agronomy

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Adaptability Mechanisms of Japonica Rice Based on the Comparative Temperature Conditions of Harbin and Qiqihar, Heilongjiang Province of Northeast China

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Abstract: Japonica rice has been considerably impacted from climate change, mainly regarding temperature variations. Adjusting the crop management practices based on the assessment of adaptability mechanisms to take full advantage of climate resources during the growing season is an important technique for japonica rice adaptation to climate changed conditions. Research based on the adaptability mechanisms of japonica rice to temperature and other environmental variables has theoretical and practical significance to constitute a theoretical foundation for sustainable japonica rice production system. A contrived study was arranged with method of replacing time with space having four different japonica cultivars namely Longdao-18, Longdao-21, Longjing-21, and Suijing-18, and carried out in Harbin and Qiqihar during the years 2017–2019 to confer with the adaptability mechanisms in terms of growth, yield and quality. The formation of the grain-filling material for superior and inferior grains was mainly in the middle phase which shared nearly 60% of whole grain-filling process. Maximum yield was noticed in Longdao-18 at Harbin and Qiqihar which was 9500 and 13,250 kg/ha, respectively. The yield contributing components fertile tillers, number of grains per panicle, and 1000-grain weight were higher at Qiqihar; therefore, there was more potential to get higher yield. The data for grain-filling components demonstrated that the filling intensity and duration at Qiqihar was contributive to increase the grain yield, whereas the limiting agents to limit yield at Harbin were the dry weights of inferior grains. The varietal differences in duration and time of day of anthesis were small. Across all cultivars and both study sites, nearly 85% of the variation of the maximum time of anthesis could be justified with mean atmospheric temperature especially mean minimum temperature. Mean onset of anthesis was earliest in Longdao-21 at Harbin, whereas it was latest in Longdao-18 at Qiqihar. The maximum time to end anthesis and the longest duration of anthesis were taken by Longdao-18, i.e., 9.0 hasr and 4.2 h, respectively. Chalkiness and brown rice percentages were elevated at Qiqihar showing Harbin produced good quality rice. This study investigated the adaptability mechanisms of japonica rice under varying temperature conditions to distinguish the stress tolerance features for future sustainability and profitability in NEC. It was concluded that there is an adaptive value for anthesis especially regarding T_{min} and, moreover, earlier transplantation may produce tall plants. The results demonstrated that high temperature at the onset of anthesis at the start of the day enhanced the escape from high temperature later during the day. Early transplantation is recommended in NEC because earlier anthesis during humid days rendered for potential escape from high ambient temperature later during that day. Temperature influenced japonica rice significantly and coherently, whereas the influence of growing season precipitation was not significant. Daily mean sunshine influenced the japonica rice significantly, but the impact was less spatially coherent. The results foregrounded the response of the japonica rice to external driving factors focusing climate, but ignored socioeconomic suggesting emphasis on both driving factors to target future research and render important insights into how japonica rice can adapt in mid-high-latitude regions.

Citation: Shahbaz Farooq, M.; Gyilbag, A.; Virk, A.L.; Xu, Y. Adaptability Mechanisms of Japonica Rice Based on the Comparative Temperature Conditions of Harbin and Qiqihar, Heilongjiang Province of Northeast China. *Agronomy* **2021**, *11*, 2367. https://doi.org/10.3390/agronomy11112367

Academic Editor: Arnd Jürgen Kuhn

Received: 6 October 2021
Accepted: 16 November 2021
Published: 22 November 2021

Keywords: japonica rice; adaptability mechanisms; grain-filling; anthesis; grain yield; Northeast China

1. Introduction

Global mean surface temperatures are expected to be higher from the present by 1–3 °C at the end of year 2100 [1]. China's climate has become drier and warmer compared to the 20th century [2]. Northeast China (NEC), one of the major rice producing regions in China, experienced the most obvious warming since last century [3], but the most evident warming has been observed since the 1980s with an annual mean temperature rise of 1.0–2.5 °C. In NEC, reduction in precipitation was seen during summer as the mean rainfall has been decreasing since 1965 [3], whereas increase in temperature has been observed in winter [4]. In NEC, the temperature was higher during 1920–1930, after three decades, it started to decrease, and thereafter again during the 1970s–1980s, it started to become higher [5]. For NEC, the average rise in daily minimum temperature was more obvious than the daily maximum temperature which noticeably narrowed the diurnal temperature range [6]. There is vulnerability to semi-arid areas in NEC because of periodic drought stress as most of the lakes are even disappearing because of declining precipitation and ground water levels.

Production of cereals and majorly rice is one of the major characteristics of food security and grown in over 100 countries around the globe, fulfilling the dietary requirements of millions of people, and considered as an extremely thermosensitive cereal [7,8]. Heat stress events are expected to become frequent, and intensely impact crop growth and grain yield [9–11]. In recent decades, the global temperature has increased due to activities of continuously increasing global population such as deforestation, spread of industrial setups, and enhanced emissions of greenhouse gases (GHGs) [12,13]. Extreme climatic events are adverse for crop growth and development, such as heat stress produce impacts on net yield [14]. High temperature stress on reproductive growth stage rice has become a global issue. Therefore, researching the mechanisms of impacts of climatic variability during different rice growth stages and tolerance against this variability to minimize the losses have become interest among global scientists.

Cereals share 27% of total cultivable area in China where rice is the major crop, sharing 35% of the total food demand nationwide [10,15]. NEC harvests 20% of the China's marketable food grain where rice shares highest quantity [16,17]. Rice is considered as a highly climate-sensitive cereal, and NEC has been observed as one of the most susceptible regions to climate change [10]. Several studies have shown an increase in mean surface temperature with an average warming trend of 0.38–0.65 °C per decade during last five decades [18] which favored the cultivation of seasonal flooded rice. Seasonally grown flooded rice in NEC has brought significant changes in recent decades as it is a major source of methane emissions [19], as over 10% of global methane emissions are being released in the atmosphere due to rice cultivation [20]. Consequently, the dynamic changes in the rice statistics and relationship with climatic variabilities in NEC along with other causes of GHGs emissions are of great importance for eco-efficient japonica rice sustainability [21,22].

In NEC particularly in Heilongjiang Province, rice cultivation has been motivated among local communities by many features such as balance in market prices and climatic variabilities [23–25]. Over the last three decades (1980–2010), rice production in Heilongjiang Province has been increased from 3 to 13% of total national rice production, mostly owing to the speedy growth of rice cultivating areas in NEC [15]. Many studies have done the investigations on variation of rice production due to the impacts of climatic variabilities in NEC—though up till now the outcomes are still confusing with none of the sound adjustive measures—by assessing the adaptability mechanisms regionally [26–28]. Ref. [27] revealed that net grain yield is reduced due to the effect of climate warming, but research conducted in South China and NEC unveiled a boost in rice grain yield at high-latitude regions [26,28].

Rice grain yield is comprised of two major fundamentals: rice yield and planting area [29]. Previous studies uncovered that a nearly 92% increase (about 4.23 mha) in single rice cropping regions in China has occurred in NEC between 1949 and 2013 [23]. Only native yield analyses cannot reflect the natural resource management and food security issues behind higher production of rice perfectly [15,21,30]. Moreover, the primary association among climate variability with japonica rice growth and development, adaptability mechanisms of japonica rice, and production have received fewer attention in high latitudes of China.

The japonica rice growth has been severely affected due to high temperature above the normal range in areas where the temperature has surpassed the optimum range (28/22 °C). It has been reported that rice yield decreased by 7–8% with an increase of each 1 °C temperature at the maximum daytime/minimum night time from 28/21 to 34/27 °C, respectively [31,32]. Moreover, rice production was greatly impacted due to variation in internal climate with an increase in the interannual climate predicted to be highly variable under frequent temperature stress events during the reproductive growth stages [33]. Therefore, this prediction rejects the hypothesis of expected benefits of estimated rise in atmospheric CO_2 on rice plant growth [34].

Among all critical growth stages, booting and flowering are comparatively more sensitive to temperature stresses [35,36]. During early stages of booting, the plant is occupied with low panicles, often at or below flood water level, and is safer due to plant tissues. However, cells undergoing the meiosis have been noticed with damages of cold temperature stress [37,38] during microspore release from tetrads [39]. Sensitive stage of booting starts approximately 7 and 15 d between panicles' initiation and the end of panicle initiation, respectively [40,41]. The upper part of the plant and the spikelets exposed and emerged during the flowering phase are more vulnerable to temperature stress [38,42], which may cause failure or damage of the pollens [38,43,44]. Climatic variability greatly affects the grain yield due to impacts on grain-filling. There are several explanations for poor grain-filling and low grain weight of the superior and inferior spikelets such as low enzyme activity in the conversion of sucrose to starch [11,45–47], hormonal imbalance [11,45], and assimilating transportation barriers [46,48]. It has been revealed that at the early grain-filling stage, the concentrations of soluble carbohydrates in the inferior spikelets are higher than those in the superior spikelets, suggesting that assimilating the supply is not the main reason for poor spikelet grain-filling among inferior grains [47].

Warming stress at flowering and grain-filling stages can reduce the net grain yield through spikelet sterility and shortening the duration of the grain-filling phase [49,50]. The growing degree days (GDD) for a specific cultivar for flowering are almost the same when grown under varying temperature conditions within the temperature ranges of optimum and base temperatures. Growth of superior and inferior grains was faster at higher temperatures but with a reduced grain-filling period [51]. There is an inverse correlation of the length of daily average temperature with the ripening period; therefore, the temperature below or above the optimum range will reduce the grain-filling period. Poor grain-filling decreases the grain weight as a result of rice plant exposure to frequent and continuous high temperature stress during the grain-filling stage [50]. Meanwhile, higher temperature stress during the grain-filling stage enhances the demand for more assimilations avoiding the production of chalky grains [52]. Higher temperature also impacts the developmental and cellular processes leading towards poor grain quality [53,54]. Drought prevalence during grain-filling adversely impacts the grain weight of superior and inferior grains and also reduces the grain quality [55]. Considering the declining water resources in NEC, the future research studies must be focusing on a genotype selection tool in future breeding varietal development programs for screening of drought tolerant japonica rice cultivars with considerations of the adaptability mechanisms of specific cultivars during the grain-filling period for efficient grain-filling duration and rate.

The research gap in NEC is calling the researchers' focus to address climate change impacts on japonica rice growth and yield, thereby suggesting the possible concrete adjustive measures for sustainable japonica rice production systems in NEC. Climatic variabilities have already been exacerbated under climate change, e.g., temperature stress including high and low, humidity, drought, soil salinity, and submergence [8]. Higher temperature stress can greatly damage rice yield by two principles: firstly, high maximum temperature stress combined with higher humidity causing spikelet sterility and reduced quality of grains [54]. Secondly, through higher night-time temperature stress which usually reduces the process of assimilates accumulation. Thus, if response mechanisms could have been investigated at regional and local scales of NEC, then it could possibly help in development of improved rice germplasm with better resistance against specific climatic stress.

Past research in NEC has not focused on the japonica rice adaptation to climate change in NEC. Limited literature is available to apprehend the adaptability mechanisms of the japonica rice cultivars under varying temperature conditions of NEC. Majorly, previous studies have ignored to comprehend the transitions in eco-physiology of japonica rice cultivars to temperature variations. Furthermore, a lack in understanding of the self-adaptability of japonica rice for its necessary threatened the adaptation which was possible with suitable outside interventions. A lack of evaluation of adaptability mechanisms and thereby possible adjustive measures reduced the adaptation process of japonica rice in NEC. To evaluate the sound possible adjustive measures against environmental variabilities in NEC, it is necessary to analyze the adaptability mechanisms of japonica rice cultivars to different temperature conditions. Comparative assessment of japonica rice adaptability mechanisms under climatic variations at regional and local scales of NEC is necessary to overcome the main research gap of past studies. Rice originally is a semiaquatic phylogenetic plant with unique features of susceptibility and self-adaptability against climatic variability [56] which help to possibly adjust the rice production system. Therefore, there are considerable risks to japonica rice system sustainability branching from climatic variability, but addressing the adaptability mechanisms at local scales in NEC and then delivering necessary adjustive strategies can produce a sustainable and wide range of japonica rice production system under varying climatic conditions to encourage the regional sustainability of japonica rice in NEC [57]. Therefore, this study hypothesized that deep investigations of adaptability mechanisms among short- and long-duration japonica rice cultivars under varying temperature conditions pave the way for better adaptation with possible adjustive measures in management practices. To have concrete estimations of the adaptability mechanisms of japonica rice to different temperature changed conditions, this study was designed with the following objectives: (1) providing deep insights into the adaptability mechanisms of japonica rice to climatic driving factors at different growth phases; (2) identifying and evaluating possible potential adjustive measures in management practices to adapt and sustain japonica rice production.

2. Material and Methods

2.1. Description of Study Area

This research was conducted in one of the three provinces of NEC, i.e., Heilongjiang located between 121°13′–135°05′ E longitude and 43°22′–53°24′ N latitude. The northernmost province of China has a territory of 454,000 km^2 and population of 38.18 million with a continental monsoon climate. Annual temperature in Heilongjiang Province ranges between −4 and 4 °C. Winter is long and frigid, whereas summer is short and cool. Annual rainfall averages 500–600 mm, where 70% is received in summer. Its topography is dominated by a few mountain ranges which accounts for 59% of the total area. The interior of the province is relatively flat with low altitude. After a year of land reclamation, Heilongjiang Province has become one of the most important bases of agricultural products like rice.

From Heilongjiang Province, two regions were selected for this research, i.e., Harbin, the capital city of Heilongjiang Province and the other was Qiqihar. Harbin city is situated between 45°25′–45°30′ N latitude and 126°20–126°25′ E longitude. The north of Harbin is occupied by low hilly areas and mountains, whereas the general terrain is high towards southeast side and low towards northwest side. The mean annual temperature is 3.2 °C and the mean annual frost-free season is 130 days. The annual precipitation ranges between 400 to 600 mm. Winter at Harbin is dry with freezing cold where the 24-h mean temperature in January is −17.6 °C. Spring and autumn are constituted by brief transition phases with continuously varying wind direction. Summers can be become hot with a July average temperature of 23.1 °C. Qiqihar is situated between 47°21′15.65′′ N latitude and 123°55′5.47′′ E longitude and it is the second largest city in the Heilongjiang, located in the west-central part of Heilongjiang Province. It has a cold, monsoon-influenced, and humid continental climate with long, bitterly cold, but dry winter where 24-h average temperature in January is −18.6 °C, but the annual mean temperature is 3.9 °C. Spring and autumn are mild with short and frequent transitions. Summers are usually warm and humid, where the 24-h average temperature in July is 23.2 °C, and the average annual precipitation is 415 mm, most of which comes in summer.

2.2. Study Plan and Data Source

The study was conducted during the rice growing seasons of 2017, 2018, and 2019. The study was conducted in a randomized complete block design (RCBD) with three replications. The seed rate to raise the nursery was selected @35 kg per hectare for all selected cultivars. Transplantation was done manually, taking 2–3 seedlings at 15 × 15 spacing. Weeding was done thrice during the growing season, the first 15 days after transplanting (DAT), the second 30 DAT, and the third 45 DAT. Pendimethalin herbicide was also sprayed at 8 DAT with optimum moisture condition. Net plot size was 6 × 3 m. Fertilizer management was done based on the local recommendations, i.e., nitrogen (N), phosphorus (P), and potassium (K) were amended at a recommended rate of 90-60-60 kg ha^{-1}, respectively. The sources for N application were synthetic Urea fertilizer (46% N) and compost made of poultry manure (1% N), whereas the source of P was synthetic diammonium phosphate (DAP). The supply of N and P from compost was calculated. All the remaining P and K were applied as basal dose of synthetic sources. All compost was applied as the basal dose, and the remaining required N was applied in three equal splits of synthetic urea as the basal dose, at active tillering and panicle initiation. The study was conducted in RCBD design as there were two factors involved: The first was different cultivars and second was different temperature sites. The first factor involved four different cultivars chosen based on the local adoptability in NEC—namely, Longdao-18, Longdao-21, Longjing-21, and Suijing-18—whereas the second factor included different temperature sites of Heilongjiang where all 4 cultivars were grown randomly, thereby recommending the possible adjust-control measures as an adaptation process. The earlier two cultivars were late-maturing and the late two were early-maturing. Japonica rice growth duration is a basic and critical variable of crop production and shifts in growth duration either shortening or lengthening are beneficial for the implementation of sustainable japonica rice system. Different growth duration cultivars were selected to compare the overall performance of short- and long-duration japonica rice in terms of adaptability mechanisms, and to identify the essential characteristics of short- and long-duration japonica rice cultivated under varying climatic conditions of NEC. Currently, it is well known that further changes in growth durations of japonica rice would change the flexibilities of crop rotation and ultimately intensify the crop systems under wide-scale farming set-ups.

2.2.1. Crop Data

Specific leaf area (SLA) was calculated where one sided area of a fresh leaf was divided by its dry weight. For SLA, leaf area was calculated by the manual destructive method. SLA was measured at four growth stages, i.e., tillering, booting, heading, and maturity.

Crop growth rate (CGR) was also calculated by recording the dry biomass at the above-mentioned four growth stages selected for SLA. Hunt, in 1978, gave the following formula for the calculation of CGR:

$$\mathrm{CGR} = \frac{\mathrm{W_2 - W_1}}{\mathrm{t_2 - t_1}}$$

where W_2 and W_1 are the dry biomass weights at the two respective growth stages and the difference of t_2 and t_1 is the time difference between the two respective growth stages.

Plant height was recorded at different growth stages by randomly selecting the 20 plant samples at each growth stage and the maturity average was taken. The number of productive tillers was counted by randomly selecting the 1-m^2 area in each plot. For calculation of spike weight, spike length, and number of grains per panicle, 20 panicles of primary tillers were taken randomly from each plot and then the average was taken for each of these three parameters. To estimate the 1000-grain weight, 1000 grains were randomly weighed by taking five samples from each plot, and then the average was taken. The final grain yield was calculated after threshing the crop which was done at 14% grain moisture level. The record for time taken by a specific growth stage, namely phenological data record, was also noted for sowing, transplanting, tillering, booting, heading, grain-filling, and maturity. To have a record for dry weight accumulation and grain-filling rate at grain-filling stage, each plot was labeled with 200 panicles and the date of the labeling day was 0 days (d). Samples were taken at 1, 4, 8, 12, 16, 20, 26, 32, 38, and 44 d after labeling. A total of 10 spikes were taken each time, and separation and counting of superior and inferior grains was done. Grains were counted and separated through basic ideas about superior and inferior grains, i.e., grains of the three primary branches directly at the top were the superior ones, whereas the grains of the three branches at the bottom of the panicle were the inferior ones. After separation, superior and inferior grains were separately dried to have dry weight accumulation and grain-filling rate record for each plot. The dry weight accumulation was measured in mg grain^{-1}, whereas the grain-filling rate was calculated in mg grain^{-1} day^{-1}. Using Richard's growth equation with reference to the formula given by [58], the grain-filling rate was calculated:

$$\mathrm{G} = \mathrm{kW/N}(1 - (\frac{\mathrm{W}}{\mathrm{A}})^{\mathrm{N}})$$

where W is the grain weight (mg), A is the final grain weight (mg), t is the time in days (d) after anthesis, and B, k, and N are the constants/coefficients calculated after regression (data not given in results).

For calculation of time of day of anthesis (TOA) and duration of anthesis, a square of 1 m^2 area was selected. Every square was named as the sub-plot and was observed every day during the entire flowering period every 30 min or less, from sunrise until the termination of anthesis on the last spikelets about midday or early afternoon. Onset of anthesis is defined as the time of day when at least 5 panicles in the observational sub-plot started anthesis of at least one opened spikelet visible per panicle. The maximum of anthesis is when all panicles of the sub-population of panicles attained anthesis of at least one spikelet opened on every panicle, and the end of anthesis is when all the panicles in sub-plot terminated the anthesis as shown by stamens' droopiness, change of color of stamens, and spikelet closure. The TOA was expressed as hours after sunrise (hasr) and duration of anthesis was noted in hours (h).

2.2.2. Meteorological Data

Average daily weather parameters were recorded during each growing season of japonica rice at both study sites through manual installation of the automated and computed weather station in experimental plots which was interlinked with the main weather station of respective study site. Variation in weather parameters was calculated every five minutes. The meteorological data record during the growth season for both sites was made for average, maximum, and minimum atmospheric temperature (°C), soil temperature (°C) at different depths, relative humidity (%), daily precipitation (mm), CO_2 concentration (ppm), and daily radiation accumulation (MJ/m^2).

2.2.3. Statistical Analysis

For analysis of variance (ANOVA), Tukey's HSD test at 0.05 probability level was used for the comparison of the differences among cultivars' means. Duncan's multiple range test (DMRT) was also used to measure the specific differences among treatment means. One-way ANOVA (as the study design was RCBD) was run through Tukey's HSD test and it provided the differences in treatment means, but it did not provide any information regarding which means are different. Thus, DMRT was used to have clear differentiation between pairs of means. For the statistical analysis of data, "Statistix-8.1" software was used, whereas to draw the figures and graphs, "SigmaPlot-14.0" and "Microsoft Excel-2016" were used.

3. Results

3.1. Yield Components Data

The data for yield components, the importance, and magnitude of factors recorded during all three study years are given in Tables 1 and 2. Average aggregated data for yield components represented that the mean values were evidentiarily varying among cultivars within a site as well as between study sites. Discoursing the plant height, maximum values were ascertained in Longdao-18 at both Harbin and Qiqihar study regions viz. 105.6 cm and 113.5 cm, respectively, during rice growth season in 2018. Comparatively, the mean values regarding plant height at both study sites showed less values in 2017 and 2019 (Table 1). Suijing-18 followed the same trend and stood second after longdao-18 at Harbin, but at Qiqihar, Longdao-21 showed higher mean values after Longdao-18 (Table 1). Mean values for spike length were highest in Longdao-21 during all three study years with the highest value of 22.6 cm in 2018 followed by Longdao-18 at Harbin, whereas at Qiqihar, mean maximum spike length was noticed in Longdao-18 during all study years with highest value of 21.3 cm in 2018 followed by Longjing-21 as presented in Table 1. This trend was the same in 2017, but the average values were less as compared to 2018 (Table 1). Moreover, cultivars showed increased or decreased values in 2019 for spike length as compared to the previous two years because of positive or negative correlated effects of internal growth make-up of cultivars and prevailing environmental conditions. The number of productive tillers is important in ciphering the overall yield compared to the total number of tillers. Productive tillers were counted per hill for all cultivars and the highest numbers were seen in Suijing-18 at Harbin with mean values of 17 and 15, respectively, in 2018 and 2019, whereas a similar trend was seen at Qiqihar with mean values of 13 and 12, respectively in 2018 and 2019 (Table 1). All cultivars showed a decreasing trend for productive tillers at Qiqihar in 2019, but Longjing-21 comparatively showed increasing values as shown in Table 1. Mean values regarding grains per panicle were highest in Longdao-18 at Harbin with the highest values of 161 and 151 in 2018 and 2017, respectively, but the trends varied with other cultivars; for example, Longjing-21 showed higher number of grains per panicle at Qiqihar region, but at Harbin it produced a smaller number of grains. The mean values for net grain yield were highest for all cultivars in 2018 than in 2017 and 2019 at Harbin where the maximum grain yield was observed in Longdao-18 in 2018, which was 9500 kg/ha. At Qiqihar, the same trend was seen, where Longdao-18 produced 13,250 kg/ha (Table 1). The increasing trend in the net grain yield among all cultivars at Harbin in 2018 compared to 2017 and 2019 can be justified undergoing that the yield components' values were greater in respective cultivars. Comparatively, all cultivars negated the same trends at both study regions for net grain yield as the net grain yield was highest in 2018 and decreased in 2019 except for Longjing-18, wherein the yield increased in 2019 as speechified in Table 1.

Table 1. Impacts of different environmental conditions on yield and yield components of four different cultivars at Harbin and Qiqihar during rice growing seasons of 2017, 2018, and 2019 (a, b, c, d = DMRT test values to differentiate the treatment means in different traits for different cultivars).

Site	Cultivar	Year	Plant Height (cm) mv ± sd * a **	Prod. Tillers/Hill mv ± sd	Spike Weight (g) mv ± sd	Grains/Panicle mv ± sd	1000-Grain Weight (g) mv ± sd	Spike Length (cm) mv ± sd	Grain Yield (kg/ha) mv ± sd
Harbin	Longdao-18	2017	103.1 ± 3.1 a	13 ± 2 b	57.4 ± 3.7 a	151 ± 15 a	23.5 ± 0.4 c	21.5 ± 0.7 a	9367 ± 369 a
		2018	105.6 ± 3.5 a	14 ± 2 b	59.1 ± 9.4 a	161 ± 15 a	25.3 ± 0.7 b	20.8 ± 0.7 b	9500 ± 400 a
		2019	100.5 ± 4.0 a	13 ± 1 b	55.9 ± 5.5 a	146 ± 11 a	22.5 ± 0.4 c	21.6 ± 1.6 a	7705 ± 297 a
	Longdao-21	2017	93.4 ± 4.7 c	12 ± 1 b	60.8 ± 7.3 a	144 ± 23 a	23.7 ± 1.1 c	20.0 ± 1.5 b	9017 ± 283 a
		2018	95.8 ± 4.2 c	14 ± 1 bc	63.4 ± 4.2 a	151 ± 23 a	26.0 ± 0.6 ab	22.6 ± 1.5 a	9166 ± 289 a
		2019	95.5 ± 1.6 a	12 ± 2 bc	58.6 ± 9.8 a	144 ± 13 a	22.7 ± 1.1 c	22.4 ± 0.5 a	7167 ± 133 a
	Longjing-21	2017	95.1 ± 1.8 bc	11 ± 1 c	46.9 ± 5.4 b	106 ±14 b	26.9 ± 0.8 a	16.3 ± 0.7 c	7050 ± 296 c
		2018	96.7 ± 2.5 bc	12 ± 1 c	49.9 ± 5.7 b	146 ± 15 a	27.0 ± 0.6 a	17.4 ± 0.7 c	7166 ± 305 c
		2019	96.9 ± 2.9 a	11 ± 2 c	42.0 ± 6.2 b	101 ± 18 b	25.9 ± 0.8 a	16.2 ± 0.5 c	6962 ± 117 a
	Suijing-18	2017	98.1 ± 1.6 b	15 ± 1 a	53.1 ± 4.9 ab	141 ± 7 a	25.2 ± 0.4 b	17.4 ± 0.6 c	8200 ± 176 b
		2018	100.0 ± 1.3 b	17 ± 1 a	56.1 ± 7.0 ab	149 ± 8 a	26.1 ± 0.7 ab	18.5 ± 0.6 c	8333 ± 208 b
		2019	97.2 ± 2.5 a	15 ± 1 a	49.6 ± 1.8 ab	136 ± 13 a	24.1 ± 0.2 b	18.6 ± 0.9 b	7309 ± 98 a
Qiqihar	Longdao-18	2017	111.7 ± 0.4 a	11 ± 1 a	34.2 ± 9.1 b	154 ± 4 a	24.1 ± 0.6 a	20.5 ± 1.0 a	12,267 ± 453 a
		2018	113.5 ± 0.5 a	12 ± 1 a	36.9 ± 12.3 b	158 ± 4.0 a	25.2 ± 0.3 a	21.3 ± 1.0 a	13,267 ± 351 a
		2019	93.9 ± 2.9 a	11 ± 1 a	30.6 ± 8.1 c	155 ± 9 a	22.2 ± 1.0 a	19.6 ± 0.4 ab	7350 ± 300 c
	Longdao-21	2017	99.2 ± 0.6 b	11 ± 1 ab	40.3 ± 5.1 ab	153 ± 7 a	24.6 ± 0.1 a	19.8 ± 0.8 ab	11,133 ± 305 a
		2018	100.7 ± 0.7 b	12 ± 2 a	43.5 ± 7.9 ab	150 ± 7 ab	25.7 ± 0.2 a	20.1 ± 0.8 a	13,133 ± 350 a
		2019	83.1 ± 1.9 c	12 ± 1 a	38.4 ± 7.8 b	144 ± 11 b	22.6 ± 2.9 a	21.0 ± 0.7 a	9217 ± 75 b
	Longjing-21	2017	94.6 ± 0.5 c	10 ± 1 ab	51.8 ± 3.7 a	133 ± 4 b	24.2 ± 0.3 a	19.0 ± 1.4 ab	9733 ± 208 b
		2018	96.5 ± 0.5 c	11 ± 1 a	53.1 ± 11.8 a	132 ± 3 c	25.3 ± 0.4 a	20.9 ± 1.4 a	10,500 ± 225 b
		2019	86.7 ± 0.5 bc	13 ± 2 a	58.4 ± 6.8 a	138 ± 7 bc	22.9 ± 2.1 a	18.0 ± 0.9 ab	11,383 ± 120 a
	Suijing-18	2017	94.1 ± 1.7 c	10 ± 1 b	35.8 ± 7.9 b	142 ± 9 ab	24.0 ± 0.2 a	18.1 ± 0.3 b	9634 ± 57 b
		2018	94.5 ± 1.2 d	13 ± 1 a	37.2 ± 11.7 b	143 ± 8 bc	25.1 ± 0.3 a	19.2 ± 0.3 a	9700 ± 100 c
		2019	92.4 ± 2.2 ab	12 ± 2 a	30.2 ± 4.3 c	134 ± 13 c	18.5 ± 2.0 b	17.6 ± 1.2 b	7048 ± 150 d

* mean values ± standard deviation, ** DMRT test values to differentiate the groups of treatment means.

Table 2. Impacts of different environmental conditions prevailed at Harbin and Qiqihar on yield and yield components traits of four different cultivars.

Region		Year	SL * (cm)	PT/P **	G/P ***	SS [0] (%)	1000-GW [1] (g)	GY [2] (kg/ha)
Harbin	MV	2017	20.07	11.00	121.00	0.93	21.53	9367.73
		2018	21.17	13.00	124.00	0.95	22.09	9500.00
		2019	18.6	14.00	118.00	0.90	20.10	7313.09
	CV (%)	2017	11.18	6.80	11.79	2.53	4.32	7.52
		2018	11.37	7.01	12.13	2.75	4.59	7.83
		2019	10.81	6.23	11.94	2.61	4.11	7.08
Qiqihar	MV	2017	18.84	12.00	139.00	0.86	24.90	10,528.75
		2018	19.16	13.00	137.00	1.11	25.10	10,978.12
		2019	18.19	11.00	145.00	1.19	21.2	9217.00
	CV (%)	2017	17.39	12.89	9.23	7.64	5.78	5.28
		2018	17.62	13.03	9.52	8.12	6.21	5.73
		2019	16.28	13.08	8.98	7.92	5.89	5.51

* spike length, ** productive tillers per plant, *** grains per panicle, [0] seed set, [1] 1000-grain weight, [2] grain yield.

Here the subject matter is exploring why the values for yield and yield components were higher in 2018. The most possible explanation is the larger differences in prevailing environmental conditions during the respective study years which suited well with the requirements of the respective cultivars. Overall values regarding yield contributing parameters were highest in Longdao-18 comparative with other cultivars, but maximum 100-grain weight was recorded in Longjing-21 with a value of 27.0 g in 2018. Unlike Harbin, the interaction among all cultivars at Qiqihar was non-significant as they reported almost the same 1000-grain weight during 2017 and 2018, where the highest value was recorded in Longdao-21 with a value of 25.7 g in 2018, as shown in Table 1. Considering the spike weight, all cultivars at Harbin had higher values in 2018 than 2017 and 2019, where the highest value was noticed in Longdao-21 which was 63.4 g, whereas Longjing-21 had a higher spike weight at Qiqihar having value of 58.4 g in 2019. Based on the recorded findings, insights into the adaptability mechanisms in terms of yield and yield components bristle the suitability of average prevailed environmental conditions with respective growth phases of all cultivars. Therefore, conclusively the higher yield was recorded in 2018, followed by 2017, and minimum values were observed in 2019. Table 2 represents the mean value of all genotypes regarding the variations in yield and yield components' traits to understand the importance and magnitude of the environmental variables, and their impacts on traits. Table 2 presents the impacts of different environmental conditions prevailed at Harbin and Qiqihar on yield and yield components traits of four different cultivars.

3.2. Crop Growth Rate (CGR) and Specific Leaf Area (SLA)

One of the main purposes of this study was to approximate how different climatic conditions influence the growth of rice at different stages and to suggest the most suitable and possible managemental adjustments. Leaf area is the informant to evaluate how the crop is growing and what the final yield would be.

SLA determines the canopy growth and expansion by effecting the total leaf area per plant. Moreover, it also determines the canopy light interception and light use efficiency (LUE). It is a crucial invariable for plant growth estimation because it ascertains how much new leaf area to deploy for each unit of biomass production. The variation in SLA for all four cultivars at both study regions during three growing years is shown in Figure 1. A progressive increase in SLA was observed up to the end of the grand growth stage and measured at four growing stages viz. tillering, booting, heading, and maturity. All cultivars had larger differences in SLA when comparing the two study sites. SLA increased gradually till the grain-filling stage. After that, SLA started to decrease for both sites. At Harbin, the maximum SLA was recorded in Longdao-18 during all study seasons with a maximum value of 32.88 m^2 kg^{-1} in 2018. In the same way, at Qiqihar Longdao-18 had the highest SLA in 2018 with a value of 30.95 m^2 kg^{-1}, whereas the minimum was seen in Longjing-21 with a value of 19.50 m^2 kg^{-1}. At booting, Longjing-21 and Longdao-21 had almost the same SLA as shown in Figure 1. Comparing the mean SLA trend at Harbin and Qiqihar, the former showed better values for SLA than the latter. Overall, mean SLA was highest during 2018 followed by 2017, and the minimum was seen in 2019 (Figure 1) at both study sites. Overall, the values for SLA were higher at Harbin during all study years than Qiqihar. Thus, between study sites, there were no significant differences in SLA among all cultivars, but within a site the difference was significant.

CGR can be outlined as the per unit area dry matter accumulation. More specifically, it can be defined as a measure of mass increase in crop biomass per unit area per unit time. CGR exhibited a very similar trend as with SLA which gradually increased. Then after grain-filling as crop advanced towards maturity, CGR started to decrease. Maximum CGR at Harbin was observed in Longdao-21 in 2018 which was 26.94 g m^{-2} day^{-1}, but in 2017 and 2019, the highest values for CGR were noticed in Longjing-21 with values of 21.66 and 21.02 g m^{-2} day^{-1}, respectively. Mean values of CGR from tillering to maturity was similarly higher in Longdao-18, and Suijing-18 at Harbin. Due to the variation in prevailing environmental components at respective growth stages, the cultivars had larger differences in CGR values as shown in Figure 2. Though the highest values of CGR were highest in Longjing-21 at Harbin, a decreasing trend was fragmentally rapid compared to other cultivars, as in maturity the CGR value was comparatively less than 10 g m^{-2} day^{-1}, whereas for other cultivars it was higher than 10 g m^{-2} day^{-1} as presented in Figure 2. At Qiqihar, the trend was different, maximum CGR unlike Harbin was recorded in Longdao-18 with values of 29.39 and 24.23 g m^{-2} day^{-1} in 2018 and 2019, respectively due to substantial and fluent growth along the whole crop growth period. But at maturity the CGR values for Longdao-18 were less as in maturity Longdao-21 had higher CGR values (Figure 2). Overall, the mean CGR values were higher in Longdao-18 at Qiqihar as for Harbin. Minimum values for CGR were observed in Longjing-21 during 2018 as shown in Figure 2. The decreasing trend for Suijing-18 was rapid compared to other cultivars.

At Qiqihar, in 2018, CGR was recorded at four growth stages, whereas during the other two years it was recorded at three growth stages. The mean values for CGR during 2019 were higher among all cultivars in Harbin than in Qiqihar, but during the other two years (2017 and 2018) the mean values were higher at Qiqihar than at Harbin (Figure 2). All cultivars had significant differences among their CGR values within a site, whereas between two study sites the comparative trend was highly significant. Water and temperature are considered as the most influential factors impacting the growth of crop. Their impact and relevance of results against different environmental components are given in discussion part of the paper.

3.3. Variation in Time of Day of Anthesis and Duration

Time of day of anthesis was recorded in 2018 and 2019 and was explicated as hours after sunrise (hasr) whereas duration was recorded during same years elucidated as hours (h) (Table 3) because length of day and time of solar noon changed between environments. Mean onset of anthesis was earliest in Longdao-21 during 2018 and 2019 study years at Harbin with values of 5.7 hasr and 4.8 hasr, respectively, whereas mean onset was latest in Longdao-18 (Table 3). Longjing-21 and Suijing-18 were intermediate. Time to attain maximum anthesis was minimum in Longdao-21 in 2019 with value of 5.9 hasr. Maximum time to end anthesis was taken by Longdao-18 which was 9.0 hasr in 2019. Differences between two study environments were highly significant for time of day of anthesis values and standard error mean was small because of higher number daily recordings throughout the flowering phase. In Qiqihar, the mean onset of anthesis was earliest in Longdao-18 and latest in Longjing-21 with values of 5.0 and 5.4 hasr in 2018, whereas in 2019 it was earliest in Longjing-21 (Table 3). The mean maximum anthesis time was earliest in Longdao-18, and latest in Longjing-21 in 2018, but in 2019 it was latest in Suijing-18 and Longdao-21 with a value of 7.7 hasr. Longdao-21 took more time than other cultivars to reach the mean end of anthesis.

The differences in time of day of onset of anthesis were endured to maximum anthesis (when all spikelets on that day were open) and end of flowering on that day (when all spikelets had closed again). Thus, the degree of variation in the duration of anthesis was less than the time of day of anthesis between 2.9 h for Suijing-18 to 4.2 h for Longdao-21 at Harbin, whereas it was 2.9 in Harbin and 3.8 h in Qiqihar (Table 3). Genotypic variations in time of day of anthesis and duration of anthesis were modest and did not have any consistency between environments.

Within a given study site, there was no significant effect of environment on the time of day of anthesis due to small difference in the variability of environmental conditions. Across cultivars and environments, nonetheless, variable factors of time of day of anthesis were correlated with all observed components of environment except solar radiation. The probable prognosticator variable was the daily minimum temperature along with mean higher temperature. Consequently, low values of minimum air temperature were linked with delayed onset and end of anthesis. Environment components related to environmental humidity such as relative humidity or potential evapotranspiration were typically associated with anthesis variables describing dry atmospheric conditions delayed the onset and end of anthesis. Day length had a positive association with anthesis variables, but solar radiation did not show any significant effect. Possibly, the apparent day length upshots were caused by strong associations among environmental components and day length effects as climatic variables are not independent because linked to season. Probably, the mean low minimum temperature delayed the mean onset of anthesis, and it can be hypothecated that anthesis in reality occurred at a different time of day but at the same ambient prevailed temperature. This hypothesis can be proven false as all cultivars began anthesis at almost the same temperature at Harbin, but this temperature was significantly lower at Qiqihar in 2019. Among all cultivars, anthesis began significantly at low temperatures in Qiqihar than in Harbin. Consequently, the detained anthesis under low daily minimum temperatures made anthesis to begin under warmer conditions but this impact did not bring any isothermal pattern of onset of anthesis across the study sites. Therefore, there is no single defined value of critical temperature for onset of anthesis. Table 4 presents variations in environmental variables prevailed during anthesis at both study sites.

3.4. Grain-Filling Data

Grain weight accumulation and the grain-filling rate for all four selected cultivars at Harbin were recorded during the 2018 and 2019 growing years and are presented in Figures 3 and 4, respectively, whereas at Qiqihar they are showcased in Figures 5 and 6, respectively. Grain weight accumulation for superior grains showed a typical S-shaped trend line with high grain-filling rates, whereas the dry weights of inferior grains, though increased throughout the grain-filling period, had very low-filling rates. The record for grain-filling components was comprised of 44 days for Harbin, but for Qiqihar because of varying environmental conditions, it was fragmentally short in 2018. At Harbin, dry weight accumulation for superior and inferior grains was utmost in Longdao-21 with values of 25.40 and 23.81 mg grain^{-1} in 2018 and 2019, respectively, Longdao-18 had lesser values for dry weight accumulation which were 23.08 and 23.09 as shown in Figures 3 and 4. The dry weight accumulation for inferior grains increased at extremely high rates, and as the end of grain-filling approached, the dry weight of inferior grains in Longdao-18 became almost the same as of superior grains. Superior grains among all cultivars accumulated higher dry weights in 2018 than 2019. Moreover, the dry weight accumulation among inferior grains of all cultivars was less in 2019 due to low filling-rate. Therefore, the dry weights of inferior grains during 2019 were less comparative to 2018 (Figures 3 and 4).

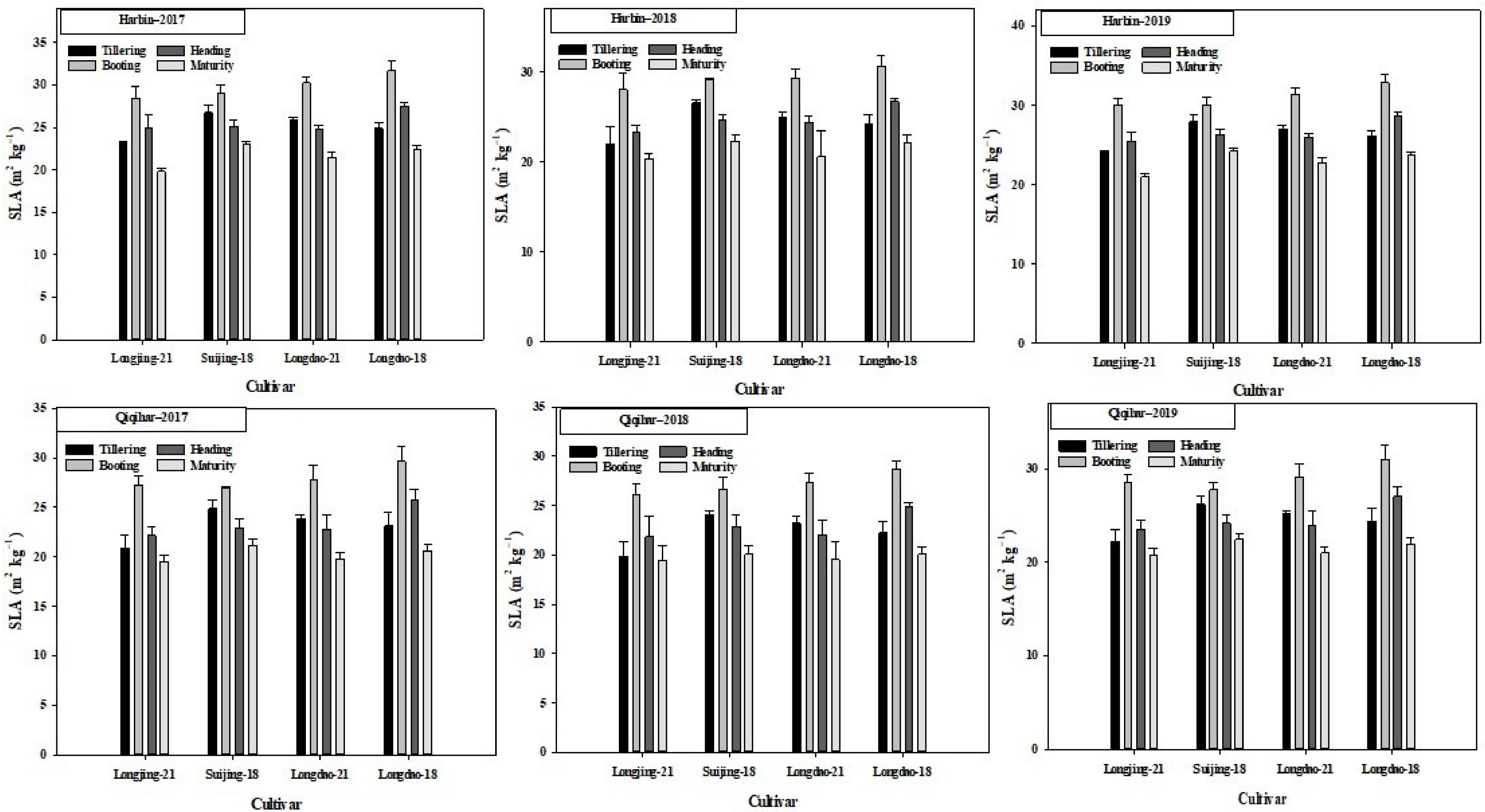

Figure 1. Impact of variation in environmental components on specific leaf area (SLA) (m^2 kg^{-1}) of all four cultivars during 2017, 2018, and 2019 at Harbin and Qiqihar.

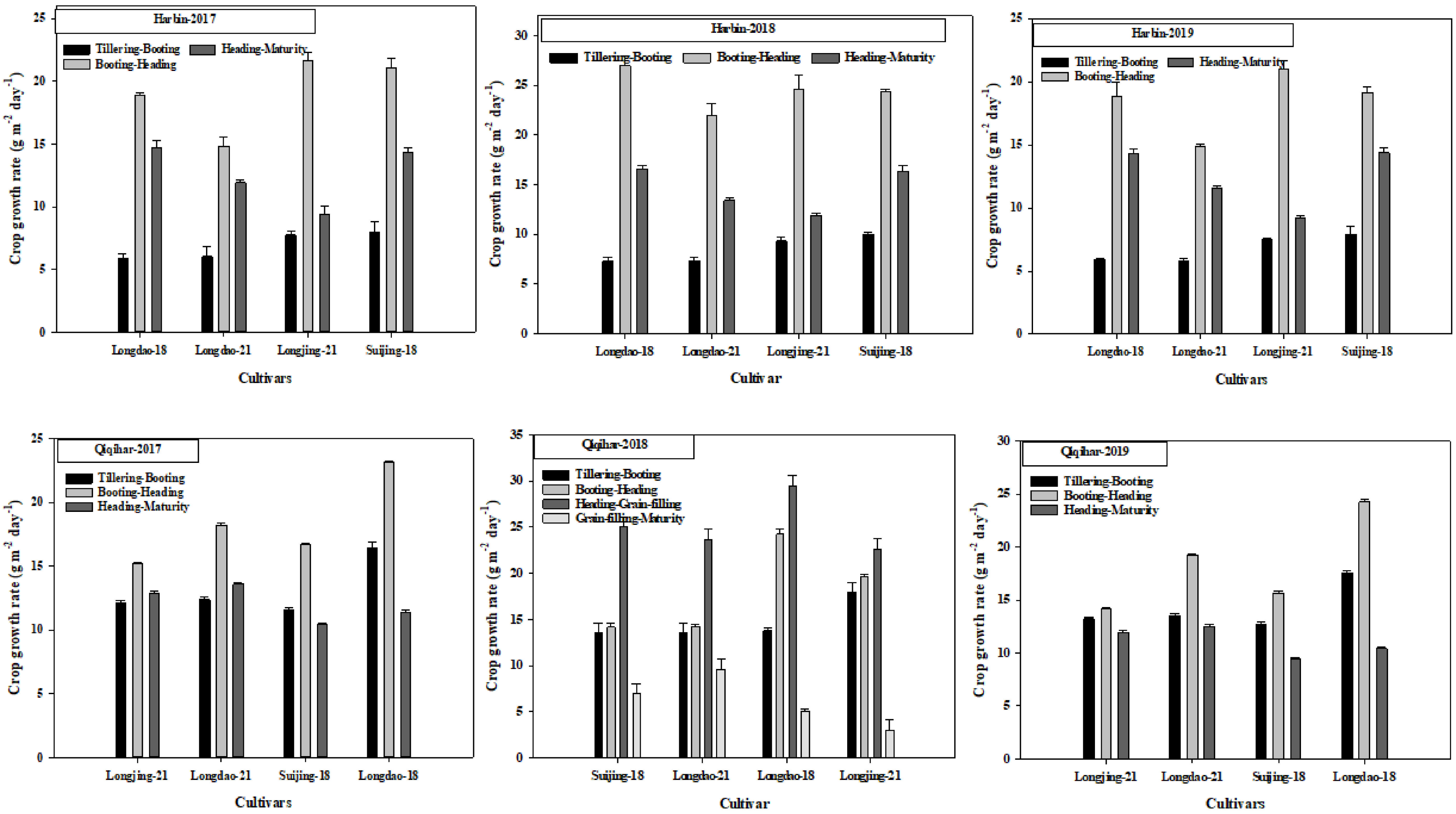

Figure 2. Impact of variation in environmental components on crop growth rate (CGR) (g m^2 day^{-1}) of all four cultivars during 2017, 2018, and 2019 at Harbin and Qiqihar.

Table 3. Impact of environmental variability on time of day of anthesis (hours after sunrise, hasr) and duration of anthesis (time from onset to end of anthesis (h) for 4 cultivars in 2 environments). (a, b, c, d = DMRT test values to differentiate the treatment means in different traits for different cultivars).

Site	Cultivar	Time of Day of Anthesis (hasr) Mean Onset mv ± sd * a ** 2018	2019	Mean Max mv ± sd 2018	2019	Mean End mv ± sd 2018	2019	Duration (h) Mean mv ± sd 2018	2019
Harbin	Longdao-18	5.9 ± 0.1 a	5.3 ± 0.1 a	6.6 ± 0.1 a	6.3 ± 0.1 a	9.0 ± 0.1 a	9.0 ± 0.1 a	3.1 ± 0.1 ab	3.7 ± 0.2 ab
	Longdao-21	5.7 ± 0.1 a	4.8 ± 0.1 c	6.7 ± 0.2 a	5.9 ± 0.1 b	9.0 ± 0.1 a	8.7 ± 0.1 b	3.1 ± 0.1 a	4.2 ± 0.4 a
	Longjing-21	5.8 ± 0.1 a	5.1 ± 0.1 b	6.6 ± 0.3 a	6.2 ± 0.1 a	9.0 ± 0.1 a	8.7 ± 0.1 b	3.1 ± 0.1 ab	3.9 ± 0.1 ab
	Suijing-18	5.8 ± 0.1 a	5.1 ± 0.1 b	6.7 ± 0.1 a	6.3 ± 0.1 a	8.8 ± 0.1 a	8.7 ± 0.1 b	2.9 ± 0.1 b	3.6 ± 0.2 b
Qiqihar	Longdao-18	5.0 ± 0.1 b	6.5 ± 0.2 a	6.1 ± 0.2 b	7.4 ± 0.1 c	8.7 ± 0.1 b	8.9 ± 0.1 b	3.6 ± 0.1 ab	2.4 ± 0.2 ab
	Longdao-21	5.1 ± 0.2 b	6.4 ± 0.1 a	6.1 ± 0.1 b	7.7 ± 0.1 a	8.9 ± 0.1 a	9.1 ± 0.1 a	3.8 ± 0.1 a	2.7 ± 0.1 a
	Longjing-21	5.4 ± 0.1 a	6.2 ± 0.1 a	6.7 ± 0.1 a	7.5 ± 0.1 b	8.7 ± 0.1 b	9.1 ± 0.1 a	3.3 ± 0.1 b	2.9 ± 0.1 a
	Suijing-18	5.1 ± 0.1 b	6.4 ± 0.1 a	6.6 ± 0.3 a	7.7 ± 0.1 a	8.7 ± 0.1 ab	9.1 ± 0.1 a	3.7 ± 0.1 ab	2.7 ± 0.1 ab

* mean values ± standard deviation, ** DMRT test values to differentiate the groups of treatment means

Table 4. Environmental variables prevailed at anthesis in 2018 and 2019 at Harbin and Qiqihar.

Cultivars	Region	Year	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	CO_2 (ppm)	Rad. Accum. (MJ/m^2)	RH (%)	Soil Temp. (5 cm) (°C)	Soil Temp. (10 cm) (°C)
Suijing-18	Harbin	2018	23.58	28.80	18.08	396.63	12.48	87.61	23.80	23.35
		2019	24.97	27.13	16.65	384.11	11.93	82.13	21.42	20.17
	Qiqihar	2018	23.26	28.36	18.89	374.36	10.53	85.59	23.99	22.53
		2019	23.57	28.14	18.51	388.28	12.91	84.37	23.60	22.48
Longjing-21	Harbin	2018	23.12	28.31	17.65	408.87	12.07	85.78	21.87	22.51
		2019	24.51	27.82	17.31	374.58	12.08	81.43	21.75	20.04
	Qiqihar	2018	22.73	27.78	18.63	399.35	11.06	83.42	23.47	21.97
		2019	23.10	27.79	17.74	402.18	13.31	82.94	23.41	21.93
Londao-21	Harbin	2018	22.91	27.98	18.39	407.64	12.83	84.39	24.78	21.98
		2019	24.18	26.79	16.23	386.75	12.32	81.95	20.93	20.21
	Qiqihar	2018	23.56	28.49	17.95	396.63	10.82	84.38	24.06	22.17
		2019	22.92	27.86	17.97	406.36	13.11	83.11	22.90	22.01
Longdao-18	Harbin	2018	23.01	28.23	17.91	402.53	12.30	86.75	22.47	23.63
		2019	24.40	26.92	17.10	392.76	12.58	80.24	22.01	19.63
	Qiqihar	2018	23.13	27.92	19.05	401.65	10.35	82.88	23.28	22.31
		2019	23.08	28.03	17.18	407.13	12.76	81.42	23.14	22.37

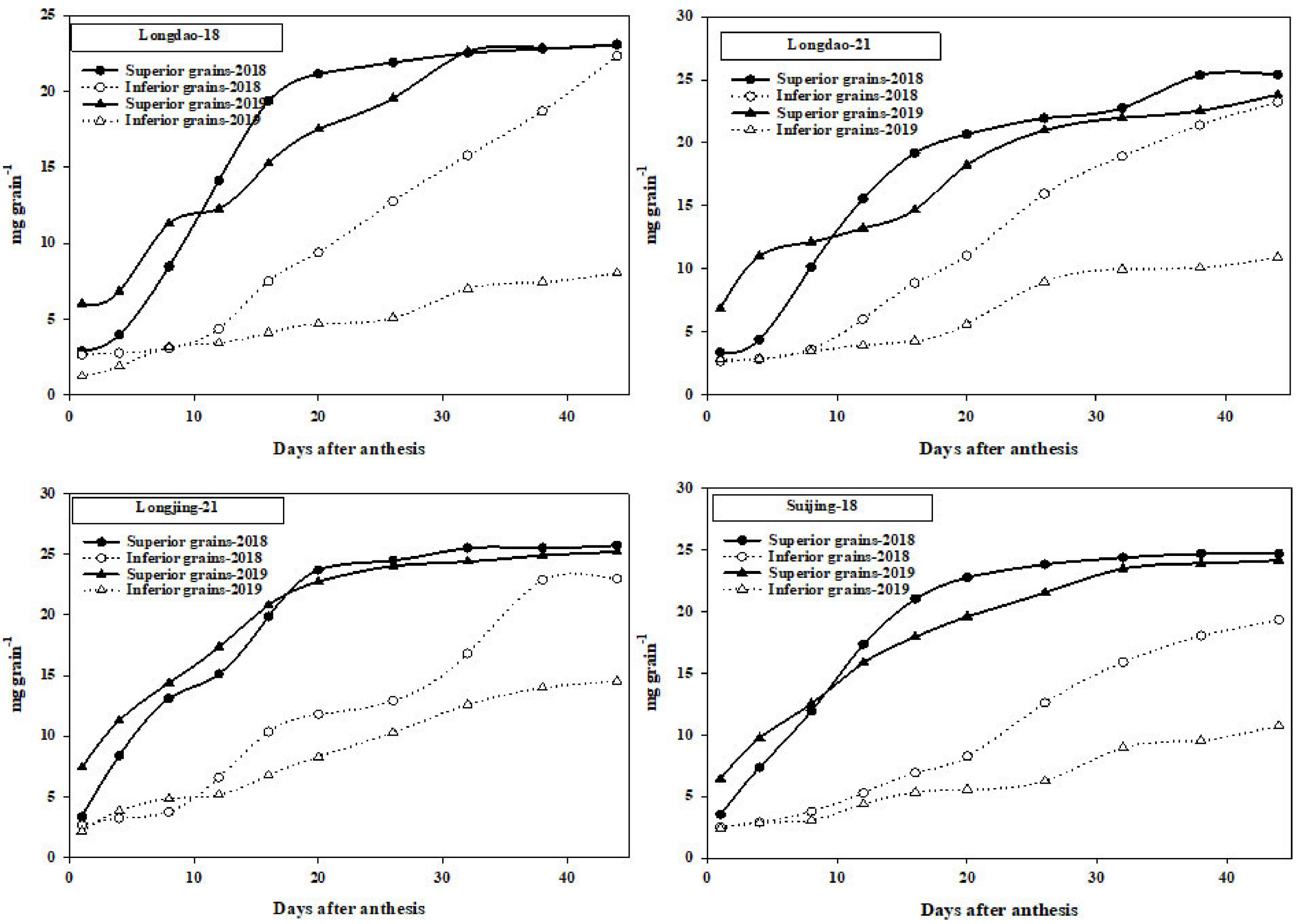

Figure 3. Impact of variation in environmental components on grain weight accumulation (mg grain^{-1}) of all four cultivars during 2018, and 2019 at Harbin.

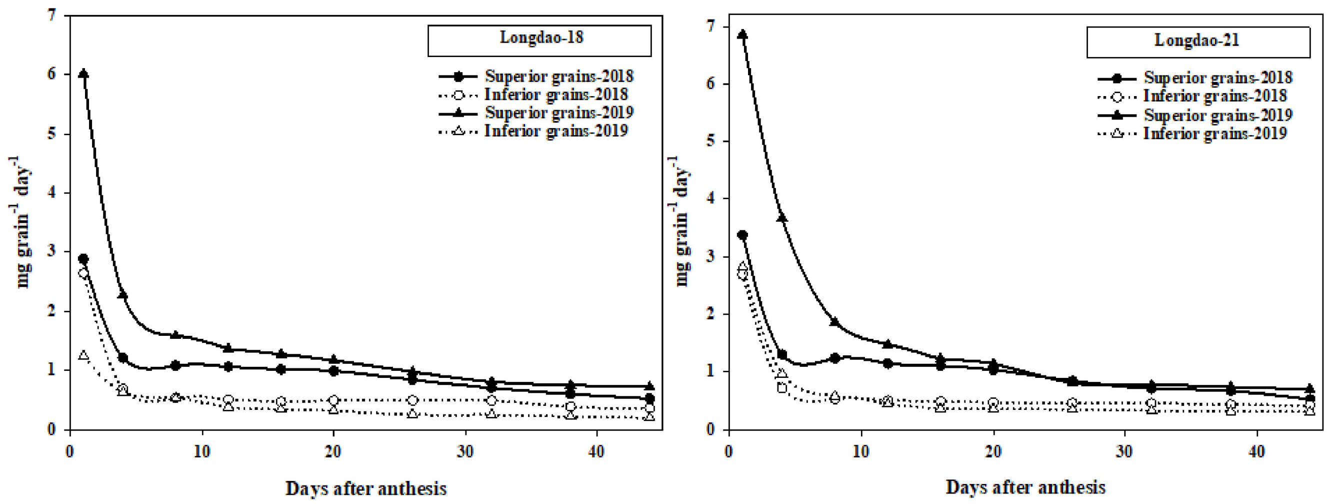

Figure 4. *Cont.*

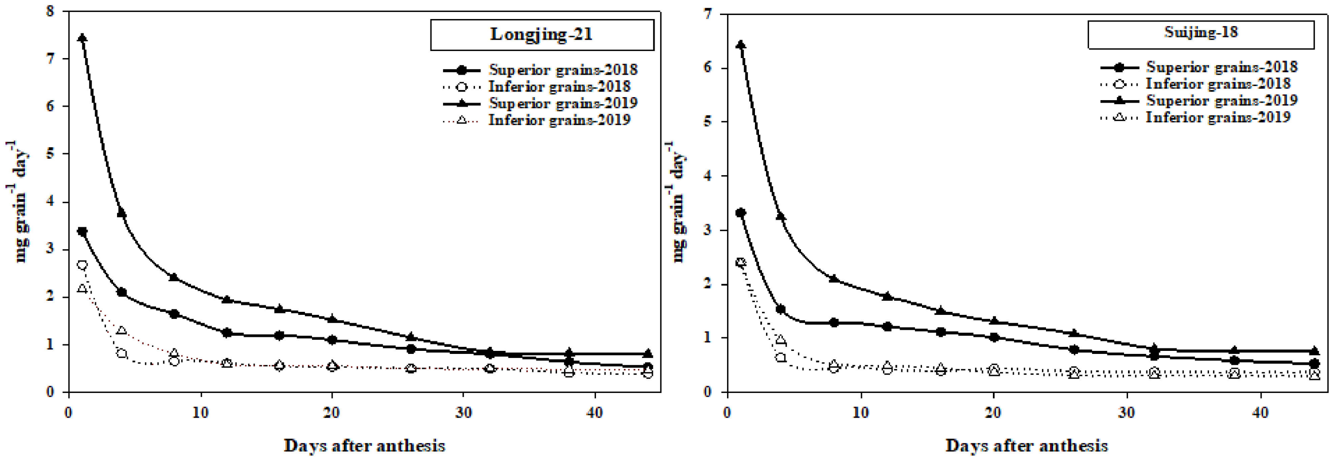

Figure 4. Impact of variation in environmental components on grain-filling rate (mg grain^{-1} day^{-1}) of all four cultivars during 2018 and 2019 at Harbin.

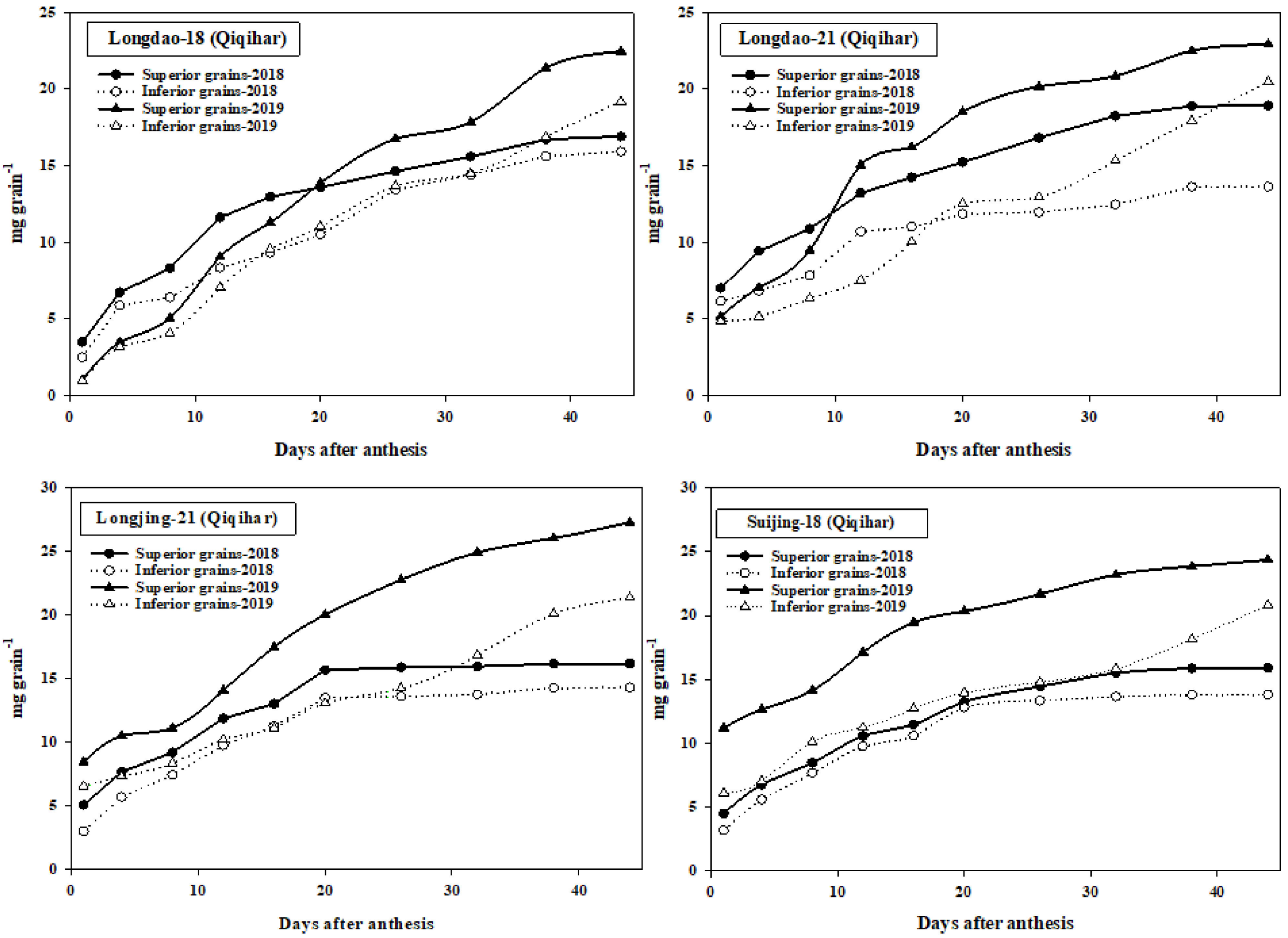

Figure 5. Impact of variation in environmental components on grain weight accumulation (mg grain^{-1}) of all four cultivars during 2018 and 2019 at Qiqihar.

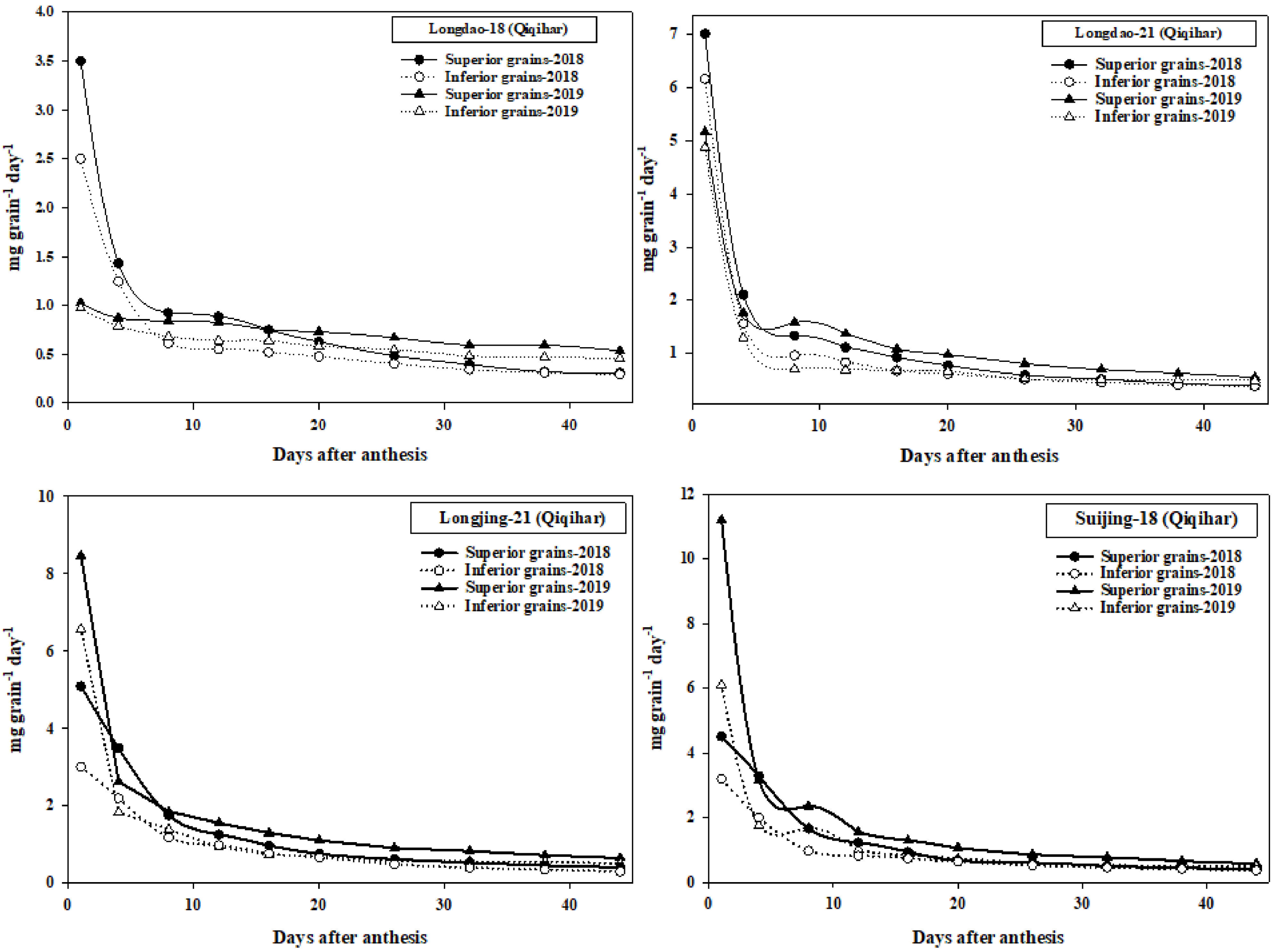

Figure 6. Impact of variation in environmental components on grain-filling rate (mg grain^{-1} day^{-1}) of all four cultivars during 2018 and 2019 at Qiqihar.

Comparing the grain weight accumulation of cultivars for both study sites, the cultivars showed low dry weight accumulation at Qiqihar during 2018 as the highest value for superior grains was recorded in Longdao-21 which was 18.91 mg grain^{-1}, whereas in 2019, the values were higher in Qiqihar and the highest was observed in Longjing-21 with value of 27.31 mg grain^{-1} (Figures 5 and 6). The grain weight accumulation among inferior grains for all cultivars at Qiqihar was low comparative to Harbin. The highest dry weight accumulation for inferior grains was seen in Longdao-18 with value of 15.91 mg grain^{-1} in 2018 whereas in 2019 it was highest in Longjing-21 with value of 21.37 mg grain^{-1} as the filling rate was higher among inferior grains in 2019 as shown in Figures 5 and 6. The varying trend for dry weight accumulation and grain-filling rate was different in 2018 and 2019 as the mean values for grain weight accumulation for all cultivars were less in 2018. Moreover, the mean values of dry weight accumulation for inferior grain among all cultivars were exceedingly high in 2019 compared to the dry weights of superior grains among all cultivars in 2018 (Figures 5 and 6). The environmental variables prevailed during the grain-filling stage at Harbin and Qiqihar for 2018 and 2019, as given in Table 5.

The grain-filling rate for superior and inferior grains at Harbin for all cultivars was comparatively high up till harvest and showed uttered loop-shaped trend lines among all cultivars during both seasons of 2018 and 2019 (Figures 3 and 4). The filling-rate trend line for all cultivars at Qiqihar did not have typical loop-shape expression between superior and inferior grains. Qiqihar had higher filling-rates for superior as well as inferior grains for Longdao-18 and Longdao-21 in 2019, whereas in Longjing-21 and Suijing-18 it was higher for superior grains but for inferior grains, and the filling-rate was almost the same among all cultivars during both study years. Comparing the two study seasons, the grain-filling rate for superior grains was higher in 2019 but for the inferior grain it was higher in 2018 except for Longjing-21, where filling rate was nearly the same during both study years for inferior grains (Figure 3).

At Qiqihar, the low-filling rate for inferior grains could not be associated with temperature differences between superior and inferior grains, as the T_{max} and T_{min} during both study years were comparatively unvarying, more significantly in 2018. Low-filling rates among inferior grains at Qiqihar directed slow grain weight accumulation, thus slow and incomplete filling of the inferior grains resulted in a continuous increase of grain weight up till harvest. Having interaction comparison for grain-filling between study years, it was noticed that grain-weight accumulation for superior and inferior grains was significantly higher during 2018 and the grain-filling rate for superior grains was 2.5 times advanced than for inferior grains. During 2018, 25 days after anthesis, it was noticed that the filling-rate became almost the same for inferior grains as for the superior grains (Figures 3 and 4). Therefore, the environmental variants fluctuated during the grain-filling growth phase, and both study years brought variations in grain-filling rate and ultimately the grain weight accumulation among cultivars at both sites.

Among all environmental variables, temperature is considered as one of the main variants affecting grain-filling phase; therefore, the fluctuations in daily mean temperature most probably are the causative component in bringing changes in the filling-rate. Temperature suitability at the grain-filling stage at Harbin had strongly favored the reason behind higher grain weight accumulation at Harbin than Qiqihar as the mean daily temperature during the grain-filling growth phase was more suitable at Harbin than Qiqihar. The mean growing temperature necessarily required for healthy grain-filling in japonica rice is 20–27 °C, and the average temperature at start of grain-filling at Harbin was more feasible than in Qiqihar. Transplantation of nursery was done on different dates at Harbin and Qiqihar, which caused an obvious time difference in attaining the peak of grain-filling curve for superior as well as inferior grains, demonstrating that the difference in environmental variables had varying degree of influence on each cultivar. Based on the total growth period of all cultivars, it was observed that the completion of the grain-filling phase for inferior grains between Longdao-18 and Longjing-21 varied by 7 and 4 days, respectively, and Qiqihar was earlier than Harbin in 2018. The grain-filling among inferior grains in Longdao-18 varied by 5 days between Harbin and Qiqihar, where grain-filling was completed early at Harbin than at Qiqihar in 2018. It has been foreshadowed that the different environmental components at two different study sites had impacted differently on two early-maturing varieties of the second accumulative temperate zone and first accumulative temperate zone, and had a great impact on dry weight accumulation of the grain filling of the Suijing-18 and Longjing-21, whereas the dry weights and grain-filling rate were less influenced in Longdao-21 and Longdao-18 during both study years.

Overall, the grain-filling growth phase majorly consisted of three sub-phases, viz. starting sub-phase, middle sub-phase, and later sub-phase, to have better consideration regarding the impact of environmental components on respective stage of grain-filling. Based on this division, it was observed that during the starting, middle, and late sub-phases of grain-filling at Harbin, the contribution rates were 39.43%, 61.54%, and 29.80%, respectively, in 2018, whereas, in 2019 it varied at rates of 37.23%, 59.22%, and 33.51%, respectively. Concludingly, the grain-filling for superior and inferior grains among all cultivars under each study sites during both study years were mainly constituted in the middle sub-phase of grain-filling growth phase, which accounted for almost 60% of the whole grain-filling.

3.5. Quality Assessment

The quality of japonica rice was observed for two study years in 2018 and 2019 and is presented in Table 6. The observed data demonstrated that the chalkiness degree and brown rice percentage were higher in Qiqihar than Harbin among all cultivars during both study years as given in Table 5. At Harbin, higher protein contents were observed in Longjing-21 during both study years 2018 and 2019 with values of 9.34% and 9.15%, respectively, whereas at Qiqihar, Longjing-21 had the highest protein contents in 2018, but in 2019 they were high in Suijing-18 with a value of 7.70% (Table 6). Amylose contents were highest in Longdao-18 during both study seasons at Harbin, but at Qiqihar, a different trend was observed, as in 2018, they were the highest in Longdao-18, but in 2019, Longdao-21 had comparatively high amylose contents. The length to width ratio of japonica rice grains among all cultivars was also higher at Harbin with very little difference. Overall, the mean fine rice percentages were advanced during both seasons at Harbin than Qiqihar. Generally, it can be concluded that the quality of japonica rice was better at Harbin relative to Qiqihar, but not with big differences as shown in Table 6. Moreover, the variation in time of phenological phases during the three study years at Harbin and Qiqihar is presented in Table 7.

3.6. The Relationship between Climatic Variables and Japonica Rice Growth and Yield

The correlative analysis between environmental variables and rice growth and yield denoted that temperature is the major and significant component in impacting the rice growth over remaining variables. Therefore, climatic changes in Heilongjiang Province majorly referred to the changes in temperature (T_{min} and T_{max}). There was no significant correlation observed between rice growth and precipitation, mentioning that rainfall had not been the main controlling variable to rice yield due to well conditional irrigation facilities, though precipitation during anthesis impacted the flowering at Qiqihar. Therefore, based on the observed results, it is suggested that temperature-based indices over all climatic variables such as GDD and meteorological standard index should be applied in future studies covering NEC to observe the overall relationship analysis. In this study, cold stress events during sensitive growth periods caused chilling injuries which suggests necessarily incorporating chilling injury indices and diurnal variations of the temperature in future climatic-rice studies in NEC, as past studies denoted only one temperature component (T_{min}, T_{max}, or T_{avg}) was considered to observe the temperature variation impacts on rice yield in NEC. The approved methods to evaluate the impacts in past studies were national standard indices, meteorological standards indices, or cumulative temperature indices that can only consider one temperature variable, strongly ignoring the diurnal variations of the temperature. Therefore, the results of this study suggested utilizing a GDD method in evaluation of temperature impacts on critical growth phases and interannual shifts in japonica rice yield in NEC as this method considers different threshold levels.

Both high and low temperature stresses at sensitive growth stages cause injuries to japonica rice. Boosting the high temperature tolerance in rice during sensitive growth stages may prove vital under varying and warming climates. This study provided the evidence that how tolerance comprises several components of escape to high temperature stress: firstly, initiation of panicle emergence, time of spikelet openings against the occurrence of temperature stress during a day, and self-adaptability and absolute tolerance under high temperature stress. The variability of climatic components especially high temperature and impacts on growth at Harbin and Qiqihar provided essential basis for evaluation of impacts of warming on rate of spikelet anthesis. Generally, flowering in both indica and japonica rice varieties occurs over a five-day period, but in Harbin and Qiqihar continued to a 7-d period depending on the cultivars and growing conditions where maximum spikelet anthesis reached around 8 to 9 h. Although the cultivars were the same at both sites, it is worth understanding that the cultivars flowered earlier during the day at Harbin than Qiqihar with more than 95% spikelets by nearly 8.5 h. This observance provided a useful and potential escape mechanism that should be introduced in breeding programs. The daily average temperature and monthly mean precipitation at Harbin and Qiqihar are presented in Figures 7 and 8, respectively.

Table 5. Environmental variables prevailed during grain-filling growth stage in 2018 and 2019 at Harbin and Qiqihar.

Cultivars	Region	Year	T_{avg} (°C)	T_{max} (°C)	T_{min} (°C)	CO_2 (ppm)	RH (%)	Soil Temp. (5 cm) (°C)	Soil Temp. (10 cm) (°C)	Rad. Accum. (MJ/m^2)
Suijing-18	Harbin	2018	20.1	26.1	15.0	407.6	82.8	21.7	20.2	17.6
		2019	19.2	25.4	14.2	386.2	80.1	22.2	20.7	17.9
	Qiqihar	2018	18.3	24.8	12.6	416.1	80.9	19.7	18.3	16.7
		2019	19.1	25.4	13.5	409.7	78.1	21.0	20.3	16.9
Longjing-21	Harbin	2018	20.3	26.0	15.9	402.5	82.7	21.8	20.5	17.7
		2019	21.1	27.8	16.3	385.5	80.4	22.7	21.4	17.9
	Qiqihar	2018	18.7	24.4	13.6	401.5	81.4	19.9	18.7	16.6
		2019	18.9	25.7	14.4	403.9	79.1	20.4	19.3	16.3
Londao-21	Harbin	2018	19.9	25.8	14.0	398.3	83.3	21.2	19.4	16.8
		2019	20.8	26.1	15.1	396.4	81.9	21.7	20.2	16.0
	Qiqihar	2018	16.9	22.5	11.5	402.5	77.3	18.6	17.1	16.8
		2019	17.5	23.6	13.1	438.3	79.1	20.0	18.6	17.1
Longdao-18	Harbin	2018	20.1	25.2	14.9	379.9	83.3	21.4	20.6	17.0
		2019	21.5	26.2	16.3	396.8	81.4	22.1	19.6	17.5
	Qiqihar	2018	17.5	23.9	12.5	401.3	79.8	19.2	17.2	16.5
		2019	18.1	24.3	14.8	417.2	80.6	21.0	19.7	17.1

Table 6. Impact of variation in environmental variables on quality of japonica rice cultivars during study years of 2018 and 2019 at Harbin and Qiqihar (BR = brown rice; FR = fine rice; L-W = length–width; GL = grain length; GW = grain width; a, b, c, d = DMRT test values to differentiate the treatment means in different traits for different cultivars).

Region	Cultivar	Year	Protein (%) mv ± sd * a **	Amylose (%) mv ± sd	BR (%) mv ± sd	FR (%) mv ± sd	L-W Ratio mv ± sd	GL (mm) mv ± sd	GW (mm) mv ± sd	Chalkiness mv ± sd
Harbin	Longdao-18	2018	7.92 ± 0.5 c	18.91 ± 0.1 a	77.63 ± 2.7 a	67.90 ± 2.9 a	2.01 ± 0.07 a	5.12 ± 0.07 a	2.51 ± 0.1 b	1.01 ± 0.07 bc
		2019	7.21 ± 0.6 c	17.90 ± 0.3 a	75.71 ± 2.1 a	68.71 ± 2.2 a	2.20 ± 0.01 a	5.73 ± 0.05 ab	2.71 ± 0.01 b	1.20 ± 0.12 b
	Longdao-21	2018	7.83 ± 0.7 c	18.35 ± 0.5 ab	76.24 ± 5.6 a	65.97 ± 4.2 a	2.02 ± 0.01 a	4.84 ± 0.03 b	2.32 ± 0.02 c	0.52 ± 0.18 c
		2019	7.10 ± 0.2 c	17.53 ± 0.3 ab	74.42 ± 5.2 a	66.53 ± 5.1 a	2.11 ± 0.01 b	5.51 ± 0.02 a	2.62 ± 0.03 c	0.71 ± 0.11 c
	Longjing-21	2018	9.34 ± 0.5 a	16.82 ± 0.8 c	78.95 ± 4.1 a	68.71 ± 3.8 a	1.83 ± 0.03 b	4.62 ± 0.09 c	2.72 ± 0.03 a	2.09 ± 0.4 a
		2019	9.15 ± 0.5 a	15.81 ± 0.7 c	76.12 ± 4.7 a	69.03 ± 3.1 a	1.51 ± 0.01 c	4.41 ± 0.04 b	2.91 ± 0.02 a	2.31 ± 0.10 a
	Suijing-21	2018	8.76 ± 0.6 b	17.77 ± 0.5 b	77.67 ± 3.3 a	68.36 ± 2.0 a	1.93 ± 0.03 b	4.82 ± 0.08 b	2.71 ± 0.04 a	1.10 ± 0.61 bc
		2019	8.37 ± 0.1 b	17.23 ± 0.3 b	75.36 ± 3.4 a	68.75 ± 2.8 a	2.01 ± 0.1 b	5.13 ± 0.09 ab	2.83 ± 0.02 a	1.21 ± 0.21 b

Table 6. *Cont.*

Region	Cultivar	Year	Protein (%) mv ± sd * a **	Amylose (%) mv ± sd	BR (%) mv ± sd	FR (%) mv ± sd	L-W Ratio mv ± sd	GL (mm) mv ± sd	GW (mm) mv ± sd	Chalkiness mv ± sd
Qiqihar	Longdao-18	2018	6.85 ± 0.5 c	17.92 ± 0.1 a	79.62 ± 2.1 a	65.78 ± 2.5 a	1.91 ± 0.02 a	4.30 ± 0.25 ab	2.31 ± 0.02 b	0.81 ± 0.21 c
		2019	6.31 ± 0.5 c	16.30 ± 0.4 ab	78.31 ± 2.8 a	64.71 ± 2.7 a	1.10 ± 0.02 b	4.93 ± 0.28 a	2.90 ± 0.01 a	1.21 ± 0.03 b
	Longdao-21	2018	6.67 ± 0.33 c	17.57 ± 0.4 ab	78.13 ± 6.1 a	63.34 ± 3.1 a	1.92 ± 0.04 a	4.31 ± 0.1 ab	2.31 ± 0.01 b	0.82 ± 0.28 c
		2019	6.23 ± 0.3 c	16.65 ± 0.7 a	77.54 ± 6.1 a	62.39 ± 3.1 a	1.82 ± 0.04 a	4.80 ± 0.11 a	2.63 ± 0.01 b	0.91 ± 0.09 b
	Longjing-21	2018	7.81 ± 0.53 a	15.51 ± 0.9 c	79.49 ± 4.3 a	66.11 ± 3.9 a	1.80 ± 0.02 ab	4.30 ± 0.06 ab	2.53 ± 0.07 a	2.31 ± 0.43 a
		2019	7.33 ± 0.3 b	14.83 ± 0.2 c	78.87 ± 4.3 a	65.10 ± 3.9 a	1.71 ± 0.02 ab	4.32 ± 0.09 b	2.60 ± 0.08 b	2.91 ± 0.07 a
	Suijing-21	2018	7.23 ± 0.6 b	16.82 ± 0.3 b	78.96 ± 4.3 a	65.32 ± 2.1 a	1.73 ± 0.03 b	4.43 ± 0.09 a	2.43 ± 0.06 a	1.21 ± 0.41 b
		2019	7.70 ± 0.6 a	14.10 ± 0.6 c	77.63 ± 4.3 a	64.39 ± 2.1 a	1.93 ± 0.03 a	4.41 ± 0.10 b	2.52 ± 0.09 b	1.53 ± 0.11 b

* mean values ± standard deviation, ** DMRT test values to differentiate the groups of treatment means

Table 7. Impact of variation in environmental variables on time of phenological phases of japonica rice cultivars during study years of 2017, 2018, and 2019 at Harbin and Qiqihar.

Site	Cultivar	Year	Sowing	Transplanting	Emergence	Tillering	Booting	Heading	Grain-Filling	Maturity
Harbin	Longdao-21	2017	4/18	5/24	6/04	6/20	7/27	8/10	8/16	9/18
		2018	4/17	5/18	5/30	6/11	7/20	7/28	8/03	9/20
		2019	4/17	5/16	5/28	6/13	7/25	8/01	8/04	9/23
	Longdao-18	2017	4/18	5/24	6/04	6/19	7/22	8/06	8/12	9/17
		2018	4/17	5/18	5/30	6/11	7/18	7/23	7/31	9/20
		2019	4/17	5/16	5/28	6/13	7/24	7/31	8/06	9/25
	Longjing-21	2017	4/18	5/24	6/04	6/18	7/17	8/04	8/08	9/14
		2018	4/17	5/18	5/30	6/11	7/12	7/22	7/28	9/15
		2019	4/17	5/16	5/28	6/13	7/19	7/24	7/29	9/20
	Suijing-18	2017	4/18	5/24	6/04	6/18	7/16	8/04	8/12	9/15
		2018	4/17	5/18	5/30	6/11	7/15	7/23	8/01	9/15
		2019	4/17	5/16	5/28	6/13	7/18	7/23	7/28	9/20
Qiqihar	Longdao-21	2017	4/17	5/27	6/05	6/27	8/2	8/19	8/24	9/29
		2018	4/17	5/31	6/09	6/21	7/23	8/05	8/12	10/03
		2019	4/17	5/29	6/07	6/21	7/23	7/29	8/05	9/25
	Longdao-18	2017	4/17	5/27	6/05	6/27	7/30	8/19	8/24	9/26
		2018	4/17	5/31	6/09	6/21	7/23	8/05	8/12	10/03
		2019	4/17	5/29	6/07	6/21	7/23	7/29	8/05	9/25
	Longjing-21	2017	4/17	5/27	6/05	6/23	7/29	8/13	8/20	9/22
		2018	4/17	5/31	6/09	6/21	7/19	7/29	8/07	9/27
		2019	4/17	5/29	6/07	6/21	7/19	7/23	7/29	9/17
	Suijing-18	2017	4/17	5/27	6/05	6/23	7/29	8/13	8/20	9/24
		2018	4/17	5/31	6/09	6/21	7/19	7/29	8/07	9/27
		2019	4/17	5/29	6/07	6/21	7/19	7/23	7/29	9/17

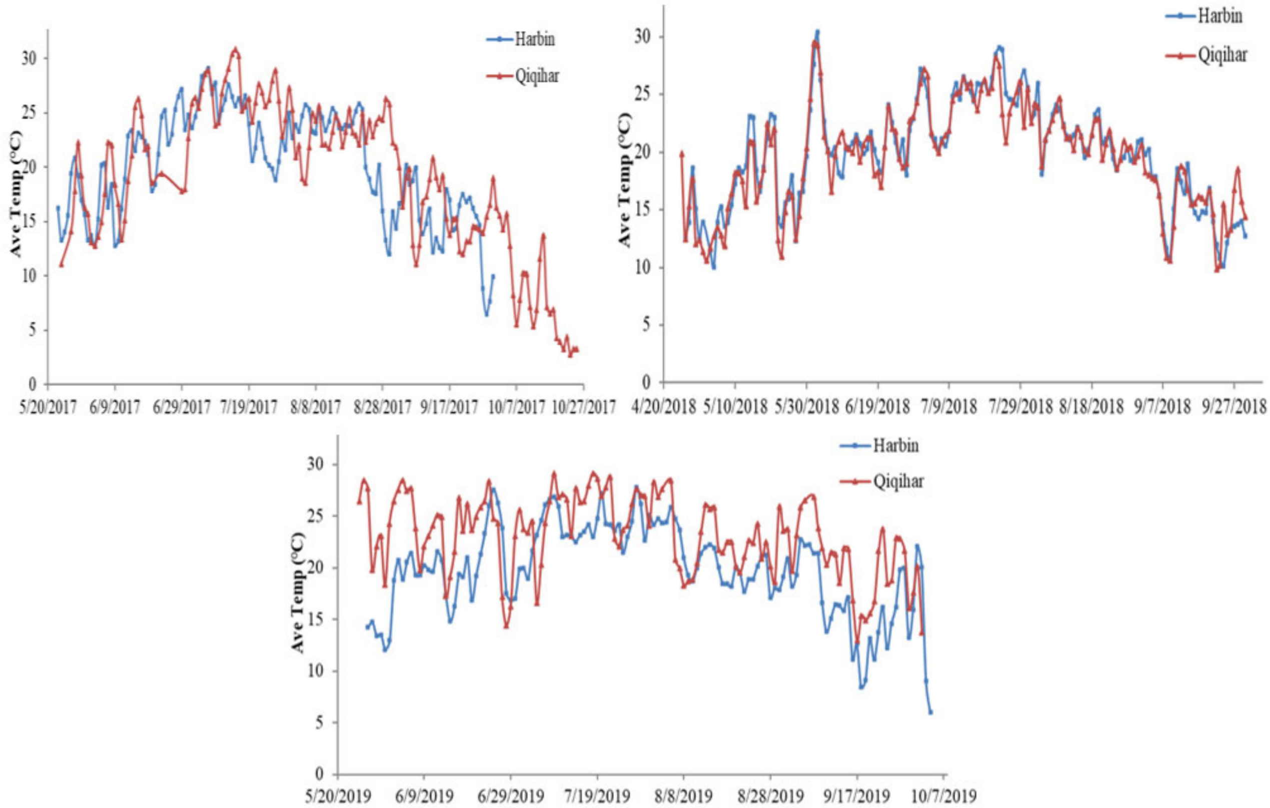

Figure 7. Daily average temperature conditions at Harbin and Qiqihar during rice growing seasons of 2017, 2018, and 2019.

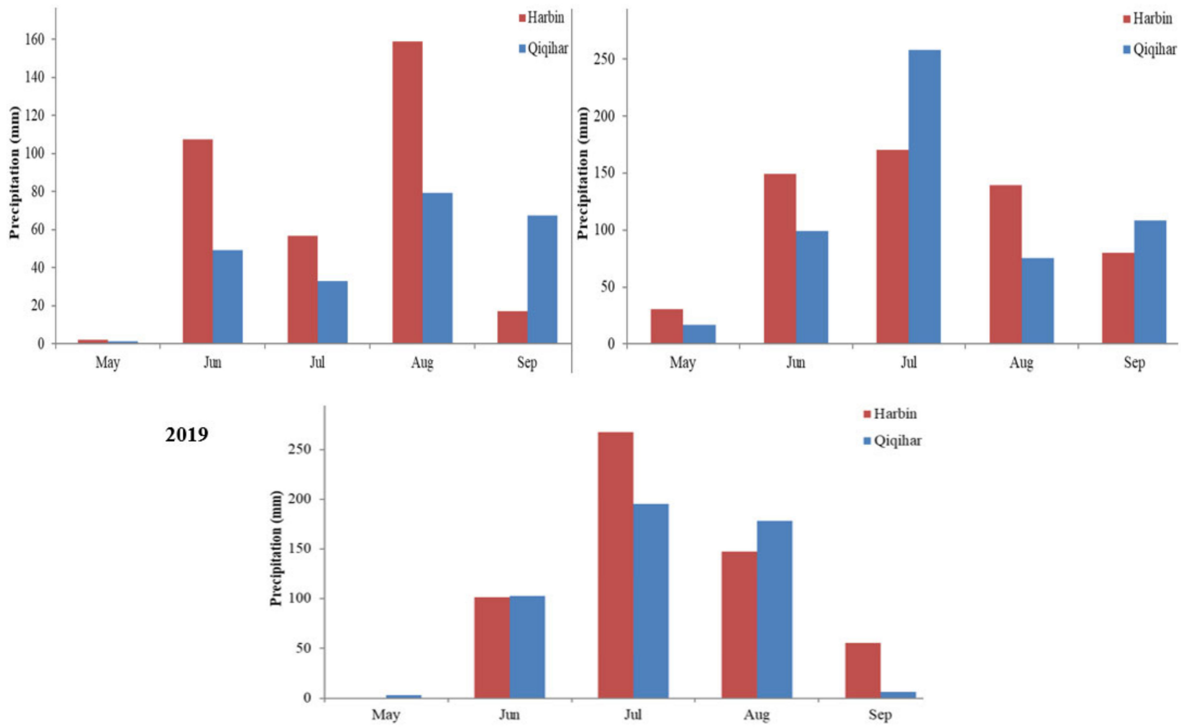

Figure 8. Monthly average precipitation at Harbin and Qiqihar during rice growing seasons of 2017, 2018, and 2019.

At Harbin, the peak anthesis occurred nearly 25–40 min with mean high temperature of 28.4 °C during a day, which presumptively indicated a thermal response mechanism of general rate of development towards spikelet temperature exposure whose optimum temperature might be apparently different. Additionally, the rate of spikelet opening during the day increased proportionally with temperature at both sites, as after 3 d anthesis was observed at a peak at a temperature of 30.8 at Harbin and 30.3 °C at Qiqihar. However, when temperature prevailed above these values, this caused the spikelet opening to reduce by 23% at Harbin when temperature range was above 31 °C and by 36% in Qiqihar when temperature was above than 32 °C. By contrast, warming temperature stress delayed or reduced the spikelet opening during the day at both sites. Although warming did not impact the anthesis so adversely, the number of superior grains during grain-filling was strongly reduced which meant that spikelet sterility in japonica rice at both sites increased with increased days (d) of exposure warming. Spikelet sterility in japonica rice is associated with a smaller number of germinated pollens or low number of overall viable pollens on the stigma; therefore, the warming stress caused acute changes in anther dehiscence before and during anthesis. Thus, it is concluded that temperature had a significant interaction with the rate and duration of spikelet opening.

A significant positive correlation was noticed between temperature variation from transplantation to maturity and japonica rice yield, declaring that the decline in heat during the growing period generally caused the decline in rice yield due to the injuries caused by chilling as seen in Qiqihar during later growth stages. Sterility among panicles due to exposure to cold days showed the strong positive correlation with a number of cold days during anthesis period, inferring that the characterized low temperature events in July caused the reduction in yield due to cold injuries. Precipitation periods at both study sites did not show the same anomaly during both study years.

Generally, it was debated that positive change in rice yield per unit area in NEC happened due to inclusion of improved non-climatic factors, but the correlation between climatic variables and rice yield in this study also demonstrated that rice yield was not happening only due to improvements in technology, but change share could be attributed to the suitable change in climatic components, particularly shifts in temperature. Cold injuries during anthesis caused by a delayed type of chilling due to heavy rainfall during the growing season had significant impacts on japonica rice yield which could decrease with each 1 °C of temperature increase. Frequent prevalence of cold temperature periods during sensitive growth stages such as anthesis and grain-filling in July and August caused serious concerns to the rice yield. Generally, it was observed that every 1 °C rise in temperature anomaly during the early growth period from panicle initiation to booting and late growth period from heading to flowering caused reduction in rice yield. Injuries caused by precipitation and cold periods cannot be ignored as in this study two type of cold injuries during later growth stages in July and August were observed: the sterile type and delayed type. Though shifts in temperature during previous decades favored rice yield and rice land-use, if climate continues to change with the anomaly since the 1970s, it would cause serious threats to rice yield through T_{min} and T_{max} stresses.

Although global warming has had great attributions with increases in temperature in NEC across the last four decades, the extent of variation in temperature (T_{avg}, T_{min}, and T_{max}) indicated variations in the three-year study from transplantation to maturity. Moreover, this study noticed heavy rainfalls once or twice during growing seasons, but historical study trends showed a decline in precipitation, inferring this decline in precipitation may cause threats to rice yield. Therefore, the current study necessarily denoted a few major threats that are needed to be addressed in Heilongjiang Province; firstly, relatively unaccented rise in temperature during sensitive growth phases of japonica rice may threaten the rice growth and yield. Secondly, increase in precipitation during critical growth phases and decline in precipitation during whole growing season may call for serious concerns. Thirdly, no distinctive decrease in cold injuries whether sterile-type or delayed-type chilling injuries during sensitive growth periods may threaten the overall japonica rice productivity.

4. Discussion

4.1. Yield and Yield Components

Plant height is one of the main components contributing to overall biological production. Comparing the plant height of both sites, it was determined that rice plants were taller at Qiqihar than Harbin. The temperature requirement for enhanced aerial growth of japonica rice is 18–33 °C after transplanting. Therefore, plant height usually increases till the heading stage approaches, where the plant ceases its vegetative growth. Plants on both sites increased their aerial growth till the heading stage and showed higher plant height values but if comparing the interaction, it was showing the values were marginally higher at Qiqihar though interaction was non-significant. These results are in accordance with findings reported by [51] who concluded that the enhancement in plant height was steeper under high temperature than normal ambient conditions. During early weeks, plant height increased slowly, but later, it increased more steeply as the ambient temperature was high. Rice grain yield in any given environment is usually determined by yield components (panicle length, productive tillers, and grains per panicle) developed at different phenophases. It was determined that the cultivars grown in a specific environment, the grain yield is impacted by the respective prevailed environmental conditions plant experienced at different growth stages. Rice production systems along an altitude gradient, for example in Heilongjiang Province, have been traditionally graded into three types of altitudes, i.e., low-, mid-, and high-altitude environments. Cultivars specifically chosen according to a region's environment were bred for those environments and well adapted to those areas based on local cropping calendar aiming higher yields. Due to climatic variabilities, there is an executed relationship between cultivars' adaptation and the respective growing environment conditions, since environmental conditions would keep on varying significantly every year, e.g., temperature, intensity, and frequency of precipitation, intensity, and the accumulation of solar radiation may become more intense or mild [8,59]. Thereby, fluctuating environmental conditions may bring in new combinations such as lower or higher temperature, which may cause new combination with pest existence along the altitude (Weerakoon et al. 2008). Moreover, high temperature at anthesis may bring in new combinations of fertility of spikelets or appearance of new pests across the gradient depending on availability of water [60,61]. Thus, the variations in yield and yield components observed at both sites revealed the possible existence of new combinations that supported the increase in yield values or harmed the overall grain yield. Therefore, based on the adaptability mechanisms of japonica rice in terms of yield and yield components, possible adjustive measures are necessarily suggested to optimize the yield loss through adjustments in agronomic practices for example shifts in planting dates for nursery, changes in dates for transplantation or changes in methods and types of external inputs which may lead towards significant shifts in japonica rice production and duration across altitude gradient for its sustainability [62].

Other logical justification for yield variation was growing cultivars not adapted to a specific environment, different from the ones it was adapted for, which increased the risk of whole crop failure or may be risk in production loss and vice versa. The results suggested that yield sustainability in such cases among different environments could be attained with shifts in agronomic management practices through possible adjustments where yield target could be achieved by having plentiful crop production under selectively favorable high-yielding climatic conditions [63,64]. Our results are also in line with Lu et al. (2008) who reported that the changes in yield components and grain yield in different cultivars within a region and among multiple selected regions can be justified by possibility of non-adaptability of a cultivar to a specific environment or may be temperature and precipitation changes on a specific growth stage [65]. The variations in yield and yield components are also supported by other reports which found that cold as well as heat stress can cause spikelet sterility and can disturb the pathways for source-sink in japonica rice [62].

The findings of this study revealed that only temperature does not impact the grain yield for all genotypes among different study sites, rather than shifts that happened due to the combined effects of other environmental components prevailing during the different growth and developmental stages. The results of this study uncovered how different environments acted upon the individual yield component at a respective growth stage, e.g., panicle length enhancement, 1000-grain weight, productive tillers, etc. Based on the findings, it was observed that variation in total number of productive tillers brought changes in overall grain yield where the increased number of productive tillers per hill with fertile spikelets per panicle supported the yield increase. These results are in consistence with [66] who found that an increase in the total number of tillers and reducing the unfertile tillers per hill does not have more positive impact on the yield. However, productive tillers with a high number of fertile spikelets impacted the yield positively, so having a more productive tiller number with a high number of fertile spikelets is most important among yield components to increase the grain yield across different environments and different planting dates [67]. The results of yield components are also supported by research which found that tillers per hill had little influence on the net grain yield, but productive tillers had great impact, as the fertility of tillers was found to be the environment-dependent trait [68,69]. It was observed that grains per panicle could be regarded as the ultimate sink potential, but had less environment dependency and showed more dependence on genetic control [69,70], though an indirect influence of temperature on panicle length was noticed [70]. It was concluded that the number of total filled spikelets is a clearly temperature-dependent trait and influence can only be reduced by avoiding prejudicial environmental conditions.

4.2. Variation in Time of Day of Anthesis (Hasr)

Under a continuously changing global climate, extreme cold or hot stress events are likely to be more frequent in the future depending on the regions where rice will be subjected to untoward abiotic stresses. Therefore, this study suggested the need to improve the resistance against climatic stresses in japonica rice genotypes at reproductive stages, especially during anthesis to get adapted under highly dynamic climatic conditions [71]. Moreover, the results depicted that intensifying the absolute stress tolerance in japonica rice could make it possible to carry out the important physiological processes (such as pollen germination, pollination, anther dehiscence, fertilization) to have a higher rate of spikelet fertility under stressful conditions [72]. The cultivars at Qiqihar took a longer time for anthesis and had longer duration of daily anthesis, which favored higher spikelet fertility which is also reported by [60] who found that anthesis under varying environments might feasibly determine the fertility of spikelets. Temperature prevalence at the study sites was more in the optimum range during the anthesis and preceding events at Harbin than Qiqihar, and less intensity and frequency of precipitation positively influenced the anthesis. Similar results were reported by [60] who indicated that cold responsiveness among cultivars might cause the infertility of the spikelets. Generally, anther dehiscence may affect the number of pollen grains on the stigma [60]. However, the reason behind anther dehiscence at both sites was that anthers still dehisced under stress due to spikelet flowering and poor swelling of pollen grains, which might cause in losing their viability, resulting in unfertilized pollen as reported by [41]. Strong variations were seen regarding onset and end of anthesis between study sites, whereas the duration of anthesis showed less variations. Across two study sites, atmospheric T_{min} averaged over the 7 days preceding any respective anthesis event was the one of the major causes behind almost all variations as observed by [73], whereas higher temperature impacted spikelets to open earlier in the morning, but no significant influence of solar radiation observed on anthesis duration. There was no environmental influence on anthesis time within a site because of insufficient environmental variabilities, but the effects were caused by other factors such as irrigational management practices, fertilizer amendments etc. The results are supported by [73] who observed that reduction in day length by 1 h (or application of a dark treatment before anthesis time) could delay or advance the onset of flowering. Ref. [74] proposed that rice spikelet sterility is influenced by thermal stress majorly at two critical periods, one during microscopic stage at meiosis and the second two weeks later during anthesis when pollination is about to start. The first phase is usually affected by cold or chilling stress but rarely by heat.

4.3. Japonica Rice Quality of Superior and Inferior Grains

Temperature variation more specifically high temperature influence the quality of rice if prevailed during grain-filling phase [75–77]. The rate and extent of grain-filling of japonica rice depends on the arrangement and position of grains in the spikelet and panicle. Mainly the superior grains are positioned at the primary branches that increase their weight due to higher translocation rate. Meanwhile, inferior grains are located at the secondary branches with low and slow translocation rates which make them unsuitable for human consumption [78,79]. The same case has been noticed in the current study where the maximum and average grain-filling rate and grain quality were significantly affected by temperature variations at both experimental locations. The length–width ratio of superior grains at Harbin was powerfully but negatively correlated with the maximum temperature. Our results are in consistence with [80] who observed that higher temperature increased the grain-filling rate but it crumbled the grain weight and quality. Maximum grain weight was also negatively correlated with length-width ratio of superior grains at Harbin site, whereas at Qiqihar the fine rice percentage was positively strongly correlated with the occurrence of maximum temperature. The remaining quality parameters including whole milled rice, chalkiness degree, and length–width ratio were negatively correlated with the prevalence of maximum temperature. However, amylose contents in superior grains had no acquaintance with maximum temperature at Qiqihar, but amylose contents in superior grains were highly positively correlated with the maximum grain weight. These results are in agreement with [81,82], who found that the retention of endosperm starch has been controlled by genetic make-up and environmental factors during progressive plant development. It was observed that the variations in ambient temperature could enhance the apparent amylose contents and bring adjustments in primary structure of starch granules such as crystalline structure and granular shape, thus bringing major changes in the quality of storage starches. Distinctiveness in overall amylose contents depended chiefly on specific rice cultivars, however, it was suggested that such fluctuations in cold weather conditions had role to widened amylose contents in the same cultivar as also reported by [81,82].

It was interpreted that for inferior grains, protein and amylose contents had a strong negative correlation with initial growth phase. In contrast, the same quality indicators were found with strong positive significant relationship with maximum temperature at Harbin. Similarly, the length to width ratio was also negatively correlated with the beingness of maximum temperature for inferior grains at Harbin. Similar result was reported by [81,82] who indicated that amylose contents in rice endosperm were reported to be determined by the ambient temperature at an early development stage (5–15 days after anthesis at 25.8 °C). If temperature variation continues to prevail even during night, then grain will be occupying higher degree of chalkiness [83]; therefore, chalkiness degree was positively correlated with the existence of maximum temperature at the same site in inferior grains. Ref. [84] also described that the induction of heat stress during grain-filling stage among different cultivars crumbled the overall grain quality and grain yield by 53–83%. Perceptibly, amylose contents with the maximum grain weight and protein contents with average grain-filling rate were significantly correlated among inferior grains at Harbin and Qiqihar, respectively. Amylose and protein contents were negatively correlated with the number of days of filling for inferior grains as proved by [47]. Similar to our findings [85], who reported that owing to high temperatures during the ripening phase, abnormal morphology and coloration occur in rice, probably due to decreased enzymatic activity in grain-filling, respiratory ingestion of assimilation products, and decreased sink activity.

4.4. Grain-Filling of Superior and Inferior Grains

Based on the findings of the current study and limited knowledge, the grain-filling growth phase was positively correlated with the environmental conditions at Harbin and negatively correlated at Qiqihar because stressful environmental conditions that prevailed during the grain-filling period were fractionally imprudent. Dry weight accumulation for superior as well as inferior grains was elevated in Longdao-21 followed by Longjing-21 and Suijing-18. Longdao-18 had attenuated values for dry weight accumulation as the rate of grain growth was faster and therefore, grain-filling period was shorter as higher temperatures approached [51,86]. Our results are consistent with findings of [49] who reported that the high temperature at flowering and grain-filling reduced grain yield through spikelet sterility and shortened grain-filling period. For a specific cultivar, the GDD necessary for flowering were comparatively assonant at different growing temperatures within the temperature approximate range between base and optimum temperatures. The findings also confirmed that grain weight accumulation for inferior grains was relatively low at Qiqihar probably due to the anticipated fluctuations in temperature at the grain-filling phase. In contrast, dry weight accumulation at Harbin was comparatively higher. These results are in line with [51] who reported that high temperature encouraged the ripening of grains and shortened the grain-filling phase. Ref. [87] explicated that the high temperature negatively impacted the rate of photosynthesis through diminution in root activities. It has also been observed previously that a high temperature at the flowering and grain-filling phase reduced net grain yield by enhancing spikelet sterility and shortening the grain-filling period [49,88]. The findings of this study illustrated where the prevalence of environmental conditions, i.e., solar radiation and temperature were in optimal range during flowering and grain-filling, the grain-filling rate, and duration potentiated there. It has been observed previously that duration of grain-filling phase directly depends on optimal solar radiation and temperature which determines the final grain yield [89].

4.5. Prevailed Environmental Components and Different Growth Phases

The possible forthcoming menace to japonica rice production and quality is changes in climate that will impact rice morphology, growth, physiology, biology, and ultimately, causing serious food security threats [50]. The relationship between environmental variables and growth phases of japonica rice excavated major alterations at both experimental sites. During early crop stages, average temperature, sunshine hours, solar radiation, and relative humidity had little impact on the initial growth cycle (from transplanting to booting). But these factors exerted negative correlation with the initial specific growth period of the japonica rice. However, in current study, the second half growth period of the rice plant is mostly affected by the prevailing environmental factors at both sites. Soil temperature at different depths, average sunshine hours, and daily radiation had strong negative correlation from booting to maturity at Harbin, whereas relative humidity was positively correlated with the later crop stages at Harbin. In contrast, average sunshine hours significantly bestowed ($r = 0.958^*$) from booting to maturity at Qiqihar along with daily radiation accumulation that was statistically insignificant. These findings are consistent with [90] who demonstrated that fluctuations in day and night temperatures and other environmental components impacted growth, yield and yield contributing components, and quality due to higher temperature stress and also affected physiological processes. Japonica grain quality became poorer when either higher day or night temperatures were applied to the panicle or the whole plant. The logical reason behind a decrease in the grain quality due to high night temperature was not because of the deficiency of carbohydrates in the leaves and the culms, as exposing the vegetative parts of the plant to this temperature did not reduce the quality of rice grain [91].

4.6. Impacts of Environmental Factors on Specific Leaf Area and Crop Growth Rate

One of the main measurements to note the crop photosynthesis is leaf area measurement. At different growth stages, it was aimed to brief the changing relationship between crop growth and leaf area development among different japonica rice cultivars grown under contrasting environments. The results of current study are supported by [92] who concluded that the temperature-dependent processes in leaf area development such as appearance and elongation of the leaf responded positively to high temperatures at different growth stages. However, as higher temperature continued to prevail till the sensitive growth stage such as flowering, the biomass production was reduced because of combined effects of other environmental components for example radiation interception by the plant and its absorption efficiency. Leaf area was higher at Harbin than Qiqihar and the decreasing trend after heading at Qiqihar was steeper. Temperature stress, either cold or heat, impacted the vegetative as well as reproductive growth stages and brought changes in a specific growth phase. It has been reported previously that temperature variation caused a decrease in leaf area and total dry matter accumulation [93,94]. The results of this study are in agreement with findings of [95] who demonstrated that leaf area development and maturity of crop strongly depended on temperature fluctuations, and variations in altitudes. Crop duration strongly influenced by changes in temperature and altitude, and seasonal mean temperature varied due to the altitudinal temperature gradient by 7 °C per km at 60% air humidity.

Increased leaf area was probably due to constant relative humidity, and inversions in day and night temperatures at a specific study site. Rendering that plant growth is compelled by photosynthetic carbon fixation during the daytime [96], higher growth rates could probably occur under higher day temperature, since maximum assimilation rates for japonica rice were in the range of 30–35 °C regardless of the growing temperature [94]. In addition, the process of respiration increased under higher night temperatures, which devoured a large quantity of daily available assimilates, therefore limiting the biomass accumulation [97]. In contrast, under semi-arid environments, leaf area development [98] and stomatal conductance [99] of japonica rice were observed to be strongly positively correlated with night temperature.

It was noticed that shifts in day and night temperatures solely did not significantly impact the crop growth rate and total dry matter, but had a significant effect on the zoning between plant organs and leaf area development. Leaf area development and total plant dry matter were higher under high night temperature which supports our findings of increased in leaf area development under high night temperature in duration of constant relative humidity. Under field conditions, relative humidity in the night was usually closer to 100% and considerably declined during the day. In temperature-controlled or greenhouses or growth chambers, diurnal relative humidity often showed less fluctuations, and even though the absolute quantity of water in air remains constant, relative humidity proportionally decreased with increasing temperature. Therefore, findings of this study indicated that leaf area development responded to temperature applicable only to field conditions may not be applicable to controlled conditions. Figure 9 represents the conceptual conclusions of the study conducted at Harbin and Qiqihar of NEC.

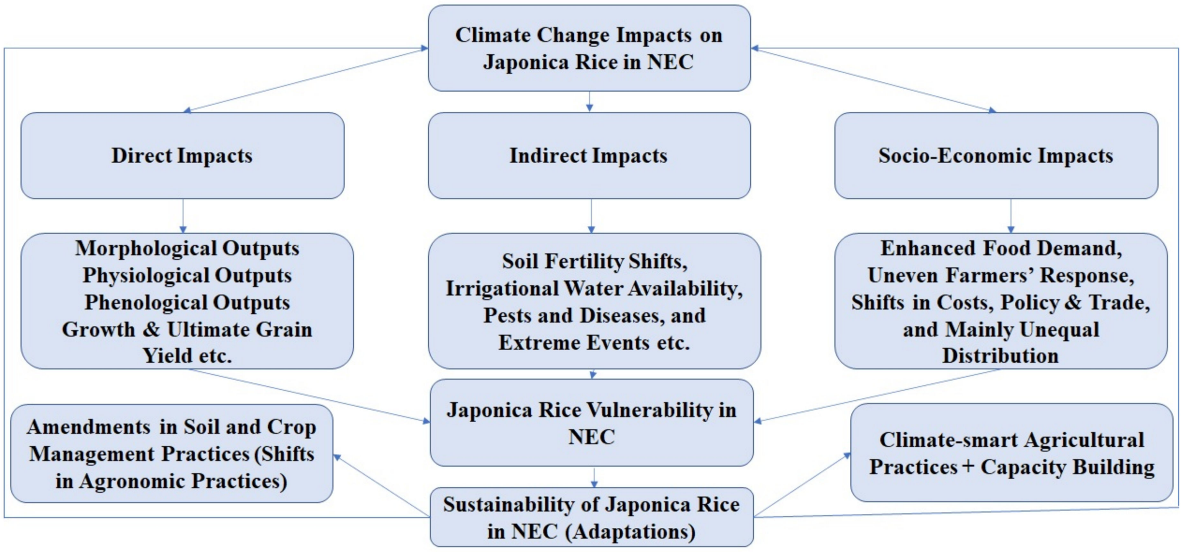

Figure 9. Conceptual conclusive remarks for future sustainability of japonica rice in NEC based on 3-year experiment (2017–2019).

Relative humidity not only influenced the plant growth response to shifts in temperature, but also had a strong direct impact on crop growth rate and leaf area. High humidity during the day light period combined with low humidity during the night dark period resulted in higher crop growth rate than in other possible combinations of low and high, day and night relative humidity, but in general a positive impact of higher relative humidity on crop growth rate has been reported [100]. SLA was not only highly affected by water availability but also by relative humidity across both sites. Although a strong positive correlation was noticed between SLA and shifts in night temperature, it was retracted that the relationship between changes in day and night temperature rather than night temperature itself authorized SLA. Findings of this study are supported by previous study who showed that low soil temperatures especially in rootzone decreased SLA [101], whereas another study showed a decrease in SLA under high night temperature [102]. Contrastingly, another study reported a strong positive correlation between SLA and temperature where an increase in SLA was seen with increase in temperature amplitude especially high day time temperature [103]. Moreover, it has been reasoned that SLA started to decrease when leaf expansion was more affected by variations in environmental factors rather than photosynthesis. Under warm and humid days, SLA started to decrease, and any decrease in SLA might be owing to low area development rate during the night, triggered by low temperature, low water availability. and relative humidity, whereas, based on the collected results, Figure 10 represents the clear two-dimensional visualization of the environment-by-trait table encoded as a grid of colored cells to understand the similarities between different environments and traits.

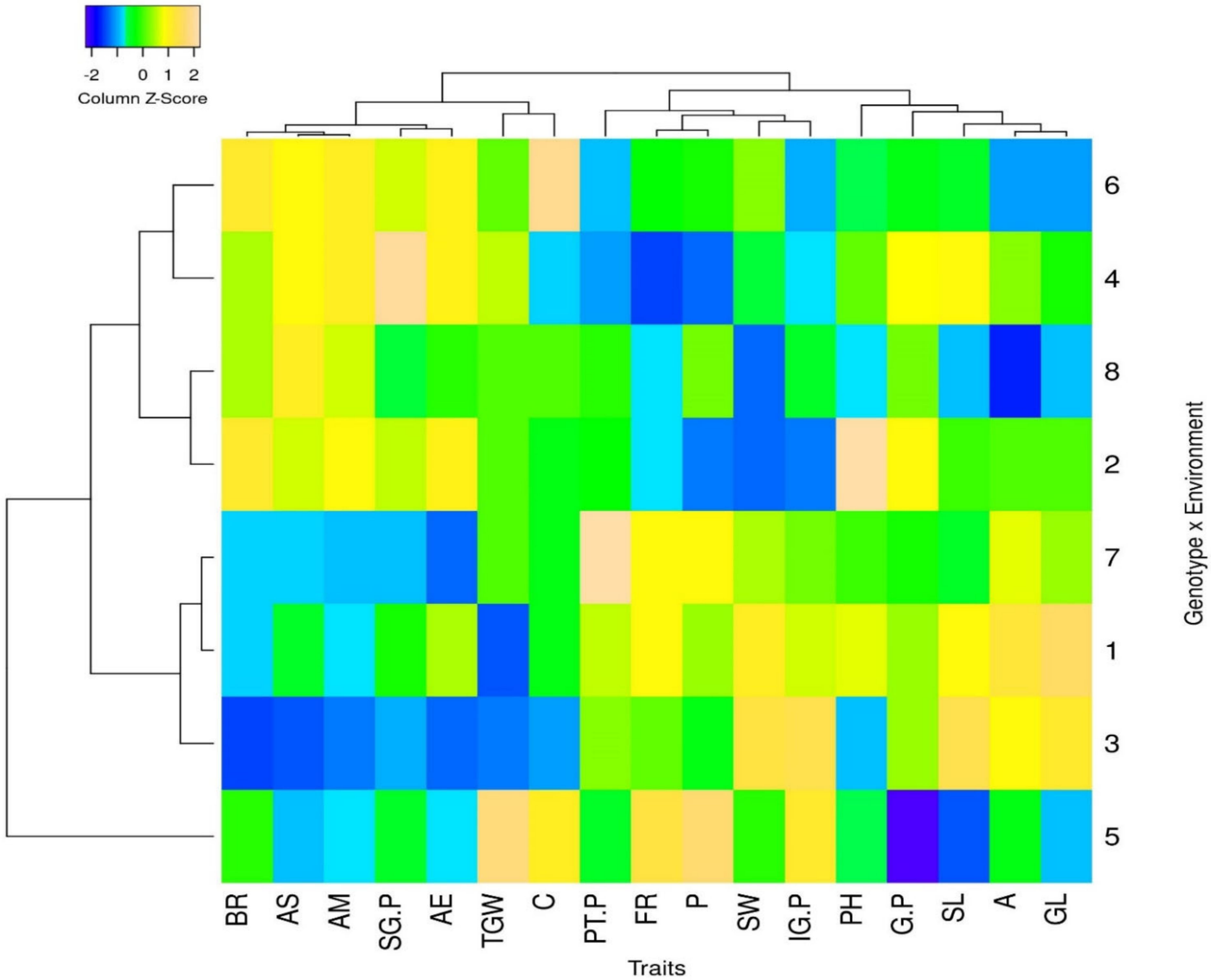

Figure 10. Two-dimensional visualization of environment-by-trait table to differentiate the similarities between the environments and traits (PT.P: productive tillers/plant, G.P: grains/panicle, TGW: 1000-grain weight (g), PH: plant height (cm), SW: spike weight (g), SL: spike length (cm), IG.P: inferior grains/panicle, SG.P: superior grains/panicle, GY: grain yield, BR: brown rice (%), FR: fine rice (%), GL: grain length (mm), AS: anthesis start (hasr), AM: anthesis mid (hasr), AE: anthesis end (hasr), C: chalkiness, A: amylose (%), P: protein (%), 1, 2: Longdao-18 at Harbin and Qiqihar, respectively, 3, 4: Longdao-21 at Harbin and Qiqihar, respectively, 5, 6: Longjing-21 at Harbin and Qiqihar, respectively, 7, 8: Suijing-18 at Harbin and Qiqihar, respectively).

5. Conclusions

This research provides indications of strong impacts of variations in weather, notably the effects on critical growth phases such as the grain-filling stage and time of day of anthesis in japonica rice. The current study evidenced the correlative potent impacts of varying environmental conditions on different growth stages of japonica rice and ultimately effects on grain-filling of superior and inferior grains, anthesis, yield and yield components, and quality of rice. This research provides an adaptive value, especially for scenarios of global warming, where heat induces a great spikelet sterility expectedly to be a major constraint to high net grain yield. Taking as another factor for escape from climatic stresses, the collective and aggregated duration of flowering at the panicle stage and quantification of population was also done, denoting a risk diffusing mechanism.

Adaptability mechanism of japonica rice observed on anthesis depicts those prevailing high temperatures on the start of the day at earlier anthesis intensified the exceedance of escape from even the higher temperature stress later during that day. Humid environmental conditions on earlier anthesis made the rice plant capable of potentially escaping from higher ambient temperature late during the day. The observed variations in the phenology of japonica rice rendered that those cultivars transplanted earlier produced a higher net yield, and provided the positive correlation between yield and transplantation, i.e., the earlier the transplantation, the taller plants will be and higher the net grain yield will be. Moreover, undergoing the correlation between transplantation dates and net grain yield, cultivars with earlier transplantation dates escaped well from the high precipitation and low temperature stresses during later growth stages such as anthesis. Short duration cultivars are recommended in Heilongjiang specifically to avoid the low temperature stress periods on later growth stages majorly on anthesis and grain-filling. Models that predict the temperature-based panicle sterility in rice are necessarily needed in future research focusing NEC to abstract the temporal malleability of the anthesis process along with precise simulation of spikelet temperature during the critical growth phases of japonica rice.

Different trends for air and soil temperature, sunshine, and precipitation impacted the phenological variables and ultimately had impacts on the growth and production of early and late maturing cultivars. Since the phenological variables of rice are mainly controlled by climatic components and management practices, better adaptation through shifts in management practices should be encouraged which is majorly controlled by farmers. Using NEC's data of weather variables and rice production in current study, the positive and negative correlative responses of japonica rice to environmental variables were empirically identified. Adverse impacts of abnormal weather may invite the changes in soil fertility at a specific growth stage, therefore motivation for incorporation of management measures based on climate smart agriculture is necessary to avoid the worsened impacts on production. The abnormalities in temperature may lead to a shortage of inputs (such as labor), impacting the rice production. Thus, in summary both direct and indirect impacts of climatic variabilities on japonica rice yield cannot be ignored.

Aiming to sustain the future japonica rice production, awareness of climate-smart agriculture and optimized use of inputs is necessary. Strengthening the technological programs to offset the negative impacts of climate variabilities is indispensable. Pre- and post-disaster measures taken by relevant local authorities are necessary by rationalizing the optimized japonica rice farming. It is also proposed that more advanced statistical techniques for deep studies integrated with mechanized approaches should be explored for deeper investigations of impacts of climatic variables on different growth stages. Additionally, based on the observed results, it is suggested that temperature-based indices over all climatic variables such as GDD, meteorological standard indices, etc. should be applied in future climate-rice studies in NEC to observe the relationship analysis. Cold periods during critical growth phases caused chilling injuries and yield decline which suggested to necessarily have chilling injury indices in future research, but previous research in NEC denoted that only one temperature component (T_{min}, T_{max}, or T_{avg}) was considered to observe the temperature variation impacts on rice yield due to traditional evaluation methods. The most commonly and approved methods to evaluate the impacts in past studies were national standard indices, meteorological standards indices, or cumulative temperature indices etc. that can only consider one temperature variable ignoring the diurnal variations of the temperature. Therefore, the results of this study suggested the need of have modern GDD methods in evaluation of temperature impacts on critical growth phases and to have interannual shifts in japonica rice yield in NEC because these methods consider different threshold levels of the environmental variables such as temperature.

Author Contributions: Data collection and data analysis of the research was done by first and second authors M.S.F. and A.G., respectively. The third author A.L.V. helped in the write up process of the article, whereas the mentor of the research group and corresponding author of this article Y.X. did the financial arrangements for the conduction of the field trials. Moreover, he helped for necessary revisions in the draft. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the Climate Change Adaptation Lab of Institute of Environment and Sustainable Development in Agriculture (IEDA), Chinese Academy of Agricultural Sciences (CAAS).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The authors would like to express their gratitude for technical support by the field staff and workers at the research sites of Heilongjiang Academy of Agricultural Sciences (HAAS) at Harbin and Qiqihar.

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

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