DR2, ZZ39 + FYY299. It was equivalent to a preliminary experiment in 2015. The aim was to explore whether there were significant differences in yield under different nitrogen application patterns. The experiment explored more objectively, systematically, and deeply the analysis of yield and nitrogen use efficiency of double-cropping rice in China under different nitrogen application patterns in 2016.

All treatments used the same water management and planting density. After grouting, water was stored to keep about one inch, with the irrigation method of a thin water layer (10–20 mm), and a non-water layer used in other periods. Mechanical insertion and receivers were used in all tests; the mechanical insertion density was 25 cm × 14 cm. The ridges of the intercropping field were separated, and the ridges were covered with film to prevent fertilizer and water from irrigating. Drainage and irrigation were carried out separately in each community. The plot design, transplanting method, and planting density of early- and late-season rice were kept the same. The early-season rice was harvested by machine, with no-tillage planting, before planting herbicide and slightly leveling the rice field.

2.4. Methods of Sample Collection and Analysis

2.4.1. The Soil Chemical Properties

Before the early-season rice preparation, and after the early-season rice harvest and the late-season rice harvest, the test field was divided into five areas, and five soil samples were drilled from the top 0–20 cm layer. After the soil samples were dried naturally in the laboratory, the residual litter and roots were picked out and ground through a 0.25 mm sieve for the determination of soil chemical indexes. The soil organic matter was determined by the potassium dichromate method. Total N was determined by the Kjeldahl method. Total P was determined by NaOH melting and molybdenum–antimony resistance colorimetry. Total K was determined by NaOH fusion-flame photometry. Effective N was determined by the alkali-hydrolyzed diffusion method. Effective P was determined by molybdenum–antimony resistance colorimetry. Effective K was determined by the neutral ammonium acetate extraction method [31].

2.4.2. Yield and Yield Components

At the maturity stage of rice, 2 m^2 of plants was threshed in each plot for the measurement of grain yield (marginal line three was not taken), and the water content of rice was measured with a moisture meter (LDS-1G, Shanghai Nongao Instrument Limited Company, China). The corrected water content was 15%, which was then converted into the actual yield. Sixty effective panicles were investigated in each plot at the maturity stage. According to the average sampling method, five plants from each plot were used to investigate the filled grain percentage, spikelets per panicle, and 1000-grain weight.

2.4.3. Dry Matter Accumulation of Rice

According to the average number of tillers (twenty effective tillers were investigated in each plot), samples were taken at the tillering, heading, and maturity stages in each experimental plot, respectively. Three plants were extracted from each plot, and the stems, leaves, and panicles were separated and packed separately. The dry matter weight of each part was determined after oven drying at 80 °C for 48 h until a constant weight was achieved. The dry matter weight of the plant (PDM) and transportation of dry matter (TDM) were calculated using Equations (1) and (2):

$$\text{PDM}\ (\text{t}\cdot\text{ha}^{-1}) = \text{DM}_\text{S} + \text{DM}_\text{L} + \text{DM}_\text{P}, \quad (1)$$

$$\text{TDM}\ (\text{t}\cdot\text{ha}^{-1}) = \text{DM}_\text{OHS} - \text{DMO}_\text{MAS} \quad (2)$$

DM_S, DM_L, and DM_P are the dry matter weight of the stem, the leaf, and the panicle ($t \cdot ha^{-1}$), respectively, and DMO_{HS} and DMO_{MAS} present the dry matter of organs at the heading stage and maturity stage ($t \cdot ha^{-1}$), respectively.

2.4.4. Nitrogen Content

Dried samples of rice were taken at the tillering stage, heading stage, and maturity stage, and the nitrogen content was measured in each part of the plant after crushing the stem, leaf, and panicle. After the sample was digested with H_2SO_4–H_2O_2, the volume was fixed, filtered, and the total nitrogen content was determined with a flow injection analyzer (SAN^{++}, scalar, Netherlands). The nitrogen accumulation (NA), transportation of nitrogen (TN), transportation ratio of nitrogen (TNR), and total nitrogen accumulation of plant (PTNA) were calculated using Equations (3)–(6):

$$\text{NA}\ (\text{kg}\cdot\text{ha}^{-1}) = \text{DM} \times \text{NC}, \quad (3)$$

$$\text{TN}\ (\text{kg}\cdot\text{ha}^{-1}) = \text{NAO}_\text{HS}\text{-NAO}_\text{MA}, \quad (4)$$

$$\text{TNR}\ (\%) = \text{TN}/\text{NAO}_\text{HS} \times 100\%, \quad (5)$$

$$\text{PTNA}\ (\text{kg}\cdot\text{ha}^{-1}) = \text{NA}_\text{S} + \text{NA}_\text{L} + \text{NA}_\text{P}, \quad (6)$$

DM and NC are the dry matter weight (kg·ha^{-1}) and nitrogen content, respectively, and NAO_{HS} and NAO_{MAS} present the nitrogen accumulation of organs at the heading stage and maturity stage (kg·ha^{-1}), respectively. NA_S, NA_L, and NA_P are the dry nitrogen accumulation of the stem, the leaf, and the panicle (kg·ha^{-1}), respectively,

2.4.5. Net Photosynthetic Rate

During the main growth stages of rice (tillering, heading, and milk stages), two representative plants were selected in each plot between 9:00 and 11:30 a.m., and the blade leaf was measured at the heading stage and milk stage. Three representative leaves were selected from each plant and measured once for each leaf. The net photosynthetic rate (Pn) in the middle of the leaves of rice plants was measured with an LI-6400 photosynthesis system (Li-CorInc., Lincoln, NE, USA).

2.4.6. Leaf Area

Samples were extracted at the tillering, heading, and milk stages, according to the average number of tillers. Three plants were extracted from each plot. The leaf area was measured with a leaf area meter (LI-3000C, LI-COR, Lincoln, NE, USA), and the leaf area index (LAI) was calculated using the following formula:

$$\text{LAI} = \text{leaf area}/\text{land area}, \quad (7)$$

2.4.7. Related Formula of Nitrogen Use Efficiency

The nitrogen recovery efficiency (NRE), nitrogen agronomic efficiency (NAE), and nitrogen partial productivity (NPFP) were calculated using Equations (8)–(13) [32]:

$$\text{NRE (\%)} = (\text{PTNA}_{\text{N}} - \text{PTNA}_{\text{NO}})/\text{NAA} \times 100\%, \quad (8)$$

$$\text{NAE (kg·kg}^{-1}) = (\text{Y}_{\text{N}} - \text{Y}_{\text{NO}})/\text{NAA}, \quad (9)$$

$$\text{NPFP (kg·kg}^{-1}) = \text{Y}/\text{NAA}, \quad (10)$$

$$\text{annual NRE (\%)} = (\text{annual PTNA}_{\text{N}} - \text{annual PTNA}_{\text{NO}})/\text{annual NAA} \times 100\%, \quad (11)$$

$$\text{annual NAE (kg·kg}^{-1}) = (\text{annual Y}_{\text{N}} - \text{annual Y}_{\text{NO}})/\text{annual NAA}, \quad (12)$$

$$\text{annual NPFP (kg·kg}^{-1}) = \text{annual Y}/\text{annual NAA}, \quad (13)$$

$PTNA_N$, $PTNA_{NO,}$ and NAA are the nitrogen accumulation with N fertilizer, the nitrogen accumulation without N fertilizer, and nitrogen application amount, respectively, and Y_N, $Y_{NO, and}$ Y present yield with N fertilizer, yield without N fertilizer, and yield, respectively.

2.5. Statistical Analysis

Analysis of variance (ANOVA) was performed using the IBM SPSS statistics 20 software (International Business Machines Corporation, New York, NY, USA). The means were compared by the least significant difference (LSD) test at the 0.05 and 0.01 probability levels. The Pearson method was used for correlation analysis. All figures were constructed using Origin 2021 (Origin Lab Corporation, Northampton, MA, USA).

3. Results

3.1. Effects of Nitrogen Application Patterns on Yield and Matter Production of Double-Cropping Rice

3.1.1. Grain Yield

The annual grain yield of the double-cropping rice system (DR1) under different N treatments in 2015 ranged from 14.01 to 17.25 t·ha^{-1}, which was greater than the annual yield in 2016 (12.69–14.67 t·ha^{-1}) in this test (Figure 1). Planting different varieties in the double-cropping rice system also caused the yield to be different. The DR2 was greater than the DR1 in 2016. Compared to the other treatments, the E treatment increase range was 7.27–13.85% and 4.33–36.3% in the early- and late-season in 2015-DR1, respectively. In 2016-DR1, ER had the highest yield under D treatment (7.14 t·ha^{-1}), and the yield of ER was the highest under E treatment (7.93 t·ha^{-1}); in 2016-DR2, the yield of ER was the highest under E treatment (7.97 t·ha^{-1}) and the yield of LR was the highest under D treatment (7.38 t·ha^{-1}). In both years, the annual yield of E was the greatest, whereas that of B was the lowest.

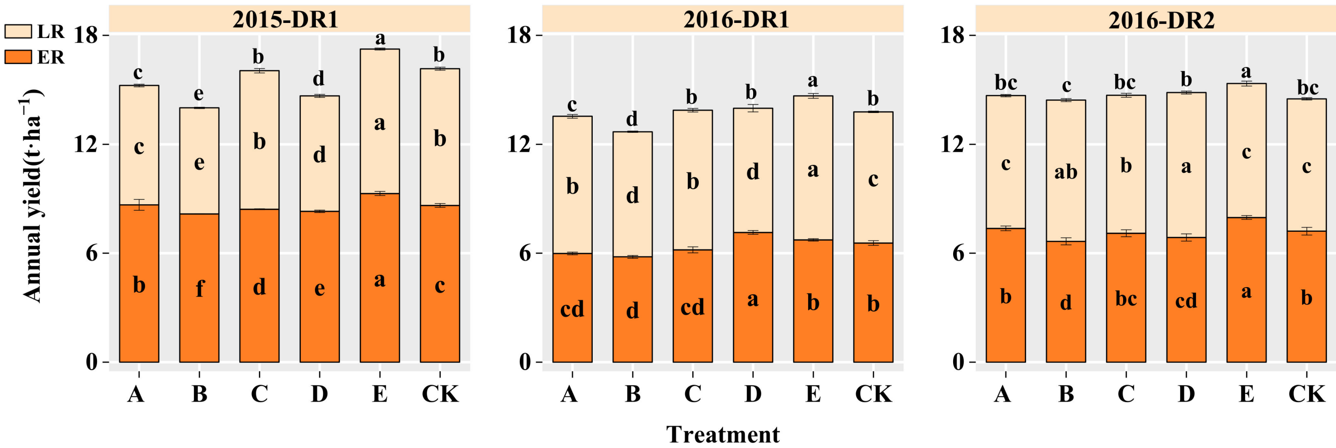

Figure 1. The annual yield in a double-cropping rice system. Annual yield is the sum of early- and late-season rice yields. The data are presented as mean (±standard error). Different lowercase letters indicate significant differences between different treatments in a double-cropping system at $p < 0.05$. ER, early-season rice; LR, late-season rice. 2015, in 2015; 2016, in 2016. DR, double-season rice system; DR1, LLY996 + YZX; DR2, ZZ39 + FYY299.

3.1.2. Yield Components

In the early- and late-season rice of 2015, spikelets per panicle with the E treatment were significantly higher than in CK. There were differences in yield components between the two cultivars in the early- and late-season rice in 2016. Spikelets per panicle under the E treatment of ER1 and LR1 were higher than those of CK, while spikelets per panicle under the D treatment of ER2 and LR2 were higher than those of CK in 2016. No consistent rule was found for other yield component factors (Table 4).

Table 4. Effect of different treatments on yield components in 2015 and 2016.

Year	Season	Treatment	EP	FGP (%)	SNP	KGW (g)
2015	ER1	A	12.81 ab	80.74 a	122.12 bc	28.38 a
		B	11.7 6 c	74.66 b	126.99 b	28.43 a
		C	13.8 ab	71.29 c	117.94 c	27.8 bc
		D	13.41 ab	68.75 d	123.57 bc	27.41 c
		E	14.19 a	63.08 e	146.31 a	27.93 ab
		CK	13.63 ab	75.49 b	118.77 c	28.32 a
	LR1	A	11.71 ab	63.78 c	150.18 a	27.95 a
		B	11.07 b	59.17 d	145.21 a	27.54 b
		C	13.12 a	71.92 b	134.98 b	27.96 a
		D	12.62 ab	76.06 a	135.17 b	27.52 b
		E	12.84 ab	62.51 c	144.21 a	27.93 a
		CK	13.36 a	65.38 c	136.60 b	27.90 a

Table 4. *Cont.*

Year	Season	Treatment	EP	FGP (%)	SNP	KGW (g)
2016	ER1	A	10.56 a	62.51 d	144.21 c	27.93 a
		B	10.08 b	59.17 d	145.21 ab	27.54 b
		C	9.12 d	71.92 b	134.98 c	27.96 a
		D	9.61 c	63.78 cd	150.18 a	27.95 a
		E	9.37 cd	76.06 a	135.17 c	27.52 b
		CK	9.94 b	65.38 c	136.60 c	27.90 a
	LR1	A	16.00 a	68.99 c	109.74 a	29.35 a
		B	14.20 d	65.72 d	110.54 a	29.09 a
		C	15.58 ab	71.64 c	103.27 b	28.18 b
		D	14.54 cd	71.01 bc	102.98 b	27.82 b
		E	14.97 bc	75.54 a	109.08 a	27.25 c
		CK	13.88 d	73.23 ab	105.98 ab	28.05 b
	ER2	A	8.92 ab	81.13 ab	158.15 a	26.66 a
		B	9.21 a	76.74 c	140.70 c	26.32 b
		C	8.41 c	82.50 ab	139.61 c	26.69 a
		D	8.69 bc	79.83 b	153.93 ab	26.64 a
		E	8.77 b	83.69 a	158.32 a	26.3 b
		CK	8.97 ab	75.65 c	152.35 b	26.56 a
	LR2	A	11.33 c	78.12 b	138.96 c	30.04 a
		B	12.06 b	77.26 bc	142.69 b	29.33 c
		C	12.64 a	75.12 de	140.68 bc	28.47 d
		D	12.07 b	74.71 e	148.63 a	29.59 bc
		E	11.81 b	76.43 cd	141.46 bc	29.78 ab
		CK	10.90 c	79.76 a	142.88 b	29.41 c

EP, FGP, SNP, and KGW represent the effective panicle, filled grain percentage, spikelets per panicle, and 1000-grain weight, respectively. ER, early-season rice; LR, late-season rice. ER1, LLY996; LR1, YZX; ER2, ZZ39; LR2, FYY299. Different lowercase letters indicate significant differences between different treatments at $p < 0.05$.

3.1.3. Analysis of Variance in Experimental Factors

Variance analysis showed (Table 5) that the effects of years, varieties, and treatments on yield and its components were extremely significant. The interaction between variety and N treatment had no significant effect on the effective panicle, but all the other components were significantly affected. The interaction between variety and N treatment, and the interaction between variety and N treatment on yield and its components, were extremely significant. The interaction of year, variety, and treatment had a significant effect on yield, filled grain percentage, and spikelets per panicle.

Table 5. Analysis of variance for grain yield, yield components among years, varieties, and N treatments.

Source of Variation	GY	EP	FGP	SNP	KGW
Year (Y)	1279.73 **	1215.38 **	109.76 **	351.33 **	178.64 **
Variety (V)	270.48 **	694.49 **	81.94 **	953.62 **	425.41 **
N treatment (N)	141.22 **	12.09 **	18.72 **	31.57 **	19.64 **
Y × V	1881.56 **	0.48 ns	711.12 **	18.65 **	81.8 **
Y × N	33.87 **	21.09 **	60.62 **	22.09 **	5.9 **
V × N	39.59 **	6.06 **	18.09 **	9.15 **	12.79 **
Y × V × N	35.67 **	1.41 ns	49.44 **	26.83 **	2.33 ns

GY, EP, FGP, SNP, and KGW represent grain yield, the effective panicle, filled grain percentage, spikelets per panicle, and 1000-grain weight, respectively. Values followed by different letters in the same column mean significant at the 5% levels, respectively; ** mean significant at 1% levels, respectively. ns means not significant at the 5% level. The numbers in the table are F value.

3.1.4. Dry Matter Accumulation and Translocation

There were significant differences in the dry matter weight and translocation during the main growth stages under different nitrogen application treatments (Table 6). For the change in dry matter weight of plants, there was a significant upward trend between the different nitrogen application treatments from the tillering stage to the maturity stage. In the tillering stage, the dry matter weight of all cultivars was the highest with a single application of nitrogen fertilizer, except for ER1 in 2015; at the heading and maturity stage of early-season rice, the E treatment was higher than CK; a single application of nitrogen fertilizer was the highest at the heading of late-season rice. For the change in the dry matter weight of the panicle, the panicle accumulation of rice was the highest under the E treatment. There were differences in the transport capacity of the stem among different cultivars. For ER1, this transport capacity was still the highest under the E treatment, while for LR1 and ER2, the highest transport capacity appeared at the A treatment. For LR2, the CK was the highest. Overall, the D and E treatment could result in a higher biomass than other nitrogen application patterns in the early-season rice; however, the A or B treatment could obtain a higher biomass in the late-season rice.

Table 6. Effect of different treatments on grain yield and yield components in 2015 and 2016.

M	Season	Treatment	PDM (t·ha^{-1})			Heading to Maturity		
			Stage			DM Transportation (t·ha^{-1})		DM (t·ha^{-1})
			TS	HS	MAS	Stem	Leaf	Panicle
2015	ER1	A	4.76 bc	11.44 c	16.10 d	0.05 b	0.44 a	10.95 d
		B	4.48 bcd	11.63 bc	16.37 cd	0.56 ab	0.87 a	11.26 d
		C	4.82 b	11.66 bc	18.49 b	0.29 b	0.95 a	12.64 b
		D	4.03 d	10.63 d	17.33 c	0.05 b	0.58 a	11.59 cd
		E	4.34 cd	13.49 a	19.7 a	0.98 a	1.00 a	14.60 a
		CK	5.72 a	12.28 b	18.57 b	0.42 b	0.87 a	12.16 bc
	LR1	A	2.57 a	10.88 b	16.2 b	1.36 a	0.47 b	8.95 ab
		B	2.31 b	12.92 a	17.38 a	0.26 b	1.54 a	8.92 ab
		C	0.87 c	8.96 c	14.65 c	0.28 b	0.27 b	8.32 b
		D	0.78 c	7.66 c	12.55 d	0.49 b	0.39 b	7.33 c
		E	0.99 c	8.92 c	15.88 b	0.60 ab	0.36 b	9.63 a
		CK	1.08 c	7.82 c	12.48 d	0.60 ab	0.31 b	7.12 c
2016	ER1	A	1.69 a	13.06 c	17.82 b	2.35 ab	0.97 a	10.47 b
		B	1.38 bcd	12.14 c	16.79 c	1.36 b	0.77 ab	9.37 d
		C	1.17 d	12.35 c	18.34 b	1.53 ab	0.49 ab	10.51 b
		D	1.51 ab	15.64 a	19.23 a	2.76 a	0.20 b	9.70 cd
		E	1.19 cd	14.77 ab	19.08 a	2.19 ab	0.99 a	10.85 a
		CK	1.47 abc	14.31 b	17.12 c	2.67 a	0.90 a	9.88 c
	LR1	A	1.29 a	14.32 a	19.02 a	2.00 a	0.96 a	10.73 b
		B	1.34 a	11.43 c	16.61 d	1.18 c	0.81 a	9.20 d
		C	1.07 b	12.12 b	18.43 b	1.69 b	0.49 b	10.85 b
		D	1.31 a	10.85 d	15.86 e	0.91 c	0.48 b	8.70 e
		E	1.07 b	11.92 b	18.51 b	2.21 a	0.35 b	11.53 a
		CK	1.31 a	12.08 b	17.34 c	1.61 b	0.40 b	9.81 c
	ER2	A	1.85 a	15.05 a	18.74 b	2.45 ab	1.12 a	11.28 d
		B	1.3 b	13.91 ab	18.09 c	2.70 a	0.87 ab	11.55 cd
		C	1.34 b	13.67 ab	18.57 b	1.91 ab	0.92 ab	11.83 bc
		D	1.15 b	14.01 ab	19.90 a	0.47 c	0.06 c	11.81 bc
		E	1.39 b	12.54 bc	19.85 a	0.47 c	0.83 ab	12.62 a
		CK	1.1 bc	12.4 bc	18.77 b	1.5 bc	0.61 b	11.99 b

Table 6. *Cont.*

M	Season	Treatment	PDM (t·ha^{-1})			Heading to Maturity		
			Stage			DM Transportation (t·ha^{-1})		DM (t·ha^{-1})
			TS	HS	MAS	Stem	Leaf	Panicle
	LR2	A	1.61 b	11.74 b	16.30 c	2.55 c	0.92 ab	10.55 bc
		B	1.82 a	12.19 a	17.38 a	2.31 d	1.00 a	11.07 a
		C	1.48 c	11.21 c	16.14 c	2.78 b	0.75 bc	10.67 b
		D	1.55 bc	11.55 bc	16.75 b	2.94 b	0.72 c	11.36 a
		E	1.30 d	11.12 c	16.00 c	2.55 c	0.44 d	10.66 b
		CK	1.55 bc	12.52 a	15.83 c	3.25 a	0.9 ab	10.3 c

PDM, plant dry matter weight, represents the total dry matter weight of stem, leaf and panicle. DM, dry matter weight; TS, tillering stage; HS, heading stage; MAS, maturity stage. ER, early-season rice; LR, late-season rice. ER1, LLY996; LR1, YZX; ER2, ZZ39; LR2, FYY299. Different lowercase letters indicate significant differences between different treatments at $p < 0.05$.

3.1.5. Net Photosynthetic Rate, Leaf Area Index

Under different nitrogen management modes, the leaf area index (LAI) reached the maximum at the heading stage. At the tillering stage, the basal N application was beneficial to increasing the LAI. At the heading stage and the milk stage, the LAI of different rice seasons was different (Table 7). At the heading stage, the LAI under the A or B treatment was the highest, followed by that under the CK treatment; the leaf area index under the E treatment was relatively small. During the late growth stage, the leaf area index of each treatment began to decline, among which the LAI of A and B treatments decreased rapidly in 2015. In addition, the LAI of rice at the milk stage could be the highest under a single basal fertilizer application in 2015 and 2016, while ER1 was an exception.

Table 7. Effect of different treatments on LAI and Pn in 2015 and 2016.

Year	Season	Treatment	LAI			Pn (μmol·m^{-2}·s^{-1})		
			Stage			Stage		
			TS	HS	MS	TS	HS	MS
2015	ER1	A	5.19 a	7.58 a	3.45 bc	22.21 a	20.54 a	14.78 bc
		B	4.06 b	6.39 b	3.84 ab	21.07 bcd	18.64 b	14.18 c
		C	1.99 d	6.01 b	5.05 a	20.99 cd	20.59 a	15.86 b
		D	1.7 e	4.85 c	4.38 ab	22.11 ab	20.32 a	17.23 a
		E	1.7 e	4.56 c	4.32 ab	20.25 d	19.9 ab	17.67 a
		CK	3.66 c	6.56 b	2.54 c	21.82 abc	18.56 b	17.55 a
	LR1	A	6.16 a	6.88 c	4.5 ab	24.07 a	16.65 bc	13.57 c
		B	5.02 b	9.39 a	4.92 a	20.14 bc	16.09 c	14.87 b
		C	1.95 c	4.66 d	3.91 bc	21.37 b	18.94 a	15.58 ab
		D	1.98 c	4.66 d	3.38 c	20.24 bc	16.97 bc	15.94 a
		E	1.28 d	4.37 d	2.63 d	20.65 bc	17.51 b	16.04 a
		CK	5.95 a	8.29 b	3.66 c	19.02 c	16.86 bc	15.53 ab
2016	ER1	A	1.53 a	4.70 a	4.01 b	22.54 a	16.28 b	18.83 a
		B	1.17 bc	3.84 b	3.65 c	21.46 a	16.58 b	17.8 b
		C	0.98 d	4.39 ab	4.2 ab	21.72 a	18.1 a	19.01 a
		D	1.27 b	4.75 a	4.31 a	22.03 a	16.63 b	19.95 a
		E	1.1 c	3.58 c	3.16 d	21.1 a	16.98 b	20.27 a
		CK	1.21 b	4.64 a	4.35 a	21.98 a	15.22 c	17.58 b

Table 7. *Cont.*

Year	Season	Treatment	LAI			Pn (μmol·m^{-2}·s^{-1})		
			Stage			Stage		
			TS	HS	MS	TS	HS	MS
	LR1	A	1.99 c	7.88 b	6.15 b	30.2 bc	21.08 b	19.14 c
		B	2.08 b	8.14 a	6.44 a	31.25 a	22.57 a	19.38 bc
		C	1.66 d	6.21 b	5.34 c	28.01 d	20.37 c	19.82 abc
		D	1.6 d	5.63 c	5.31 c	30.12 bc	21.93 a	20.21 ab
		E	1.59 d	5.47 c	5.4 c	30.26 abc	22.11 a	20.12 ab
		CK	1.86 a	6.34 b	5.01 d	29.25 c	20.83 bc	20.29 a
	ER2	A	1.28 a	4.15 a	3.48 a	24.86 a	21.54 a	16.72 a
		B	0.99 b	3.4 b	3.26 a	23.24 ab	19.87 ab	15.57 a
		C	0.97 b	4.05 a	3.19 a	22.56 ab	19.04 b	17.03 a
		D	0.91 b	3.92 a	3.01 a	24.09 ab	20.83 ab	17.55 a
		E	0.96 b	3.15 b	2.89 a	21.32 b	21.96 a	16.93 a
		CK	0.78 c	4.07 a	3.33 a	23.29 ab	19.86 ab	14.71 b
	LR2	A	2.73 a	7.35 b	5.76 b	29.80 a	19.73 bc	18.79 bc
		B	2.83 a	7.88 a	6.31 a	28.56 b	18.13 e	17.21 d
		C	2.08 c	7.17 b	5.42 c	28.17 c	18.66 de	18.42 c
		D	1.87 d	6.88 c	4.92 d	28.76 b	19.55 c	19.4 b
		E	1.71 e	6.11 d	5.52 bc	29.64 a	21.15 a	20.5 a
		CK	2.23 b	7.22 b	5.34 c	28.72 d	20.46 ab	19.25 bc

TS, tillering stage; HS, heading stage; MS, milk stage. ER, early-season rice; LR, late-season rice. ER1, LLY996; LR1, YZX; ER2, ZZ39; LR2, FYY299. Different lowercase letters indicate significant differences between different treatments at $p < 0.05$.

At the tillering stage, the photosynthetic rates for a single basal application of nitrogen fertilizer (A or B) were the highest out of all the treatments. There was no significant difference in Pn among all treatments of ER1 at the tillering stage of 2016. The E treatment of all cultivars of 2015 and 2016 at the heading stage was higher than CK. At the milk stage, five treatments without CK were separated into two distinct levels: A and B treatments were comparable, but were significantly lower than those for D and E. At the late stages (the heading and milk stages), averaged over all measurements in all varieties of 2015 and 2016, photosynthetic rates differed significantly between treatments and could be ranked in clear order: (C, D, E) > (A, B); the mean photosynthetic rate attained for C was 18.82 μmol m^{-2} s^{-1}, the highest of the six treatments at the heading stage; E was the highest (18.41 μmol m^{-2} s^{-1}), followed by D (18.26 μmol m^{-2} s^{-1}), while A was the lowest (16.42 μmol m^{-2} s^{-1}) at the milk stage.

3.2. Effects of Nitrogen Application Patterns on Nitrogen Use Efficiency of Double-Cropping Rice in 2016

3.2.1. Nitrogen Use Efficiency

The nitrogen use efficiencies of different nitrogen application patterns are given in Figure 2. The NRE of treatment A was significantly lower than B in all cultivars, whereas the NAE and NPFP of treatment A were significantly higher than B, excluding LR2. In the DR1 system, the annual NRE of E treatment was the highest because the NRE of late-season rice under E treatment was higher than that of other treatments; however, E of the DR2 system was the highest in early-season rice. NAE and NPFP of ER2 and the late-season variety LR1 were the highest under the E treatment and were significantly higher than other treatments ($p < 0.05$). However, the NAE and NPFP of ER1 and LR2 were the highest in the D treatment, which was significantly higher than other treatments. NAE and NPFE under the E treatment were the highest in double-cropping rice annual systems. In conclusion, compared to CK, the NRE, NAE, and NPFP of E treatment were increased by 13–47%, 5–29%, and 1–9% in four cultivars, respectively. The NRE of four varieties of A decreased by 8–9% compared to CK.

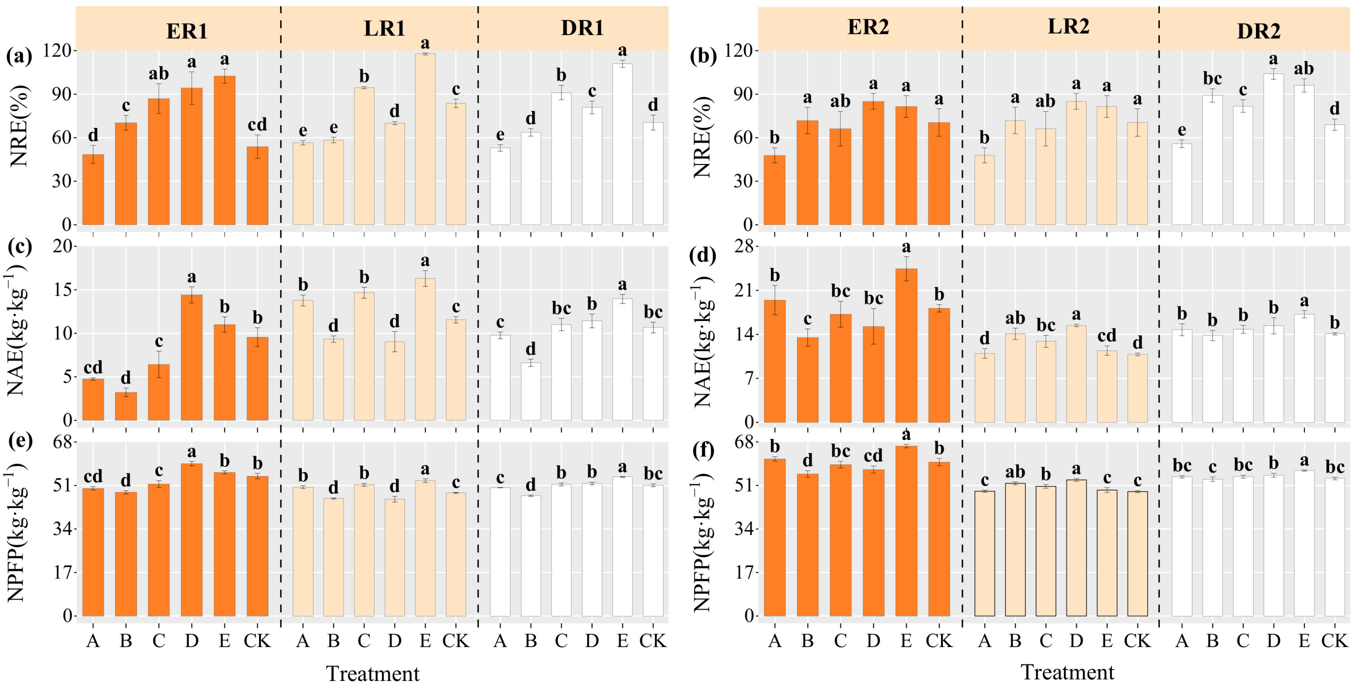

Figure 2. Effect of different nitrogen application patterns on nitrogen use efficiency in 2016. The data are presented as mean (±standard error). Different lowercase letters indicate significant differences between different treatments at $p < 0.05$. ER, early-season rice; LR, late-season rice. ER1, LLY996; LR1, YZX; ER2, ZZ39; LR2, FYY299. DR, double-season rice; DR1, LLY996 + YZX; DR2, ZZ39 + FYY299. (**a**), the NRE in DR1; (**b**), the NRE in DR2; (**c**), the NAE in DR1; (**d**), the NAE in DR2; (**e**), the NPFP in DR1; (**f**), the NPFP in DR2. NRE, nitrogen recovery efficiency; NAE, nitrogen agronomic efficiency; NPFP, nitrogen partial productivity.

3.2.2. Nitrogen Uptake

In the early-season rice of 2016, the nitrogen translocation rate of stems and leaves (ER1-stem and ER1-leaf) in the B treatment was higher than that in C and D (Figure 3a). The nitrogen translocation rate of the stem under E treatment was significantly higher than the CK treatment in the late season. For the leaf nitrogen translocation rate of LR1, B was significantly higher than CK, improving by 26%. The annual nitrogen translocation rate of stems in B was higher than that in C and D. There were no significant differences in annual leaf nitrogen transport rates A, B, and CK, but they were significantly higher than those of C, D, and E (DR1). On the whole, the nitrogen translocation rate in the leaf was higher than that in the stem; the nitrogen translocation rate of a single basal application of nitrogen fertilizer was higher than those which applied panicle-N (Figure 3a,b).

Figure 3c,d shows the translocation nitrogen of the stem and leaf nitrogen increment of panicle in 2016. We observed that the translocation of nitrogen in leaves for B was the highest, ranging from 60.25 to 93.49 kg·ha^{-1} among the four varieties. The E showed the highest translocation nitrogen volume of the stem in late-season rice, but the two varieties of early rice were different. CK was the highest in ER1, and B was the highest in ER2. The annual translocation nitrogen volume of stems was the highest in treatment E, while that of leaves was the highest in treatment B. In 2016, the nitrogen increment of A was significantly lower than CK. In the annual nitrogen increment of the panicle, the E treatment of DR1 was the highest, while the D treatment of DR2 was the highest.

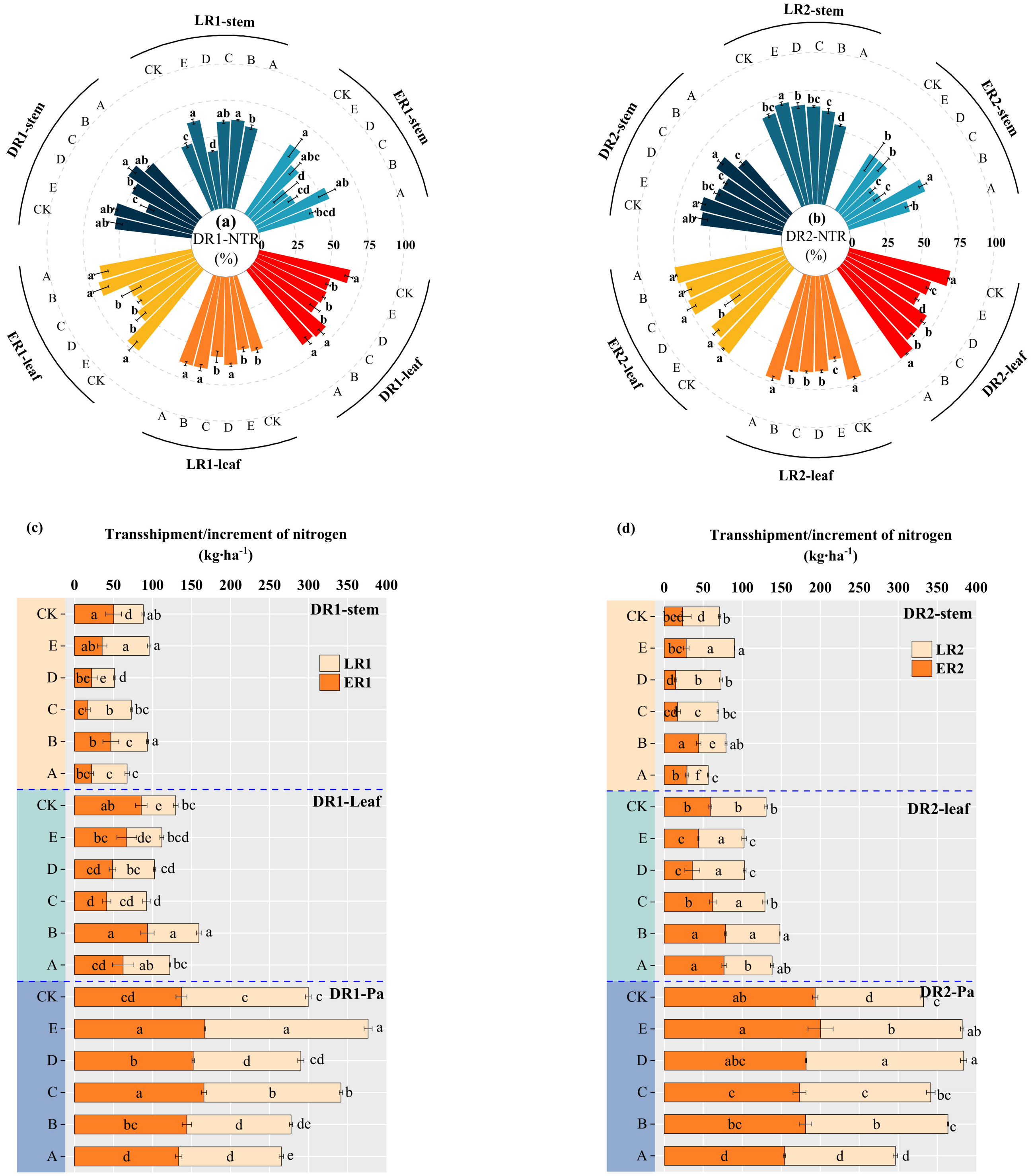

Figure 3. Translocation of nitrogen in rice organs under different nitrogen application patterns in 2016. (**a**), the translocation rate of nitrogen in DR1; (**b**), the translocation rate of nitrogen in DR2; (**c**), the translocation of nitrogen in DR1; (**d**), the translocation of nitrogen in DR2. Translocation of nitrogen in rice stem and leaf, the increment of nitrogen in rice panicle in (**c**,**d**). The data are presented as mean (±standard error). Different lowercase letters indicate significant differences between different treatments at $p < 0.05$. ER, early-season rice; LR, late-season rice. ER1, LLY996; LR1, YZX; ER2, ZZ39; LR2, FYY299. DR, double-season rice; DR1, LLY996 + YZX; DR2, ZZ39 + FYY299; NTR, the translocation rate of nitrogen; Pa, panicle.

3.3. Correlation Analysis

Table 8 showed the correlation analysis between all indexes in the article and grain yield, NUE, respectively. The effective panicle was positively ($p < 0.01$) correlated with grain yield, while being negatively ($p < 0.01$) correlated with the NPFP of rice. Most of the measured parameters, such as the dry matter weight of the panicle at maturity, plant dry matter weight at tillering, net photosynthesis rate at heading, and nitrogen accumulation of panicle, were positively ($p < 0.01$) correlated with rice grain yield. Moreover, the net photosynthesis rate at the milk stage and nitrogen increment of panicle were positively ($p < 0.05$ or $p < 0.01$) correlated with NRE. The filled grain percentage and dry matter weight of the panicle at maturity were positively ($p < 0.01$) correlated with NAE and NPFP. However, the effective panicle, kilogram grain weight, plant dry matter weight at tillering, plant dry matter weight at heading, leaf area index at tillering, leaf area index at heading, leaf area index at the milk stage, nitrogen translocation rate of leaves, and nitrogen transportation of stems were negative ($p < 0.05$ or $p < 0.01$) correlated with NPFP. The correlation between the net photosynthesis rate at heading and NPFP was also positively significant.

Table 8. Correlations between the measured parameters and grain yield and nitrogen use efficiency for grain yield of rice.

Measured Parameters	Grain Yield	Nitrogen Use Efficiency		
		NRE	NAE	NPFP
The effective panicle	0.45 **	0.18	−0.15	−0.67 **
Filled grain percentage	0.31	0.22	0.71 **	0.46 *
Spikelets per panicle	−0.26	−0.05	0.27	0.62 **
Kilogram grain weight	0.16	0.16	−0.38	−0.68 **
Dry matter weight transportation of stems	−0.28	0.11	−0.12	−0.13
Dry matter weight transportation of leaves	−0.12	−0.48 *	−0.02	0.04
Dry matter weight of panicle at maturity	0.49 **	0.23	0.76 **	0.73 **
Plant dry matter weight at tillering	0.58 **	−0.17	−0.05	−0.68 **
Plant dry matter weight at heading	−0.17	−0.31	0.14	−0.61 **
Plant dry matter weight at maturity	0.09	0.20	0.11	−0.16
Leaf area index at tillering	0.13	0.09	−0.18	−0.62 **
Leaf area index at heading	0.14	0.10	−0.17	−0.66 **
Leaf area index at milk stage	0.00	0.15	−0.26	−0.73 **
Net photosynthesis rate at tillering	0.04	0.18	−0.01	0.02
Net photosynthesis rate at heading	0.59 **	0.38	−0.10	0.47 *
Net photosynthesis rate at milk stage	−0.18	0.48 *	−0.22	−0.22
Nitrogen translocation rate of stem	0.22	−0.04	0.25	0.16
Nitrogen translocation rate of leaf	0.23	−0.01	−0.08	−0.44 *
Nitrogen increment of panicle	0.58 **	0.63 **	0.35	0.00
Nitrogen transportation of stem	0.35	0.37	−0.09	−0.41 *
Nitrogen transportation of leaf	−0.30	−0.36	−0.32	−0.15

Data used for calculations are from the above tables and figures. NRE, nitrogen recovery efficiency; NAE, nitrogen agronomic efficiency; NPFP, nitrogen partial productivity. *, significant at the 0.05 probability level; **, significant at the 0.01 probability level, according to the LSD test.

4. Discussion

4.1. Effects of Nitrogen Management on Yield and Nitrogen Use Efficiency

Reasonably adjusting the proportion of basal fertilizer, tillering fertilizer, and panicle fertilizer can achieve the goal of higher yield and nitrogen use efficiency [10,33,34]. Cheng et al. (2021) reported that the grain yield and NUE were significantly improved due to increasing the application of N at the panicle stage [35]. Similar results were found in our experiment, in which the E treatment achieved a higher annual yield than other treatments on double-cropping rice systems (Figure 1). Because the differences in the nutrient demand of different plant growth stages were also reflected in their response to split the application of N, rice was more sensitive to N at the panicle stage, but not at the early-tillering period. It was proposed that the nitrogen fertilizer could be reduced in the early-tillering period to avoid adverse consequences [36]. Urea as a topdressing panicle-N increased rice yields by increasing spikelets per panicle [37]. In addition, Huang et al. (2018) reported that consolidating the number of panicles and pursuing large panicles could improve rice yield [38]. Similarly, this study found that rice yield had a very significant correlation with the number of effective panicles (Table 4). Under different ecological and cultivation conditions, the appropriate application ratio of nitrogen fertilizer to basal, tillering, and panicle fertilizer would have different conclusions in different rice production areas, which is mainly affected by many factors such as climatic conditions, soil fertility, rice cultivars, planting methods, and planting basic seedlings [13,39–42]. In our experiment, the yield and its components of rice were significantly affected by year, variety, N treatment, and the interaction among them (Table 5).

The yield and NUE could be effectively increased by increasing the spikelet-developing N at the panicle period to 30% and decreasing the N in the early-tillering period in this study. Furthermore, the annual NAE and NPPE were the highest under the E treatment (Figure 2). When the nitrogen application rate was 105–300 kg·ha^{-1}, NRE increased correspondingly by reducing basal and tillering fertilizer and increasing panicle fertilizer, which was similar to the results of our study [18,43]. However, there was no consistent conclusion about the effect of the multi-split N application at the panicle stage on NUE. A lower N with more splits had a higher NUE [32]. In contrast with the conclusion of Ye et al. (2022), who believed that when 30% or 40% N was twice applied as the panicle-N (once at the panicle stage and again 5–7 d before flowering), the NUE was not greater than that in the corresponding treatments of panicle-N applied once [15]. In our study, the E treatment consisting of the tiller and twice-split application of panicle nitrogen fertilizer could effectively increase NUE. On the one hand, the development of a moderate canopy increases lodging resistance and reduces diseases [32]. On the other hand, the annual dry matter weight and nitrogen increment of panicles and the nitrogen transportation of stems were improved under E treatment. Additionally, the improvement of the net photosynthesis rate at the milk stage also significantly increased the nitrogen recovery efficiency. Therefore, to alleviate the problem of a labor shortage during the busy farming season, as well as to increase the yield and NUE, nitrogen fertilization should be applied with the ratio of E, providing a good reference for nitrogen fertilizer management in Chinese double-cropping rice areas.

4.2. Effects of Nitrogen Management on Matter Production Characteristics

The coordination of the source–sink relationship is an important approach to achieving a high yield of rice. Generally speaking, the leaf and stem of rice are the most important "source" organs, and the "panicle" can be understood as an important storage sink [44]. In this study, the maximum annual grain yield of E was ascribed to the greatest biomass accumulation in early-season rice, dry matter weight of panicle at maturity, and the nitrogen accumulation of panicle and nitrogen transportation of stems. The yield mainly depends on the biomass, especially the biomass in the middle and later stages. It is generally considered that rice grain yield increases with the increase in total dry matter accumulation, and 90% of rice yield comes from photosynthetic products after the heading stage. Dry matter weight of panicles at maturity was positively ($p < 0.01$) correlated with grain yield.

Dry matter production and distribution are the basis of high yield, and depend on photosynthesis. Photosynthesis plays an important role in improving rice yield and nitrogen use efficiency under the conditions of postponing nitrogen [27,45]. The research by Evans Jr. showed that within a certain range of nitrogen supply, an increase in nitrogen application would promote an increase in leaf nitrogen content [46]. However, when the nitrogen content of leaves was too high, the net photosynthetic rate of leaves would decrease. The proper application of the nitrogen fertilizer at the panicle stage could significantly improve the net photosynthetic rate of flag leaves, delay the senescence of flag leaves, and prolong the photosynthetic time [20,47–49]. Applying more nitrogen after the tillering stage would promote the accumulation of more biomass after the heading stage; thus, increasing the yield [11,50]. In this study, applying nitrogen at the panicle stage was conducive to delaying the net photosynthetic rate which decreased rapidly at later stages, transforming the assimilation products of vegetative organs before heading and the photosynthetic products after heading directly to the panicle to enhance the grain yield (Figure 1, Table 5). By contrast, our results indicated that a single basal application of nitrogen fertilizer (A or B) obtained the highest biomass at maturity (Table 5). The dry matter transport to the panicle mainly depended on the stem, and the accumulated number of panicles was highest under E or D in 2016. In a word, the high yield of E or D was not directly dependent on the transformation of the rice stem and leaf, but due to the nutrient stimulation of the panicle by nitrogen fertilizer at the panicle stage.

A suitable leaf area is the driving force for a high photosynthetic rate [48]. The panicle-N was beneficial to maintaining the leaf area index after the panicle stage, and improved the rice population quality [9,51]. A heavy application of base fertilizer without panicle-N would lead to a lack of nutrients in the late growth period of rice, while long-time and sufficient panicle-N supply extended the longevity of functional leaves; hence, the photosynthetic capacity and grain yield improved [20,49]. Our study showed that the LAI of rice reached the maximum at the heading stage, and a one-time basal nitrogen application could significantly improve LAI. The LAI decreased slowly for panicle-N treatments from heading to milk ripening, especially in 2015. This does not mean that the larger the leaf area, the higher the yield. Whereas a suitable LAI is more conducive to photosynthesis, the enhancement of photosynthesis could promote nitrogen absorption and translocation.

The leaves' nitrogen transport was larger than the stems'. While the nitrogen increment in the panicle was highest under the E or D treatment, the nitrogen increment in the panicle improved the rice grain and NRE. A one-time basal fertilizer application could increase the dry matter accumulation of late rice and maximum leaf area index in double-cropping rice systems. However, in pursuit of the double-win goals of maximum yield and high nitrogen use efficiency, E was one of the most recommended in Chinese double-cropping rice systems. Of course, it is necessary to consider the influence of rice cultivars, the regional environment, and other factors on nitrogen fertilizer management.

5. Conclusions

Our findings demonstrated that the yield, NUE, and matter production under nitrogen application patterns were different. Moreover, the year and rice variety had a significant effect on the yield. A single basal application of nitrogen fertilizer (A or B) could increase the dry matter accumulation of late-season rice and the leaf area index of early- and late-season rice. However, it demonstrated a lower grain yield and NUE compared to CK. This means that plants with a large biomass and a high leaf area index do not necessarily have a higher yield. Moreover, the nitrogen application ratio of E in basal, tiller, spikelet-promoting, and spikelet-developing fertilizer was 0:4:3:3, which could significantly improve the rice annual grain yield, NAE, and NPFP compared to other treatments. Therefore, E is recommended as an alternative approaches to synchronously increase the grain yield and NUE.

Author Contributions: Z.F. designed the experiments; W.Z. and W.L. performed the experiments and analyzed the data; W.Z. wrote the manuscript; H.W., Y.X. and P.L. provided writing guidance. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Technology Integration and Demonstration Project of Ecological and High-Quality Rice Production in Northern Hunan (2018YFD0301003), the Agriculture and Rural Affairs Department of Hunan Province, Research and demonstration of rice high-efficiency model and disaster avoidance technology, and the National Natural Science Foundation of China (31501277).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We sincerely thank Huang Min for her guidance and suggestions on this article. We would like to thank the Hunan Academy of Agricultural Sciences for providing slow-release fertilizers and the Hunan Hybrid Rice Research Center for seeds.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Xu, M.; Li, D.; Li, J.; Qin, D.; Hosen, Y.; Shen, H.; Cong, R.; He, X. Polyolefin-coated urea decreases ammonia volatilization in a double rice system of southern China. *Agron. J.* **2013**, *105*, 277–284. [CrossRef]
2. Mi, W.; Yang, X.; Wu, L.; Ma, Q.; Liu, Y.; Zhang, X. Evaluation of nitrogen fertilizer and cultivation methods for agronomic performance of rice. *Agron. J.* **2016**, *108*, 1907–1916. [CrossRef]
3. Peng, S.B.; Huang, J.L.; Zhong, X.H.; Yang, J.C.; Wang, G.H.; Zou, Y.-B.; Zhang, F.-S.; Zhu, Q.-S.; Buresh, R.; Witt, C. Challenge and opportunity in improving fertilizer-nitrogen use efficiency of irrigated rice in China. *Agric. Sci. China* **2002**, *1*, 776–785.
4. Cassman, K.G.; Peng, S.; Olk, D.; Ladha, J.; Reichardt, W.; Dobermann, A.; Singh, U. Opportunities for increased nitrogen use efficiency from improved resource management in irrigated rice systems. *Field Crop. Res.* **1998**, *56*, 7–39. [CrossRef]
5. Peng, S.; Buresh, R.J.; Huang, J.; Yang, J.; Zou, Y.; Zhong, X.; Wang, G.; Zhang, F. Strategies for overcoming low agronomic nitrogen use efficiency in irrigated rice systems in China. *Field Crop. Res.* **2006**, *96*, 37–47. [CrossRef]
6. Lemaire, G.; Gastal, F. N uptake and distribution in plant canopies. In *Diagnosis of the Nitrogen Status in Crops*; Springer: Berlin/Heidelberg, Germany, 1997; pp. 3–43.
7. Vitousek, P.M.; Naylor, R.; Crews, T.; David, M.B.; Drinkwater, L.E.; Holland, E.; Johnes, P.J.; Katzenberger, J.; Martinelli, L.A.; Matson, P.A.; et al. Nutrient imbalances in agricultural development. *Science* **2009**, *324*, 1519–1520. [CrossRef]
8. Thakur, A.K.; Mohanty, R.K.; Patil, D.U.; Kumar, A. Impact of water management on yield and water productivity with system of rice intensification (SRI) and conventional transplanting system in rice. *Paddy Water Environ.* **2014**, *12*, 413–424. [CrossRef]
9. Li, M.; Zhang, H.; Yang, X.; Ge, M.; Ma, Q.; Wei, H.; Dai, Q.; Huo, Z.; Xu, K.; Luo, D. Accumulation and utilization of nitrogen, phosphorus and potassium of irrigated rice cultivars with high productivities and high N use efficiencies. *Field Crop. Res.* **2014**, *161*, 55–63. [CrossRef]
10. Ling, Q.; Zhang, H.; Dai, Q.; Ding, Y.; Ling, L.; Su, Z.; Xu, M.; Que, J.; Wang, S. Study on precise and quantitative N application in rice. *Sci. Agric. Sin.* **2005**, *38*, 2457–2467.
11. Chen, X.; Cui, Z.; Fan, M.; Vitousek, P.; Zhao, M.; Ma, W.; Wang, Z.; Zhang, W.; Yan, X.; Yang, J.; et al. Producing more grain with lower environmental costs. *Nature* **2014**, *514*, 486–489. [CrossRef]
12. Chuan, L.; He, P.; Jin, J.; Li, S.; Grant, C.; Xu, X.; Qiu, S.; Zhao, S.; Zhou, W. Estimating nutrient uptake requirements for wheat in China. *Field Crop. Res.* **2013**, *146*, 96–104. [CrossRef]
13. Wang, D.; Xu, C.; Ye, C.; Chen, S.; Chu, G.; Zhang, X. Low recovery efficiency of basal fertilizer-N in plants does not indicate high basal fertilizer-N loss from split-applied N in transplanted rice. *Field Crop. Res.* **2018**, *229*, 8–16. [CrossRef]
14. Sui, B.A.; Feng, X.M.; Tian, G.L.; Hu, X.Y.; Shen, Q.R.; Guo, S.W. Optimizing nitrogen supply increases rice yield and nitrogen use efficiency by regulating yield formation factors. *Field Crop. Res.* **2013**, *150*, 99–107. [CrossRef]
15. Ye, C.; Ma, H.Y.; Huang, X.; Xu, C.M.; Chen, S.; Chu, G.; Zhang, X.F.; Wang, D.Y. Effects of increasing panicle-stage N on yield and N use efficiency of indica rice and its relationship with soil fertility. *Crop J.* **2022**, in press. [CrossRef]
16. Ye, C.; Huang, X.; Chu, G.; Chen, S.; Xu, C.; Zhang, X.; Wang, D. Effects of Postponing Topdressing-N on the Yield of Different Types of japonica Rice and Its Relationship with Soil Fertility. *Agronomy* **2019**, *9*, 868. [CrossRef]
17. Kamiji, Y.; Yoshida, H.; Palta, J.A.; Sakuratani, T.; Shiraiwa, T. N applications that increase plant N during panicle development are highly effective in increasing spikelet number in rice. *Field Crop. Res.* **2011**, *122*, 242–247. [CrossRef]
18. Wang, D.; Xu, C.; Yan, J.; Zhang, X.; Chen, S.; Chauhan, B.S.; Wang, L.; Zhang, X. 15 N tracer-based analysis of genotypic differences in the uptake and partitioning of N applied at different growth stages in transplanted rice. *Field Crop. Res.* **2017**, *211*, 27–36. [CrossRef]
19. Xu, H.; Zhong, G.; Lin, J.; Ding, Y.; Li, G.; Wang, S.; Liu, Z.; Tang, S.; Ding, C. Effect of nitrogen management during the panicle stage in rice on the nitrogen utilization of rice and succeeding wheat crops. *Eur. J. Agron.* **2015**, *70*, 41–47. [CrossRef]
20. Yi, J.; Gao, J.; Zhang, W.; Zhao, Y.; Zhao, C.; Zhao, Y.; Li, Z.; Xin, W. Delayed timing of tillering fertilizer improved grain yield and nitrogen use efficiency in japonica rice. *Crop Sci.* **2020**, *60*, 1021–1033. [CrossRef]
21. Zhou, W.; Lv, T.; Zhang, P.; Huang, Y.; Chen, Y.; Ren, W. Regular nitrogen application increases nitrogen utilization efficiency and grain yield in indica hybrid rice. *Agron. J.* **2016**, *108*, 1951–1961. [CrossRef]
22. Nowicka, B.; Ciura, J.; Szymańska, R.; Kruk, J. Improving photosynthesis, plant productivity and abiotic stress tolerance current trends and future perspectives. *J. Plant Physiol.* **2018**, *231*, 415–433. [CrossRef] [PubMed]
23. Cechin, I.; Valquilha, É.M. Nitrogen effect on gas exchange characteristics, dry matter production and nitrate accumulation of *Amaranthus cruentus* L. *Braz. J. Bot.* **2019**, *42*, 373–381. [CrossRef]
24. Inthapanya, P.; Sihavong, P.; Sihathep, V.; Chanphengsay, M.; Fukai, S.; Basnayake, J. Genotype differences in nutrient uptake and utilisation for grain yield production of rainfed lowland rice under fertilised and non-fertilised conditions. *Field Crop. Res.* **2000**, *65*, 57–68. [CrossRef]

25. Fu, Y.Q.; Zhong, X.H.; Zeng, J.H.; Liang, K.M.; Pan, J.F.; Xin, Y.F.; Liu, Y.Z.; Hu, X.Y.; Peng, B.L.; Chen, R.B.; et al. Improving grain yield, nitrogen use efficiency and radiation use efficiency by dense planting, with delayed and reduced nitrogen application, in double cropping rice in South China. *J. Integr. Agric.* **2021**, *20*, 565–580. [CrossRef]
26. Hooper, P.; Zhou, Y.; Coventry, D.R.; McDonald, G.K. Use of nitrogen fertilizer in a targeted way to improve grain yield, quality, and nitrogen use efficiency. *Agron. J.* **2015**, *107*, 903–915. [CrossRef]
27. Zhou, C.; Jia, B.; Wang, S.; Huang, Y.; Wang, Y.; Han, K.; Wang, W. Effects of Nitrogen Fertilizer Applications on Photosynthetic Production and Yield of Japonica Rice. *Int. J. Plant Prod.* **2021**, *15*, 599–613. [CrossRef]
28. Yang, J.C.; Zhang, H.; Zhang, J.H. Root Morphology and Physiology in Relation to the Yield Formation of Rice. *J. Integr. Agric.* **2012**, *11*, 920–926. [CrossRef]
29. Chu, G.; Chen, T.; Wang, Z.; Yang, J.; Zhang, J. Morphological and physiological traits of roots and their relationships with water productivity in water-saving and drought-resistant rice. *Field Crop. Res.* **2014**, *165*, 36–48. [CrossRef]
30. Xu, G.W.; Lu, D.K.; Wang, H.Z.; Li, Y. Morphological and physiological traits of rice roots and their relationships to yield and nitrogen utilization as influenced by irrigation regime and nitrogen rate. *Agric. Water Manag.* **2018**, *203*, 385–394. [CrossRef]
31. Lu, R. *Soil Chemical Analysis Method for Agriculture*; Agriculture Science and Technique Press: Beijing, China, 2000.
32. Chen, Y.; Peng, J.; Wang, J.; Fu, P.; Hou, Y.; Zhang, C.; Fahad, S.; Peng, S.; Cui, K.; Nie, L.; et al. Crop management based on multi-split topdressing enhances grain yield and nitrogen use efficiency in irrigated rice in China. *Field Crop. Res.* **2015**, *184*, 50–57. [CrossRef]
33. Chen, L.; Xie, H.; Wang, G.; Qian, X.; Wang, W.; Xu, Y.; Zhang, W.; Zhang, H.; Liu, L.; Wang, Z. Reducing environmental risk by improving crop management practices at high crop yield levels. *Field Crop. Res.* **2021**, *265*, 108123. [CrossRef]
34. Jiang, L.; Dai, T.; Jiang, D.; Cao, W.; Gan, X.; Wei, S. Characterizing physiological N-use efficiency as influenced by nitrogen management in three rice cultivars. *Field Crop. Res.* **2004**, *88*, 239–250. [CrossRef]
35. Ju, C.; Liu, T.; Sun, C. Panicle nitrogen strategies for nitrogen-efficient rice varieties at a moderate nitrogen application rate in the lower reaches of the Yangtze River, China. *Agronomy* **2021**, *11*, 192. [CrossRef]
36. Ju, C.; Zhu, Y.; Liu, T.; Sun, C. The effect of nitrogen reduction at different stages on grain yield and nitrogen use efficiency for nitrogen efficient rice varieties. *Agronomy* **2021**, *11*, 462. [CrossRef]
37. Fu, J.; Huang, Z.; Wang, Z.; Yang, J.; Zhang, J. Pre-anthesis non-structural carbohydrate reserve in the stem enhances the sink strength of inferior spikelets during grain filling of rice. *Field Crop. Res.* **2011**, *123*, 170–182. [CrossRef]
38. Huang, M.; Chen, J.; Cao, F.; Zou, Y. Increased hill density can compensate for yield loss from reduced nitrogen input in machine-transplanted double-cropped rice. *Field Crop. Res.* **2018**, *221*, 333–338. [CrossRef]
39. Zhang, H.; Wu, G.; Huo, Z.; Xu, K.; Gao, H.; Wei, H.; Wan, L.; Huang, Y. Precise postponing nitrogen application and its mechanism in rice. *Acta Agron. Sin.* **2011**, *37*, 1837–1851. [CrossRef]
40. Deng, F.; Wang, L.; Ren, W.-J.; Mei, X.-F.; Li, S.-X. Optimized nitrogen managements and polyaspartic acid urea improved dry matter production and yield of indica hybrid rice. *Soil Tillage Res.* **2015**, *145*, 1–9. [CrossRef]
41. Zhang, Q.; Yang, Z.; Zhang, H.; Yi, J. Recovery efficiency and loss of ^{15}N-labelled urea in a rice-soil system in the upper reaches of the Yellow River basin. *Agric. Ecosyst. Environ.* **2012**, *158*, 118–126. [CrossRef]
42. Zhang, H.; Hou, D.P.; Peng, X.L.; Ma, B.J.; Shao, S.M.; Jing, W.J.; Gu, J.F.; Liu, L.J.; Wang, Z.Q.; Liu, Y.Y.; et al. Optimizing integrative cultivation management improves grain quality while increasing yield and nitrogen use efficiency in rice. *J. Integr. Agric.* **2019**, *18*, 2716–2731. [CrossRef]
43. Pan, S.G.; Huang, S.Q.; Zhai, J.; Wang, J.P.; Cao, C.G.; Cai, M.L.; Zhan, M.; Tang, X.R. Effects of N management on yield and N uptake of rice in central China. *J. Integr. Agric.* **2012**, *11*, 1993–2000. [CrossRef]
44. Haque, M.M.; Pramanik, H.R.; Biswas, J.K.; Iftekharuddaula, K.M.; Hasanuzzaman, M. Comparative performance of hybrid and elite inbred rice varieties with respect to their source-sink relationship. *Sci. World J.* **2015**, *2015*, 326802. [CrossRef] [PubMed]
45. Man, J.; Shi, Y.; Yu, Z.; Zhang, Y. Dry matter production, photosynthesis of flag leaves and water use in winter wheat are affected by supplemental Irrigation in the Huang-Huai-Hai Plain of China. *PLoS ONE* **2015**, *10*, e0137274. [CrossRef] [PubMed]
46. Evans, J.R. Photosynthesis and nitrogen relationships in leaves of C_3 plants. *Oecologia* **1989**, *78*, 9–19. [CrossRef]
47. Gaju, O.; Reynolds, M.P.; Sparkes, D.L. Relationships between physiological traits, grain number and yield potential in a wheat DH population of large spike phenotype. *Field Crop. Res.* **2014**, *164*, 126–135. [CrossRef]
48. Richards, R. Selectable traits to increase crop photosynthesis and yield of grain crops. *J. Exp. Bot.* **2000**, *51*, 447–458. [CrossRef]
49. Zakari, S.A.; Asad, M.A.U.; Han, Z.; Guan, X.; Zaidi, S.H.R.; Gang, P.; Cheng, F. Senescence-related translocation of nonstructural carbohydrate in rice leaf sheaths under different nitrogen supply. *Agron. J.* **2020**, *112*, 1601–1616. [CrossRef]
50. Huang, J.; He, F.; Cui, K.; Buresh, R.J.; Xu, B.; Gong, W.; Peng, S. Determination of optimal nitrogen rate for rice varieties using chlorophyll meter. *Field Crop. Res.* **2008**, *105*, 70–80. [CrossRef]
51. Mae, T. Physiological nitrogen efficiency in rice: Nitrogen utilization, photosynthesis, and yield potential. *Plant Soil* **1997**, *196*, 201–210. [CrossRef]