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Nutrient Utilization and Double Cropping Rice Yield Response to Dense Planting with a Decreased Nitrogen Rate in Two Different Ecological Regions of South China

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Abstract: An increased planting density and decreased nitrogen (N) rate combination may obtain a stable yield and enhance N utilization. However, the effects of an increased planting density and decreased N rate combination on the yield and nutrient utilization in different ecological regions are unclear. The aim of this research was to assess the interactive impacts of the N rates and planting densities on double cropping rice yields and nutrient utilization in two ecological regions in field experiments during 2018 and 2019. The results showed that, at Shanggao, increased planting densities of 67% and 200% compensated for the biomass, nutrient uptake and yield losses from N application reductions of 20% and 27% and increased the nutrient utilization of the early and late seasons. However, at Xingguo, compared with the N_2D_1 treatment (165 kg ha^{-1} with 57 plants per m^2), the late rice yield under the N_1D_2 treatment (120 kg ha^{-1} with 114 plants per m^2) decreased by 6.71% and 5.02% in 2018 and 2019, respectively. The photosynthetic rate and nutrient uptake were likely related to the positive interaction on the double cropping rice yield in the two ecological regions. Our results indicate that dense planting is a feasible cultivation strategy to decrease N inputs for double cropping rice, but the low soil nutrient supplies negatively affect stable yields in different ecological regions.

Keywords: ecological region; planting density; nitrogen application; nutrient utilization; double cropping rice; yield

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1. Introduction

Rice is one of most important food crops worldwide, and more than 60% of China's population lives on rice [1]. Double cropping rice is a typical rice production system that can effectively increase the multiple cropping index and rice yield in South China [2,3]. With the progress of cultivation technology, the improvement of varieties and the sufficient supply of chemical fertilizers, the crop production capacity has increased steadily. China feeds 14% of the world's population with only 7% of the world's arable field [4]. In China, grain production still faces the challenges of global warming [5], greenhouse gas emissions [6], heavy metal pollution [7] and other environmental problems. With the improvement of socioeconomic conditions and living standards, rice production has shifted from high-yield to high-quality types [8]. Therefore, high-quality, efficient and sustainable development has become an important goal of food security production.

Nitrogen (N) is an important element required in rice and has an important effect on the leaf area index, leaf photosynthesis and biomass formation and distribution. N application can effectively promote rice productivity [9]. At present, to obtain higher yields, rice farmers apply excessive N fertilizer. Excessive N fertilizer application not only leads to the lodging of rice [10], the prolongation of the growth period [11] and a low seed setting rate [12] but also to changes in the soil acidification [13], N runoff [14], water eutrophication [15] and soil microbial diversity [16]. Many cultivation technologies have been studied to reduce N loss and increase N utilization efficiency in paddy fields, such as real-time and site-specific N fertilizer management [17], controlled-release N fertilizer management [18], deep lateral N fertilizer management [19] and N fertilizer management in different growth periods [20]. To sum up the appeal, the scientific and rational N application is conducive to the high yield and N utilization for rice production.

Plant density is an important factor in the formation of rice populations and affects canopy formation and yield [21]. Sparse planting promotes the development of individual rice plants but reduces the population canopy productivity and cannot give full play to the yield potential of the variety [22]. Appropriate dense planting promotes the interception of solar radiation and increases canopy productivity and dry matter accumulation [23]. Reasonably increased planting density increases the panicle number, leaf area index, biomass and yield in double cropping rice systems [24]. The high planting density of the rice population results in fierce interspecific competition, unbalanced population development and easy lodging [25]. In short, an appropriate planting density can obtain the best rice canopy productivity and yield.

The N fertilizer management and plant density together play an important role in rice yield and N utilization [26,27]. Increasing the N rate and plant density enhances the population structure, leaf area index, solar radiation interception efficiency and crop growth rate and has a consistent positive effect on aboveground biomass [28]. Zhu et al. [29] found that, compared with a low seedling number and high N rate treatment, an increased seedling number and a decreased basal fertilizer N application rate treatment increased rice yield and N use efficiency. Hou et al. [30] showed that a reasonably increased plant density and amount of N fertilizer enhanced the photosynthetically active radiation and N utilization that could promote an increase in crop productivity. Huang et al. [31] indicated that dense planting enhanced N uptake and utilization in rice, which effectively avoided the yield reduction caused by N application reduction. These studies include many reports on the response of the yield to N application and plant density at a single ecological region, but the cooperative relationship between N application and plant density on the yield, N, phosphorus and potassium utilization in different ecological regions is not clear. The purposes of this study are to (1) clarify the differences in the response of double cropping rice yield and nutrient utilization to increased planting density with reduced N application in different ecological regions and (2) identify the key factors affecting the difference.

2. Materials and Methods

2.1. Site Description

The field experiment was carried out with a two-factor randomized trial of double cropping rice in Zengjia village, Shanggao County (28.28′ N, 115.12′ E) and Gaohu village, Xingguo County (26.48′ N, 115.32′ E), Jiangxi Province, China, during 2018 and 2019. The mean annual solar radiation, annual maximum temperature, annual minimum temperature and precipitation were 4270.54 and 4401.69 MJ m^{-2}, 23.36 and 24.33 °C, 15.81 and 16.28 °C and 1486.90 and 1532.34 mm at Shanggao and Xingguo, respectively, and the two ecological regions are characterized by a subtropical monsoon climate. The Shanggao and Xingguo soil types are classified as red acid soils. The soil organic matter, total N, total phosphorus, total potassium, pH, available N, available phosphorus and available potassium for the 15 cm layer of Shanggao and Xingguo are 32.9 and 21.3 g kg^{-1}, 1.99 and 1.35 g kg^{-1}, 0.83 and 0.54 g kg^{-1}, 22.2 and 14.9 g kg^{-1}, 5.41 and 5.23, 154.8 and 103.5 mg kg^{-1}, 14.4 and 8.8 mg kg^{-1} and 124.6 and 65.8 mg kg^{-1}, respectively. The main nutrient demands of rice consist of four elements: carbon, N, phosphorus and potassium. Eight rice field soil nutrient parameters, including soil organic matter, total N, total phosphorus, total potassium, available N, available phosphorus, available potassium and pH, were selected as the indicators for the comprehensive evaluation of soil fertility [32,33]. The soil fertilities of Shanggao and Xingguo are high and medium, respectively, among the rice fields of South China. The solar radiation, maximum and minimum temperatures and precipitation in the double cropping rice seasons at Shanggao were 3277.35 and 3087.36 MJ m^{-2}, 29.23 and 29.08 °C, 20.91 and 20.68 °C and 876.55 and 1238.57 mm in 2018 and 2019, respectively. The solar radiation, maximum and minimum temperatures and precipitation in the double cropping rice seasons at Xingguo were 3243.23 and 3113.48 MJ m^{-2}, 30.71 and 30.64 °C, 20.96 and 21.17 °C and 887.42 and 1239.21 mm in 2018 and 2019, respectively (Figure 1).

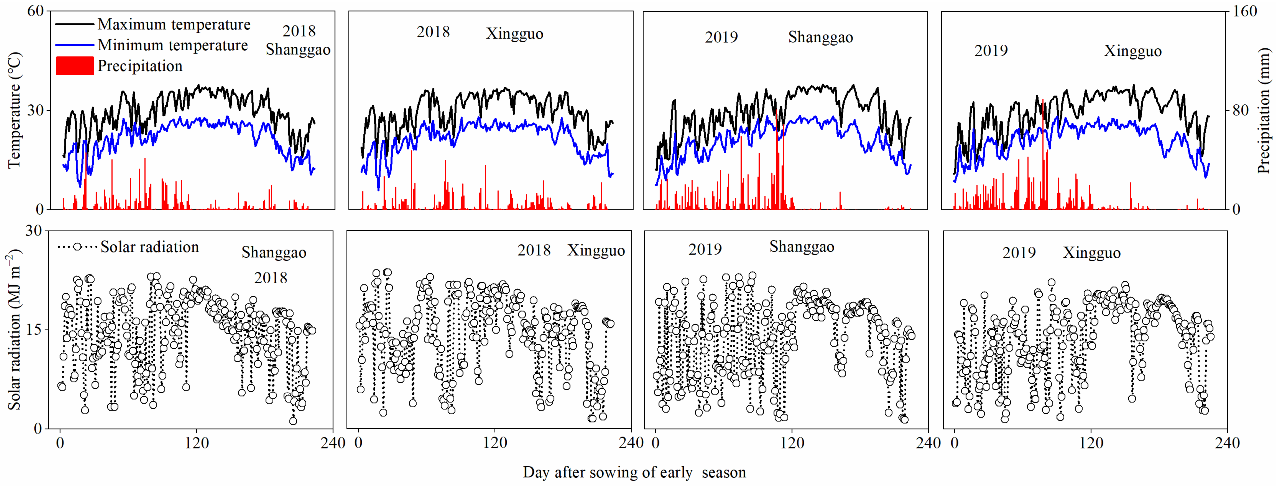

Figure 1. Solar radiation, maximum and minimum temperatures and precipitation of the early and late seasons in the two ecological regions in 2018 and 2019.

2.2. Experiment Design and Field Management

Qiliangyou 2012 and Meixiangzhan 2 (high-quality rice) were selected for sowing in the early and late seasons. Two N application levels (120 and 150 kg ha^{-1} (N_1 and N_2) for early rice and 120 and 165 kg ha^{-1} (N_1 and N_2) for late rice) and three planting densities (86, 143 and 200 plants per m^2 (D_1, D_2 and D_3) for the early season and 57, 114 and 172 plants per m^2 (D_1, D_2 and D_3) for the late season) were applied to Shanggao and Xingguo. The N application rates and plant densities were selected based on the local recommendations of rice production. Treatments with 150 kg ha^{-1} and 86 plants per m^2 (N_2D_1) and 165 kg ha^{-1} and 57 plants per m^2 (N_2D_1) represented the rice farmers' high-yield models and control plots in the early and late seasons. Models with 120 kg ha^{-1} and 143 or 200 plants per m^2 (N_1D_2 and N_1D_3 in early season) and 120 kg ha^{-1} and 114 or 172 plants per m^2 (N_1D_2 and N_1D_3 in late season) represented an increased plant density with a decreased N rate. The area of a plot was 30 m^2, the treatments were conducted in triplicate and the planting spacing was 25 cm × 14 cm. The treatments were divided by the field ridge covered with plastic film and were drained and irrigated separately. The sowing dates of the early season in 2018 and 2019 were 24 March and 23 March, respectively, and the sowing dates of the late season in 2018 and 2019 were 23 June and 25 June. In the N_1 treatment, 30, 36 and 54 kg ha^{-1} was divided into basal, tiller and panicle fertilizer in the early season. In the N_2 treatment, 60, 36 and 54 kg ha^{-1} was divided into basal, tiller and panicle fertilizer in the early season. In the N_1 treatment, 15, 42 and 63 kg ha^{-1} was divided into basal, tiller and panicle fertilizer in the late season. In the N_2 treatment, 60, 42 and 63 kg ha^{-1} was divided into basal, tiller and panicle fertilizer in the late season. The application rates of the phosphorus and potassium fertilizers in each plot were the same. The application rates of the phosphorus (P) fertilizer were 75 and 80 kg ha^{-1} P in the early and late season, respectively, all of which were applied as basal fertilizer. The application rates of the potassium (K) fertilizer were 150 and 165 kg ha^{-1} K in the early and late season, respectively, which were divided into basal and panicle fertilizers in the same amount. Other management practices were operated according to conventional high-yield cultivation measures and were consistent in the two ecological regions.

2.3. Data Collection

2.3.1. The Soil Properties

Before the transplanting of the early season, 15 cm soil layer samples were taken according to the method (five soil cores per plot), and the soil organic matter, total N, available N, total phosphorus, available phosphorus, total potassium, available potassium and pH of eight parameters were measured by the methods [34]. The soil organic matter was measured with the potassium dichromate oxidation-oil bath heating method (digested by potassium dichromate and sulfuric acid) [34]. The total N was measured by the Kjeldahl method (digested by sulfuric acid) with a instrument (Kjeldahl 8400, Foss, Beijing, Denmark), and the available N was measured with a microdiffusion technique after alkaline hydrolysis (digested by sodium hydroxide) [35]. The total phosphorus and potassium were measured with the molybdenum blue colorimetry method (digested by sulfuric acid and perchloric acid) and the flame photometry method (digested by sodium hydroxide), respectively [35]. The available phosphorus and available potassium were determined by the Olsen method and by the flame photometry method (extracted by ammonium acetate), respectively [34,36]. The pH instrument (Qiwei, Hangzhou, China) determined the pH [35].

2.3.2. Yield and Yield Compositions

At maturity, 10 plants were taken diagonally in each plot, and after threshing, the panicle number, 1000-grain weight and spikelet filling percentage were measured by the water-bleaching method [37]. The panicle number and yield were determined through the 4 m^2 acreage in the center of each plot, and the actual yield was calculated with a conversion factor of 13.5% fresh weight.

2.3.3. Biomass and N, Phosphorus and Potassium Uptake

At the mid-tillering, panicle differentiation II period, heading and maturity, 10 plants were collected from each plot according to a diagonal method. For the samples, the stem, leaves and panicle (heading and mature stage) were separated and packed in kraft paper bags. The plants were oven dried at 105 °C for 30 min, after which the temperature was lowered to 80 °C until the constant weight was reached, and the biomass was weighed by a balance scale. The aboveground plants from the four growth periods were pulverized with a pulverizer, the plant nitrogen content was measured by the micro Kjeldahl digestion method with a instrument (Kjeldahl 8400, Foss, Beijing, Denmark) and the plant phosphorus and potassium contents were measured by the flame photometry and the molybdenum-blue colorimetric methods in accordance with Fang et al. [38] and Dinh et al. [39].

The following parameters [40] are calculated:

$$\text{Nutrient (N, Phosphorus and Potassium) uptake (kg ha}^{-1}\text{) = Nutrient (N, Phosphorus and Potassium) content of plant} \times \text{Biomass} \quad (1)$$

$$\text{Grain production per kg nutrient (GPN, GPP, GPK) (kg) = Yield/Nutrient (N, Phosphorus and Potassium) uptake} \quad (2)$$

$$\text{Nutrient (N, Phosphorus and Potassium) utilization (PFP}_\text{N}\text{, PFP}_\text{N}\text{, PFP}_\text{N}\text{) (kg kg}^{-1}\text{) = Yield/N, Phosphorus and Potassium fertilizer application rate} \quad (3)$$

2.3.4. Photosynthetic Rate

At the heading stage, 10 flag leaves with the same growth were selected from each plot, and the photosynthetic rate was measured from 9:00 AM to 11:00 AM by a photosynthetic apparatus (Li-6400, Li-cor, Lincoln, NE, USA) in triplicate.

2.4. Data and Analysis

The data analysis was processed with SPSS 25 software (SPSS, Chicago, IL, USA), the figures were generated with Origin 9 (Origin Lab Corporation, Northampton, MA, USA) and the significance testing used the least significant difference method ($p < 5\%$).

3. Result

3.1. Yield and Yield Compositions

The N rate and plant density had different effects on the double cropping rice yields at Shanggao and Xingguo, respectively (Tables 1 and 2). In the two ecological regions, compared with the N_1 treatment, the yields under the N_2 treatment in the double cropping rice increased significantly; compared with the D_1 treatment, the yields under the D_2 and D_3 treatments increased. There were no differences in the double cropping yields among three treatments (the N_2D_1, the N_1D_2 and the N_1D_3 treatment) at Shanggao. At Xingguo, the yields under the N_2D_1 treatment were 6.24% and 6.25% higher than those under the N_1D_2 and N_1D_3 treatments for late rice.

Table 1. Double cropping rice yield and yield compositions response to the nitrogen (N) rate and plant density at Shanggao in 2018 and 2019.

Season	Treatment	Panicle Number ($\times 10^4$ hm^{-2})		Spikelets per Panicle		Spikelet Filling Percentage (%)		Thousand Kernel Weight (g)		Yield (t ha^{-1})	
		2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Early rice	N_1D_1	331.03e	321.87e	131.1a	130.59a	70.19d	70.39b	25.11a	25.07a	6.98c	6.83c
	N_1D_2	410.50c	398.56c	112.62b	111.68b	71.39c	71.09b	25.06a	25.11a	7.57b	7.42b
	N_1D_3	466.22a	445.96a	95.35c	94.68c	74.29b	73.89a	25.16a	25.21a	7.59b	7.44b
	N_2D_1	346.27d	335.69d	129.95a	128.79a	70.05d	70.59b	25.14a	25.17a	7.31b	7.16b
	N_2D_2	420.40b	407.59b	113.52b	110.68b	74.10b	74.89a	25.08a	25.07a	7.92a	7.77a
	N_2D_3	460.79a	449.16a	98.53c	97.89c	75.44a	74.99a	25.21a	25.16a	7.91a	7.76a
	N	20.48 **	169.73 **	NS	NS	34.55 **	60.69 **	NS	NS	137.11 **	604.84 **
	D	2508.89 **	10,808.49 **	207.34 **	1323.97 **	169.28 **	111.80 **	NS	NS	199.10 **	878.29 **
	N × D	18.21 **	21.22 **	NS	8.56 **	15.26 **	24.57 **	NS	NS	NS	NS
Late rice	N_1D_1	389.35d	399.52d	129.56a	126.89ab	77.82b	77.49b	18.87a	18.92a	7.21c	7.33c
	N_1D_2	417.95c	428.20c	124.42b	124.42ab	80.25ab	80.35ab	18.92a	18.93a	7.81b	8.01b
	N_1D_3	441.83ab	452.14b	117.33c	117.00b	81.54a	82.05a	18.91a	18.73a	7.82b	8.04b
	N_2D_1	411.08c	422.19c	129.12a	128.79a	78.58b	78.51b	18.89a	18.90a	7.61b	7.87b
	N_2D_2	437.39b	451.70b	124.57b	124.57ab	80.54ab	79.83ab	18.92a	18.94a	8.26a	8.47a
	N_2D_3	457.70a	470.29a	120.32c	121.32ab	81.12a	80.79ab	18.87a	18.91a	8.24a	8.51a
	N	109.51 **	58.40 **	NS	NS	NS	NS	NS	NS	337.43 **	566.67 **
	D	248.96 **	108.30 **	121.50 **	20.40 **	51.93 **	16.15 **	NS	NS	324.29 **	454.43 **
	N × D	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

N_1 and N_2 represent 120 and 150 kg ha^{-1} for early rice and N_1 and N_2 represent 120 and 165 kg ha^{-1} for late rice. D_1, D_2 and D_3 represent 86, 143 and 200 plants per m^2 for early rice and D_1, D_2 and D_3 represent 57, 114 and 172 plants per m^2 for late rice. Values followed by different lowercase letters are significantly different at the 0.05 level. NS and ** represent no significant difference and significant difference at the 1% levels.

In the two ecological regions, an increased N application rate and planting density increased the panicle number in the early and late rice. The increase in the panicle number from the increased N application was lower than that from the increased planting density; the panicle numbers under the N_1D_2 and N_1D_3 treatments increased compared with those under the N_2D_1 treatment. The grain number per panicle decreased with the increased plant density; the highest value occurred in the D_1 treatment, and the lowest value occurred in the D_3 treatment. The trend in the seed setting rate was inconsistent among the treatments. There were no significant differences in the impacts of the plant density and the N application rate on the 1000-grain weight.

3.2. GPN, GPP and GPK

In the two ecological regions of the double cropping rice, a higher N application rate reduced the GPN, GPP and GPK, and the GPN, GPP and GPK under the D_2 and D_3 treatment were slightly higher than those under the D_1 treatment (Figure 2). Compared with the N_2D_1 treatment, the GPN, GPP and GPK under the N_1D_2 treatment of early rice at Shanggao increased by 6.10%, 13.17% and 3.85%, respectively, and those at Xingguo increased by 7.11%, 15.47% and 4.00%, respectively. Compared with the N_2D_1 treatment, the GPN, GPP and GPK under the N_1D_2 treatment of late rice at Shanggao increased by 7.45%, 13.21% and 6.69%, respectively, and those at Xingguo increased by 5.36%, 16.91% and 3.01%, respectively. There were no differences in the GPN, GPP and GPK between the N_1D_2 treatment and the N_1D_3 treatment of the double cropping rice in the two ecological regions.

Table 2. Double cropping rice yield and yield compositions response to the N rate and plant density at Xingguo in 2018 and 2019.

Season	Treatment	Panicle Number ($\times 10^4$ hm^{-2})		Spikelets per Panicle		Spikelet Filling Percentage (%)		Thousand Kernel Weight (g)		Yield (t ha^{-1})	
		2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Early rice	N_1D_1	227.28e	224.69e	125.24a	124.13a	71.59d	71.08d	25.37a	25.38a	5.06c	4.91c
	N_1D_2	259.21c	256.89c	112.81b	111.70b	75.71c	75.20c	25.35a	25.29a	5.47b	5.32b
	N_1D_3	292.07b	288.79b	95.25c	94.14c	80.91a	80.40a	25.33a	25.24a	5.55b	5.40b
	N_2D_1	239.33d	236.71d	126.13a	125.02a	71.58d	71.07d	25.39a	25.39a	5.42b	5.27b
	N_2D_2	300.32b	292.78b	111.55b	110.44b	76.52c	76.01c	25.36a	25.17a	5.91a	5.76a
	N_2D_3	332.56a	328.94a	98.82c	97.71c	77.85b	77.34b	25.15a	25.23a	6.01a	5.86a
	N	67.19 **	201.98 **	NS	NS	NS	29.58 **	NS	NS	204.24 **	279.84 **
	D	144.96 **	480.06 **	61.85 **	663.04 **	172.81 **	1065.02 **	NS	NS	129.21 **	177.04 **
	N × D	6.33 *	17.96 **	NS	4.72 *	11.72 **	72.26 **	NS	NS	NS	NS
Late rice	N_1D_1	320.74d	331.02d	126.64a	126.33a	76.18a	76.91a	18.89a	18.93a	5.77c	5.94c
	N_1D_2	364.76b	375.19bc	120.12bc	120.12ab	72.95bc	73.62ab	18.90a	18.93a	5.98b	6.25b
	N_1D_3	389.78a	400.35a	116.89c	116.89b	70.26c	70.79b	18.89a	18.94a	5.96b	6.27b
	N_2D_1	345.17c	358.73c	127.38a	127.38a	77.35a	77.26a	18.88a	18.91a	6.41a	6.58a
	N_2D_2	379.77ab	390.19ab	124.13ab	124.46ab	74.48ab	75.33ab	18.91a	18.91a	6.60a	6.75a
	N_2D_3	398.08a	408.61a	120.25c	119.25b	72.96bc	73.57b	18.90a	18.93a	6.58a	6.71a
	N	201.95 **	49.35 **	34.87 **	10.22 **	9.37 *	NS	NS	NS	1550.18 **	1159.32 **
	D	1015.87 **	207.35 **	114.23 **	39.45 **	25.90 **	13.44 **	NS	NS	63.86 **	102.72 **
	N × D	17.48 **	5.56 *	4.77 *	NS	NS	NS	NS	NS	NS	14.67 **

N_1 and N_2 represent 120 and 150 kg ha^{-1} for early rice and N_1 and N_2 represent 120 and 165 kg ha^{-1} for late rice. D_1, D_2 and D_3 represent 86, 143 and 200 plants per m^2 for early rice and D_1, D_2 and D_3 represent 57, 114 and 172 plants per m^2 for late rice. Values followed by different lowercase letters are significantly different at the 0.05 level. NS, * and ** represent no significant difference and significant difference at the 5% and 1% levels.

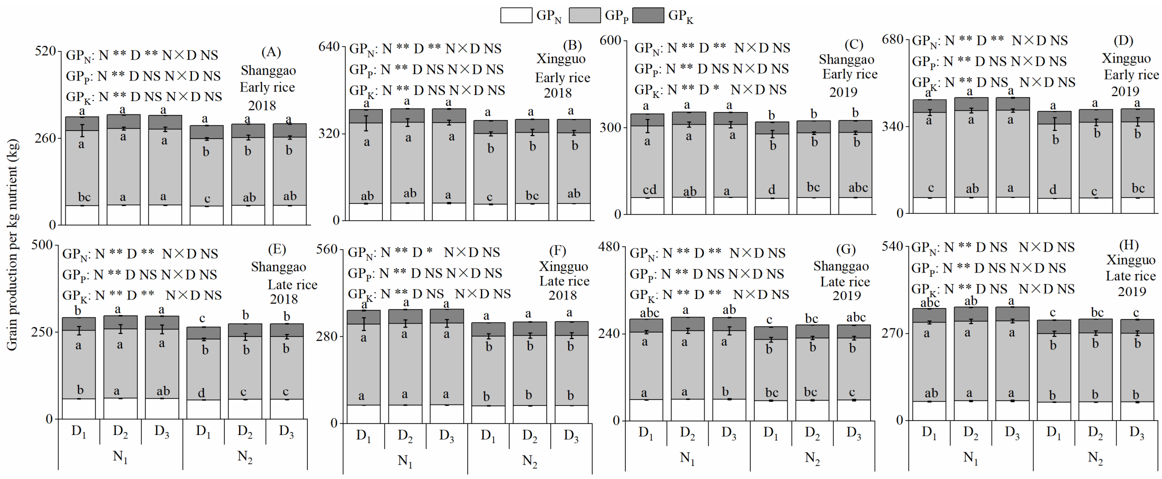

Figure 2. GP_N, GP_P and GP_K of double cropping rice (**A**–**H**) response to the nitrogen (N) rate and plant density in two different ecological regions in 2018 and 2019. N_1 and N_2 represent 120 and 150 kg ha^{-1} for early rice and N_1 and N_2 represent 120 and 165 kg ha^{-1} for late rice. D_1, D_2 and D_3 represent 86, 143 and 200 plants per m^2 for early rice and D_1, D_2 and D_3 represent 57, 114 and 172 plants per m^2 for late rice. Values followed by different lowercase letters are significantly different at the 0.05 level. NS, * and ** represent no significant difference and significant difference at the 5% and 1% levels.

3.3. PFP_N, PFP_p and PFP_k

In the two ecological regions of the early and late seasons, the PFP_N under the N_1 treatment was higher than that under the N_2 treatment, but the PFP_p and PFP_k under the N_1 treatment were lower than those under the N_2 treatment (Figure 3); the PFP_N, PFP_p and PFP_k under the D_1 treatment were lower than those under the D_2 and D_3 treatments. At Shanggao, compared with the N_2D_1 treatment, the PFP_N under the N_1D_2 treatment of early and late rice increased by 29.49% and 40.52%, respectively; the PFP_p and PFP_k under the N_1D_2 treatment of early and late rice increased slightly. At Xingguo, compared with the N_2D_1 treatment, the PFP_N under the N_1D_2 treatment of early and late rice increased by 26.17% and 29.43%, respectively; the PFP_p and PFP_k under the N_1D_2 treatment of early rice increased slightly, and those of the late rice decreased by 5.86% and 5.87%, respectively.

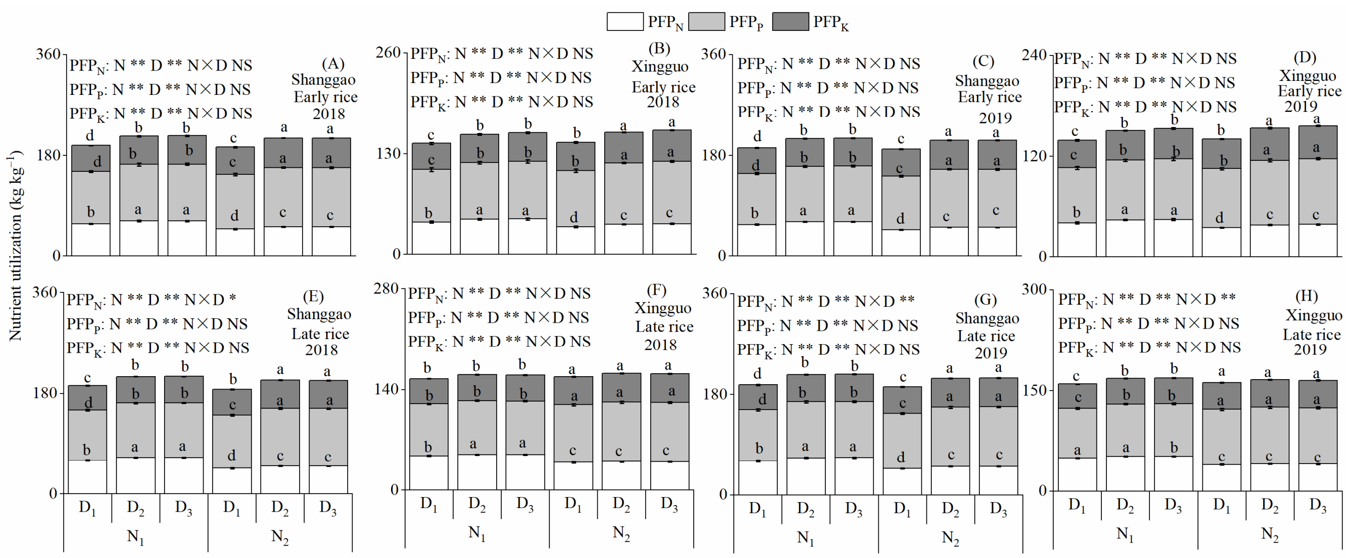

Figure 3. PFP_N, PFP_P and PFP_K of double cropping rice (**A**–**H**) response to the N rate and plant density in two different ecological regions in 2018 and 2019. N_1 and N_2 represent 120 and 150 kg ha^{-1} for early rice and N_1 and N_2 represent 120 and 165 kg ha^{-1} for late rice. D_1, D_2 and D_3 represent 86, 143 and 200 plants per m^2 for early rice and D_1, D_2 and D_3 represent 57, 114 and 172 plants per m^2 for late rice. Values followed by different lowercase letters are significantly different at the 0.05 level. NS, * and ** represent no significant difference and significant difference at the 5% and 1% levels.

3.4. Biomass

In the two ecological regions, increased nitrogen application and planting density increased the biomass at four stages for the early and late seasons (Figure 4). In the two ecological regions, the biomass under the N_2 treatment at the mid-tillering, panicle differentiation II, heading and maturity in the early and late season was higher than that under the N_1 treatment; the biomass under the D_2 and D_3 treatment at the mid-tillering, panicle differentiation II, heading and maturity of the early and late season was higher than that under the N_1 treatment. There was no difference in the biomass between the N_1D_2, N_1D_3 and N_2D_1 treatment of the double cropping rice at Shanggao and of the early rice at Xingguo. At Xingguo, compared with the N_2D_1 treatment, the N_1D_2 treatment for the late season at the mid-tillering, panicle differentiation II, heading and maturity decreased by 6.42%, 6.25%, 6.68% and 8.51%, respectively; there was no difference in the biomass between the N_1D_2 and N_1D_3 treatments. Among the N rate and plant density treatments, the highest biomass at maturity for the double cropping rice season in the two ecological regions was obtained under the N_2D_2 treatment (15.53, 16.36, 11.26 and 12.69 t ha^{-1}), and a consistent trend was obtained at the mid-tillering stage.

3.5. Photosynthetic Characteristics

In the two ecological regions, the planting density did not affect the photosynthetic characteristics for the early and late season; the photosynthetic rate and intercellular CO_2 concentration for the early and late season under the N_2D_1 treatment were higher than those under the N_1D_2 treatment (Figure 5). At Shanggao, the photosynthetic rate and intercellular CO_2 concentration of early rice under the N_1D_2 treatment were 8.52% and 7.14% lower than those under the N_2D_1 treatment, and those of the late rice were 8.86% and 6.36% lower than those under the N_2D_1 treatment. At Xingguo, compared with the N_2D_1 treatment, the photosynthetic rate in early and late rice under the N_1D_2 treatment decreased by 10.27% and 16.27%, respectively, and the intercellular CO_2 concentration under the N_1D_2 treatment decreased by 7.61% and 10.22%, respectively.

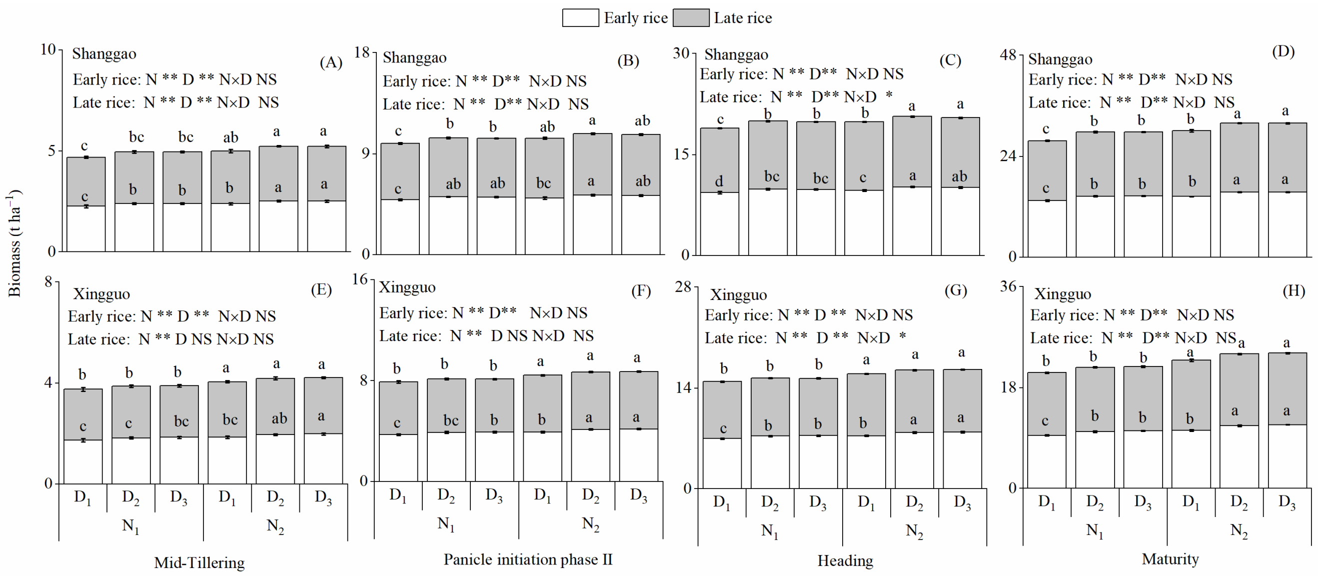

Figure 4. Biomass accumulation dynamics of double cropping rice (**A**–**H**) response to the N rate and plant density in two different ecological regions in 2018. N_1 and N_2 represent 120 and 150 kg ha^{-1} for early rice and N_1 and N_2 represent 120 and 165 kg ha^{-1} for late rice. D_1, D_2 and D_3 represent 86, 143 and 200 plants per m^2 for early rice and D_1, D_2 and D_3 represent 57, 114 and 172 plants per m^2 for late rice. Values followed by different lowercase letters are significantly different at the 0.05 level. NS, * and ** represent no significant difference and significant difference at the 5% and 1% levels.

3.6. N, Phosphorus and Potassium Uptake

In the two ecological regions, the N, phosphorus and potassium uptake under the D_2 and D_3 treatments at the mid-tillering, panicle differentiation II period, heading and maturity for the double cropping rice season were slightly higher than those under the D_1 treatment, and there was no difference between the D_2 and D_3 treatments. Compared with the N_1 treatment, the N, phosphorus and potassium uptake under the N_2 treatment at the mid-tillering, panicle differentiation II period, heading and maturity of the double cropping rice significantly increased (Figures 6–8). There were no differences in the N, phosphorus and potassium uptake between the N_1D_2, N_1D_3 and N_2D_1 treatments at the mid-tillering, panicle differentiation II period, heading and maturity of the double cropping rice at Shanggao and the early rice at Xingguo. At Xingguo, compared with the N_2D_1 treatment, the N uptake under the N_1D_2 treatment at the mid-tillering, panicle differentiation II period, heading and maturity for late season decreased by 13.87%, 11.96%, 15.38% and 10.71%; the phosphorus uptake under the N_1D_2 treatment at the mid-tillering, panicle differentiation II period, heading and maturity for late season decreased by 14.11%, 15.98%, 17.87% and 20.43%; the potassium uptake under the N_1D_2 treatment at the mid-tillering, panicle differentiation II period, heading and maturity for the late season decreased by 6.96%, 6.28%, 7.25% and 9.23%, respectively. There were no differences in the N, phosphorus and potassium uptake between the N_1D_2 and N_1D_3 treatments at the mid-tillering, panicle differentiation II period, heading and maturity for the late season at Xingguo.

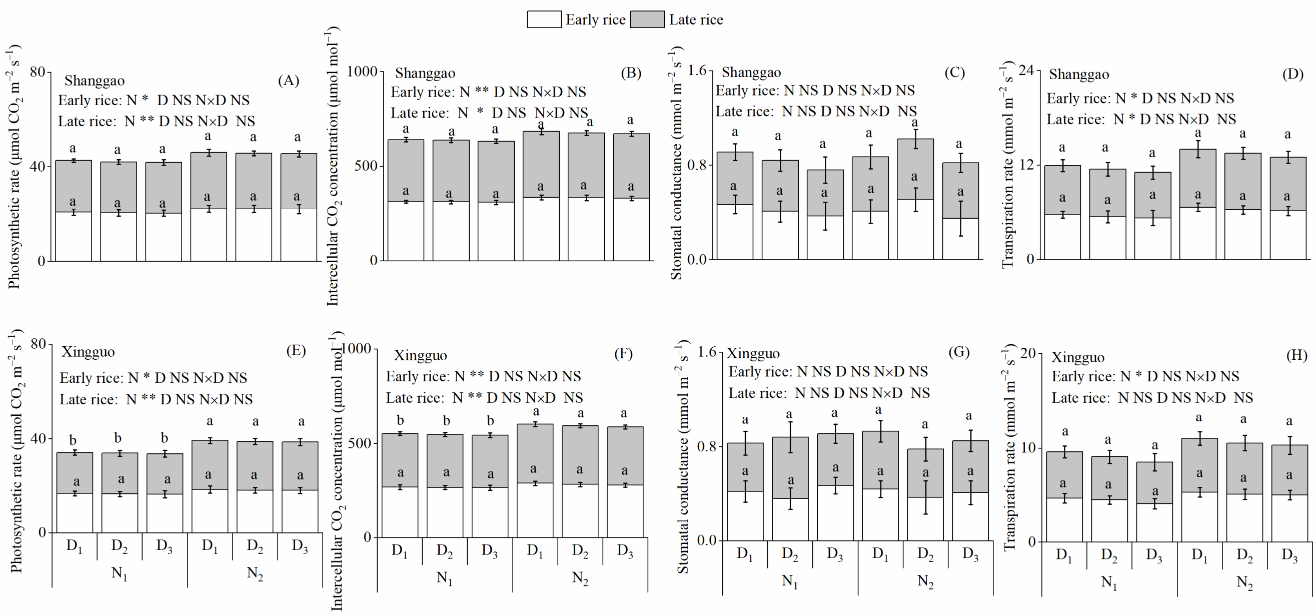

Figure 5. Photosynthetic characteristics of double cropping rice (**A**–**H**) response to the N rate and plant density in two different ecological regions in 2018. N_1 and N_2 represent 120 and 150 kg ha^{-1} for early rice and N_1 and N_2 represent 120 and 165 kg ha^{-1} for late rice. D_1, D_2 and D_3 represent 86, 143 and 200 plants per m^2 for early rice and D_1, D_2 and D_3 represent 57, 114 and 172 plants per m^2 for late rice. Values followed by different lowercase letters are significantly different at the 0.05 level. NS, * and ** represent no significant difference and significant difference at the 5% and 1% levels.

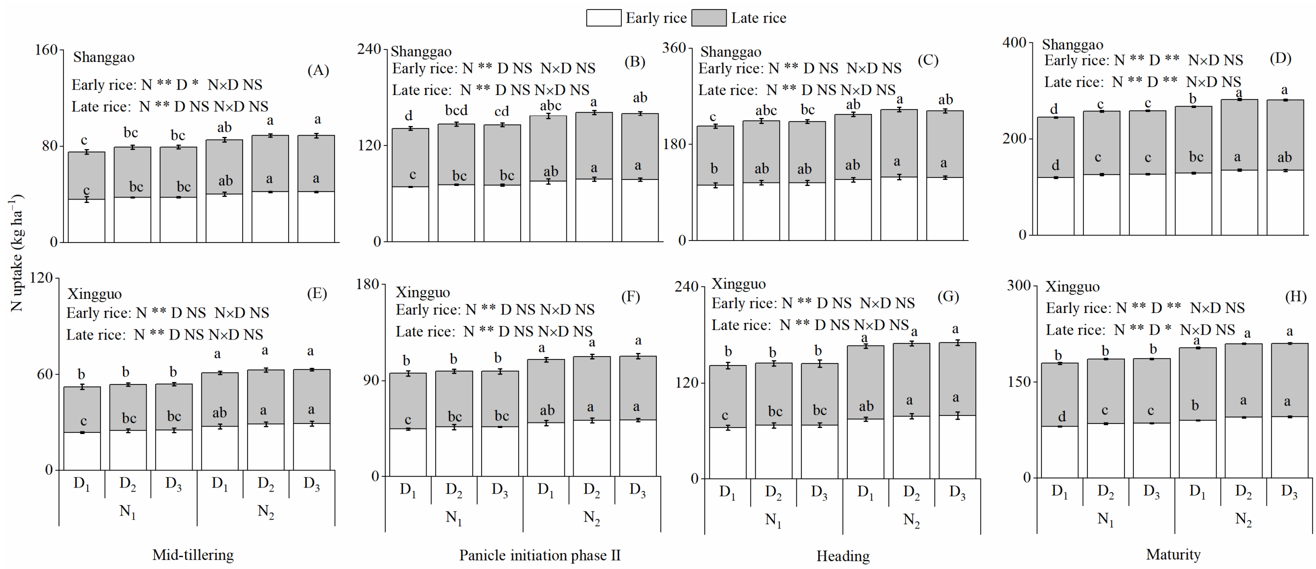

Figure 6. N absorption dynamics of double cropping rice (**A**–**H**) response to the N rate and plant density in two different ecological regions in 2018. N_1 and N_2 represent 120 and 150 kg ha^{-1} for early rice and N_1 and N_2 represent 120 and 165 kg ha^{-1} for late rice. D_1, D_2 and D_3 represent 86, 143 and 200 plants per m^2 for early rice and D_1, D_2 and D_3 represent 57, 114 and 172 plants per m^2 for late rice. Values followed by different lowercase letters are significantly different at the 0.05 level. NS, * and ** represent no significant difference and significant difference at the 5% and 1% levels.

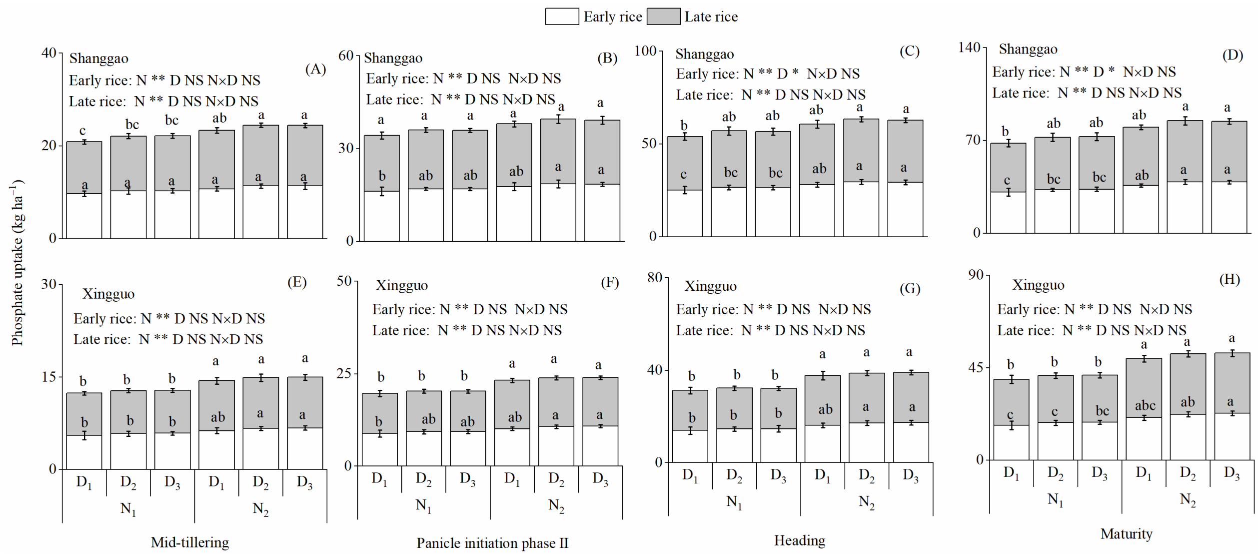

Figure 7. Phosphate absorption dynamics of double cropping rice (**A**–**H**) response to the N rate and plant density in two different ecological regions in 2018. N_1 and N_2 represent 120 and 150 kg ha^{-1} for early rice and N_1 and N_2 represent 120 and 165 kg ha^{-1} for late rice. D_1, D_2 and D_3 represent 86, 143 and 200 plants per m^2 for early rice and D_1, D_2 and D_3 represent 57, 114 and 172 plants per m^2 for late rice. Values followed by different lowercase letters are significantly different at the 0.05 level. NS, * and ** represent no significant difference and significant difference at the 5% and 1% levels.

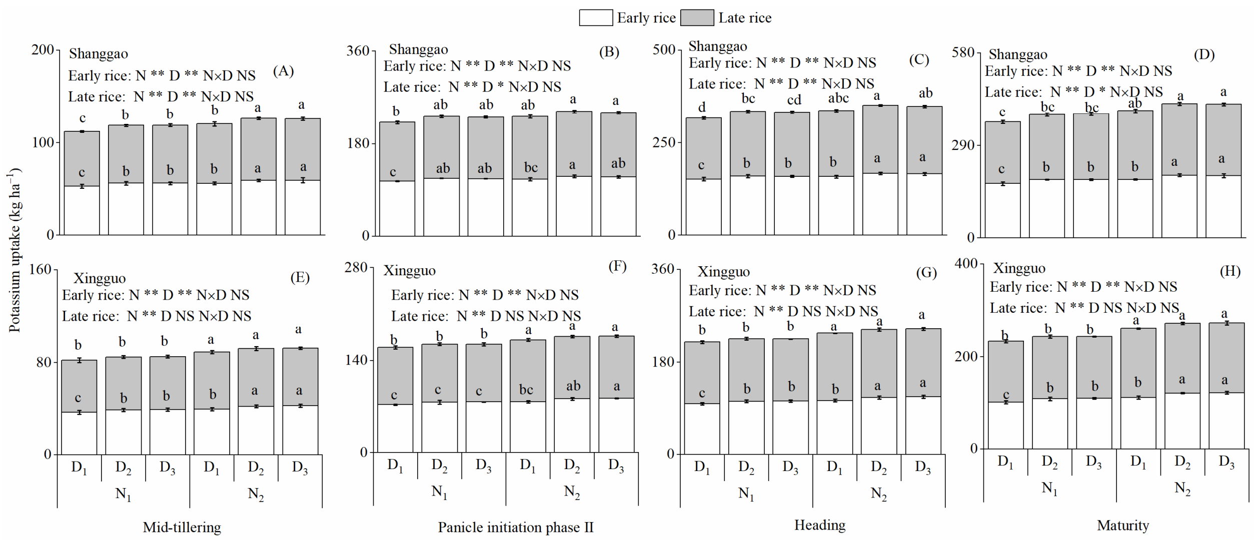

Figure 8. Potassium absorption dynamics of double cropping rice (**A**–**H**) response to the N rate and plant density in two different ecological regions in 2018. N_1 and N_2 represent 120 and 150 kg ha^{-1} for early rice and N_1 and N_2 represent 120 and 165 kg ha^{-1} for late rice. D_1, D_2 and D_3 represent 86, 143 and 200 plants per m^2 for early rice and D_1, D_2 and D_3 represent 57, 114 and 172 plants per m^2 for late rice. Values followed by different lowercase letters are significantly different at the 0.05 level. NS, * and ** represent no significant difference and significant difference at the 5% and 1% levels.

3.7. Correlation between the Different Parameters and the Yield

In the two ecological regions, the double cropping rice yield was significantly positively ($p < 1\%$ or $p < 5\%$) related to the leaf photosynthetic rate and the N, phosphorus and potassium uptake (Figure 9).

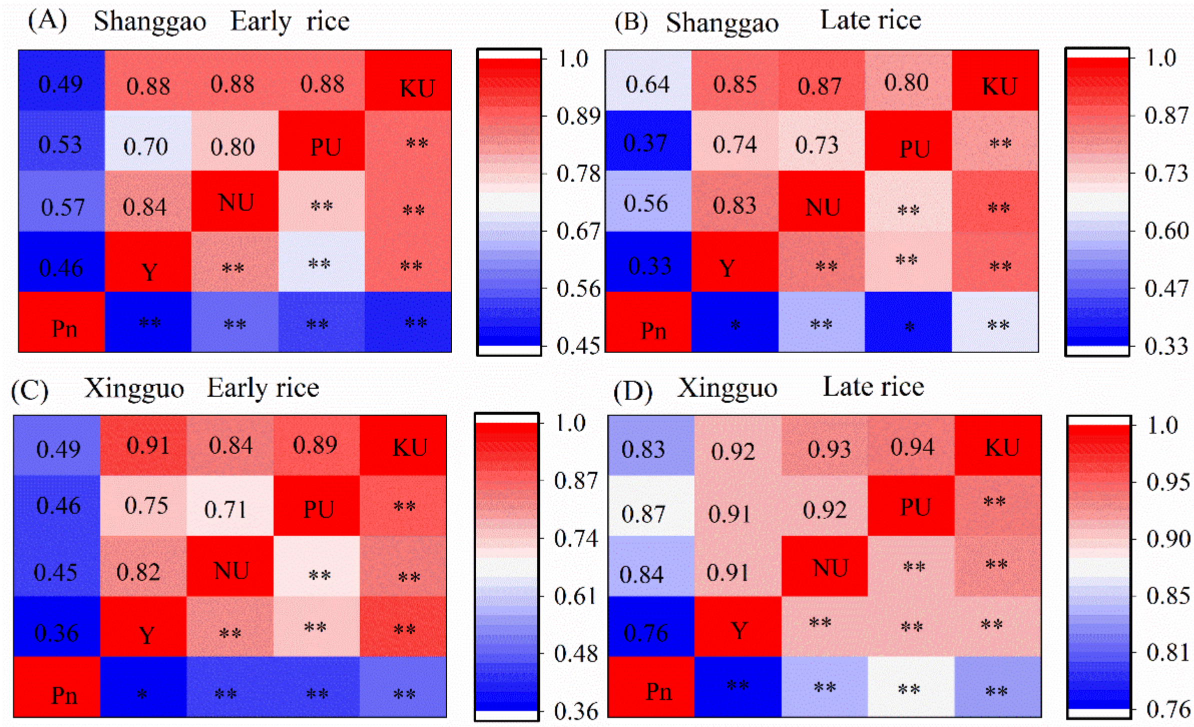

Figure 9. Correlation between the photosynthetic rate at the heading stage and the N, phosphate and potassium uptake at the mature stage of the double cropping rice yield (**A**–**D**). * and ** represent significant difference at the 5% and 1% probability levels. Pn, photosynthetic rate; Y, yield; NU, N uptake; PU, phosphate uptake; KU, potassium uptake.

4. Discussion

4.1. Response of Double Cropping Yield to the N Rate and Plant Density in Different Ecological Regions

N fertilizer is an important limiting factor affecting crop yield [41]. Increasing the N application rate can enhance the rice yield [42]. The results showed that, in the two ecological regions, the yields in the early and late season under the N_2 treatment enhanced compared with those under the N_1 treatment. The reason for this was that the higher N application increased the biomass, the panicle number and the photosynthetic rate at the heading stage, which led to enhanced rice productivity. A consistent result was discovered by a previous study [43]. This study found that the yield increases in double cropping rice that were achieved by changing the N application rate from N_1 to N_2 at Shanggao were lower than those at Xingguo, and the soil organic matter and available nutrient contents of Shanggao were higher than those of Xingguo. The ecological region with high soil fertility had a high soil available nutrient content, which led to a decrease in the dependence of the rice yield on inorganic N fertilizer [44,45]. Therefore, the high N fertilizer input decreased the yield remuneration of double cropping rice in the ecological region with high soil fertility.

Planting density affects the rice population structure, yield components and dry matter [25,46]. Xie et al. [47] showed that reasonably dense planting reduced the number of individual tillers but increased the panicle number of the population, which was more conducive to achieving full rice yield potential. The current results showed that, in the two ecological regions, compared with the D_1 treatment, the biomass and nutrient uptake of double cropping rice under the D_2 treatment increased because of the good complementarity between the panicle number, the grains per panicle and the seed setting rate. The result is similar to that observed through the previous study [31]. When the planting density was too high and the population was too large at the early growth stage, fierce intraspecific competition and unbalanced yield components occurred [28,48]. The results showed that, compared with the D_2 treatment, the D_3 treatment increased the panicle number but reduced the grains per ear, and the yield in the double cropping season did not change significantly. Moreover, there was no difference between the two ecological regions. The reason for this may be that the self-regulation ability of a population under dense planting conditions may be closely related to the genotype of the variety.

The N fertilizer application and plant density had important influences on the crop production, and there was a coupling effect between them in an ecological scenario [49,50]. Huang et al. [31] showed that, in double cropping machine-transplanted rice, reduced N application treatment led to declines in the growth rate and dry matter, but the yield negative effect of the N reduction was compensated for through the increased plant density. The results showed that dense planting could effectively make up for the yield reduction due to N reduction in double cropping rice at Shanggao. At Xingguo, the yield reduction of the late rice caused by decreased N application could not be compensated for by dense planting. The reason for this may be that the different soil fertilities affected the yield compensation ability of the rice, and the insufficient supply of soil nutrients led to a decline in rice population productivity [51]. On the other hand, the lower N application rate significantly decreased the photosynthetic rate and biomass [52]. Therefore, reasonable dense planting and N fertilizer management promoted the yield of double cropping rice in the two ecological regions, but the low soil fertility reduced the yield capacity of dense planting to compensate for the reduced N.

4.2. Response of Nutrient Uptake and the Utilization of Double Cropping Rice to the N Rate and Plant Density in Different Ecological Regions

There is a close relationship between crop biomass and nutrient uptake [53]. The nutrient uptake determines the basis of the biomass, crop yield and photosynthetic rate of the population [54]. The results showed that, in the two ecological regions, dense planting increased the biomass and the N, phosphorus and potassium uptake of double cropping rice in the whole growth period and increased the grain production per kg nutrient and nutrient utilization. Previous studies have also indicated that reasonable dense planting can effectively increase the canopy productivity, nutrient accumulation and nutrient recovery efficiency of rice populations [23,40,55]. N is an important element of leaf photosynthesis and has an influence on the biomass formation and the N, phosphorus and potassium uptake [56]. This study indicated that, compared with the N_1 treatment, the N_2 treatment increased the leaf photosynthetic rate, biomass and plant nutrient uptake of double cropping rice but reduced the grain production per kg nutrient and N utilization in the two ecological regions. Zhao et al. [57] and Huang et al. [58] showed that the high N application rate enhanced the population quality, nutrient uptake and single plant productivity but reduced the N recovery efficiency. The planting density and N application rate combinations had important effects on the biomass and N uptake and utilization [52]. The results showed that, in the two ecological regions, the photosynthetic rate, biomass and nutrient uptake are important characteristics affecting the yield compensation ability of increased plant density with a decreased N application treatment; increased plant density with a deceased N application treatment could increase the distribution of plant nutrients to grain and the N utilization of the population. The previous studies [59–61] showed that the relationship between rice population productivity and nutrient utilization under an increasing plant density with a reduced N application treatment was not relevant. In summary, the relationship between the nutrient utilization and rice population productivity under an increased plant density with a decreased N application treatment still needs further investigation in the different ecological regions.

5. Conclusions

Dense planting could make up for the yield negative impacts caused by decreased N application and increased nutrient utilization for double cropping rice in ecological regions with high soil fertility. In ecological regions with medium soil fertility, the values of the physiological characteristics (photosynthetic rate, biomass and nutrient uptake) of the population were reduced due to the low soil nutrient supply, which was not suitable for the increased plant density with the decreased N application mode of the late season. Therefore, in these two ecological regions, high soil fertility is more conducive to stable yields with high nutrient utilization under dense planting with the reduced N application mode for double cropping rice.

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