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Weak Solar Radiation Significantly Decreased Rice Grain Yield and Quality—Simulated Shading Could Be a Foretell for Climate Change

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Abstract: The southern rice-growing region plays a crucial role in ensuring national food security in China. However, rice production in this area is often affected by unfavorable weather conditions such as rainy and dim days, which significantly impact rice yield. Therefore, we conducted two field experiments to explore and compare the effects of climate variations and simulated shading on rice yield and quality. The results indicated that (a) both interannual climate variation and simulated shading had adverse effects on rice yield and quality, (b) the impact of interannual climate variation on yield was less severe compared with simulated shading, but it had a more significant negative effect on rice quality, and (c) different cultivars/quality groups of rice exhibited variations in response to weak solar radiation, with high-quality rice being more susceptible. The findings suggest that in the production of high-quality rice, it is important to select cultivars that are resilient to interannual climate variation and to develop supporting cultivation techniques to cope with growing incidence of weakened solar radiation in the future. Breeders can try to tap into potential weak-light-resistance genes and cultivators can try to use different cultivation methods to determine the optimal water and fertilizer regimes.

Keywords: interannual climate variation; simulated shading; rice grain yield; grain quality; cultivar

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1. Introduction

Due to the impact of air pollution and other effects caused by human activities, abnormal weather years are occurring more frequently [1]. The continuous rainy weather in the double-cropping rice region of Jiangxi, China in 2020 caused a large-scale reduction in rice production, which is quite thought-provoking. Decreasing solar radiation in dim leads to lower air temperatures, potentially causing a series of interannual climate variations that impact the global ecosystem [2]. The most direct result of this is that the growth of plants will be affected, which may lead to global food shortages. For instance, numerous studies have found that low solar radiation reduces rice yield and quality, challenging human needs.

Suitable temperature and sufficient solar radiation in the heading stage are critical for rice quality formation [3]. During this stage, encountering weak radiation or low temperature hinders panicle differentiation, resulting in a slow grain-filling rate, delayed maturity, or even failure to mature properly [4]. Insufficient photosynthetic products, starch accumulation, and a decrease in rice quality may occur, posing a serious threat to rice production [5]. Over the years, extensive explorations have been carried out regarding the effects of temperature and solar radiation on rice yield and quality, and many valuable theories have been proposed [6–9]. However, these studies have mainly focused on the characteristics of the rice source–sink system, the photosynthetic process, and changes in protective enzyme

activity. Comparatively scarce research has compared the response of rice cultivars of different quality to natural interannual climate variation and simulated shading.

The southern rice-growing region, represented by Jiangxi Province, is the main production area of rice in China and plays a crucial role in ensuring national food security. However, rice crops in this region often encounter unfavorable weather conditions such as rainy and cloudy days, which severely affect yield [10,11]. Interannual variations of dim weather mainly manifest as a coupling of low temperatures and weak solar radiation, occurring in stages with alternating periods of overcast and sunny weather [12]. Simulated shading, on the other hand, provides continuous weak solar radiation as a single stress factor, typically without accompanying changes in temperature but simply altering the solar radiation in the experimental area. Therefore, the variations in rice yield and quality resulting from simulated shading and interannual climate variation may be different.

The indicators of rice quality include milling quality (brown rice recovery, milled rice recovery, and head rice recovery), appearance quality (chalky grain rate, chalkiness, grain length, grain width), and taste quality (amylose content, protein content, gel consistency, starch RVA (Rapid Visco Analyzer) spectrum, and textural properties) [13]. Rice with high head rice recovery and less chalkiness has better milling quality. Both the coupled effects of weak solar radiation and low temperature caused by interannual climate variations [14] and single weak solar radiation induced by simulated shading [15] lead to reduced grain yield, significantly decreasing milled rice recovery and head rice recovery. Interannual climate variation significantly reduces the content of amylose and gel consistency and increases protein content [16], resulting in decreased cooking and eating quality. It also significantly reduces peak viscosity, hot slurry viscosity, and disintegration value, while increasing final viscosity, subtractive value, and peak time [17]. The main factor affecting chalkiness is the rice cultivar, but it is also influenced to some extent by temperature and solar radiation [18]. Weak solar radiation significantly increases chalkiness, chalky grain rate, and chalk area in rice [19]. However, some studies have shown that when solar radiation decreases, chalkiness may be reduced. Shading at 50% before the reproductive stage significantly reduces the chalky grain rate [20]. Although low temperature during the grain filling period does not have as significant an impact on chalkiness as high temperature, it still increases the occurrence of chalkiness.

The timing of weak solar radiation affects rice yield and quality differently [21]. Some studies suggest that within 21 days from heading to grain filling, when grain filling is rapid, low temperature and solar radiation have a greater impact on milling quality [22]. Solar radiation also has a greater impact on chalkiness and chalky grain rate during days 8–14 and days 15–21 of grain filling, but the impact diminishes over time. Research conducted by Zeng Yanhua et al. [23] found that low temperature during the early period (0–15 days after flowering) had the greatest impact on milling quality. Zhu et al. [24] observed a slight increase in amylose content under low-temperature treatment 3 days after flowering, possibly due to the formation of more large granules of starch under temporary low temperatures. These large-sized granules usually have a higher proportion of highly branched amylopectin with long chains that bind well with iodine. As the duration of low-temperature treatment progresses, the impact on amylose content gradually decreases, with the greatest impact occurring within the first 21 days of grain filling [23]. Low temperature and weak solar radiation during the first 21 days of grain filling have a significant impact on gel consistency and the RVA spectrum, but the impact diminishes thereafter. Staged sowing experiments have shown that the main period of low-temperature impact on the RVA spectrum is within 10 days after heading [25]. Shading treatment for 10 days after heading also increases protein content [26]. This suggests that during the early stage of rapid grain filling, external factors exert a greater influence on cooking and eating quality. Weak solar radiation has become a major obstacle hindering improvements in rice yield and quality in southern China. Currently, there is limited research on how the irregular weak solar radiation and low temperature induced by climate change during full heading and their interaction affect rice yield and quality, or on the variations in response of different rice

cultivars to interannual climate variation and simulated shading. In-depth research on the effects of weak solar radiation on rice yield and quality has the potential to accelerate the breeding of rice cultivars resistant to weak solar radiation and provide theoretical reference for stress-tolerant rice cultivation.

Overall, we assume that the impact of climate on rice yield and quality may become more severe, and varieties with different qualities will respond differently. We designed two sets of field experiments, which were carried out from 2019 to 2021, to explore the following three scientific concerns: (1) the effect of natural weak solar radiation and simulated shading on rice yield and quality; (2) the effect of weak solar radiation on the yield and quality of rice of different cultivars; (3) the differences in rice yield and quality responses to interannual climate variation and simulated shading.

2. Materials and Methods

2.1. Experimental Site

From 2019 to 2021, two sets of field experiments were conducted at the Rice Science and Technology Backyard (115°09′48″ E, 28°23′05″ N) in Zengjia Village, Sixi Town, Shanggao County, Jiangxi Province, China. The experimental site was located in the main rice-producing region of Jiangxi Province, characterized by a subtropical monsoon climate, with an altitude of 52 m. The soil was quaternary red clay, developed as paddy soil, with early rice being the previous crop. The soil texture was sandy loam, and the physicochemical properties of the top 20 cm soil layer were as follows: pH 5.45, organic matter 30.5 $g \cdot kg^{-1}$, total nitrogen 1.86 $g \cdot kg^{-1}$, available nitrogen 169.6 $mg \cdot kg^{-1}$, available phosphorus 20.1 $mg \cdot kg^{-1}$, and available potassium 115.7 $mg \cdot kg^{-1}$.

2.2. Experiment Design and Field Management

Experiment 1 was conducted from 2019 to 2021, in a randomized block design with two factors: cultivar and year (interannual variation in temperature and solar radiation). The tested rice cultivars were Wanxiangyou 982 and Yexiangyoulisi. Both of these are leading high-quality cultivars in the region, meeting at least Grade 2 of the national standard.

Experiment 2 was conducted in 2021 to testify the effects of weak solar radiation on the grain yield and quality of different cultivars. Eight rice cultivars were tested, divided into a high-quality group and a general-quality group, with four cultivars in each group. The high-quality group included Nongxiang 42, Taifengyou 208, Wanxiangyou 982, and Yexiangyoulisi. The rice quality of the high-quality cultivars met at least Grade 2 of the national standard. The general-quality group included Huajing, Jiyou T025, Jiyouhang 1573, and Keyou 5. The rice quality of the general-quality cultivars met at least Grade 3 of the national standard. Experiment 2 utilized a split-plot design with two factors: a main plot for cultivars and a sub-plot for shading during full heading. The cultivars were the high-quality group and general-quality group, and the shading treatments included no shading (S0) and 60~70% shading (S1) during full heading. Shading was controlled by a black fiberglass net, installed above the rice plants at a height of 1.0 m to ensure uniform temperature and humidity within the canopy while maintaining ventilation. The mean solar radiation above the shading net was measured at 9:00 a.m., 12:00 p.m., and 3:00 p.m., and the actual mean shading ratio for each shading treatment was determined to be 60~70%.

Within 44 days after heading, the cumulative temperature in 2020 was 885.3 °C and the cumulative solar radiation was 402.7 MJ/m^2, which were significantly lower compared with 2019 and 2021 (Table 1). The daily mean temperature variation between 2019 and 2020 followed a consistent trend (Figure 1). Moreover, the daily mean temperature and solar radiation within the 44 days after heading were lower in 2020 compared with 2019 and 2021. Additionally, the solar radiation exhibited significant fluctuations, indicating a year with naturally weak solar radiation.

Table 1. Differences in accumulated and daily mean temperature and solar radiation between 2019, 2020, and 2021 during 44 days after full heading stage (n = 44).

Full Heading Stage	Temperature (°C)		Solar Radiation (MJ/m^2)	
	Accumulated	Mean	Accumulated	Mean
2019	1089.5	24.8 a	589.7	13.4 a
2020	885.3	20.1 b	402.7	9.4 b
2021	1083.5	24.6 a	666.4	14.8 a
Single-factor analysis of variance				
Year		21.102 **		11.303 **

Different lower-case letters indicate statistically significant differences ($p < 0.05$) between years. ** Significant at 0.01 probability level.

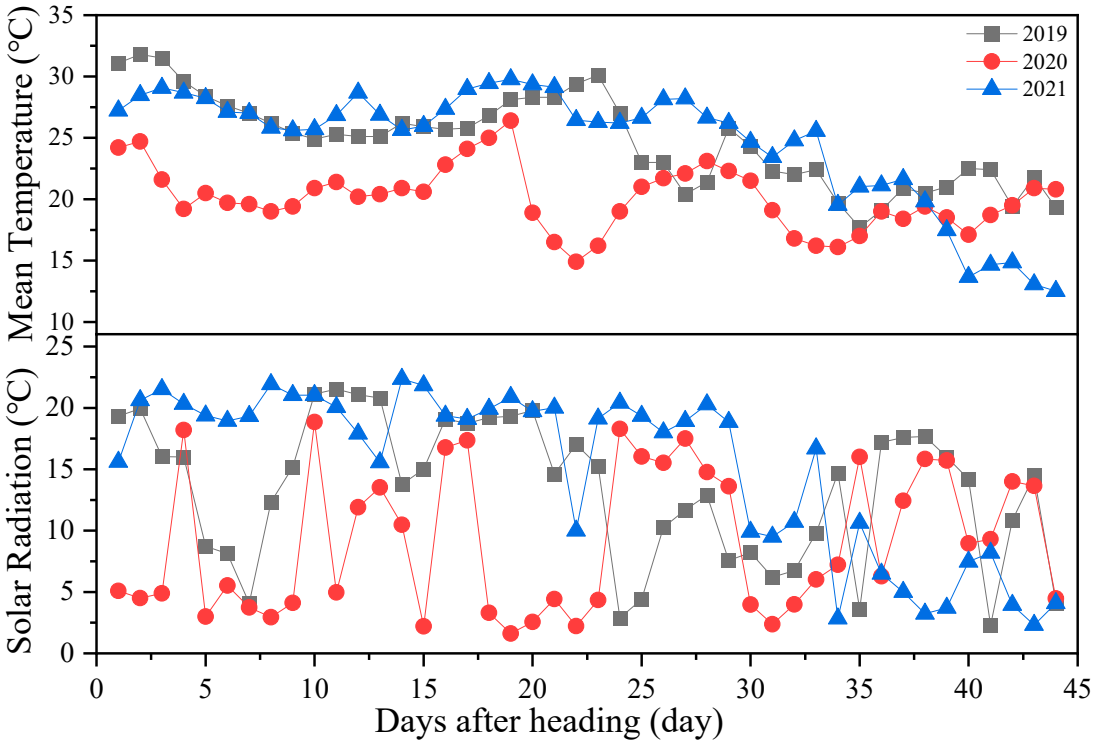


Figure 1. Everyday mean air temperature and solar radiation during 44 days after full heading stage in 2019, 2020, and 2021.

Experiment plots had an area of 15 m^2 (3 m × 5 m) and were replicated three times. In all treatments, the nitrogen fertilizer application rate was 165 kg N·hm^{-2}, phosphorus fertilizer was applied at a rate of 82.5 kg P_2O_5·hm^{-2}, and potassium fertilizer was 165 kg K_2O·hm^{-2}. Nitrogen fertilizer was applied in a 5:3:2 ratio as basal, tillering, and panicle fertilizer. The phosphorus fertilizer was applied entirely as basal fertilizer, and the potassium fertilizer was applied in a ratio of 5:5 as basal and panicle fertilizer. The basal fertilizer, tillering fertilizer, and panicle fertilizer were applied 1 day before transplanting, 7 days after transplanting, and at the heading stage, respectively (Supplementary Table S2).

The sowing was carried out from 22 June to 25 June, with seedlings reaching an age of 23 days. Transplanting took place from 15 July to 18 July. Heading occurred from 8 September to 15 September, and maturity was reached from 20 October to 2 November (Table 2). The planting density was 25 cm × 14 cm. For hybrid rice, two seedlings were planted in each hole, and for conventional rice, four seedlings were planted in each hole. Water management, pest and disease control, and weed management followed local high-yielding cultivation requirements.

Table 2. Rice cultivars used and their growth periods in experiments from 2019 to 2021.

Year	Cultivar	Sowing Date	Transplantation	Full Heading	Maturity
2019	Yexiangyoulisi	22 June	15 July	12 September	25 October
	Wanxiangyou 982	22 June	15 July	12 September	25 October
2020	Yexiangyoulisi	24 June	17 July	15 September	2 November
	Wanxiangyou 982	24 June	17 July	15 September	2 November
2021	Huajing	25 June	18 July	13 September	24 October
	Jiyou T025	25 June	18 July	8 September	20 October
	Jiyouhang 1573	25 June	18 July	11 September	22 October
	Keyou 5	25 June	18 July	8 September	20 October
	Nongxiang 42	25 June	18 July	13 September	24 October
	Taifengyou 208	25 June	18 July	8 September	24 October
	Wangxiangyou 982	25 June	18 July	11 September	22 October
	Yexiangyoulisi	25 June	18 July	12 September	24 October

2.3. Grain Sampling, Preparation, and Yield Determination

At maturity, 100 hills were harvested from the center of each plot for yield measurement. After threshing, impurities and empty grains were removed, and the yield was adjusted to 14.0% moisture content. According to national standards, grain samples were cleaned, sun-dried, and stored in a dark and dry place for 3 months. They were then dried at 45 °C for 48 h before quality determination could be conducted.

2.4. Grain Quality Analysis

Milling quality (brown rice recovery, milled rice recovery, and head rice recovery), appearance quality (chalky grain rate, chalkiness, grain length, grain width), and taste quality (amylose content, protein content, gel consistency, starch RVA (Rapid Visco Analyzer) spectrum, and textural properties given in Table 3 were analyzed in this study. The brown rice recovery, milled rice recovery, head rice recovery, chalky grain rate, chalkiness, grain length, and grain width were determined according to the national quality standards for rice (GB/T 17891-2017 [27]: High-Quality Rice, General Administration of Quality Supervision, Inspection and Quarantine, People's Republic of China, 2017). A rice grain milling machine (JZK 8014 model rice mill, Bühler Co., Uzwil, Switzerland) was used to dehull 130 g of grain samples, producing brown rice. Then, the milling machine precision was adjusted to further mill the brown rice into milled rice. All head rice grains were manually selected, and the head rice recovery was calculated. Grains with chalky areas were selected out of 100 grains of head rice and their numbers were counted three times to calculate the chalky grain rate. Additionally, 30 grains of head rice were chosen to measure grain length and width using a vernier caliper, repeated three times. The brown rice recovery (BRR, %), milled rice recovery (MRR, %), head rice recovery at milling (HRR, %), and chalky grain rate (CGR, %) were calculated as follows:

$$BRR(\%) = \frac{\text{brown rice weight (g)}}{\text{rice grain weight (g)}} \times 100\%$$

$$MRR(\%) = \frac{\text{milled rice weight (g)}}{\text{rice grain weight (g)}} \times 100\%$$

$$HRR(\%) = \frac{\text{head rice weight (g)}}{\text{rice grain weight (g)}} \times 100\%$$

$$CGR\ (\%) = \frac{\text{number of chalky rice}}{\text{number of head rice}} \times 100\%.$$

Table 3. Rice texture properties and definition.

Parameters	Sensory Definition	Instrument Definition	Unit
Firmness (g)	The force of the tooth to squeeze the sample.	The maximum force peak of the first extrusion cycle.	Newtons (N)
Stickiness	When chewing rice, the adhesion of rice grains to the upper jaw, teeth, tongue and other contact surfaces.		
Cohesiveness	The internal contraction force of the sample (the higher the value, the stronger the cohesion).	The ratio of the positive peak area of the second extrusion cycle to the positive peak area of the first extrusion cycle (must be a downward pressure test).	Ratio, dimensionless
Chewiness	The energy required to chew a solid sample.	Calculated value = Firmness value × cohesion × elasticity	Joules (J)
Springiness	The ratio of deformed samples to their original state when the extrusion pressure is removed.	The height of the sample recovered after the end of the first extrusion and before the start of the second extrusion.	Meters (m)

The milled rice was coarsely ground using a pulverizer (FZ102, Tianjin, China) and then finely ground in a ball mill (MM 200, Retsch, Haan, Germany) for the determination of amylose content, gel consistency, and protein content. The analysis of amylose content followed the national standard method (GB/T 15683-2008 [28]: General Administration of Quality Supervision, Inspection and Quarantine, People's Republic of China, 2008). The principle of analysis involved the formation of a pure blue compound when amylose reacted with iodine, exhibiting specific absorption peaks. The chemical value of gel consistency was determined according to GB/T 22294-2008 [29]. The crude protein content was determined using the Kjeldahl method of nitrogen determination (FOSS, Hillerød, Denmark) according to the national standard GB 5009.5-2016 [30]. Each sample was tested three times, and the mean value was taken. The protein concentration (PC, g kg^{-1}) was calculated as follows:

$$\text{PC (g kg}^{-1}\text{)} = \text{Nitrogen concentration (g kg}^{-1}\text{)} \times 5.95$$

where 5.95 is the conversion factor for calculating protein concentration from N concentration.

The starch RVA spectrum values were determined using an RVA-TecMaster Rapid Visco Analyzer (Perten Instruments, Stockholm, Sweden). A 3.00 g sample of 100-mesh rice flour with a moisture content of 12.0% was weighed, and 25.0 g distilled water was added. During the stirring and testing, the temperature in the container was maintained at 50 °C for 1 min, then increased to 95 °C at a rate of 11.84 °C per minute (3.75 min) and held for 2.5 min, followed by a decrease to 50 °C at a rate of 11.84 °C per minute, where it was then held for 1.4 min. The stirring speed of the mixer was 960 r min^{-1} for the first 10 s and was then maintained at 160 r min^{-1}. The RVA spectrum was expressed as peak viscosity (PV), hot slurry viscosity (HSV), disintegration value (DV), final viscosity (FV), subtractive value (SV), peak time (PT), and gelatinization temperature (GT).

The rice texture properties were measured using a TVT-6700 Food Texture Analyzer (Perten Instruments Co., Stockholm, Sweden). The sample preparation followed the national standard (GB/T 15682-2008 [31], Grain and Oil Inspection and Evaluation Method of Sensory Quality for Cooked Rice and Rice Products). For this process, 30.0 g of head rice was weighed into a stainless-steel container and rinsed with running water until it was clean. Then, 48.0 g of water was added at a water-to-rice ratio of 1.6:1, and the mixture was soaked for 30 min. Subsequently, the stainless-steel container was sealed with filter paper, and the rice was cooked in an electric rice cooker equipped with a taste analyzer, for 30 min. After the rice was cooked, it was allowed to steam for 10 min, cooled in a cooling box for 30 min, and then left for 2 h. Firmness, stickiness, cohesiveness, chewiness, and springiness were measured. For each measurement, three random grains were taken from the middle

layer and placed on the loading tray at a 120° angle. Each sample was measured six times, excluding the highest and lowest results. The mean value and deviation were calculated based on four measurements. Specific indicators and definitions can be found in Table 3.

2.5. Data Analysis

All data analysis and calculations were conducted in the data analysis system (SPSS 27.0) using the generalized linear model (GLM). The Shapiro–Wilk test was performed first to check for normal distribution. If the data did not follow a normal distribution, non-parametric tests were utilized. The factors examined in this study included year, shading, and cultivar, and the interaction between the factors were also assessed.

3. Results

3.1. Effect of Natural Interannual Climate Variations on Rice Yield and Quality

The rice cultivars Wanxiangyou 982 and Yexiangyoulisi showed no yield difference between 2019 and 2021; however, a significant yield reduction was observed in 2020 (Figure 2). Compared with 2019, Wanxiangyou 982 had a yield reduction rate of 20.8%, while the yield of Yexiangyoulisi was reduced by 15.0%. In 2020, despite the worse yield of both cultivars, the Yexiangyoulisi cultivar nevertheless yielded better than the Wanxiangyou 982 cultivar (Figure 2). There was no interaction between the two cultivars in terms of milled rice recovery, head rice recovery, grain length, and grain width across different years (Table 4). Brown rice recovery, milled rice recovery, and head rice recovery decreased in years with weak solar radiation (2020), while grain length and width were primarily influenced by the cultivar. There was an interaction between cultivar and year regarding chalky grain rate and chalkiness. Wanxiangyou 982 had a higher chalky grain rate and chalkiness compared with Yexiangyoulisi, and in years with weak solar radiation, the chalkiness and chalky grain rate of Wanxiangyou 982 significantly increased, while there was no impact on Yexiangyoulisi. The rice protein content showed an interaction between cultivar and year (Table 4). In 2020, the protein content of Wanxiangyou 982 significantly increased, while Yexiangyoulisi had a higher protein content in 2021 (normal year). There was no interaction between year and cultivar regarding amylose content or gel consistency. Both Wanxiangyou 982 and Yexiangyoulisi had reduced amylose content and gel consistency in years with weak solar radiation (Table 4).

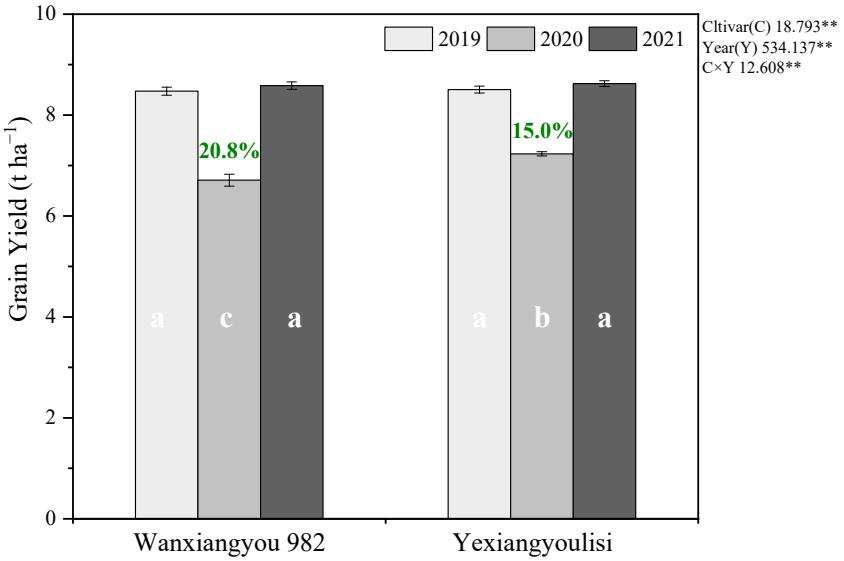


Figure 2. Average rice grain yield (2019, 2020, and 2021) as affected by cultivar and year (n = 3). ** significant at 0.01 probability level. Vertical bars represent standard error of the mean. Bars labeled with different lowercase letters indicate statistically significant differences ($p < 0.05$) between interannual climate variation within the same cultivar.

Table 4. Absolute values of rice grain quality of 2 cultivars given as amylose content (AC, %), protein content (PC, %), gel consistency (GC, mm). Texture properties are given as firmness (Fi), stickiness (St), springiness (Sp), cohesiveness (Co), and chewiness (Ch). Appearance quality is given as brown rice recovery (BRR, %), milled rice recovery (MRR, %), head rice recovery (HRR, %), grain length (GL, mm), grain width (GW, mm), chalky grain recovery (CGR, %), and chalkiness (Ch) and starch RVA spectrum is given as peak viscosity (PV), hot slurry viscosity (HSV), disintegration value (DV), final viscosity (FV), subtractive value (SV), peak time (PT), and gelatinization temperature (GT) as affected by year in 2019, 2020, and 2021 (n = 3).

Cultivar	Year	Eating Quality			Texture Properties					Appearance Quality							Starch RVA Spectrum					
		AC	PC	GC	F	St	Sp	Co	Ch	BRR	MRR	HRR	GL	GW	CGR	C	PV	HSV	DV	FV	SV	PT	GT
Wanxiangyou 982	2019	18.0 ab	6.7 c	74.3 a	2375 c	−164.0 c	0.84 a	0.45 b	1033 bc	79.2 b	68.8 c	60.2 c	7.0 a	2.0 a	8.9 b	2.4 b	3880 a	2105 a	1774 b	3077 b	−802 d	5.5 d	85.0 b
	2020	17.3 c	8.6 a	69.7 bc	2842 a	−89.6 ab	0.83 a	0.56 a	1472 a	77.9 c	66.3 d	56.5 e	7.0 a	2.0 a	13.9 a	3.9 a	2854 e	1723 b	1131 e	2412 e	−442 c	5.6 c	80.3 c
	2021	18.0 ab	8.1 b	73.5 a	2783 a	−575 e	0.82 a	0.34 c	899 c	/	/	58.2 d	7.0 a	1.9 a	11.0 b	2.8 b	3504 c	1575 c	1930 a	2573 d	−932 e	5.7 c	83.8 b
Yexiangyoulisi	2019	18.2 ab	6.9 c	69.3 bc	2121 d	−110.7 b	0.81 a	0.46 b	968 c	81.3 a	72.8 a	68.1 a	6.9 a	1.8 b	4.3 c	1.1 c	3734 b	2166 a	1568 c	3412 a	−322 b	5.9 b	87.7 a
	2020	17.9 b	7.8 b	67.3 c	2280 c	−72.5 a	0.78 a	0.50 b	1140 b	80.4 ab	70.6 b	65.0 b	6.9 a	1.8 b	5.4 c	1.3 c	2392 f	1487 c	904 f	2314 e	−78 a	6.0 b	88.7 a
	2021	18.4 a	8.6 a	71.9 ab	2616 b	−474 d	0.82 a	0.37 c	931 c	/	/	67.2 a	7.0 a	1.8 b	5.5 c	1.4 c	3053 d	1612 bc	1441 d	2929 c	−124 a	6.3 a	89.3 a
Two-factor analysis of variance																							
Cultivar (C)		**	ns	**	**	**	ns	ns	**	**	**	**	ns	**	**	**	**	ns	**	**	**	**	**
Year (Y)		**	**	**	**	**	ns	**	**	ns	**	**	ns	ns	**	**	**	**	**	**	**	**	**
C × Y		ns	**	ns	**	**	ns	ns	**	ns	ns	ns	ns	ns	**	**	**	**	**	**	**	*	**

Different lower-case letters indicate statistically significant differences ($p < 0.05$) between interannual climate variation within the same rice cultivar. * Significant at 0.05 probability level. ** Significant at 0.01 probability level. ns: not significant.

Starch RVA spectrum showed an interaction between cultivar and year (Table 4). Overall, in the year with weak solar radiation, peak viscosity, hot slurry viscosity, disintegration value, and final viscosity decreased. Compared with 2019, peak time and subtractive value significantly increased for Wanxiangyou 982 in 2020, and subtractive value significantly increased for Yexiangyoulisi. Compared with 2021, peak time showed no change for Wanxiangyou 982 in 2020, and for Yexiangyoulisi, it showed a significant increase. The gelatinization temperature varied between the two cultivars, with Wanxiangyou 982 showing a significant decrease in the year with weak solar radiation, while Yexiangyoulisi remained unaffected (Table 4). In terms of textural properties, year and cultivar had no impact on springiness, while the year with weak solar radiation showed significantly increased cohesiveness, chewiness, and stickiness for both cultivars. Firmness showed different trends between the two cultivars, with Wanxiangyou 982 experiencing an increase in the year with weak solar radiation, while Yexiangyoulisi showed no difference or a decrease (Table 4).

3.2. Effect of Simulated Shading on the Yield of Eight Rice Cultivars

The mean daily temperature in 2021 was 24.6 °C, and the mean daily solar radiation was 14.6 MJ/m^2, which showed no significant difference compared with 2019 but was significantly higher than 2020. After simulated shading was applied to the eight cultivars, the rice yield showed a significant decrease. Among them, Nongxiang 42 had the lowest decrease, which was 38.9%, and Wanxiangyou 982 had the highest decrease, which was 54.8% (Figure 3).

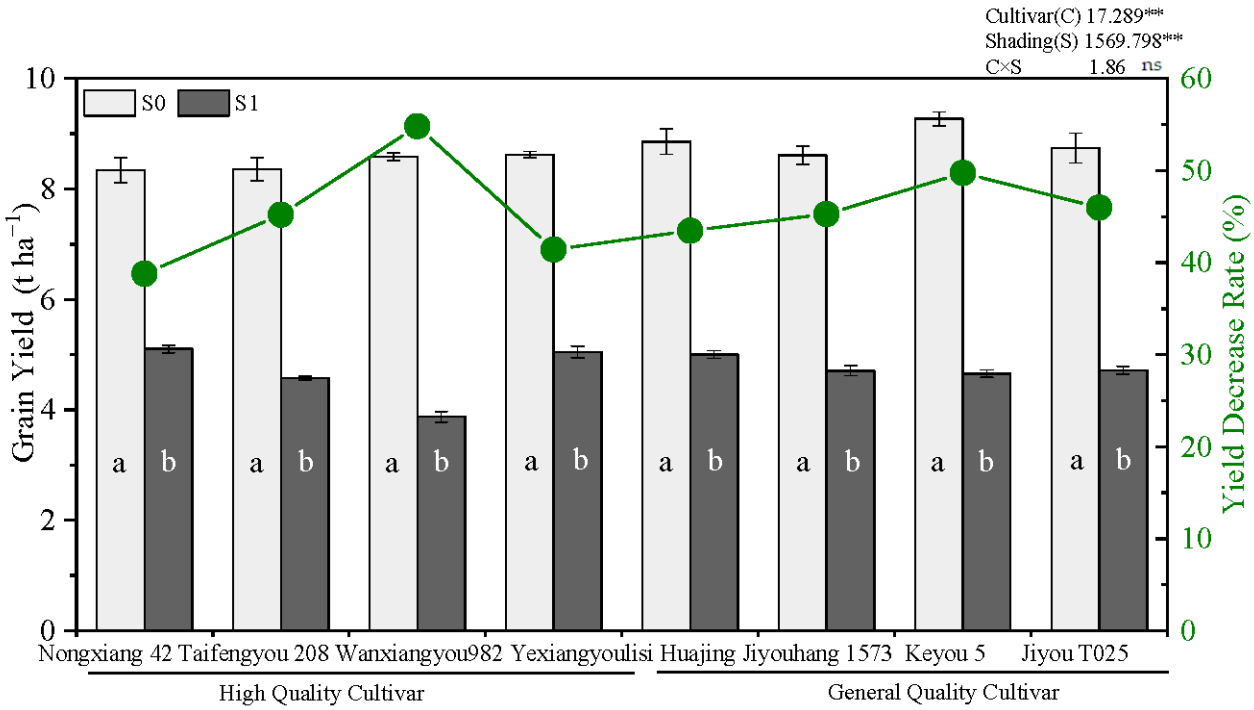


Figure 3. Average rice grain yield (2021) as affected by cultivar and shading treatment (n = 3). ** significant at 0.01 probability level; ns: not significant. Vertical bars represent standard error of the mean. Bars labeled with different lowercase letters indicate statistically significant differences ($p < 0.05$) between shading treatments within the same cultivar.

3.3. Effect of Simulated Shading on the Quality of High-Quality Rice Group

A total of eight rice cultivars cultivated in 2021 were divided into a high-quality group and a general-quality group. There was no interaction between the year and cultivar group for the appearance and milling quality indicators (Table 5). Simulated shading slightly reduced the milled rice recovery of both groups but had no impact on head rice recovery.

Simulated shading in 2021 had no effect on grain length or width or the chalkiness of either group, and the variation was mainly associated with the cultivar (Table 5). As for taste quality, shading had no effect on gel consistency in either group (Figure 4), but it significantly increased the protein content. Except for Jiyouhang 1573, the amylose content of the other seven cultivars significantly decreased after shading.

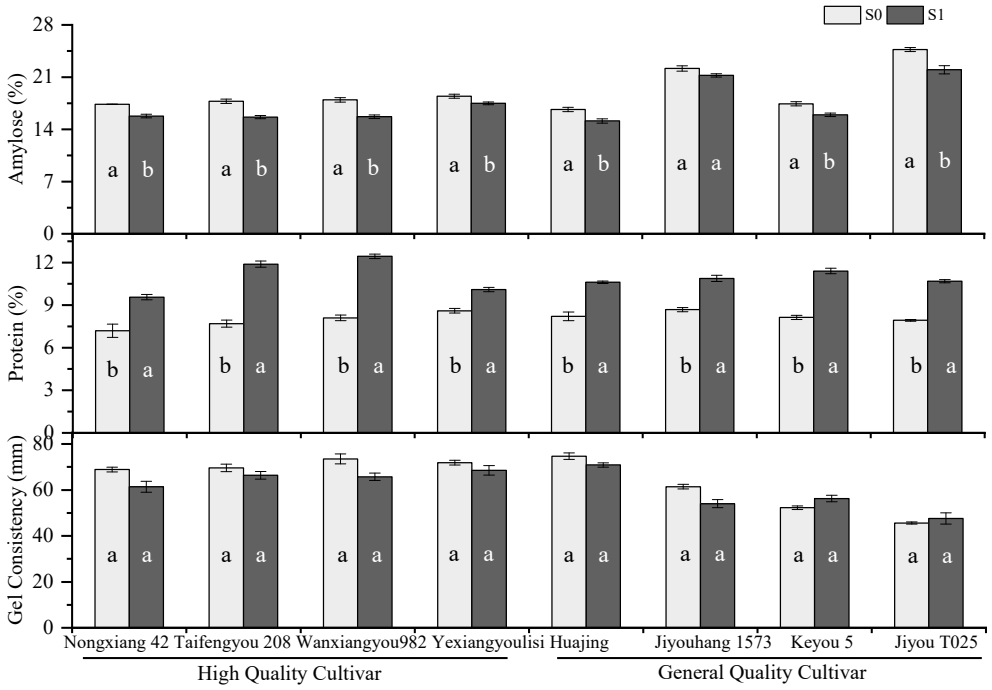


Figure 4. Amylose content, protein content, and gel consistency as affected by cultivar and shading treatment in 2021 (n = 3). Vertical bars represent standard error of the mean. Bars labeled with different lowercase letters indicate statistically significant differences ($p < 0.05$) between shading treatments within the same cultivar.

Table 5. Absolute value of rice grain appearance quality of 8 tested cultivars, given as brown rice recovery (HRR, %), head rice recovery (HRR, %), head rice recovery (HRR, %), grain length (GL, mm), grain width (GW, mm), chalky grain recovery (CGR, %), and chalkiness (Ch) as affected by different shading treatments (S) in 2021 (n = 3).

Quality	Cultivar	S	BRR	MRR	HRR	GL	GW	CGR	Ch
High quality	Nongxiang 42	S0	81.0	70.6	52.9	6.78	1.97	8.08	1.72
	Taifengyou 208	S0	81.6	73.9	69.3	6.91	1.95	9.55	2.52
	Wanxiangyou 982	S0	79.5	69.1	58.2	7.00	1.93	11.0	2.83
	Yexiangyoulisi	S0	80.9	72.7	67.2	7.02	1.83	5.53	1.44
	Nongxiang 42	S1	80.8	68.2	50.5	7.02	1.97	2.97	0.74
	Taifengyou 208	S1	81.5	72.6	66.5	6.93	1.95	9.71	2.38
	Wanxiangyou 982	S1	78.0	67.2	56.4	6.94	1.94	16.1	4.63
	Yexiangyoulisi	S1	79.7	71.2	65.3	7.09	1.83	5.67	1.43
General quality	Huajing	S0	81.5	71.6	67.7	6.61	1.95	6.94	1.80
	Jiyouhang 1573	S0	81.3	71.0	57.7	6.47	2.14	19.3	4.85
	Jiyou T025	S0	81.4	69.7	58.5	6.37	2.14	21.4	5.27
	Keyou 5	S0	80.9	72.1	64.1	6.06	2.26	24.3	7.13
	Huajing	S1	81.4	71.0	67.2	6.81	1.99	7.15	2.20
	Jiyouhang 1573	S1	80.9	68.4	55.3	6.45	2.12	15.1	4.20
	Jiyou T025	S1	80.8	68.7	56.4	6.44	2.16	21.0	6.37
	Keyou 5	S1	80.8	71.1	62.2	6.15	2.28	18.2	5.68

Table 5. *Cont.*

Quality	Cultivar	S	BRR	MRR	HRR	GL	GW	CGR	Ch
High quality		S0	80.8 ab	71.6 a	61.9 a	6.93 a	1.92 b	8.54 b	2.13 b
		S1	80.0 b	69.8 b	59.7 a	6.99 a	1.92 b	8.62 b	2.30 b
General quality		S0	81.3 a	71.1 ab	62.0 a	6.38 b	2.12 a	18.0 a	4.76 a
		S1	81.0 a	69.8 b	60.3 a	6.46 b	2.14 a	15.4 a	4.61 a
			Two-factor analysis of variance						
	Cultivar (C)		5.57 *	0.12	0.01	36.428 **	18.47 **	27.393 **	26.148 **
	Shading (S)		11.631 **	39.604 **	66.808 **	3.346	0.839	3.274	0.000
	C × S		2.446	1.002	1.007	0.051	0.230	3.627	0.443

Different lower-case letters indicate statistically significant differences ($p < 0.05$) between shading treatments within the same rice cultivar. * Significant at 0.05 probability level. ** Significant at 0.01 probability level.

The peak viscosity, hot slurry viscosity, disintegration value, peak time, and gelatinization temperature of the starch RVA spectra showed no interaction between cultivar and shading treatments (Table 6). However, there was an interaction between final viscosity and subtractive value. Shading reduced the peak viscosity of both groups, but had no effect on hot slurry viscosity, final viscosity, gelatinization temperature, or peak time (Table 6). After shading, the subtractive value increased and the disintegration value decreased for the high-quality group, but shading had no effect on the general-quality group.

Table 6. Absolute value of rice starch RVA spectrum of 8 tested cultivars, given as peak viscosity (PV), hot slurry viscosity (HSV), disintegration value (DV), final viscosity (FV), subtractive value (SV), peak time (PT), and gelatinization temperature (GT) as affected by different shading treatments (S) in 2021 ($n = 3$).

Quality	Cultivar	S	PV	HSV	DV	FV	SV	PT	GT
High quality	Nongxiang 42	S0	3553	1746	1806	2946	−606	5.95	74.3
	Taifengyou 208	S0	3200	1628	1572	2833	−367	5.98	82.6
	Wanxiangyou 982	S0	3504	1575	1930	2573	−932	5.69	83.8
	Yexiangyoulisi	S0	3053	1612	1441	2929	−124	6.29	89.3
	Nongxiang 42	S1	3349	2103	1246	3122	−228	6.27	75.8
	Taifengyou 208	S1	2992	1657	1335	2829	−163	6.11	83.0
	Wanxiangyou 982	S1	2919	1558	1361	2633	−286	5.98	83.6
	Yexiangyoulisi	S1	2847	1594	1253	2949	103	6.20	87.7
General quality	Huajing	S0	3444	1774	1669	3055	−389	6.09	76.5
	Jiyouhang 1573	S0	2943	2399	544	3755	812	6.38	79.6
	Jiyou T025	S0	3211	2632	579	4164	953	6.46	80.3
	Keyou 5	S0	3304	2052	1253	3600	295	6.16	83.0
	Huajing	S1	2996	1670	1326	2929	−67	6.15	75.5
	Jiyouhang 1573	S1	2842	2424	418	3495	653	6.51	79.8
	Jiyou T025	S1	2938	2575	362	3753	816	6.73	80.3
	Keyou 5	S1	3016	2179	837	3453	437	6.40	82.7
High quality		S0	3327 a	1640 b	1687 a	2820 b	−507 c	5.97 c	82.5 a
		S1	3027 b	1728 b	1299 b	2883 b	−144 b	6.14 bc	82.5 a
General quality		S0	3226 a	2214 a	1011 bc	3644 a	418 a	6.27 ab	79.9 b
		S1	2948 b	2212 a	736 c	3408 a	460 a	6.45 a	79.6 b
			Two-factor analysis of variance						
	Cultivar (C)		2.5	14.226 **	18.961 **	19.753 **	23.881 **	10.063 **	14.548 **
	Shading (S)		69.154 **	1.568	95.62 **	11.457 **	23.356 **	25.038 **	0.267
	C × S		0.109	1.743	2.794	34.34 **	14.741 **	0.033	0.299

Different lower-case letters indicate statistically significant differences ($p < 0.05$) between shading treatment within the same rice cultivar. ** Significant at 0.01 probability level.

From the results of the analysis of variance, in terms of the rice's textural properties, it was observed that shading and cultivar group had an interactive effect on firmness and chewiness (Table 7). Overall, shading had no effect on the textural properties of either group; the differences in texture were mainly caused by cultivar groups.

Table 7. Absolute value of rice grain textural properties of 8 tested cultivars, given as firmness (Fi), stickiness (St), springiness (Sp), cohesiveness (Co), and chewiness (Ch) as affected by different shading treatments (S) in 2021 (n = 3).

Quality	Cultivar	S	Firmness (g)	Stickiness (g)	Springiness	Cohesiveness	Chewiness
High quality	Nongxiang 42	S0	2689	−394	0.76	0.38	966
	Taifengyou 208	S0	2573	−417	0.80	0.34	835
	Wanxiangyou 982	S0	2783	−575	0.82	0.34	899
	Yexiangyoulisi	S0	2616	−474	0.82	0.37	931
	Nongxiang 42	S1	3252	−487	0.80	0.38	1230
	Taifengyou 208	S1	3052	−537	0.86	0.38	1149
	Wanxiangyou 982	S1	3023	−534	0.81	0.39	1195
	Yexiangyoulisi	S1	2960	−427	0.82	0.39	1099
General quality	Huajing	S0	2243	−374	0.70	0.33	734
	Jiyouhang 1573	S0	4425	−159	0.67	0.55	2407
	Jiyou T025	S0	3836	−183	0.65	0.48	1923
	Keyou 5	S0	3606	−192	0.74	0.49	1775
	Huajing	S1	2947	−323	0.83	0.38	1113
	Jiyouhang 1573	S1	3818	−200	0.62	0.49	1844
	Jiyou T025	S1	3468	−191	0.62	0.46	1588
	Keyou 5	S1	3157	−272	0.73	0.41	1309
High quality		S0	2665 b	−465 b	0.80 a	0.36 b	908 c
		S1	3072 ab	−497 b	0.82 a	0.38 b	1168 bc
General quality		S0	3528 a	−227 a	0.69 b	0.46 a	1710 a
		S1	3348 a	−247 a	0.70 b	0.43 a	1463 ab
Two-factor analysis of variance							
Cultivar (C)			8.897 *	56.372 **	21.173 **	12.894 **	13.481 **
Shading (S)			1.76	3.12	0.72	0.00	0.01
C × S			11.786 **	0.17	0.10	7.174 *	16.222 **

Different lower-case letters indicate statistically significant differences ($p < 0.05$) between shading treatment within the same rice cultivar. * Significant at 0.05 probability level. ** Significant at 0.01 probability level.

3.4. Correlation among Various Indexes of Rice Quality

The taste quality of the rice, including textural properties, was significantly correlated with chalkiness and chalky grain rate (Figure 5). Chalkiness was negatively correlated with springiness and positively correlated with firmness, stickiness, cohesiveness, and chewiness. Springiness was negatively correlated with amylose content and positively correlated with gel consistency, while firmness, stickiness, cohesiveness, and chewiness were positively correlated with amylose content and negatively correlated with gel consistency. Moreover, firmness, stickiness, cohesiveness, and chewiness showed positive correlations with hot slurry viscosity, final viscosity, attenuation value, and peak time (Figure 5). Chalkiness, chalky grain rate, protein content, and amylose content were negatively correlated with disintegration value, while they were positively correlated with hot slurry viscosity, final viscosity, subtractive value, and peak time.

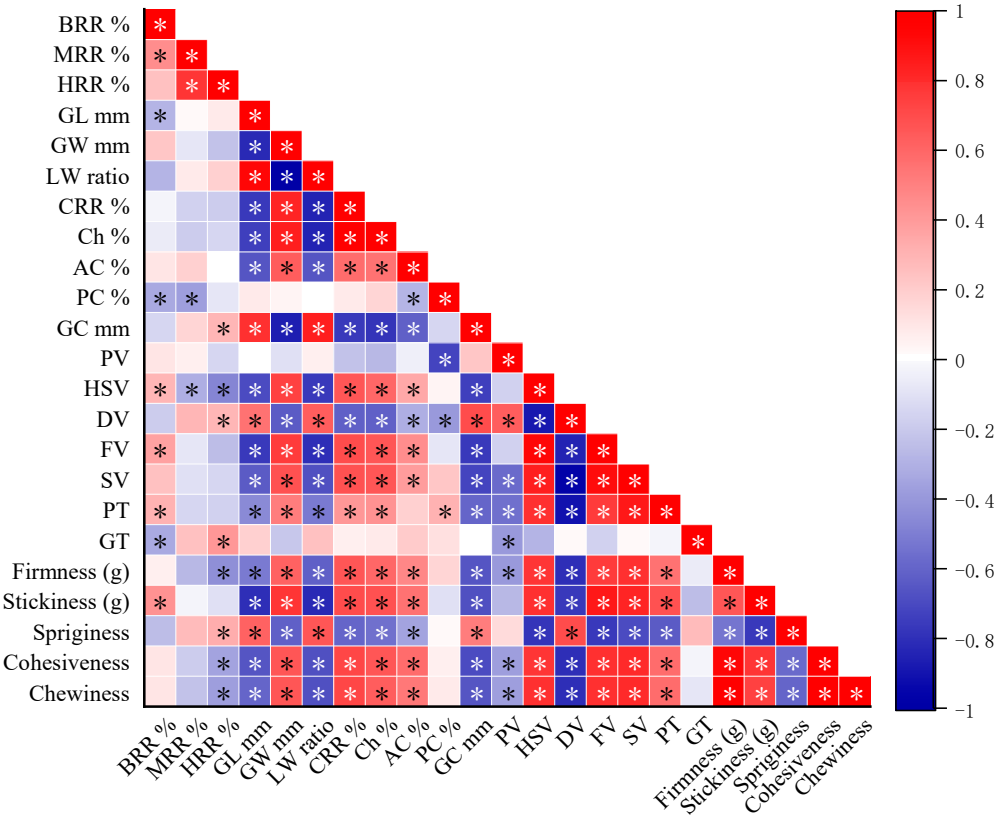


Figure 5. Correlation coefficients among appearance quality, milling quality, RVA spectrum parameters, and textural properties of rice grains. $n = 48$. * indicate significant difference at $p < 0.05$ probability level.

4. Discussion

4.1. Both Interannual Climate Variation and Simulated Shading Have Detrimental Effects on Rice Yield and Quality

The natural weak solar radiation in 2020 (Table 1) caused significantly reduced grain yield of both high-quality rice cultivars, Wanxiangyou 982 and Yexiangyoulisi (Figure 1). Previous studies have found significant differences in the effects of interannual climate variation, cultivar, and their interaction on the quality of indica rice [32]. In terms of rice milling and appearance quality, both cultivars showed a decrease in brown rice recovery, milled rice recovery, and head rice recovery, indicating a decline in milling quality due to naturally weak solar radiation (Table 4). Wanxiangyou 982 showed an increase in chalky grain rate and chalkiness, suggesting a deterioration in appearance quality. The possible reason for this could be that low annual temperature coupled with weak solar radiation hindered the formation of starch, resulting in insufficient filling of endosperm cell tissue and abnormal grain appearance [33]. In terms of taste quality, there was a negative correlation between amylose content, protein content, and gel consistency (Figure 5). The amylose content and gel consistency of the two cultivars decreased in 2020, indicating that the rice texture became harder and stickier (Table 4). Prolonged and intense cold and weak solar radiation reduced the activity of key starch synthesis enzymes, leading to a decrease in amylose content [34,35]. Changes in temperature and solar radiation during the heading stage can alter the synthesis of amylose and protein in rice, thereby altering the RVA spectrum of rice starch [36]. The RVA spectra were influenced by cultivar and interannual climate variation, with an interactive effect (Table 4). The subtractive value, disintegration value, and gelatinization temperature are the most relevant RVA spectrum indexes related to rice cooking and taste quality [37]. The lower amylose content in 2020 resulted in a higher subtractive value, lower peak viscosity, hot slurry viscosity, disintegration value, and final viscosity (Table 4), indicating faster retrogradation during the cooling process, a firmer

texture of the cooked rice, a rough chewing experience, decreased elasticity, and decreased taste quality. Gelatinization temperature is positively correlated with the required cooking time [38].

The simulated shading experiment in 2021 showed that both high-quality and general-quality rice exhibited a significant decrease in yield, indicating that shading significantly inhibited grain filling (Figure 3). However, in terms of appearance quality, shading had no effect on head rice recovery, grain length or width, or chalkiness, except for reducing the brown rice recovery and milled rice recovery in the high-quality rice group (Table 5). This may have been due to the significant reduction in yield caused by shading, which changed the source–sink relationship, ensuring relatively sufficient sources for filled grains and reducing effective sink capacity, thereby increasing the transport and filling of grain materials and reducing chalkiness [39]. Rice RVA spectrum values and textural properties can explain 80% of the variation in rice taste quality. Shading significantly increased the protein content of both rice groups, decreased the amylose content, and had no effect on gel consistency (Figure 4). The textural properties of both rice groups showed no significant response to shading either (Table 7). Looking at the RVA spectrum indicators, the impact of shading was mainly manifested in a decrease in peak viscosity, and the disintegration value and subtractive value of the high-quality group were significantly reduced, indicating a slight decline in taste quality (Table 6).

4.2. Rice Yield and Quality Differ in Response to Annual Weak Solar Radiation and Simulated Shading

Shading and annual weak solar radiation primarily differ in terms of temperature variations and the regularity of weak solar radiation [40]. Natural weak solar radiation was not only accompanied by a decrease in temperature, but the periods of weak solar radiation also showed a phased pattern. In the simulation experiment, shading persisted for 44 days after heading, providing continuous weak solar radiation. This difference can be understood as the disparity between low-temperature-coupled weak solar radiation and weak solar radiation only, as well as the difference in the duration of weak solar radiation treatment. In terms of yield, the reduction due to interannual climate variation between the years was 15.0% and 20.8% (Figure 2), significantly lower than the reduction in yield due to weak light caused by simulated shading only, which ranged from 38.8% to 54.8% (Figure 3). Simulated shading provided continuous weak light, with key enzyme activity and metabolic processes during the grain-filling stage consistently maintained at a lower level [41]. On the other hand, the impact of weak solar radiation in 2020 was intermittent, and intermittent sunny days ensured a certain level of grain filling. Additionally, in 2020, the rice growth period was prolonged (Table 2), resulting in a smaller decrease in yield compared with simulated shading.

Research indicates that the impact of low temperature coupled with weak solar radiation on milling and appearance quality is greater than that of weak solar radiation only [9], but both result in poorer milling and appearance quality, which is consistent with the findings of this study (Tables 4 and 5). Regarding the effects of temperature and solar radiation on protein content, research has shown that protein content significantly increases with decreasing light intensity, while low-temperature treatment decreases protein content [42]. In this study, shading significantly increased protein content and decreased taste value, which was unfavorable for improving the taste (Figure 4). However, the impact of natural low temperature coupled with weak solar radiation on protein content in Yexiangyoulisi showed no apparent pattern (Table 4; Figure 4), which may have been due to compensatory effects of low temperature and weak light on protein synthesis [43]. The content of amylose and the starch RVA spectrum are important indicators of taste quality [44]. Natural low temperatures coupled with weak solar radiation or simulated shading reduced both the content of amylose and the disintegration value of the rice (Tables 4 and 6; Figure 4), and interannual climate variation also significantly reduced the gel consistency and other RVA spectrum indicators (Table 4). From the perspective of the effects of different treatments,

those of the interannual climate variation were more pronounced than those of simulated shading. Previous studies have shown that low temperature during the panicle initiation stage hinders the orderly and efficient accumulation of starch, thus affecting the RVA spectrum [45,46]. Therefore, we speculate that the greater impact of interannual climate variation on the RVA spectrum was likely to have been due to the combined effect of low temperature and weak solar radiation. In addition, research suggests that low temperature or weak solar radiation during the 21 days after heading has a greater impact on the RVA spectrum than at other stages, indicating that the 21-day period after heading is a critical period for grain filling and quality formation [23]. During this period, encountering combined stress significantly reduces taste quality. This is similar to the findings of this study; Figure 1 shows that in 2020, there was a sudden period of low-temperature dim weather for about a week around 18–24 days after heading, which may also be one of the important reasons for the significant reduction in taste quality.

4.3. There Are Differences in the Response of Cultivars/Quality Groups of Rice to Changes in Temperature and Light Conditions

In 2020, Wanxiangyou 982 showed decreased appearance quality, as well as lower gelatinization temperature and shorter cooking time. Its textural properties of stickiness, cohesiveness, and chewiness increased, indicating that the rice became stickier and harder (Table 4). The adverse effects of natural weak solar radiation on Wanxiangyou 982, such as reduced yield and quality, were more severe compared with Yexiangyoulisi (Table 4; Figure 2), which could be related to the cultivar's tolerance [47]. Wanxiangyou 982 has slightly weaker cold tolerance. By comparing four high-quality rice cultivars and four general-quality rice cultivars commonly cultivated in Jiangxi Province in 2021, we found that simulated shading had a more detrimental impact on high-quality rice, while the RVA indicators of the general-quality group were less sensitive (Table 6), with no significant changes in taste quality. This may be because the larger and denser grains of high-quality rice, as well as the prolonged grain-filling period, exacerbated the adverse effects of weak solar radiation [39]. Due to the slightly longer grain-filling period, the external environmental temperature constantly fluctuated [47], which could easily have affected the grain-filling process and led to differences in grain filling, thereby influencing rice quality formation.

5. Conclusions

In conclusion, both interannual climate variation and simulated shading had adverse effects on rice yield and quality. Simulated shading had a more significant negative impact on yield compared with interannual climate variation, but its adverse effects on the appearance, milling, and taste quality of the rice were less pronounced. Shading had a greater impact on the quality of high-quality rice and a lesser impact on the quality of general-quality rice, while high-quality rice varieties also showed different tolerance. The findings suggest that low-light-tolerant rice varieties and supportive cultivation techniques should be developed to address the potential future challenges of diminished solar radiation. Simulated shading should also be utilized to study the effects of different shading degrees and wavelengths to further understand the impact of shading on yield and quality.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14081639/s1, Table S1. Field nutrient management. Figure S1. Photos of rice panicles with shading on the right and no shading on the left. Figure S2. PCA analysis among rice quality parameters in year 2019, 2020 and 2021. $n = 24$.

Author Contributions: X.X., X.P. and Y.Z. conceived and designed the research. L.G. analyzed the results and contributed to the preparation and modification of the manuscript. W.Q., Z.B., Y.W. and J.W. conducted the experiment and measured the rice quality parameters. All authors have read and agreed to the published version of the manuscript.

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