*agronomy*

*Article*

# Improving the Allocation of Light-Temperature Resources and Increasing Yield of Rice through Early Sowing and Increasing Nitrogen

**Ningning Ren [1,2,3,†], Jian Lu [4,†], Shuangbing Zhu [1], Congcong Shen [1], Bin Du [5,*] and Kai Chen [1,*]**

1 Shenzhen Branch, Guangdong Laboratory for Lingnan Modern Agriculture, Agricultural Genomics Institute at Shenzhen, Chinese Academy of Agricultural Sciences, Shenzhen 518120, China; rnn0312@126.com (N.R.); zhushuangbing@caas.cn (S.Z.); shencongcong@caas.cn (C.S.)
2 State Key Laboratory of Crop Stress Adaptation and Improvement, School of Life Sciences, Henan University, Kaifeng 475004, China
3 Shenzhen Research Institute of Henan University, Shenzhen 518000, China
4 State Key Laboratory for Conservation and Utilization of Subtropical Agro-Bioresources, College of Agriculture, South China Agricultural University, Guangzhou 510642, China; lj15090709256@126.com
5 Hubei Collaborative Innovation Center for Grain Industry, School of Agriculture, Yangtze University, Jingzhou 434025, China
* Correspondence: xiaobin@stu.scau.edu.cn (B.D.); chenkai01@caas.cn (K.C.)
† These authors contributed equally to this work.

**Abstract:** This study explored the effects of the sowing stage and nitrogen application rate on the grain yield and its allocation of light-temperature resources over a 9-year experiment from 2011 to 2019. Measurement indicators include the effective accumulative temperature on different growth durations, leaf area index (LAI), above-ground biomass production, and harvest index (HI). Methods: A split-plot design was arranged in the treatment, with N supply as the main plot and the sowing stage as the subplot. The main plots consisted of two nitrogen treatments: low nitrogen (LN: 120 kg ha$^{-1}$) and high nitrogen (HN: 180 kg ha$^{-1}$). The subplots contained two sowing stages: the early sowing stage (ES) and the late sowing stage (LS). Results: Compared with LNLS, LNES, and HNLS from 2011 to 2019, HNES of HHZ increased the grain yield by 9.5%, 2.5%, and 5.3%, while the difference in grain yield in YY8 was higher than HHZ, especially under HNES. Compared with LNLS, LNES, and HNLS from 2011 to 2019, HNES of HHZ increased the panicle number by 6.0%, 5.9%, and 1.0%, and HNES of YY8 increased by 12.7%, 11.4%, and 3.8%. Compared with HNLS of HHZ, LNES, LNLS, and HNES decreased the spikelets per panicle by 2.3%, 2.9%, and 1.1%, and decreased by 3.5%, 1.9%, and 2.2% in YY8. The early sowing or increasing N supply significantly increased the dry matter accumulated, grain weight, LAI, and HI. The higher grain yield in LNES was more closely related to the average temperature and the number of spikelets per panicle. The grain yield in HNES was more dependent on the effective accumulative temperature. Conclusions: Sowing in mid-May and increasing the N application (180 kg ha$^{-1}$) are beneficial to the allocation of light temperature and the increase in yield. Therefore, this research provides a theoretical basis for improving rice yield and optimizing the utilization of light-temperature resources in the future.

**Keywords:** rice; early-seeding; nitrogen; accumulative temperature; grain yield

check for updates

**Citation:** Ren, N.; Lu, J.; Zhu, S.; Shen, C.; Du, B.; Chen, K. Improving the Allocation of Light-Temperature Resources and Increasing Yield of Rice through Early Sowing and Increasing Nitrogen. *Agronomy* **2023**, *13*, 2989. https://doi.org/10.3390/agronomy13122989

Academic Editor: Jianbin Zhou

Received: 23 October 2023
Revised: 23 November 2023
Accepted: 28 November 2023
Published: 5 December 2023



## 1. Introduction

Rice (*Oryza sativa* L.) is one of the most important food crops in the world, meeting the dietary needs of more than half of the population [1,2]. China is the largest producer and consumer of rice, with a total cultivated area of nearly 30 million hectares and a total output of over 212 million tons in 2018, equivalent to 27% of global rice production [3,4]. It is estimated that rice production will need to increase by about 20% by 2030 to meet the needs of a growing population [5]. However, many constraints, such as population growth, sharp decline in arable land, lack of water resources, serious agricultural non-point source pollution, and frequent natural disasters, emphasize the importance of ensuring high and stable rice yields and sustainable agricultural development, which are important goals at present and even in the future [1,6].

The sowing stage has a great influence on its subsequent growth. This stage is greatly affected by extreme weather and the occurrence of pests and diseases and can be adjusted appropriately according to the weather conditions to ensure stable yield [7,8]. The advancement of the sowing stage can increase the possibility of low temperatures, which inhibit the N uptake of rice. The delay in the sowing stage can increase the damage to rice at high temperatures, which hinders starch synthesis in rice grains [9]. Finding the appropriate sowing stage can improve the biomass and nitrogen accumulation, increase the number of effective panicle numbers, improve seed setting percentage, spikelets per panicle, increase the number of spikelets per panicle, promote the development of large panicles, and increase seed setting percentage, and increase rice yields [10–12].

Nitrogen (N) is an essential element for rice growth. In order to mitigate the negative effects of climate change and changes in sowing stages on rice growth and yield, farmers used to apply a large amount of nitrogen to the early growth of rice [13–15]. Under normal temperatures, the supply of N can promote grain yield, increase dry matter accumulation, and significantly increase the yield of rice [16,17]. Appropriate N supply can partially recover the damage of carbon metabolism-related enzymes and alleviate the damage of high temperatures on grain filling and yield formation [18]. However, excessive nitrogen application made green rice, which is more susceptible to diseases and pests, prone to lodging, had a lower seed setting rate, and had reduced nitrogen use efficiency (NUE), leading to serious pesticide pollution [19–21].

The sowing stage of rice is influenced by rice age and wheat stubble, as well as the allocation of light and temperature resources during the rice growing season [22]. With the warming of the climate, the sunshine and effective accumulated temperature in the lower reaches tend to increase gradually, and the key stage of safe full heading of late rice also tends to extend, which provides more sufficient temperature and light guarantee for rice cultivars with relatively long growth stages but also puts forward new requirements for the suitable planting stage of existing two-season late japonica cultivars [23–27]. The suitable sowing stage of rice cultivars may be the key factor affecting their traits [28]. Determining the appropriate sowing stage and maintaining optimal light and temperature conditions during the setting stage of rice, which is the basis for these key techniques in cultivation management. These factors serve as the foundation for achieving a high yield and good quality of rice [29,30]. At present, there are few studies on the suitable sowing stage and N fertilizer application for different rice cultivars, and there are no reports on the yield structure. Additionally, light-temperature resource allocation among different rice cultivars under various sowing stages and N supply conditions.

To investigate the impact of temperature and light resource allocation on grain yield, we conducted a field experiment over a period of 9 years. The experiment included two sowing stages and different N treatments. The objectives of the study were: (1) to compare the variations in grain yield, yield components, biomass, LAI, and accumulative temperature; and (2) to determine the relationships between grain yield and the effective accumulative temperature during different growth stages, as well as the harvest index (HI) under different sowing stages and N treatments.

## 2. Materials and Methods

### 2.1. Experimental Environment and Materials

Field experiments were conducted at the experimental farm of Yangtze University in Jingzhou (30°21′ N, 112°31′ E, 34 m asl), Hubei Province, China. There is a subtropical agricultural climate in the area. The daily average temperature of rice during the growing season was 23.6 °C from 2011 to 2019, the daily average precipitation was 3.9 mm, and the daily average sunshine time was 5.4 h. The differences in daily average temperatures, precipitation, and sunshine time were 4.3~4.7%, 3.1~30.3%, and 2.6~20.3% from 2011 to 2019. Meteorological data during rice growth are shown in Figure 1 from 2011 to 2019. Soil samples from the upper 20 cm of the soil were taken before the experiments, and the soil properties were tested. The soil of the experimental site was calcareous alluvial with the following properties: pH 6.8, organic matter 21.5 g $kg^{-1}$, alkali-hydrolysable N 707.6 mg $kg^{-1}$, available P 51.4 mg $kg^{-1}$, and available K 115.6 mg $kg^{-1}$. Soil property data were averaged across the nine years. The experimental varieties are Huanghuazhan (HHZ) and Yongyou-8 (YY8), which have similar crop growth durations and are widely planted in southern China.

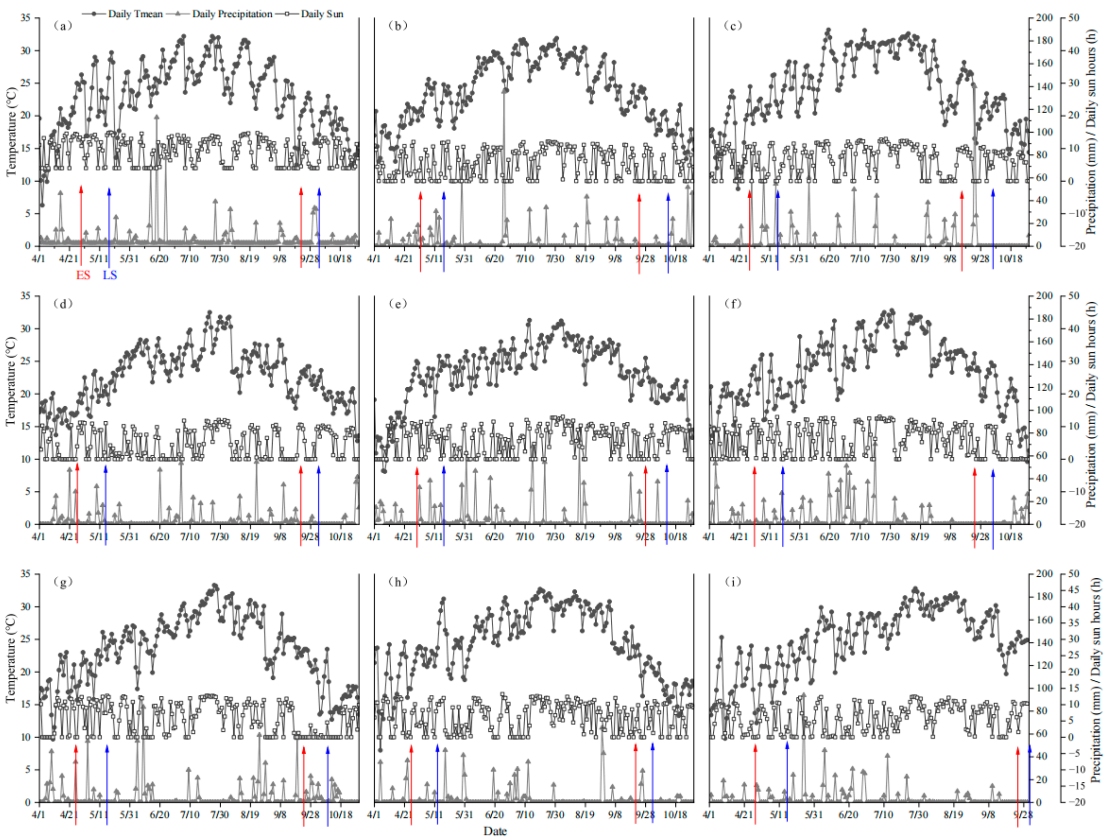

**Figure 1.** Daily average temperature (daily T mean), daily precipitation, and daily sun hours (Daily sun) in 2011 (**a**), 2012 (**b**), 2013 (**c**), 2014 (**d**), 2015 (**e**), 2016 (**f**), 2017 (**g**), 2018 (**h**), and 2019 (**i**) in Jingzhou, Hubei Province, China.

## 2.2. Field Experimental Details

A split-plot design was arranged in the treatment, with N supply as the main plot and the sowing stage as the subplot. The subplot size was 25 $m^2$, with two sowing stages, two N treatments, and five replicates. The two sowing stages are listed in Table S1. The N treatments were LN: 120 kg $ha^{-1}$ and HN: 180 kg $ha^{-1}$. N in the form of urea was split-applied at the basal, tillering, and panicle initiation stages in a ratio of 5:2:3.

Seedlings were transplanted at the age of 30~34 d, with a hill spacing of 16 cm × 30 cm and two seedlings per hill. One day before transplantation, apply phosphorus in each small area (90 kg P $ha^{-1}$ under LN and HN). Potassium (20 kg K $ha^{-1}$ under LN and HN) was split equally between the basal and panicle initiation stages. Urea, calcium superphosphate, and potassium chloride are used as sources of nitrogen, phosphorus, and potassium. Crop management followed standard cultural practices. In order to avoid biomass and yield losses, insects were intensively controlled by chemicals.

### 2.3. Measurement Items and Methods

#### 2.3.1. Measurement of Grain Yield, Yield Components, and HI

At maturity, 10 hills were sampled diagonally from a 5 $m^2$ harvest area to measure grain yield and yield components. 5 $m^2$ samples were taken at each plot's center to measure grain yields and adjusted to the standard moisture content of 0.14 g $H_2O$ $g^{-1}$. The samples were placed in a 105 °C oven for 30 min, dried at 80 °C to a stable weight, sealed, and weighed. Panicle numbers were counted on each hill to determine panicle numbers per $m^2$. Plants were separated into straws and panicles. The panicles were hand-threshed, and the filled spikelets were separated from the unfilled spikelets by submerging them in tap water. Three 30 g subsamples of filled spikelets and three 3 g subsamples of unfilled spikelets were taken to count the number of spikelets. Spikelets per panicle, grain-filling percentage, and HI were calculated. Specific parameters were calculated using the following equations:

$$\text{Grain-filling percentage} = \text{filled spikelet number}/\text{total spikelet number} \times 100\%;$$

$$\text{harvest index (HI)} = \text{filled spikelet weight}/\text{above-ground total dry weight}.$$

#### 2.3.2. Measurement of Above-Ground Biomass Production and LAI

The straw dry weight was determined after oven-drying at 70 °C to a stable weight. The dry weights of the rachis and the filled and unfilled spikelets were determined after oven-drying at 70 °C to a constant weight. Above-ground total dry weight was the total dry matter of straw, rachis, and filled and unfilled spikelets. The area of the green leaves was measured with a leaf area meter (model LI-3100C Area Meter, LI-COR, Inc., Lincoin, NE, USA).

### 2.4. Collect Climate Data

Meteorological data A small weather station (CR800 automatic weather station, Beijing Tianuo Foundation Technology Co., Ltd., Beijing, China) was installed near the experimental field to automatically collect the average daily temperature, maximum and minimum temperature, daily sun hours, and rainfall during the whole growth stage from sowing to maturity.

### 2.5. Statistical Analysis

In order to capture the trend of parameter variations caused by delayed sowing dates, a linear correlation is established between the duration of delayed sowing and the associated parameters. The constant term in the linear equation is defined as the sensitivity coefficient of delayed sowing date (SDS). The equation can be expressed as follows: V = aX + b. The equation incorporates several variables. X represents the duration of delayed sowing, with sowing date I set at 0. V represents the parameters associated with various sowing dates. The coefficient a represents the sensitivity coefficient of delayed sowing date, denoted as SDS (sensitivity coefficient of delayed sowing).

The analysis of variance (ANOVA) and principal component analysis of the data were performed using the R soft (R 4.3.1) analysis package (tidyverse, agricolae) and FactoMineR (factoextra, corrplot, ggplot2), using the minimum significant difference (LSD) test at 0.05 and 0.01 significance levels to distinguish the mean. Mapping analysis was performed using OriginPro 2021 (9.8.0.200 Learning Edition). Differences between sowing stages and N treatments were compared using a least significant difference test (LSD) at a 0.05 probability level.

## 3. Results

### 3.1. Yield and Yield Components under Different Sowing Stages and Nitrogen Treatments

There were significant differences in grain yield between HHZ and YY8 under different sowing stages and N treatments (Figure 2). The average grain yield of HHZ under HNES treatment was 6.5 $ha^{-1}$ from 2011 to 2019. Compared with LNLS, LNES, and HNLS, HNES of HHZ increased the average grain yield by 9.5%, 2.5%, and 5.3%, while the difference in average grain yield in YY8 was higher than HHZ, especially under HNES. The average grain yield of HNES was 9.3 t ha$^{-1}$ from 2011 to 2019, compared with LNLS, LNES and HNLS. HNES increased the average grain yield by 12.7%, 8.3%, and 6.9%, respectively. Grain yield is significantly different under HNLS, LNES, and LNLS, especially under the HHZ. There were significant differences in panicle number, spikelets per panicle, and grain filling by sowing stages and N treatments (Table 1). The average panicle number of HNES was 205.4 from 2011 to 2019, compared with LNLS, LNES, and HNLS. HNES of HHZ increased the average panicle number by 6.0%, 5.9%, and 1.0%, and HNES of YY8 increased by 12.7%, 11.4%, and 3.8%. Compared with HN, LN decreased the average panicle number by 10.3%. Compared with HNLS under HHZ, LNES, LNLS, and HNES decreased the average spikelets per panicle by 2.3%, 2.9%, and 1.1%, and decreased by 3.5%, 1.9%, and 2.2% in YY8. The above results showed that early sowing or increasing N supply significantly increased the grain yield and panicle number.

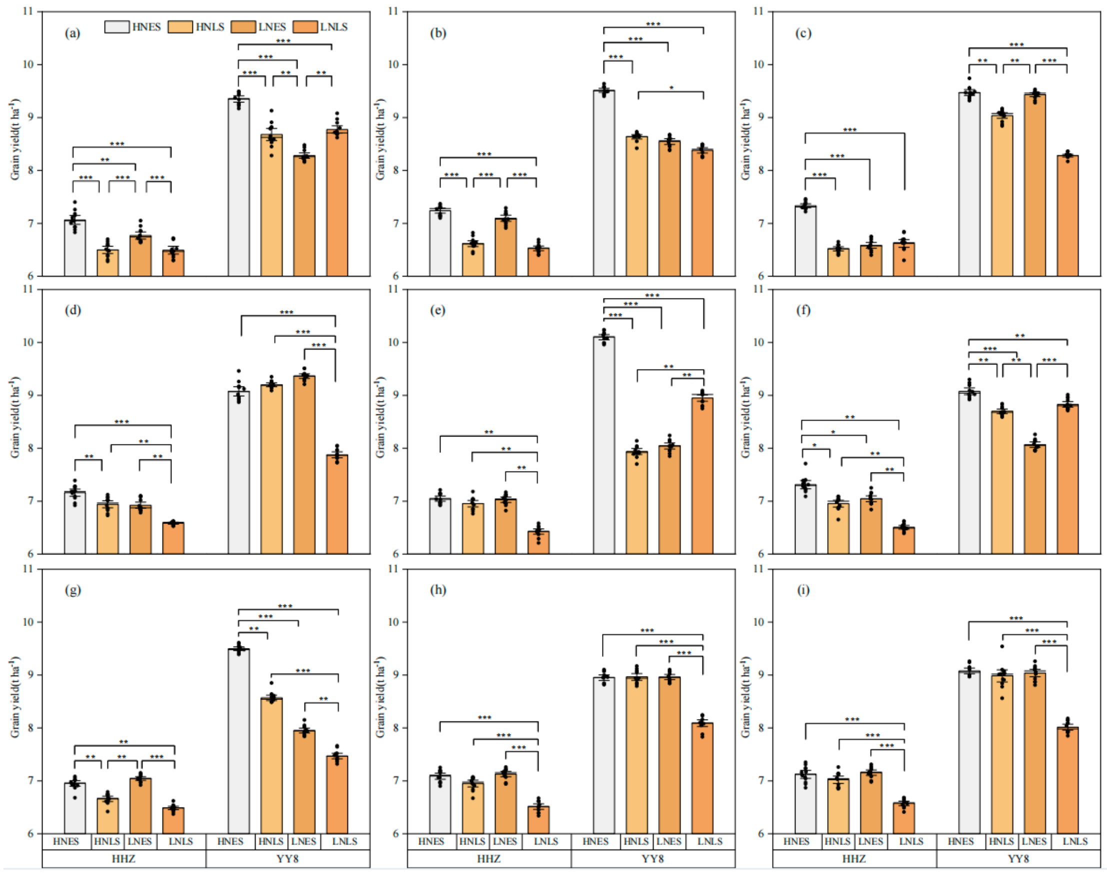


**Figure 2.** Grain yield of HHZ and YY8 under different sowing stages and nitrogen treatments in 2011 (**a**), 2012 (**b**), 2013 (**c**), 2014 (**d**), 2015 (**e**), 2016 (**f**), 2017 (**g**), 2018 (**h**), and 2019 (**i**). Vertical bars indicate standard errors ($n$ = 12). *, ** and ***, significances at $p < 0.05$, $p \leq 0.01$ and $p < 0.001$, respectively. HNES—high nitrogen early sowing stage; LNLS—low nitrogen late sowing stage; LNES—low nitrogen early sowing stage; HNLS—high nitrogen late sowing stage; HHZ—Huanghuazhan; YY8—Yongyou-8.

**Table 1.** Yield components of HHZ and YY8 under different sowing stages and nitrogen treatments in 2011–2019.

| Year | Variety | Treat | Panicles ($m^{-2}$) | Skiketes per Panicle | Grain Filling Rate (%) | 1000-Grain Weight (g) |
|---|---|---|---|---|---|---|
| 2011 | HHZ | LNLS | 222.14 a | 183.83 a | 82.09 a | 21.33 a |
| | | LNES | 209.08 a | 196.25 ab | 78.31 a | 22.21 a |
| | | HNLS | 227.53 b | 210.83 b | 80.92 a | 22.20 a |
| | | HNES | 229.40 b | 191.25 b | 82.32 a | 21.21 b |
| | YY8 | LNLS | 149.92 a | 238.17 a | 79.83 a | 28.55 a |
| | | LNES | 157.75 ab | 218.75 a | 85.33 ab | 27.45 a |
| | | HNLS | 175.46 ab | 211.33 a | 82.23 ab | 27.62 b |
| | | HNES | 186.27 b | 215.00 a | 86.35 b | 28.15 b |
| | Mean | | 194.69 | 208.18 | 82.17 | 24.84 |
| 2012 | HHZ | LNLS | 218.99 a | 192.33 a | 85.09 a | 22.03 a |
| | | LNES | 218.04 ab | 199.00 ab | 80.01 a | 21.69 a |
| | | HNLS | 228.36 ab | 198.42 ab | 81.02 a | 20.92 a |
| | | HNES | 228.20 b | 215.92 b | 82.18 a | 21.53 a |
| | YY8 | LNLS | 150.90 a | 222.50 a | 82.13 a | 27.80 a |
| | | LNES | 155.25 a | 229.42 a | 82.02 ab | 27.14 a |
| | | HNLS | 187.53 a | 223.83 a | 83.77 b | 27.7 b |
| | | HNES | 216.10 a | 205.33 a | 84.77 b | 22.06 b |
| | Mean | | 200.42 | 210.84 | 82.62 | 23.86 |
| 2013 | HHZ | LNLS | 221.33 a | 195.75 a | 83.94 a | 21.16 a |
| | | LNES | 214.31 ab | 189.58 a | 80.16 a | 22.15 a |
| | | HNLS | 223.03 ab | 207.50 a | 81.57 a | 22.12 a |
| | | HNES | 233.22 b | 193.75 a | 81.27 a | 22.67 b |
| | YY8 | LNLS | 157.48 a | 219.92 a | 83.37 a | 27.57 a |
| | | LNES | 160.35 a | 234.25 a | 86.29 ab | 28.86 ab |
| | | HNLS | 166.50 ab | 257.00 a | 83.51 bc | 28.32 b |
| | | HNES | 146.77 b | 247.33 a | 86.69 c | 27.79 b |
| | Mean | | 190.37 | 218.14 | 83.35 | 25.08 |
| 2014 | HHZ | LNLS | 211.03 a | 195.75 a | 81.45 a | 23.17 a |
| | | LNES | 221.69 a | 180.00 ab | 82.02 a | 22.15 ab |
| | | HNLS | 229.03 ab | 185.42 ab | 82.35 a | 22.46 b |
| | | HNES | 233.02 b | 202.50 b | 78.78 a | 21.70 b |
| | YY8 | LNLS | 155.12 a | 229.67 a | 82.68 a | 28.25 a |
| | | LNES | 153.43 b | 226.33 a | 83.91 a | 27.81 ab |
| | | HNLS | 157.29 b | 216.42 a | 80.74 a | 27.97 b |
| | | HNES | 184.82 b | 227.17 a | 80.85 a | 28.80 b |
| | Mean | | 193.18 | 207.91 | 81.60 | 25.29 |
| 2015 | HHZ | LNLS | 214.38 a | 182.17 a | 85.60 a | 21.39 a |
| | | LNES | 221.28 a | 189.50 a | 78.84 ab | 21.87 ab |
| | | HNLS | 231.93 ab | 199.42 a | 84.10 ab | 22.41 b |
| | | HNES | 232.95 b | 188.08 a | 82.23 b | 21.16 b |
| | YY8 | LNLS | 153.20 a | 224.50 a | 81.45 a | 27.94 a |
| | | LNES | 153.48 b | 242.42 a | 85.83 a | 27.63 ab |
| | | HNLS | 178.00 c | 224.92 a | 80.77 a | 27.42 ab |
| | | HNES | 167.11c | 233.75 a | 84.29 a | 28.36b |
| | Mean | | 194.04 | 210.59 | 82.89 | 24.77 |
| 2016 | HHZ | LNLS | 219.56 a | 183.00 a | 82.72 a | 22.92 a |
| | | LNES | 221.05 a | 183.33 ab | 80.44 a | 23.21 a |
| | | HNLS | 233.44 a | 196.08 b | 81.57 a | 22.01 ab |
| | | HNES | 231.77 a | 202.33 b | 82.97 a | 22.74 b |
| | YY8 | LNLS | 162.40 a | 218.50 a | 83.13 a | 28.41 a |
| | | LNES | 160.24 ab | 222.17 a | 82.02 a | 27.04 ab |
| | | HNLS | 149.16 bc | 238.75 a | 80.72 a | 27.39 bc |
| | | HNES | 172.46 c | 222.25 a | 83.70 a | 28.26 c |
| | Mean | | 193.76 | 208.30 | 82.16 | 25.25 |

**Table 1.** *Cont.*

| Year | Variety | Treat | Panicles ($m^{-2}$) | Skiketes per Panicle | Grain Filling Rate (%) | 1000-Grain Weight (g) |
|---|---|---|---|---|---|---|
| 2017 | HHZ | LNLS | 216.00 a | 193.50 a | 79.75 a | 21.37 a |
| | | LNES | 218.95 a | 191.83 a | 79.95 a | 22.41 ab |
| | | HNLS | 230.69 a | 185.67 a | 80.86 a | 21.51 b |
| | | HNES | 233.46 a | 174.58 a | 79.03 a | 21.98 b |
| | YY8 | LNLS | 148.64 a | 217.92 a | 78.26 a | 28.24 a |
| | | LNES | 155.22 a | 211.83 a | 85.26 a | 28.27 a |
| | | HNLS | 186.17 b | 220.58 a | 83.71 a | 27.98 a |
| | | HNES | 180.03 b | 214.17 a | 85.33 a | 28.44 a |
| | Mean | | 196.15 | 201.26 | 81.52 | 25.02 |
| 2018 | HHZ | LNLS | 215.69 a | 189.33 a | 82.63 a | 21.53 a |
| | | LNES | 224.08 a | 193.92 a | 80.17 a | 22.91 ab |
| | | HNLS | 230.09 ab | 188.83 a | 81.92 a | 22.59 bc |
| | | HNES | 229.98 b | 195.83 a | 83.13 a | 22.10 c |
| | YY8 | LNLS | 158.87 a | 217.50 a | 81.27 a | 27.89 a |
| | | LNES | 154.69 b | 229.25 a | 82.64 a | 28.18 a |
| | | HNLS | 160.69 b | 224.33 a | 82.50 a | 27.30 a |
| | | HNES | 177.71 b | 239.83 a | 84.53 a | 27.42 a |
| | Mean | | 193.97 | 209.85 | 82.35 | 24.99 |
| 2019 | HHZ | LNLS | 215.63 a | 185.58 a | 80.75 a | 21.68 a |
| | | LNES | 217.74 ab | 193.50 ab | 82.73 a | 22.30 b |
| | | HNLS | 225.40 ab | 184.42 ab | 79.38 a | 23.14 b |
| | | HNES | 229.32 b | 173.83 b | 80.51 a | 22.30 b |
| | YY8 | LNLS | 162.02 a | 216.50 a | 82.44 a | 27.85 a |
| | | LNES | 161.13 a | 224.67 b | 79.69 a | 27.32 a |
| | | HNLS | 147.14 ab | 260.67 b | 82.47 a | 28.14 a |
| | | HNES | 154.95 b | 227.83 b | 84.64 a | 27.95 a |
| | Mean | | 189.17 | 208.38 | 81.57 | 25.09 |
| | Y | | ns | 8.46 ** | ns | 8.20 ** |
| | V | | 4265.80 *** | 561.31 *** | 13.95 *** | 9322.19 *** |
| | T | | 67.42 *** | 4.51 ** | ns | ns |
| | Y × V | | 6.10 * | 5.93 * | ns | 13.56 *** |
| | Y × T | | 5.01 ** | ns | ns | ns |
| | V × T | | ns | ns | 6.37 *** | 11.11 *** |
| | Y × V × T | | 7.11 *** | 6.63 *** | ns | ns |

Note: Different lowercase letters within columns indicate significant differences at $p < 0.05$. * $p < 0.05$. ** $p \leq 0.01$. *** $p < 0.001$. ns, not significant at the $p = 0.05$ level ($n = 12$). HNES—high nitrogen early sowing stage; LNLS—low nitrogen late sowing stage; LNES—low nitrogen early sowing stage; HNLS—high nitrogen late sowing stage; HHZ—Huanghuazhan; YY8—Yongyou-8.

### *3.2. Growth Stage and Effective Accumulative Temperature under Different Sowing Stages and Nitrogen Treatments*

The duration of different sowing stages is shown in Table 2. Compared to LS, ES delayed the whole growth stage by 4–7 d, and each 1 d delayed the sowing stage by 0.1~0.35 d (SDS, 2011–2019). There was no significant difference in the duration of vegetative stage under different sowing stage and N treatments (SDS, 0.05~0.3), while there were significant differences in reproductive stage and grain filling stage. The reproductive stage was delayed by 0.05~0.3 d, and some increased the duration of grain filling, and the duration of the filling stage increased with the delay of the sowing stage. With the delay of the sowing stage, the late sowing stage remained at 36~44 d.

There were significant differences in the accumulative temperature of different growth stages under sowing stages and N treatments (Table 3). The average accumulative temperature of ES was 6995.5 °C from 2011 to 2019, compared with LS, LNLS, LNES, and HNES. ES increased the average accumulative temperature by 2.4%, 2.2%, 2.8%, and 1.2%. The average accumulative temperature of the vegetative stages of HHZ and YY8 was 1245.9 °C and 1369.9 °C at the late sowing stage, compared with ES, LS increased by 12.9% and 8.8%.

The average accumulative temperature of the reproductive stage under the late sowing stage was 1301.8 °C; compared with ES, LS increased by 12.7%. The average accumulative temperature of LN was 1226.6 °C; compared with HN, LN increased by 1.2%. Compared with HN, LN increased by 3.0% in the duration of the vegetative stage. The above results showed that LS and LN have a higher effective accumulated temperature than ES and HN.

**Table 2.** The duration of the growth stages (d) of HHZ and YY8 under different sowing stages and nitrogen treatments in 2011–2019.

| | | HHZ | | | | YY8 | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Year** | **Treatments** | **Vegetative Stage** | **Reproductive Stage** | **Grain Filling Stage** | **Whole Growth Stages** | **Vegetative Stage** | **Reproductive Stage** | **Grain Filling Stage** | **Whole Growth Stages** |
| 2011 | LNLS | 47 a | 45 b | 36 b | 128 b | 53 a | 43 b | 50 a | 146 b |
| | LNES | 47 a | 47 a | 39 a | 133 a | 53 a | 50 a | 47 ab | 150 a |
| | HNLS | 48 a | 41 c | 39 a | 128 b | 54 a | 44 b | 47 ab | 145 b |
| | HNES | 48 a | 47 a | 38 a | 133 a | 55 a | 50 a | 45 b | 150 a |
| | Mean | 47.5 | 45 | 38 | 130.5 | 53.75 | 46.75 | 47.25 | 147.75 |
| 2012 | LNLS | 45 b | 41 b | 40 b | 126 b | 51 b | 47 ab | 50 a | 148 ab |
| | LNES | 49 a | 45 a | 37 a | 131 a | 56 a | 50 a | 46 b | 152 a |
| | HNLS | 46 b | 41 b | 40 b | 127 b | 52 b | 45 b | 51 a | 148 ab |
| | HNES | 49 a | 45 a | 37 a | 131 a | 55 a | 49 a | 47 b | 151 a |
| | Mean | 47.25 | 43 | 38.5 | 128.75 | 53.5 | 47.75 | 48.5 | 149.75 |
| 2013 | LNLS | 44 b | 47 a | 38 a | 129 b | 51 b | 45 ab | 49 b | 145 b |
| | LNES | 49 a | 48 a | 36 a | 133 a | 56 a | 46 ab | 45 c | 147 b |
| | HNLS | 45 b | 43 bc | 41 bc | 129 b | 51 b | 42c | 53 a | 146 b |
| | HNES | 51 a | 45 b | 37 b | 133 a | 58 a | 49 a | 46c | 153 a |
| | Mean | 47.25 | 45.75 | 38 | 131 | 54 | 45.5 | 48.25 | 147.75 |
| 2014 | LNLS | 47 a | 39 cd | 44 cd | 130 b | 54 a | 43 b | 49 a | 146 b |
| | LNES | 44 b | 53 a | 38 a | 135 a | 50 b | 55 a | 46 b | 151 a |
| | HNLS | 47 a | 41 c | 42 c | 130 b | 54 a | 43 b | 49 a | 146 b |
| | HNES | 45 b | 45 b | 44 b | 134 a | 51 b | 53 a | 49 a | 153 a |
| | Mean | 45.75 | 44.5 | 42 | 132.25 | 52.25 | 48.5 | 48.25 | 149 |
| 2015 | LNLS | 48 a | 38 b | 42 b | 128 b | 54 a | 41 b | 51 a | 146 b |
| | LNES | 47 a | 45 a | 40 a | 132 a | 54 a | 50 a | 48 b | 152 a |
| | HNLS | 49 a | 37 b | 42 b | 128 b | 55 a | 42 b | 50 a | 147 b |
| | HNES | 48 a | 45 a | 40 a | 133 a | 54 a | 51 a | 48 a b | 153 a |
| | Mean | 48 | 41.25 | 41 | 130.25 | 54.25 | 46 | 49.25 | 149.5 |
| 2016 | LNLS | 48 a | 40 b | 39 b | 127 b | 54 a | 43 b | 51 a | 148 b |
| | LNES | 48 a | 48 a | 34 a | 130 a | 54 a | 50 a | 48 ab | 152 a |
| | HNLS | 48 a | 40 b | 39 b | 127 b | 54 a | 44 b | 50 a | 148 b |
| | HNES | 48 a | 49 a | 34 a | 131 a | 54 a | 50 a | 49 a | 153 a |
| | Mean | 48 | 44.25 | 36.5 | 128.75 | 54 | 46.75 | 49.5 | 150.25 |
| 2017 | LNLS | 49 a | 38 b | 43 a | 130 b | 55 a | 45 b | 47 a | 147 b |
| | LNES | 47 ab | 50 a | 39 b | 136 a | 53 b | 56 a | 43 b | 152 a |
| | HNLS | 49 a | 39 b | 43 a | 131 b | 56 a | 45 b | 47 a | 148 b |
| | HNES | 48 a | 49 a | 39 b | 136 a | 55 a | 54 a | 43 b | 152 a |
| | Mean | 48.25 | 44 | 41 | 133.25 | 54.75 | 50 | 45 | 149.75 |
| 2018 | LNLS | 48 a | 37 b | 44 a | 129 ab | 54 b | 46 b | 46 a | 146 b |
| | LNES | 50 a | 45 a | 38 b | 133 a | 56 a | 54 a | 40 b | 150 a |
| | HNLS | 48 a | 37 b | 44 a | 129 ab | 55 b | 46 b | 46 a | 147 b |
| | HNES | 50 a | 44 a | 39 b | 133 a | 57 a | 53 a | 41 b | 151 a |
| | Mean | 49 | 40.75 | 41.25 | 131 | 55.5 | 49.75 | 43.25 | 148.5 |
| 2019 | LNLS | 46 a | 37 b | 42 a | 125 b | 53 b | 45 b | 49 a | 147 b |
| | LNES | 44 b | 48 a | 38 ab | 130 a | 51 a | 56 a | 45 b | 152 a |
| | HNLS | 47 a | 36 b | 42 a | 125 b | 54 b | 45 b | 48 a | 147 b |
| | HNES | 45 ab | 47 a | 39 ab | 131 a | 51 a | 56 a | 46 ab | 153 a |
| | Mean | 46 | 42 | 40 | 128 | 52 | 51 | 47 | 150 |

Note: Different lowercase letters within columns indicate significant differences at $p < 0.05$ ($n = 12$).

### *3.3. Dry Matter Accumulated, LAI, and HI under Different Sowing Stages and Nitrogen Treatments*

There were significant differences in dry matter accumulated, LAI, and HI under different sowing stages and N treatments (Figures 3–5). The dry matter accumulated was significantly increased under early sowing or increasing N supply from 2011 to 2019. Compared with LNLS, LNES, and HNLS, HNES increased the average dry matter accumulated by 5.7%, 2.8%, and 3.1%. There were no significant differences between LNES and HNLS.

The accumulation of dry matter in different rice organs varied significantly under different sowing stages and N treatments, especially in the grain weight. Compared with LNLS, LNES, and HNLS, HNES increased the average grain weight by 6.3%, 3.4%, and 3.1%, and the grain weight was stable under LNES and HNLS treatments. The above results showed that early sowing or increasing N supply significantly increased dry matter accumulated and grain weight.

**Table 3.** Effect of different sowing stages and N treatments on the accumulated temperature at different growth stages of rice in 2011–2019.

| | | HHZ | | | | YY8 | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Year** | **Treatments** | **Vegetative Stage (°C)** | **Reproductive Stage (°C)** | **Grain Filling Stage (°C)** | **Whole Growth Stages (°C)** | **Vegetative Stage (°C)** | **Reproductive Stage (°C)** | **Grain Filling Stage (°C)** | **Whole Growth Stages** |
| 2011 | LNLS | 1421.3 a | 1266.7 a | 872.9 b | 3560.9 a | 1363.4 a | 1207.5 c | 1106.9 a | 3677.8 ab |
| | LNES | 1122.7 b | 1298.7 a | 1054.6 a | 3476 a | 1268.1 b | 1390.8 b | 1166.4 a | 3825.3 a |
| | HNLS | 1213.5 b | 1143 b | 965.9 a b | 3322.4 b | 1389 a | 1257.1 c | 1036.7 ab | 3657.2 ab |
| | HNES | 1148.8 b | 1304.6 a | 1022.6 a | 3476 a | 1069.9 c | 1638.9 a | 1116.5 a | 3825.3 a |
| | Mean | 1226.6 | 1253.3 | 979.0 | 3458.8 | 1272.6 | 1373.6 | 1106.6 | 3746.4 |
| 2012 | LNLS | 1144.3 a | 1201.2 a | 1034.6 a | 3380.1 a | 1314.3 a | 1381.3 a | 1151 a | 3846.6 a |
| | LNES | 1133 a | 1292.8 a | 1041.6 a | 3467.4 a | 1332.8 a | 1448.7 a | 1172 a | 3953.5 a |
| | HNLS | 1171.7 a | 1203.4 a | 1027.1 a | 3402.2 a | 1343.8 a | 1324.1 ab | 1178.7 a | 3846.6 a |
| | HNES | 1133 a | 1292.8 a | 1017.3 a | 3467.4 a | 1303 a | 1420.1 a | 1207.7 a | 3930.8 a |
| | Mean | 1145.5 | 1247.6 | 1030.2 | 3429.3 | 1323.5 | 1393.6 | 1177.4 | 3894.4 |
| 2013 | LNLS | 1585.8 a | 1435.9 a | 988.3 a | 3577 a | 1362.5 a | 1382.4 ab | 1163.4 a | 3908.3 a |
| | LNES | 1156.7 b | 1429.7 a | 1034.2 a | 3620.6 a | 1370.6 a | 1365.5 a | 1220.9 a | 3957 a |
| | HNLS | 1180.6 b | 1315.4 ab | 1081 a | 3577 a | 1362.5 a | 1290.2 a | 1278.3 a | 3931 a |
| | HNES | 1210.8 b | 1344.1 a | 1065.7 a | 3620.6 a | 1430.1 a | 1466.3 a | 1197.1 a | 4093.5 a |
| | Mean | 1283.5 | 1381.3 | 1042.3 | 3598.8 | 1381.4 | 1376.1 | 1214.9 | 3972.5 |
| 2014 | LNLS | 1175.2 a | 1087.1 b | 1049.7 a b | 3312 a | 1350.1 a | 1175.8 b | 1147.2 a | 3673.1 a |
| | LNES | 976.9 b | 1400.9 a | 983.1 b | 3360.9 a | 1140.6 b | 1484.8 a | 1095.5 a | 3720.9 a |
| | HNLS | 1175.2 a | 1133.9 b | 1002.9 b | 3312 a | 1350.1 a | 1175.8 b | 1147.2 a | 3673.1 a |
| | HNES | 1005.2 b | 1166.9 b | 1164.6 a | 3336.7 a | 1165.4 b | 1429.7 a | 1172.3 a | 3767.4 a |
| | Mean | 1083.1 | 1197.2 | 1050.1 | 3330.4 | 1251.6 | 1316.5 | 1140.6 | 3708.6 |
| 2015 | LNLS | 1196.5 a | 1057.9 b | 1070.8 a | 3325.2 a | 1346.6 a | 1144.6 b | 1222.2 a | 3713.4 b |
| | LNES | 1122.9 a | 1170.3 a | 1107.4 a | 3400.6 a | 1291.4 a | 1358 a | 1216.3 a | 3865.7 a |
| | HNLS | 1220.5 a | 1033.9 a | 1070.8 a | 3325.2 a | 1374.7 a | 1171.6 b | 890.9 b | 3889.3 a |
| | HNES | 1148.4 a | 1175 b | 1103.2 a | 3426.6 a | 1291.4 a | 1386.3 a | 1211.6 a | 3889.3 a |
| | Mean | 1172.1 | 1109.3 | 1088.1 | 3369.4 | 1326.0 | 1265.1 | 1135.3 | 3839.4 |
| 2016 | LNLS | 1436 a | 840.2 c | 1044.1 b | 3374.1 b | 1316 a | 1271.9 ab | 1255.6 a | 3843.5 a |
| | LNES | 1070.5 b | 1319.2 a | 1406.1 a | 3795.8 a | 1234.8 a | 1377.6 a | 1305.7 a | 3918.1 a |
| | HNLS | 1154.4 b | 1152.7 b | 1067 b | 3374.1 b | 1316 a | 1301.2 ab | 1226.3 a | 3843.5 a |
| | HNES | 1070.5 b | 1351.6 a | 964.4c | 3386.5 b | 1234.8 a | 1377.6 a | 1329.7 a | 3942.1 a |
| | Mean | 1182.9 | 1165.9 | 1120.4 | 3482.6 | 1275.4 | 1332.1 | 1279.3 | 3886.8 |
| 2017 | LNLS | 1236.9 a | 1133.5 b | 1107.4 a | 3477.8 a | 1412.3 a | 1329.4 b | 1079.7 a | 3821.4 a |
| | LNES | 1085 b | 1397.1 a | 1058.7 a | 3540.8 a | 1221.5 b | 1616.9 a | 1093.3 a | 3931.7 a |
| | HNLS | 1236.9 a | 1163.4 b | 1100 a | 3500.3 a | 1437.8 a | 1334 b | 1091.6 a | 3863.4 a |
| | HNES | 1109.9 b | 1372.2 a | 1058.7 a | 3540.8 a | 1271 b | 1567.4 a | 1093.3 a | 3931.7 a |
| | Mean | 1167.2 | 1266.6 | 1081.2 | 3514.9 | 1335.7 | 1461.9 | 1089.5 | 3887.1 |
| 2018 | LNLS | 1259.1 a | 1091.9 a | 1227.3 a | 3578.3 a | 1422.2 a | 1386.3 b | 1129.7 a | 3938.2 a |
| | LNES | 1189.6 a | 1293.8 b | 1126.1 a b | 3609.5 a | 1356.4 a | 1576.6 a | 1096.5 a | 4029.5 a |
| | HNLS | 1259.1 a | 1091.9 a | 1227.3 a | 3578.3 a | 1448.2 a | 1389.9 b | 1121.4 a | 3959.5 a |
| | HNES | 1189.6 a | 1262.3 b | 1157.6 a b | 3609.5 a | 1380.9 a | 1552.1 a | 1118.9 a | 4051.9 a |
| | Mean | 1224.4 | 1185.0 | 1184.6 | 3593.9 | 1401.9 | 1476.2 | 1116.6 | 3994.8 |
| 2019 | LNLS | 1165 a | 1066.9 b | 1184.4 a | 3416.3 a | 1361.3 a | 1331.7 b | 1232.6 a | 3925.6 a |
| | LNES | 980 b | 1294.5 a | 1124.2 a | 3398.7 a | 1152.5 b | 1576.3 a | 1232.9 a | 3961.7 a |
| | HNLS | 1193.9 a | 1038 b | 1184.4 a | 3416.3 a | 1386.8 a | 1335.7 b | 1203.1 a | 3925.6 a |
| | HNES | 1009.2 b | 1265.3 a | 1151 a | 3425.5 a | 1152.5 b | 1576.3 a | 1258.4 a | 3987.2 a |
| | Mean | 1087.0 | 1166.2 | 1161.0 | 3414.2 | 1263.3 | 1455.0 | 1231.8 | 3950.0 |

Note: Different lowercase letters within columns indicate significant differences at $p < 0.05$.

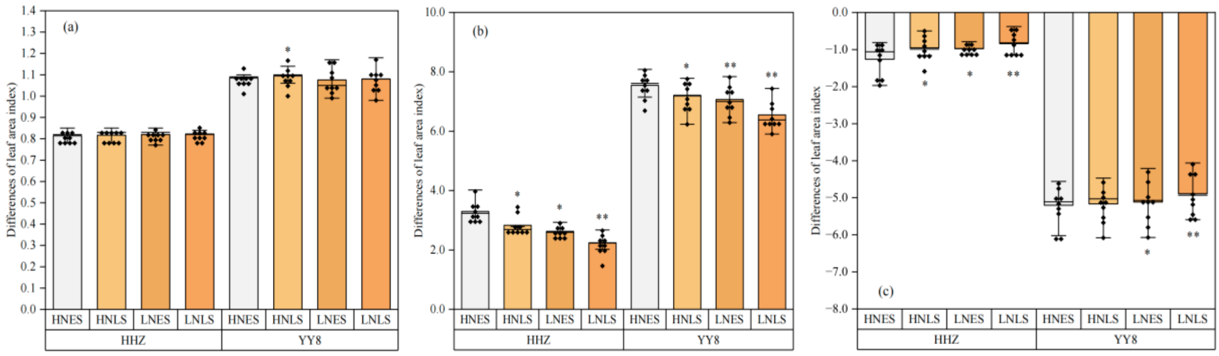


**Figure 3.** The difference in leaf average index (LAI) of HHZ and YY8 under different sowing stages and nitrogen treatments in vegetative stage (**a**), reproductive stage (**b**), and grain filling stage (**c**). * and **, significances at $p < 0.05$ and $p \leq 0.01$, respectively. HNES—high nitrogen early sowing stage; LNLS—low nitrogen late sowing stage; LNES—low nitrogen early sowing stage; HNLS—high nitrogen late sowing stage; HHZ—Huanghuazhan; YY8—Yongyou-8.

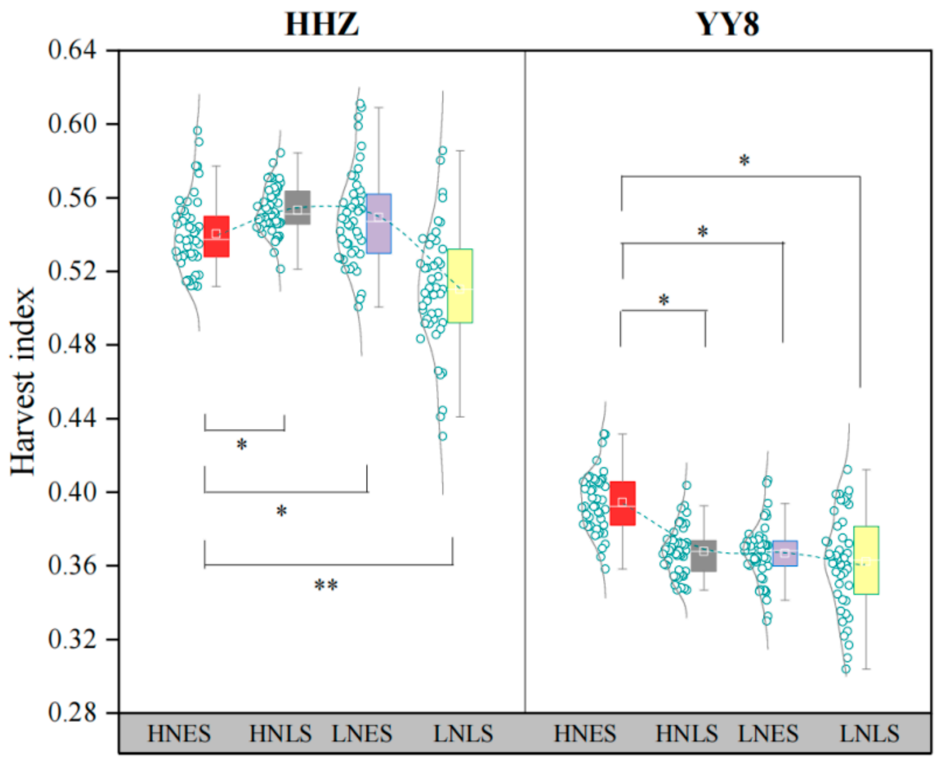


**Figure 4.** The difference in harvest index (HI) of HHZ and YY8 under different sowing stages and nitrogen treatments. * and **, significances at $p < 0.05$ and $p \leq 0.01$, respectively. Red represents HNES, Grey represents HNLS, Purple represents LNES, Yellow represents LNLS. HNES—high nitrogen early sowing stage; LNLS—low nitrogen late sowing stage; LNES—low nitrogen early sowing stage; HNLS—high nitrogen late sowing stage; HHZ—Huanghuazhan; YY8—Yongyou-8.

In a similar trend to that observed for dry matter accumulated, the average LAI of HH and ZYY8 was 0.99 and 0.97 under LNES and HNES from 2011 to 2019, higher than that of LNLS and HNLS (Figure 3). There were no significant differences in LAI in the vegetative stage, while there were significant differences in the reproductive and grain filling stages under different sowing stages and N treatments of the same variety. The average LAI of HNES was 5.5 from 2011 to 2019, compared with LNLS, LNES, and HNLS, HNES increased by 11.8%, 9.9%, and 6.0%, respectively. Compared with LNLS, LNES, and HNLS, the average LAI reduction of HNES increased by 7.6%, 10.5%, and 12.0% at the grain filling stage. The above results showed that early sowing or increasing N supply significantly increased the LAI.

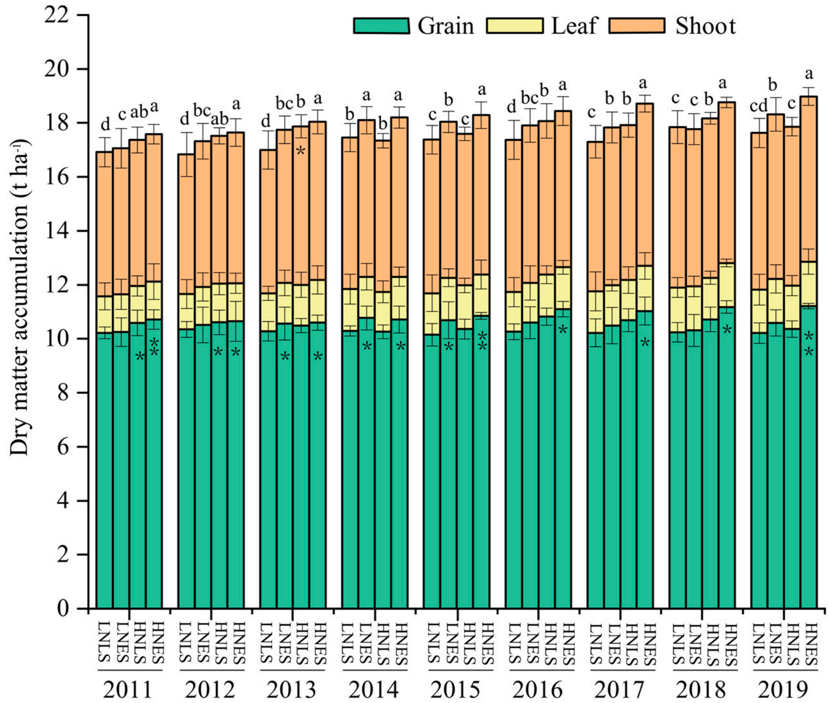


**Figure 5.** Dry matter accumulation at maturity of HHZ and YY8 under different sowing stages and nitrogen treatments in 2011–2019. Vertical bars indicate standard errors ($n$ = 12). Means followed by the same letter are not statistically different (LSD, $p < 0.05$). * and **, significances at $p < 0.05$ and $p \leq 0.01$, respectively.

There were significant differences in HI, sowing stage, and N treatments among different varieties, and late sowing stage and lower N were likely to induce lower HI (Figure 4). Compared with LNLS, LNES, and HNLS, HNES increased the average HI of HHZ by 4.4%, 2.7%, and 2.2%, respectively. The HI of YY8 increased significantly under HNES and then tended to be stable or decreased. Compared with LNLS, LNES, and HNLS, HNES increased the average HI of YY8 by 11.1%, 11.1%, and 17.6%, respectively. The above results showed that early sowing or increasing N supply increased the HI.

### 3.4. Principal Component Analysis Results

Principal component 1 is mainly the change of LAI and light-temperature resource allocation attributes in different growth stages (Figures 6 and 7); principal component 2 is the yield and yield components. There were significant differences in principal components 1 and 2 of LNLS and LNES, HNES, and HNLS, while there were only slight differences in principal component 1 of LNES and LNLS (Figure 7). Compared with LNLS, the advantages of LNLE and HNLE are mainly derived from the higher average temperature and spikelets per panicle. Moreover, stage duration, effective accumulative temperature, and average temperature had higher contributions to yield and biomass. The above results showed that the higher grain yield in LNES was more closely related to the average temperature and higher spikelets per panicle.

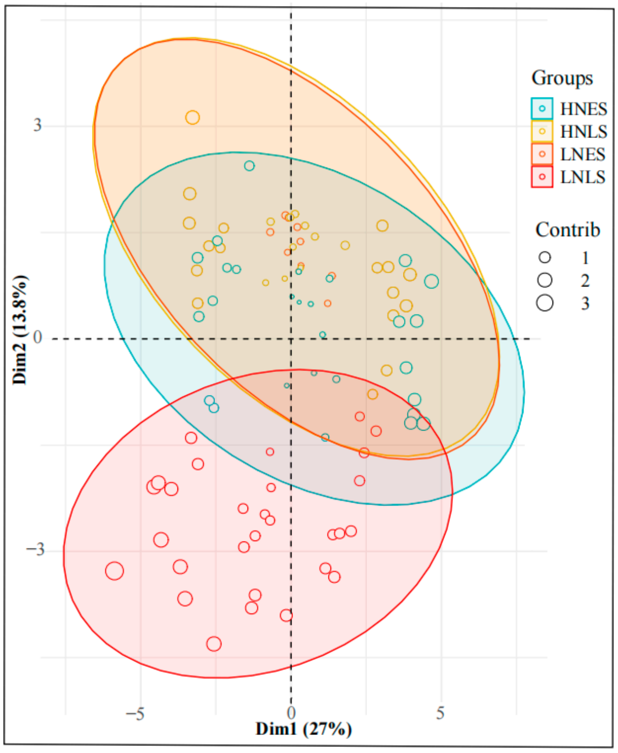


**Figure 6.** Principal components analysis (PCA) of different sowing stages and nitrogen treatments on the growth indexes, light and temperature resources, yield, and yield composition from 2011 to 2019.

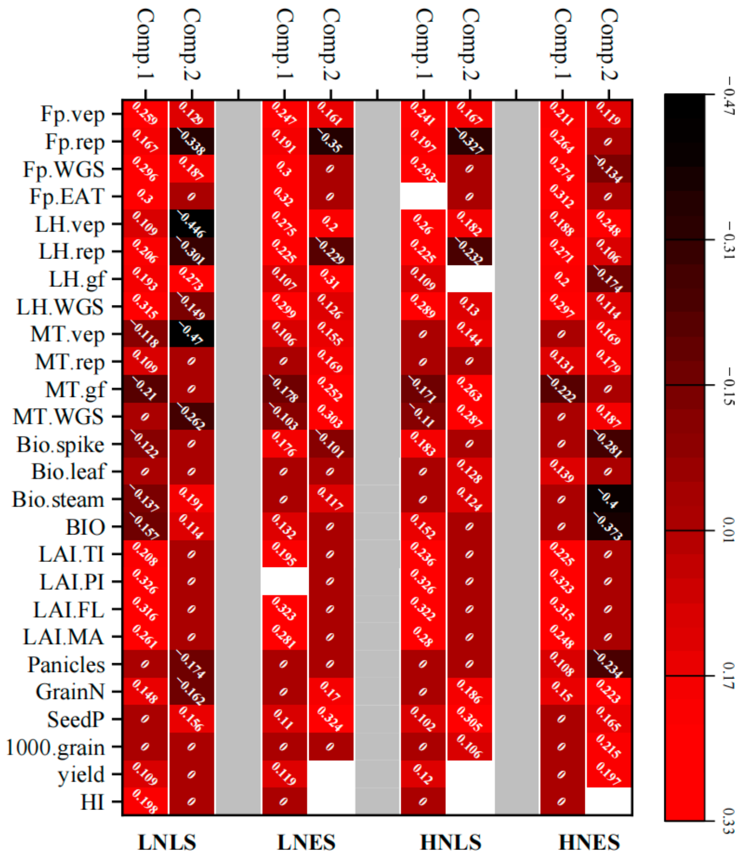


**Figure 7.** The PCA load matrix of different sowing stages and nitrogen treatments on the growth indexes, light and temperature resources, yield, and yield composition.

### 3.5. Relationships between Effective Accumulative Temperature and Grain Yield

There was a significant positive correlation between grain yield and effective accumulative temperature ($p < 0.01$), but this relationship was different among the sowing stages and N treatments (Figure 8). The higher grain yield was more closely related to accumulative temperature in HNLS and HNES ($R^2 = 0.76$, 0.56) than to LNES ($R^2 = 0.41$) and LNLS ($R^2 = 0.33$) at the vegetative stage. The grain yield depended more highly on effective accumulative temperature ($R^2 = 0.59$, $R^2 = 0.57$) in LNES and HNES at the reproductive stage, while the grain yield was more closely related to accumulative temperature in LNLS and HNLS ($R^2 = 0.52$, 0.74) than to HNES ($R^2 = 0.32$) at the grain filling stage. The grain yield under HNES depended more highly on effective accumulative temperature ($R^2 = 0.80$) at the whole growth stage. The above results showed that the grain yield in HNES depended more highly on effective accumulative temperature.

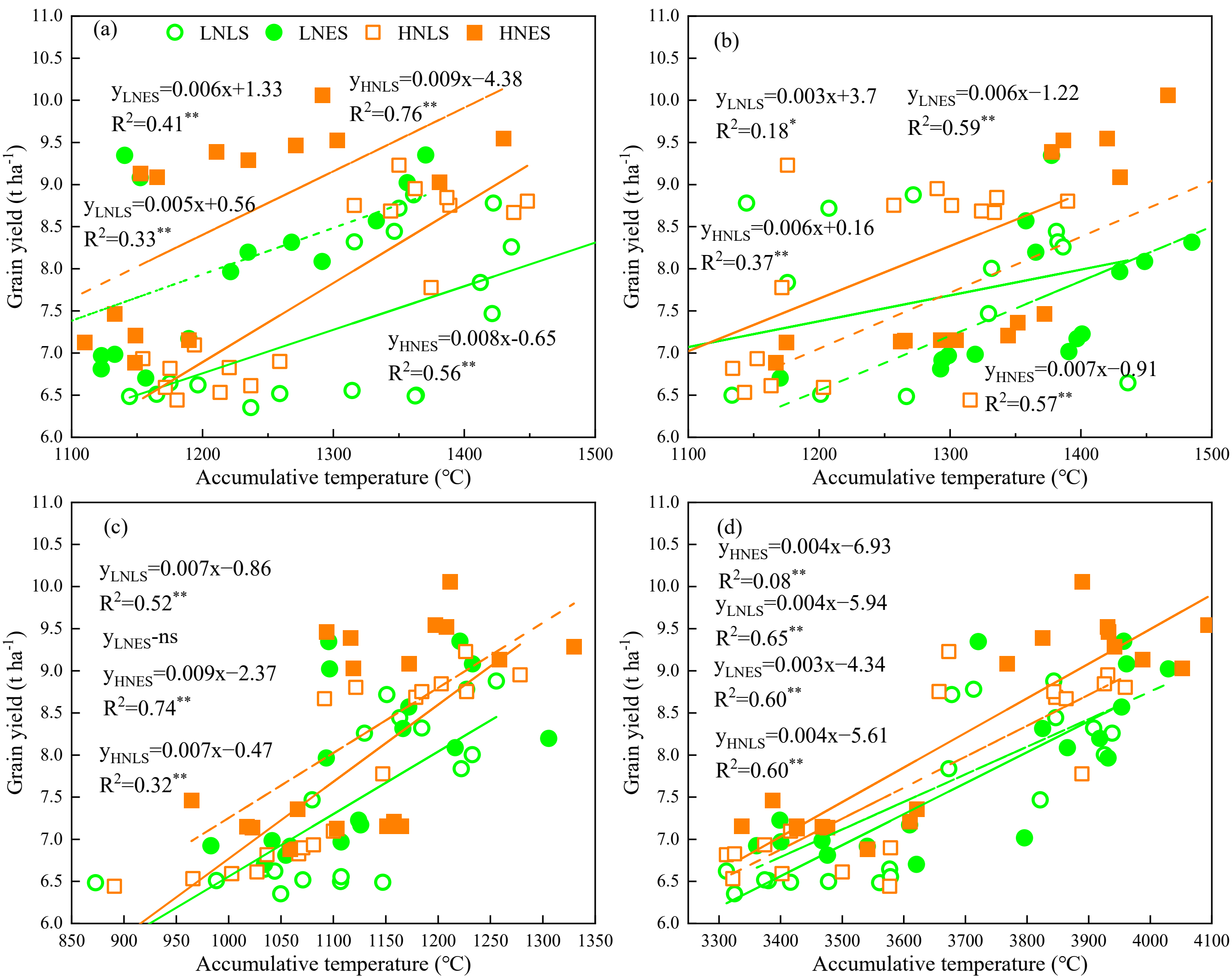


**Figure 8.** Relationships between accumulative temperature and grain yield in the vegetative stage (**a**), reproductive stage (**b**), grain filling stage (**c**), and whole growth stage (**d**). Solid symbols represent early sowing, and open symbols represent late sowing. Data were from all replicates from nine years ($n = 18$). * $p < 0.05$. ** $p \leq 0.01$. ns, not significant at the $p = 0.05$ level. Solid orange lines represent HNLS, dotted orange lines represent HNES, solid green lines represent LNLS, and dotted green lines represent LNES.

## 4. Discussion

In this study, we used HHZ and YY8 as materials to examine the effects of different sowing stages and N treatments on yield and temperature-light production from 2011 to 2019. The rice area in the middle and lower reaches of the Yangtze River is known for its traditional mixed-cropping practices, including single and double seasons, as well as the rotation of rice, wheat, and rice oil, which also have a large planting area [31,32]. Moreover, the availability of temperature-light resources in the middle and lower reaches of the Yangtze River varies compared to the traditional double-cropping rice area in the south, with one season having more resources and two seasons showing fewer resources, displaying regional differences [33]. During the late stage of rice filling, there was a lack of synchronization between low temperature and oligo-light, with low temperature preceding oligo-light, which limits the yield potential of late rice and causes unnecessary waste of light resources in the late stage of rice filling [34].

In a suitable growing season, the growth process of rice is primarily influenced by its temperature sensitivity, photosensitivity, and basic nutrient growth [35]. Based on the genetic diversity of rice varieties, the length and time distribution of different cultivars at each growth stage are different [36]. The effect of delayed sowing stages on the physiological characteristics of rice cultivars has been extensively reported [37–41]. The delayed sowing stage mainly affects the growth in the early seedling stage and the accumulation of vegetative growth in the middle tillering stage, which is related to the early and rapid growth of the population [42]. The mass of dry matter, especially the accumulation of dry matter in the early stage, will decrease with the delay of the sowing stage, resulting in a decrease in yield [43]. While maintaining the harvest index (HI), more efficient biomass accumulation will further increase yield [42]. Our findings demonstrate that early sowing provides an advantage in terms of higher effective accumulated temperature, especially during the vegetative and grain filling stages, which ultimately contributes to an increase in above-ground biomass yield.

The different effects of the sowing stage and nitrogen application rate on rice yield and yield components have been studied [8]. It has been observed that delaying the sowing stage will shorten the growth process and reduce the yield, especially in terms of spikelets per panicle and grain-filling rate [44]. The results showed that delaying the sowing stage decreased the spikelets per panicle, 1000-grain weight, and yield [34]. The study by Jiang et al. [45] tested that the number of grains per panicle of Nanjing 9108 increased first and then decreased with the delay of the sowing stage, while the 1000-grain weight had no significant difference. Li et al. [46] studied the effect of delayed sowing stages on each yield component from the change in growth stage. The vegetative growth stage of rice shortens with the delay of the sowing stage [42]. Zhang et al. [7] examined the effects of shortening the booting stage, which resulted in a decrease in panicle number and spikelets per panicle. Furthermore, the delay in the heading stage leads to a decrease in average daily temperature and effective accumulated temperature during the grain-filling stage, affecting grain filling [18,47]. Our research shows that early sowing or increased N supply significantly enhanced the panicle number, spikelets per panicle, and grain filling, particularly in HHZ (Table 1). Compared to the late sowing stage, the average panicle number, grain filling rate, and 1000-grain weight increased by 6.0%, 3.6%, and 2.4% in the early sowing stage from 2011 to 2019. The positive effects of the earlier sowing stage and nitrogen application rate on effective accumulated temperature and population increase during the flowering stage and head-filling stage. Therefore, these factors contribute to the differentiation of spikelets per panicle, the increase in grain, and the improvement of the grain filling rate.

Different stages of rice growth and development require different light and temperature conditions [29,48]. A reasonable sowing stage can coordinate the relationship between the growth and development process of rice and seasonal climate change and give full play to the high-yield potential of rice cultivars [12,49]. Xu et al. [50] found that the early sowing rice had high total dry matter and yield, and the dry matter accumulation significantly decreased with the delay of the sowing stage. N helps to promote cell division and growth, increase LAI, and improve photosynthesis efficiency, thus promoting crop growth [34]. However, over-application of nitrogen is easy to cause overgrowth of nutrients, shading of fields, and waste of nutrients [51]. Therefore, it is the key to determining a reasonable nitrogen application for a high and stable crop yield [52]. The yield of hand-inserted rice and hand-planted rice increases as the N supply increases in the range of 0~300 kg/hm$^2$ N supply. The N supply has a significant impact on the number of effective panicles per unit area and the total number of grains per panicle, resulting in a significant increase in the panicle number and the spikelets per panicle. However, it has a minimal effect on the grain filling rate and 1000-grain weight [53,54]. Guo et al. [55] and Melissa et al. [56] discovered that the rice yield initially increased and then gradually decreased as the N application rate increased. To attain a high yield, it is essential to enhance the panicle number and spikelets per panicle while maintaining a stable grain filling rate and 1000-grain weight. The reasonable sowing stage and nitrogen nutrition play a crucial role in ensuring the stability and sustainability of high yields [36]. Late sowing has been found to weaken the growth potential of crops and reduce their nitrogen absorption capacity, ultimately leading to a decrease in annual nitrogen use efficiency [8]. However, if the sowing stage is delayed or advanced, it has been suggested that adding nitrogen supply can be an effective measure to increase and stabilize crop yield.

The results indicated that both the sowing stage and nitrogen application had significant impacts on yield. The highest yield of rice was observed under the HNES treatments, while there was no significant difference between the yield of LNES and HNLS treatments (Table 1). This suggests that rice prefers warmth, which influences its growth and development in response to variations in the external nitrogen supply. It appears that increasing nitrogen supply can offset yield losses resulting from early sowing and low temperatures.

## 5. Conclusions

From our findings, early sowing combined with N supply has been shown to significantly enhance grain yield in rice. This improvement is attributed to increased panicle number, higher above-ground biomass at maturity, elevated LAI during the reproductive stage, and a higher effective cumulative temperature throughout the growth period. Given the benefits of rice cultivation in the Yangtze River region, the sowing stage and cumulative temperature are considered pivotal in determining yield outcomes. Therefore, sowing in mid-May and increasing the N application (180 kg ha$^{-1}$) could be a better agronomic practice for increasing the grain yield. Furthermore, the careful administration of N supply can effectively optimize the utilization of light and temperature resources in early sowing conditions, ultimately resulting in increased grain yield.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13122989/s1. Table S1: Growth stages of different treatments in 2011–2019.

**Author Contributions:** Methodology, J.L.; validation, S.Z. and C.S.; formal analysis, J.L.; investigation, J.L. and B.D.; data curation, J.L. and K.C.; writing—original draft preparation, N.R. and J.L.; writing—review and editing, N.R., J.L., and K.C.; project administration, B.D.; funding acquisition, K.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This word was supported by the Agricultural Science and Technology Innovation Program and the Science, Technology and Innovation Commission of Shenzhen Municipality to KC (grants JCYJ20200109150713553).

**Data Availability Statement:** Data are contained within the article.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References


1. Zhou, Y.; Li, Y.; Xu, C. Land consolidation and rural revitalization in China: Mechanisms and paths. *Land Use Policy* **2020**, *91*, 104379. [CrossRef]
2. Du, B.; Luo, H.W.; He, L.X.; Zhang, L.H.; Liu, Y.F.; Mo, Z.W.; Pan, S.G.; Tian, H.; Duan, M.Y.; Tang, X.R. Rice seed priming with sodium selenate: Effects on germination, seedling growth, and biochemical attributes. *Sci. Rep.* **2019**, *9*, 4311. [CrossRef] [PubMed]
3. FAOSTAT. *FAO Statistical Databases*; Food and Agriculture Orgnization (FAO) of the United Nations: Rome, Italy, 2018.
4. Tilman, D.; Balzer, C.; Hill, J.; Befort, B.L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 20260–20264. [CrossRef] [PubMed]
5. Peng, S.B.; Tang, Q.Y.; Zou, Y.B. Current Status and Challenges of Rice Production in China. *Plant Prod. Sci.* **2018**, *12*, 3–8. [CrossRef]
6. Yu, Y.Q.; Huang, Y.; Zhang, W. Changes in rice yields in China since 1980 associated with cultivar improvement, climate and crop management. *Field Crop. Res.* **2012**, *136*, 65–75. [CrossRef]
7. Zhang, W.J.; Zhao, Y.; Li, L.Y.; Xu, X.; Yang, L.; Luo, Z.; Wang, B.B.; Ma, S.Y.; Fan, Y.H.; Huang, Z.L. The Effects of Short-Term Exposure to Low Temperatures During the Booting Stage on Starch Synthesis and Yields in Wheat Grain. *Front. Plant Sci.* **2021**, *12*, 684784. [CrossRef] [PubMed]
8. Pal, R.; Mahajan, G.; Sardana, V.; Chauhan, B.S. Impact of sowing date on yield, dry matter and nitrogen accumulation, and nitrogen translocation in dry-seeded rice in north-west India. *Field Crop. Res.* **2017**, *206*, 138–148. [CrossRef]
9. Yu, P.; Li, X.H.; Ye, S.H.; Zhao, X.Y.; Zhai, R.R.; Jin, Q.S.; Zhang, X.M. Effects of sowing date on agronomic characters and yield of conventional late japonica rice varieties in Zhejiang Province. *Acta Agric. Nucl. Sin.* **2016**, *30*, 978–987.
10. Dou, Z.; Tang, S.; Li, G.H.; Liu, Z.H.; Ding, C.Q.; Chen, L.; Wang, S.H.; Ding, Y.F. Application of nitrogen fertilizer at heading stage improves rice quality under elevated temperature during grain-filling stage. *Crop Sci.* **2017**, *57*, 2183–2192. [CrossRef]
11. Jiang, S.C.; Wang, J.M.; Luo, H.W.; Xie, Y.M.; Feng, D.H.; Zhou, L.; Shi, L.; Chen, H.; Xu, Y.Y.; Wang, M.; et al. Effect of meteorology and soil fertility on direct-seeded rice (*Oryza sativa* L.) performance in central China. *Appl. Ecol. Environ. Res.* **2019**, *17*, 12397–12406. [CrossRef]
12. Ding, Y.M.; Wang, W.G.; Zhuang, Q.L.; Luo, Y.F. Adaptation of paddy rice in China to climate change: The effects of shifting sowing date on yield and irrigation water requirement. *Agric. Water Manag.* **2020**, *228*, 105890. [CrossRef]
13. Xu, G.W.; Lu, D.K.; Wang, H.Z.; Li, Y.J. 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]
14. Mueller, N.D.; Gerber, J.S.; Johnston, M.; Ray, D.K.; Ramankutty, N.; Foley, J.A. Closing yield gaps through nutrient and water management. *Nature* **2012**, *490*, 254–257. [CrossRef] [PubMed]
15. Fiaz, S.; Wang, X.K.; Khan, S.A.; Ahmar, S.; Noor, M.A.; Riaz, A.; Ali, K.; Abbas, F.; Mora-Poblete, F.; Figueroa, C.R.; et al. Novel plant breeding techniques to advance nitrogen use efficiency in rice: A review. *GM Crop. Food.* **2021**, *12*, 627–646. [CrossRef] [PubMed]
16. Wang, J.S.; Chen, Q.; Ge, X.F. Effect of nitrogen fertilizer application on rice yield. *Mod Agri.* **2015**, *12*, 44–45.
17. Zhou, J.; Liang, S.; Ponce, K.; Marundon, S.; Ye, G.Y.; Zhao, X.Q. Factors affecting head rice yield and chalkiness in indica rice. *Field Crop. Res.* **2015**, *172*, 1–10. [CrossRef]
18. Cong, X.H.; Shu, F.Z.; Ruan, X.M.; Luo, Y.X.; Wang, Y.L.; Xu, Y.Z.; Luo, Z.X. Effects of nitrogen application rate on nitrogen utilization and key enzymes of carbon and nitrogen metabolism in different rice varieties. *J. Henan Agric. Univ.* **2019**, *53*, 325–330.
19. Wang, Y.L.; Zhang, Y.P.; Zeng, Y.H.; Wu, H.; Xiang, J.; Chen, H.Z.; Zhang, Y.K.; Zhu, D.F. Effect of high temperature on differentiation and degradation of spikelets during panicle differentiation of rice. *Agri. China* **2015**, *36*, 724–731.
20. Ju, C.X.; Buresh, R.J.; Wang, Z.Q.; Zhang, H.; Liu, L.J.; Yang, J.C.; Zhang, J.H. Root and shoot traits for rice varieties with higher grain yield and higher nitrogen use efficiency at lower nitrogen rates application. *Field Crop. Res.* **2015**, *175*, 47–55. [CrossRef]
21. Yuan, S.; Nie, L.X.; Wang, F.; Huang, J.L.; Peng, S.B. Agronomic performance of inbred and hybrid rice cultivars under simplified and reduced-input practices. *Field Crop. Res.* **2017**, *210*, 129–135. [CrossRef]
22. Chen, T.Y.; Yuan, J.Q.; Liu, Y.Y.; Xu, K.; Guo, B.W.; Dai, Q.G.; Huo, Z.Y.; Zhang, H.C.; Li, G.H.; Wei, H.Y. Effects of different sowing dates on annual rice-wheat crop yield, quality and utilization of temperature and light resources in the lower reaches of Jianghuai River. *Acta Agron. Sin.* **2020**, *46*, 1566–1578.
23. Liu, K.; Yang, R.; Lu, J.; Wang, X.; Lu, B.; Tian, X.; Zhang, Y. Radiation use efficiency and source-sink changes of super hybrid rice under shade stress during grain-filling stage. *Agron. J.* **2019**, *111*, 1788–1798. [CrossRef]
24. Zhang, Y.; Tang, Q.; Zou, Y.; Li, D.; Qin, J.; Yang, S.; Chen, L.; Xia, B.; Peng, S. Yield potential and radiation use efficiency of super hybrid rice grown under subtropical conditions. *Field Crop. Res.* **2009**, *114*, 91–98. [CrossRef]
25. Liu, Q.H.; Wu, X.; Ma, J.Q.; Li, T.; Zhou, X.B.; Guo, T. Effects of high air temperature on rice grain quality and yield under field condition. *Agron.J.* **2013**, *105*, 446–454. [CrossRef]
26. Liang, C.G.; Chen, L.P.; Wang, Y.; Liu, J.; Xu, G.L.; Tian, L. High temperature at grain-filling stage affects nitrogen metabolism enzyme activities in grains and grain nutritional quality in rice. *Rice Sci.* **2011**, *18*, 210–216. [CrossRef]
27. Yin, M.; Liu, S.W.; Chu, G.; Xu, C.M.; Wang, D.Y.; Zhang, X.F.; Chen, S. Differences in yield and growth traits of different japonica varieties in the double cropping late season in the lower reaches of the Yangtze River. *Sci. Agric. Sin.* **2020**, *53*, 890–903.
28. Khalifa, A. Physiological evaluation of some hybrid rice varieties under different sowing dates. *Aust. J. Crop Sci.* **2009**, *3*, 178–183.

29. Zhang, J.; Zhang, H.C.; Huo, Z.Y.; Li, G.Y.; Dong, X.B.; Hua, J.; Guo, B.W.; Zhou, P.J.; Cheng, F.H.; Huang, D.S.; et al. Effects of cultivation methods on yield and utilization of temperature and light of late Japonica rice in southern double cropping rice areas. *Sci. Agric. Sin.* **2013**, *46*, 2130–2141.
30. Bai, H.Z.; Xiao, D.P.; Zhang, H.; Tao, F.L.; Hu, Y.H. Impact of warming climate, sowing date, and cultivar shift on rice phenology across China during 1981–2010. *Int. J. Biometeorol.* **2019**, *63*, 1077–1089. [CrossRef]
31. Lu, W.S.; Zeng, Y.J.; Shi, Q.H.; Pan, X.H.; Huang, S.; Shang, Q.Y.; Tan, X.M.; Li, M.Y.; Hu, S.X.; Zeng, Y.H. Changes in safe production dates and heat–light of resources of double cropping rice in Jiangxi province in recent 30 years. *Chin. J. Rice Sci.* **2016**, *30*, 323–334.
32. Xie, Y.Y.; Huang, S.E.; Tian, J.; Wang, Y.; Ye, Q. Spatial-temporal characteristics of thermal resources and its influence on the growth of double cropping rice in the middle and lower reaches of the Yangtze River. *Chin. J. Appl. Ecol.* **2016**, *27*, 2950–2958.
33. Wang, M.J.; Yin, M.; Chu, G.; Liu, Y.H.; Xu, C.M.; Zhang, X.F.; Wang, D.Y.; Chen, S. Ecological differences in yield, growth period and the utilization of temperature and light resources of double–cropping late japonica rice in the middle and lower reaches of the Yangtze River. *Chin. J. Rice Sci.* **2021**, *35*, 475–486.
34. Zhou, Y.J.; Li, X.X.; Cao, J.; Li, Y.; Huang, J.L.; Peng, S.B. High nitrogen input reduces yield loss from low temperature during the seedling stage in early-season rice. *Field Crop. Res.* **2018**, *228*, 68–75. [CrossRef]
35. Wei, X.J.; Xu, J.F.; Jiang, L.; Wang, H.J.; Zhou, Z.L.; Zhai, H.Q.; Wan, J.M. Genetic analysis for the diversity of heading date of cultivated rice in China. *Acta Agron. Sin.* **2012**, *38*, 10–22. [CrossRef]
36. Chen, S.; Ge, Q.Y.; Chu, G.; Xu, C.M.; Yan, J.X.; Zhang, X.F.; Wang, D.Y. Seasonal differences in the rice grain yield and nitrogen use efficiency response to seedling establishment methods in the Middle and Lower reaches of the Yangtze River in China. *Field Crop. Res.* **2017**, *205*, 157–169. [CrossRef]
37. Liu, J.; Wang, X.L.; Zhang, Y.L.; Deng, B.; Wang, Z.; Zeng, K. Effects of sowing date on growth, development and yield formation of one-season rice in Jianghuai. *Jiangsu Agric. Sci.* **2020**, *48*, 49–55.
38. Yao, Z.L.; Zhou, B.Y.; Zhang, H. Effects of staging sowing on rice growth characteristics and yield in central Guizhou. *Guizhou Agric. Sci.* **2019**, *47*, 13–17.
39. Yuan, J.Q.; Liu, Y.Y.; Xu, K.; Li, G.H.; Chen, T.Y.; Zhou, Y.H.; Guo, B.W.; Huo, Z.Y.; Dai, Q.G.; Zhang, H.C. Nitrogen density treatment improved resource utilization and yield of late planting japonica rice. *Acta Agron. Sin.* **2022**, *48*, 667–681. [CrossRef]
40. Sun, J.J.; Zhang, H.C.; Yin, H.Q.; Chen, B.; Guo, B.W.; Wei, H.Y.; Dai, Q.G.; Wang, S.X.; Chen, X.G.; Jiang, Y.H.; et al. Effects of planting date on yield, growth period and temperature and light utilization of machine-inserted rice in different ecological regions. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 113–121.
41. Sun, J.J.; Zhang, H.C.; Wang, S.X.; Guo, B.W.; Chen, B.; Wei, H.Y.; Dai, Q.G.; Xu, K.; Yin, H.Q.; Huo, Z.Y.; et al. Effect of sowing date on growth characteristics of different varieties of machine-inserted rice. *Trans. Chin. Soc. Agric. Eng.* **2015**, *31*, 76–86.
42. Deng, F.; Zhang, C.; He, L.H.; Liao, S.; Li, Q.P.; Li, B.; Zhu, S.L.; Gao, Y.T.; Tao, Y.F.; Zhou, W.; et al. Delayed sowing date improves the quality of mechanically transplanted rice by optimizing temperature conditions during growth season. *Field Crop. Res.* **2022**, *281*, 108493. [CrossRef]
43. Huang, M.; Fang, S.L.; Cao, F.B.; Chen, J.N.; Shan, S.L.; Liu, Y.; Lei, T.; Tian, A.; Tao, Z.; Zhou, Y.B. Early sowing increases grain yield of machine-transplanted late-season rice under single-seed sowing. *Field Crop. Res.* **2020**, *253*, 107832. [CrossRef]
44. Huang, M.; Cao, J.L.; Zhang, R.C.; Chen, J.N.; Cao, F.B.; Liu, L.S.; Fang, S.L.; Zhang, M. Delayed sowing does not improve palatability-related traits in high-quality rice. *Food Chem. Adv.* **2022**, *1*, 100096. [CrossRef]
45. Jiang, D.; Yu, W.Y.; Lu, H.C.; Liu, G.; Chao, D.P. Effects of seeding time on the population growth characteristics and yield in direct-seeded rice-Nanjing9108. *Shanghai Agric. Sci. Tech.* **2020**, *1*, 48–49.
46. Li, X.F.; Jia, Y.; Huang, Y.C.; Zang, X. Effects of seeding time on grain yield components and growth duration in different rice varieties. *Chin. J. Ecol.* **2004**, *05*, 98–100.
47. Yao, Y.; Huo, Z.Y.; Zhang, H.C.; Xia, Y.; Ni, X.C.; Dai, Q.G.; Xu, K.; Wei, H.Y. Effects of sowing dates in different ecological regions on growth period and utilization of temperature and light in direct sowing rice. *Sci. Agric. Sin.* **2012**, *45*, 633–647.
48. Zhou, Z.L.; Wei, X.J.; Jiang, L.; Liu, K.; Xu, D.Y.; Zhai, H.Q.; Wan, J.M. Genetic analysis of heading date of Japonic a rice varieties in southwest China. *Chin. J. Rice Sci.* **2011**, *18*, 287–296. [CrossRef]
49. Hu, X.V.; Huang, Y.; Sun, W.J.; Yu, L.F. Shifts in cultivar and planting date have regulated rice growth duration under climate warming in China since the early 1980s. *Agric. For. Meteorol.* **2017**, *247*, 34–41. [CrossRef]
50. Xu, K.; Sun, Z.; Huo, Z.Y.; Dai, Q.G.; Zhang, H.C.; Liu, J.; Song, Y.S.; Yang, D.L.; Wei, H.Y.; Wu, A.G.; et al. Effects of seeding date and variety type on yield, growth stage and utilization of temperature and sunshine in rice. *Sci. Agric. Sin.* **2013**, *46*, 4222–4233.
51. Zhao, C.; Huang, H.; Qian, Z.H.; Jiang, H.X.; Liu, G.M.; Xu, K.; Hu, Y.J.; Dai, Q.G.; Huo, Z.Y. Effect of side deep placement of nitrogen on yield and nitrogen use efficiency of single season late japonica rice. *J. Integr. Agric.* **2021**, *20*, 1487–1502. [CrossRef]
52. Lin, D.X.; Fan, X.H.; Hu, F.; Zhao, H.T.; Luo, J.F. Ammonia Volatilization and Nitrogen Utilization Efficiency in Response to Urea Application in Rice Fields of the Taihu Lake Region, China. *Pedosphere* **2007**, *17*, 639–645. [CrossRef]
53. Liu, L.J.; Liu, C.Y.; Wang, Z.H. Effects of different cultivation methods and nitrogen application on rice yield. *Hebei Agric. Sci.* **2015**, *54*, 2061–2064.
54. Wu, S.N. Effect of nitrogen application on yield of high-quality japonica rice. *North Rice* **2017**, *47*, 33–35.

55. Guo, X.H.; Lan, Y.C.; Xu, L.Q.; Yin, D.W.; Li, H.Y.; Qian, Y.D.; Zheng, G.P.; Dong, Y. Effects of nitrogen application rate and hill density on rice yield and nitrogen utilization in sodic saline-alkaline paddy fields. *J. Integr. Agric.* **2021**, *20*, 540–553. [CrossRef]
56. Melissa, A.F.; Susan, R.M.; Robert, D.H. Not just a grain of rice: The quest for quality. *Trends Plant Sci.* **2008**, *14*, 133–139.