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Influence of precipitations and sunshine hours on yield of paddy field grown wheat (*Triticum aestivum* L.) in Northern Kyushu, Japan

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ABSTRACT

Relationships between wheat (*Triticum aestivum* L.) yield components and growing season weather conditions (e.g. temperature, precipitation, and sunshine duration) were investigated for a rice-wheat rotation paddy system situated in Northern Kyushu, Japan over a 17-year period (2000–2016). A 1.0 mm increase in precipitation from 21 to 32 days after sowing decreased wheat yield by about 27 kg ha⁻¹ at early seedling stage with one to two leaves (Zadoks (Z) growth stage Z1.1–1.2). Number of tillers and spikes showed significant negative correlations to the amount of precipitation during the period. An hour increase in mean daily sunshine hours from 94 to 111 days after sowing resulted in an 328 kg ha⁻¹ rise in grain yield at stem elongation stage with the first and second node detection (Z3.1–3.2). The grain number per square meter also showed strong positive correlations to sunshine hours during the same period. However, this positive effect of sunshine was negated when precipitation exceeded about 30 mm during the early seedling stage. Consequently, precipitations at early seedling stage and sunshine hours at stem elongation stage mostly determined wheat yield in Northern Kyushu paddy field. Increasing precipitations during the early seedling stage highlights the pressing need for effective paddy field drainage management from wheat sowing through harvest.

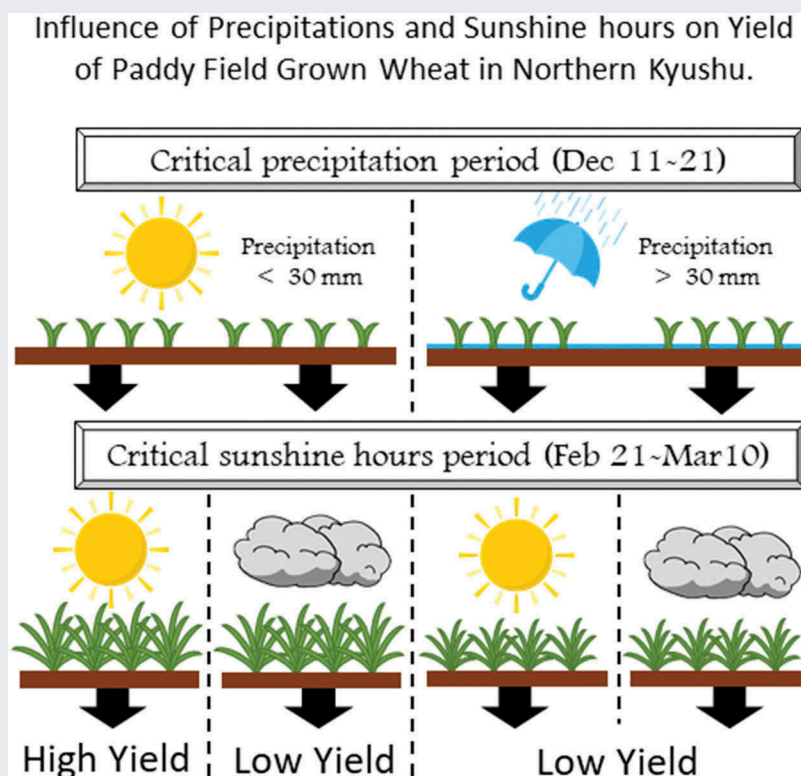
Abbreviations: CP: Chikushi Plains; FARC: Fukuoka prefectural Agriculture and Forestry Research Center; SARC: Saga prefectural Agricultural Research Center; DAS: days after sowing

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Wheat; paddy field; critical precipitation period; early seedling stage; critical sunshine period; stem elongation stage; cumulative sunshine hours



1. Introduction

Staple food's widespread production increasingly requires high yielding varieties and advanced cultivation and management methods to maintain a sufficient supply. Worldwide wheat (*Triticum aestivum* L.) consumption expected to rise by 1.0% between 2017–18 and 2018–19, to an all-time peak of 509.7 million tons per year (FAO, 2018). However, its production is estimated to decline by 6% °C⁻¹ of future climate-change-driven rise and yields would become more erratic in both space and time concomitantly (Asseng et al., 2015). Apart from high temperature stress, more frequency and intensity of precipitation events forecasted to occur around the world, and recurring waterlogging is an anticipated outcome of the predicted climate change patterns (IPCC, 2014).

The paddy field crop production system implemented in Northern Kyushu, Japan has a high crop production potential by rotating two crops, usually rice (*Oryza sativa* L.) with either wheat or barley (*Hordeum vulgare* L.) within a year. Paddy fields in the Northern Kyushu region of Japan produce about 10% of the nation's wheat (MAFF, 2016). The rotation system has several advantages: weeds are controlled through a combined seasonal flooding-drying cycle implemented through irrigation and drainage, and a natural nitrogen supply is provided through irrigation water and algae. However, wheat is vulnerable to humid environments and its growth suffers in the presence of excess water such as occurs under poor drainage. Thus, wheat production in a paddy field rotation is rather erratic compared to rice. Indeed, mean wheat yields in Japan's Northern Kyushu area have dropped by over 40% from 2007 to 2011 (MAFF, 2016), and it is necessary to confirm whether such a large decrease occurs due to weather factors.

Soil waterlogging occurs worldwide, affecting about 10–15% of worldwide wheat production areas (Setter & Waters, 2003). Reported waterlogging-related wheat yield losses varying widely: from 39 to 44% (Zhou, 2010), or from 8 to 55% (Robertson et al., 2009). Severe waterlogging damage of wheat crops has been reported in several major wheat production regions, including Southern China, the southeastern United States, Western Australia, and Mediterranean (Bassu et al., 2009; Setter et al., 2009; Yang et al., 2017).

After wheat germination and emergence, the two phenological stages during which waterlogging most influences wheat yields are 'seedling' and 'anthesis' (Araki et al., 2012; Setter & Waters, 2003). When plants were exposed to waterlogging at early vegetative stages (Leaf 1 to Leaf 4), the appearance of the first tiller was delayed, and the rate of tiller appearance was significantly reduced (de San Celedonio et al., 2016). When

wheat suffered from hypoxic roots at heading, post-heading respiration rates of plants were abnormally high (Araki et al., 2012). In addition, abnormal early ripening (AER) that reduce wheat yield occurs frequently in waterlogging-prone fields of Northern Kyushu (Araki et al., 2012). Since excess water stresses arises through a complex combination of factors (e.g. poor drainage, excessive precipitation), an evaluation of the effects of climate on crop production under field conditions is indispensable for best management practices (BMPs).

Hence, we investigated the relationships between the crop phenological stages, including yield components and meteorological data (temperature, precipitation, and sunshine duration) over a 17-year period in Northern Kyushu, Japan. We examined the relationships between weather parameters and yield, and yield components (e.g. tiller, spike, and grain numbers) to elucidate the weather parameters and their interactions on wheat yield and agronomic characteristics by long-term field tests data. We tried to identify the most influential factors for wheat yield at the specific period, and inform effective crop managements for high yield production in paddy field rotation.

2. Materials and methods

2.1. Wheat yield and yield components data

We collected yield component data for the soft red wheat cultivars 'Chikugoizumi' and 'Shiroganekomugi'; 'Chikugoizumi' was grown at the Fukuoka prefectural Agriculture and Forestry Research Center (FARC), Chikushino, Fukuoka (33°30'N, 130°34'E), and 'Shiroganekomugi' was grown at the Saga prefectural Agricultural Research Center (SARC), Kawasoe, Saga (33°13' N, 130°19' E) (Figure 1) from 2000 to 2016. We rotated wheat and rice in the same plots every year, and a gray lowland soil was present at both sites. Experimental plot size was 19.6 m² with three replicates for FARC and 40 m² with five replicates for SARC. Sowing density was 150 plants m⁻² at FARC using four row seeders with a 0.25 to 0.40 m row spacing, and 120 plants m⁻² at SARC using two row seeders with a 0.25 m row spacing. In each year and for both sites, we sowed on around November 19 (Table 1). Nitrogen was applied at a rate of 50 kg ha⁻¹ at FARC and 55 kg ha⁻¹ at SARC at sowing, supplemented at the end of January with a further 40 kg ha⁻¹ at FARC and 45 kg ha⁻¹ at SARC, and further supplemented (topdressed) in early March with 20 kg ha⁻¹ at FARC and 40 kg ha⁻¹ at SARC. Phosphorus was applied at a rate of 50 kg ha⁻¹ at FARC



Figure 1. Map of the Chikushi Plains, Northern Kyushu, Japan, and location of Fukuoka prefectural agriculture and forestry research center (FARC), Saga prefectural agricultural research center (SARC), and 'AMeDAS' (Automated Meteorological Data Acquisition System) at 8 sites (Asakura, Dazaifu, Kurume, Omuta, Saga, Shiroishi, Ureshino, Yanagawa).

Table 1. Mean wheat crop phenology and yield component traits for two wheat varieties, 'Chikugoizumi' grown at FARC, and 'Shiroganekomugi' grown at SARC for the period of 2000 to 2016. FARC, Fukuoka prefectural Agriculture and Forestry Research Center; SARC, Saga prefectural Agricultural Research Center; DAS, days after sowing.

Traits	Zadoks growth stage	Chikugoizumi (FARC)	Shiroganekomugi (SARC)	t-test
		Mean \pm S.E.	Mean \pm S.E.	
Phenology				
Sowing date	Z0.1	19-Nov (0DAS) \pm 0.3	19-Nov (0DAS) \pm 0.2	-
Emergence date	Z1.0	29-Nov (10 DAS) \pm 0.5	3-Dec (14 DAS) \pm 0.9	-
Days to emergence (days)	Z0.1–1.0	10.2 \pm 0.4	13.2 \pm 0.8	**
First node detectable date	Z3.1	26-Feb (99 DAS) \pm 1.2	20-Feb (93 DAS) \pm 1.7	-
Heading date	Z5.5	10-Apr (142 DAS) \pm 1.1	7-Apr (139 DAS) \pm 1.1	-
Maturing date	Z9.2	31-May (193 DAS) \pm 0.9	28-May (190 DAS) \pm 0.9	-
Grain filling duration (days)	Z5.5–9.2	50.7 \pm 0.8	51.3 \pm 0.7	n.s.
Yield components				
No. of tillers/m ²				
20-Jan (62 DAS)	Z1.3&Z2.1	494 \pm 36	385 \pm 28	**
10-Feb (83 DAS)	Z1.4&Z2.2	696 \pm 43	663 \pm 39	n.s.
1-Mar (102 DAS)	Z3.1–3.2	808 \pm 41	842 \pm 38	n.s.
20-Mar (121 DAS)	Z3.2–3.3	751 \pm 32	761 \pm 33	n.s.
No. of spikes/m ²	Z9.2	514 \pm 17	511 \pm 16	n.s.
Culm length (cm)	-	85.6 \pm 1.3	82.3 \pm 0.8	*
Spike length (cm)	-	8.4 \pm 0.1	8.8 \pm 0.1	*
1000 grain weight (g)	-	39.0 \pm 0.6	35.8 \pm 0.5	**
No. of grains/m ²	-	13,910 \pm 490	16,360 \pm 450	**
Yield (t/ha)	-	5.41 \pm 1.9	5.87 \pm 2.0	*

and 51 kg ha⁻¹ at SARC at sowing, supplemented at the end of January with 63 kg ha⁻¹ at SARC. Potassium was applied at a rate of 50 kg ha⁻¹ at FARC and 45 kg ha⁻¹ at

SARC at sowing, supplemented at the end of January with 40 kg ha⁻¹ at FARC and 55 kg ha⁻¹ at SARC, and further supplemented (topdressed) in early March with

20 kg ha⁻¹ at FARC and 30 kg ha⁻¹ at SARC. We measured the number of tillers per culms unit surface at 62, 83, 102, and 121 days after sowing and number of spikes at late maturing stage over a 0.50 m length of the second row inside the plot border, then converted to per square meter. We measured culm and spike length for 10 randomly-selected spikes in each plot at late maturing stage. We determined the growth stage of wheat plant according to Zadoks growth scale (Zadoks et al., 1974) that represents number of leaves and tillers at each measuring stage. Heading date, maturation date, days from heading to maturation, thousand-grain weight, test weight, and the yield were recorded for each plot, and we employed the mean of replicates for subsequent analyses. Number of grains per square meter was calculated from the yield per square meter and thousand-grain weight. Specifically, we collected mean and total wheat yield data from 27 municipalities on the Chikushi Plains close to 220 km² of wheat fields situated in the Chikushi Plains area (Figure 1), representing 88% of wheat fields in the Northern Kyushu region. We collected each municipal's yield data from crop statistics from the Japanese Ministry of Agriculture, Forestry and Fisheries from 2000 to 2016 (MAFF, 2016). Typical sowing dates for wheat growers in the Chikushi Plains are between November 20 to beginning of December. In the present analysis, 'Chikugoizumi' and 'Shiroganekomugi' were planted to 32.1 and 44.8% of the total Northern Kyushu wheat fields in 2016, respectively. Both cultivars have been continuously major in Northern Kyushu, Japan throughout analyzed period, and they have low vernalization requirements, as they are typical spring wheat varieties.

2.2. Weather data and statistical analysis

Between 2000 and 2016, air temperature, precipitation and sunshine duration data were collected from 'AMeDAS' (Automated Meteorological Data Acquisition System, Japan Meteorological Agency) stations situated at 8 sites in the Chikushi Plains [Asakura, Dazaifu, Kurume, Omuta, Shiroishi, Saga, Ureshino, Yanagawa (only precipitation)] (Figure 1). We employed weather data from the site closest to each plot for subsequent analysis. Over the 2000 to 2016 study period, mean annual temperature, precipitation and sunshine duration at Chikushi Plains AMeDAS sites averaged 10.4°C, 664.7 mm, and 971.4 h during wheat growth period, respectively (Figure 2). We conducted correlation analysis across years between yield components and agronomic characteristics (culm length, spike length, number of spikes per square meter, number of grains per square meter, heading date, maturation date, days from heading to maturation, thousand-grain weight and yield) and 10-day temperature means, 10-day precipitation, and 10-day cumulative hours of sunshine exceeding 0.432MJ m⁻² in energy. These temperature, precipitation and sunshine parameters are abbreviated according to the period they cover: e.g. $\overline{\text{T}}_{110XII}$, ΣP_{110XII} , ΣSH_{110XII} , respectively, for the period of December 1 to December 10. We calculated photothermal quotient (PTQ) as the quotient of solar radiation to temperatures minus 4.5°C (Nix, 1976) using heading date. Solar radiation data was obtained from Saga station of AMeDAS.

We conducted correlation analysis between wheat yield at each site and local 10-day mean temperature, 10-day precipitation, and 10-day cumulative sunshine hours within

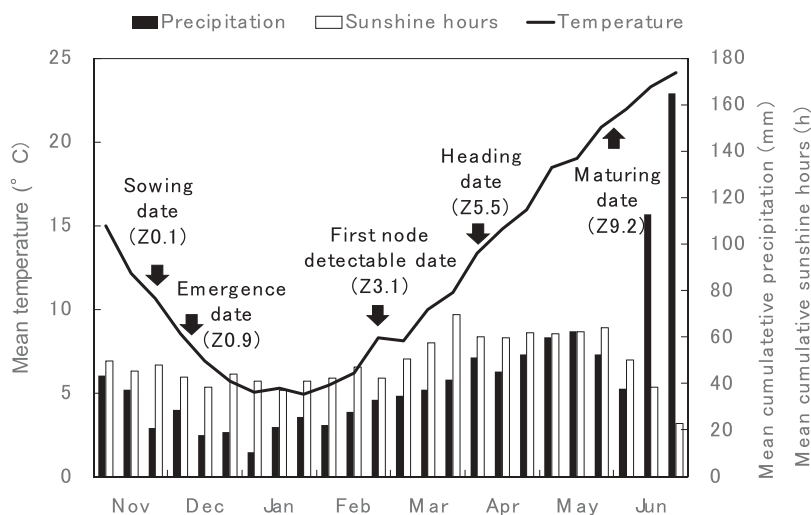


Figure 2. Mean temperature, cumulative precipitation, and sunshine duration of every 10 days in the Chikushi Plains, Northern Kyushu, Japan from 2000 to 2016. Mean sowing date, first node detectable date, Heading date and maturing date and Zadoks growth stage (Z) of each stage from 2000 to 2016 at Fukuoka prefectural agriculture and forestry research center and Saga prefectural Agricultural Research Center are indicated by arrows.

Table 2. Correlation coefficients between wheat yield and 10-day mean temperature, 10-day precipitation, and 10-day cumulative sunshine hours at Northern Kyushu, Japan from 2000 to 2016.

Period of the season (days after sowing, DAS) N	Zadoks growth stage	vs. Mean temperatures			vs. Precipitations			vs. Cumulative sunshine hours		
		CP 17	FARC 17	SARC 17	CP 17	FARC 17	SARC 17	CP 17	FARC 17	SARC 17
<i>Critical precipitation period (during early seedling stage)</i>										
Dec 10–21 (21–32 DAS)	Z1.1–1.2	0.03	0.24	–0.15	–0.72**	–0.58*	–0.68**	0.37	0.29	0.42
<i>Critical sunshine period (during stem elongation stage)</i>										
Feb 21–Mar10 (94–111 DAS)	Z3.1–3.2	–0.53*	–0.61**	–0.55*	–0.36	–0.21	–0.25	0.42	0.33	0.29
Nov 21–30 (2–11 DAS)		0.15	0.34	–0.10	–0.14	–0.02	–0.26	0.11	0.01	0.20
Dec 1–10 (12–21 DAS)	Z1.0	–0.15	0.18	–0.33	–0.06	–0.06	–0.06	0.17	0.25	0.03
Dec 11–20 (22–31 DAS)		0.08	0.27	–0.08	–0.50*	–0.51*	–0.44	0.24	0.17	0.38
Dec 21–31 (32–42 DAS)		0.28	0.44	0.04	–0.09	–0.33	–0.05	0.23	0.42	0.06
Jan 1–10 (43–52 DAS)		0.42	0.66**	0.21	0.08	–0.14	–0.02	0.28	0.25	0.44
Jan 11–20 (53–62 DAS)	Z1.3&Z2.1	0.27	0.09	0.29	0.25	0.18	0.07	–0.16	0.08	–0.10
Jan 21–31 (63–73 DAS)		0.11	0.08	0.23	–0.30	0.05	–0.42	–0.03	–0.31	0.11
Feb 1–10 (74–83 DAS)	Z1.4&Z2.2	–0.20	–0.18	–0.30	–0.03	–0.31	0.26	–0.24	–0.17	–0.54*
Feb 11–20 (84–93 DAS)		–0.10	–0.14	–0.32	–0.13	–0.32	–0.06	0.40	0.40	0.26
Feb 21–28 (94–101 DAS)	Z3.1	–0.44	–0.51*	–0.53	–0.06	–0.09	0.00	0.30	0.18	0.22
Mar 1–10 (102–111 DAS)		–0.28	–0.32	–0.21	–0.48	–0.22	–0.42	0.41	0.36	0.28
Mar 11–20 (112–121 DAS)	Z3.2–3.3	–0.26	–0.23	–0.21	0.18	0.31	0.31	0.13	0.08	0.00
Mar 21–30 (122–131 DAS)		0.33	0.41	0.25	0.41	0.25	0.52*	–0.25	–0.13	0.02
Apr 1–10 (132–141 DAS)	Z5.5	–0.34	0.00	–0.50	–0.09	–0.23	–0.01	0.05	0.00	0.11
Apr 11–20 (142–151 DAS)		–0.04	–0.04	0.01	–0.37	–0.42	–0.13	0.26	0.24	0.16
Apr 21–30 (152–161 DAS)		–0.05	0.13	0.03	–0.45	–0.06	–0.57*	0.30	0.15	0.37
May 1–10 (162–171 DAS)		–0.19	–0.15	–0.28	–0.06	–0.13	–0.28	0.10	0.03	0.40
May 11–20 (172–181 DAS)		–0.63**	–0.49*	–0.54*	–0.14	–0.26	–0.06	–0.05	0.08	–0.10
May 21–31 (182–192 DAS)	Z9.2	0.10	0.24	0.10	0.04	–0.06	–0.03	0.26	0.32	0.44

CP, the Chikushi Plains at Northern Kyushu; FARC, Fukuoka prefectural Agriculture and Forestry Research Center; SARC, Saga prefectural Agricultural Research Center; DAS, days after sowing. * $P \leq 0.05$; ** $P \leq 0.01$

the growing season. We also conducted correlation analysis for a number of different series of days in December. Consequently, we undertook a similar correlation analysis between wheat yield and weather parameters for cases (years) when the precipitations during early seedling stage of December exceeded 30 mm or less than 30 mm (28 mm for SARC). This analysis was conducted because we found the precipitations during the critical period in December brought the significant different effects of sunshine period in February and March on wheat yield. We employed the precipitations threshold of 28 mm for SARC because the AMeDAS sites gave slightly different threshold of critical precipitation amount during early seedling stage. We conducted statistical analysis between meteorological data, phenology, and yield components using Microsoft Excel 2016 (Microsoft Co.).

3. Results

3.1. Influence of precipitation at early seedling for wheat yield

Mean wheat crop phenological and yield components data (2000–2016) show similar number of tillers increases and timing of peak numbers (maximum tillering in early March) for cultivars ‘Chikugoizumi’ at FARC

and ‘Shiroganekomugi’ at SARC (Table 1, Figure 2). Wheat yield showed a significant negative correlation with $\Sigma P_{11-20XII}$ in the Chikushi Plains ($r = -0.50$, $P \leq 0.05$, $n = 17$), at FARC ($r = -0.51$, $P \leq 0.05$, $n = 17$) but not at SARC ($r = -0.44$, $P > 0.05$, $n = 17$) (Table 2). The 12-day period of December 10 to 21 showed the strongest negative yield-precipitation ($\Sigma P_{10-21XII}$) correlations: Chikushi Plains ($r = -0.72$, $P \leq 0.01$, $n = 17$), at FARC ($r = -0.58$, $P \leq 0.05$, $n = 17$) and at SARC ($r = -0.68$, $P \leq 0.01$, $n = 17$) (Table 2, Figure 3). For further analyses, we deemed this specific period from 21 to 32 days after sowing when the Zadoks growth stage is Z1.1–1.2, as the critical precipitation period during early seedling stage. The interval between mean wheat emergence date and the onset of the early period was 6 days at SARC and 10 days at FARC.

3.2. Influence of sunshine hours at stem elongation stage for wheat yield

When $\Sigma P_{10-21XII} < 30$ mm (28 mm for SARC), wheat yield showed a strong positive correlation with mean daily sunshine hours at stem elongation stage with the first and second node detection (Z3.1–3.2), 18-day period from February 21 to March 10 ($\Sigma SH_{21/10III}/18$), 94 to 111 days after sowing (Table 3). There were strong

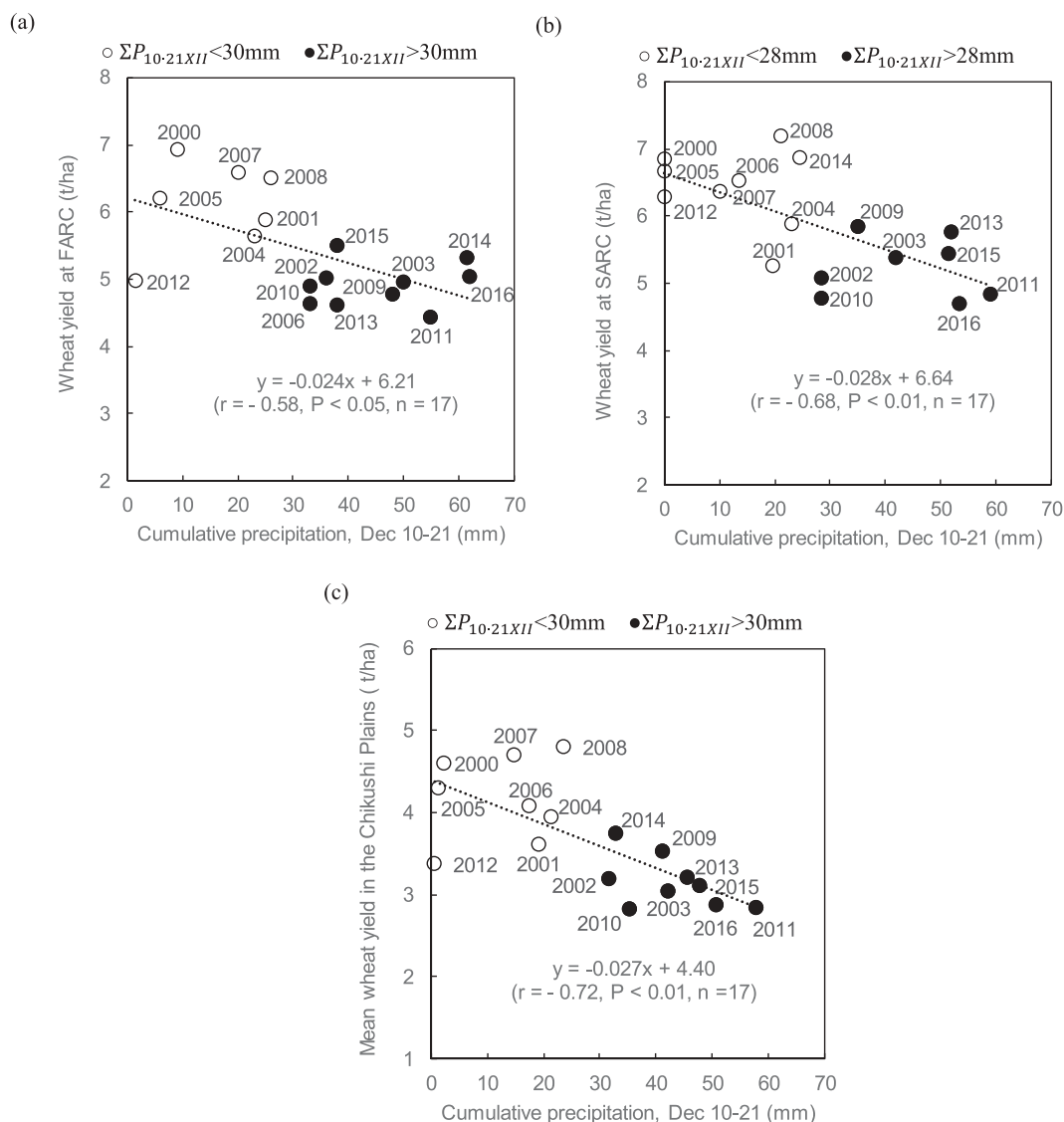


Figure 3. Relationships between mean precipitation in the critical period of early seedling stage from December 10 to 21 ($\sum P_{10-21XII}$) and mean wheat yield in Fukuoka prefectural Agriculture and Forestry Research Center (FARC), Chikushino, Fukuoka (a), Saga prefectural Agricultural Research Center (SARC), Kawasoe, Saga (b), and the Chikushi Plains (c), Northern Kyushu, Japan from 2000 to 2016. Open circles are years where $\sum P_{10-21XII} < 30$ mm ($\sum P_{10-21XII} < 28$ mm at SARC), and close circle are years where $\sum P_{10-21XII} > 30$ mm ($\sum P_{10-21XII} > 28$ mm at SARC) during the critical precipitation period.

positive correlations for the Chikushi Plains ($r = 0.87, P \leq 0.01, n = 8$) and at FARC ($r = 0.89, P \leq 0.01, n = 7$) (Table 3, Figure 4). A more moderate positive correlation ($r = 0.55, P > 0.05, n = 9$) was observed at SARC. This correlation was strengthened if we omit the year 2012, when 130 mm of precipitation occurred at sowing time ($r = 0.71, P \leq 0.05, n = 8$). We deemed this specific period as the critical sunshine period (Table 3). When $\sum P_{10-21XII} > 30$ mm, the strong positive correlation between wheat yield and $\sum SH_{21II-10III}$ disappeared (Table 3, Figure 4). The mean temperature at the end of March (booting stage), $\overline{T}_{21-30III}$, showed a significant positive correlation with yield in the Chikushi Plains ($r = 0.71, P \leq 0.05, n = 8$) and FARC ($r = 0.73, P \leq 0.05, n = 10$).

3.3. Relationships between precipitations and sunshine hours to wheat agronomic characteristics

There were strong positive correlations between yield at each experimental plot site and both the number of grains per square meter, and the mean yield across the Chikushi Plain (Table 4). Overall yield and the number of spikes showed strong positive correlations at both the FARC and SARC experimental plot sites. At both sites, there were significant negative correlations between $\sum P_{10-21XII}$ and number of tillers at 83 days (Z1.4&Z2.2), 102 days (Z3.1–3.2) and 121 days (Z3.2–3.3) after sowing, but no significant correlation at 62 days (Z1.3&Z2.1) after sowing (Table 4). When $\sum P_{10-21XII} < 30$ mm (28 mm for SARC),

Table 3. Correlation coefficients between wheat yield and 10-day mean temperature, 10-day precipitation, and 10-day cumulative sunshine hours, grouped by precipitation amounts ($\sum P_{10-21XII} < 30$ mm vs. $\sum P_{10-21XII} > 30$ mm) over the during critical precipitation period during early seedling stage (Dec 10 to 21) at Northern Kyushu, Japan from 2000 to 2016.

Period of the season (days after sowing, DAS) N	Zadoks growth stage	$\sum P_{10-21XII} < 30\text{mm}^{1)}$								
		vs. Mean temperatures			vs. Precipitations			vs. Cumulative sunshine hours		
		CP 8	FARC 7	SARC 9	CP 8	FARC 7	SARC 9	CP 8	FARC 7	SARC 9
<i>Critical precipitation period (during early seedling stage)</i>										
Dec 10–21 (21–32 DAS)	Z1.1–1.2	0.22	0.23	–0.06	0.16	0.26	–0.17	0.22	0.50	0.10
<i>Critical sunshine period (during stem elongation stage)</i>										
Feb 21–Mar10 (94–111 DAS)	Z3.1–3.2	–0.36	–0.44	–0.32	–0.78*	–0.80*	–0.51	0.87**	0.89**	0.55
Nov 21–30 (2–11 DAS)		0.04	–0.28	–0.38	0.44	0.41	0.18	–0.37	–0.39	–0.06
Dec 1–10 (12–21 DAS)	Z1.0	–0.46	–0.58	–0.50	0.07	–0.07	0.30	0.06	0.16	–0.26
Dec 11–20 (22–31 DAS)		0.26	0.25	0.01	0.01	0.16	–0.42	0.21	0.48	0.21
Dec 21–31 (32–42 DAS)		0.57	0.37	0.20	0.51	0.30	0.59	–0.30	0.06	–0.45
Jan 1–10 (43–52 DAS)		0.36	0.64	–0.07	–0.01	0.18	–0.34	0.03	0.27	0.18
Jan 11–20 (53–62 DAS)	Z1.3&Z2.1	0.52	0.37	0.73*	0.32	0.20	0.27	0.34	0.20	0.13
Jan 21–31 (63–73 DAS)		0.26	0.43	0.25	–0.13	0.05	–0.38	–0.66	–0.68	–0.20
Feb 1–10 (74–83 DAS)	Z1.4&Z2.2	0.40	0.48	–0.09	–0.54	–0.60	0.20	0.55	0.65	–0.11
Feb 11–20 (84–93 DAS)		0.09	0.08	–0.41	–0.02	–0.10	0.18	0.15	0.10	–0.27
Feb 21–28 (94–101 DAS)	Z3.1	–0.38	–0.41	–0.57	–0.76*	–0.92**	–0.56	0.81*	0.70	0.58
Mar 1–10 (102–111 DAS)		–0.08	–0.14	0.27	–0.27	–0.20	0.06	0.80*	0.93**	0.45
Mar 11–20 (112–121 DAS)	Z3.2–3.3	0.00	–0.13	–0.01	0.66	0.63	0.71*	0.36	0.33	0.02
Mar 21–30 (122–131 DAS)		0.09	0.14	–0.27	0.01	–0.65	0.39	–0.38	–0.27	0.17
Apr 1–10 (132–141 DAS)	Z5.5	–0.11	0.14	–0.25	0.08	0.46	0.21	–0.71*	–0.69	–0.50
Apr 11–20 (142–151 DAS)		–0.48	–0.70	–0.32	–0.25	–0.62	0.17	0.07	0.15	–0.26
Apr 21–30 (152–161 DAS)		–0.20	–0.55	0.16	–0.16	–0.09	–0.18	0.21	–0.04	0.24
May 1–10 (162–171 DAS)		–0.65	–0.71	–0.16	0.05	–0.26	–0.19	0.49	0.67	0.68*
May 11–20 (172–181 DAS)		–0.59	–0.60	–0.59	–0.13	–0.22	–0.03	0.22	0.15	0.03
May 21–31 (182–192 DAS)	Z9.2	0.31	0.26	0.02	0.55	0.46	0.42	0.53	0.15	0.53

CP, the Chikushi Plains at Northern Kyushu; FARC, Fukuoka prefectural Agriculture and Forestry Research Center; SARC, Saga prefectural Agricultural Research Center; DAS, days after sowing. * $P \leq 0.05$, ** $P \leq 0.01$

¹⁾28mm at SARC.

number of grains per square meter showed strong positive correlations to $\sum SH_{21II-10III}$ at both FARC ($r = 0.95$, $P \leq 0.01$, $n = 7$) and SARC ($r = 0.69$, $P \leq 0.05$, $n = 8$) (Table 4). However, the strong positive correlation entirely disappeared when $\sum P_{10-21XII} > 30$ mm. We can therefore conclude that the $\sum P_{10-21XII}$ and $\sum SH_{21II-10III}$ are the major determinants of the number of tillers, spikes and grains per square meters, and therefore yield.

There was also a significant positive correlation between yield and the number of tillers at the FARC site (but not the SARC site) between 62 days (Z1.3&Z2.1) and 83 days (Z1.4&Z2.2) after sowing. Correlations between yield and culm length ($P \leq 0.05$), and 1000-grain weight ($P \leq 0.01$) were only significant at the SARC. No significant correlations existed between wheat yield and spike length, heading date, maturation date or the grain filling duration at either site ($P > 0.05$).

Overall, excess precipitation during the critical precipitation period at the one to two leaves stage (Z1.1–1.2) (early seedling stage) specifically inhibited the increase in tiller numbers, and negated the increase on grains number per square meter by sunshine duration ($\sum SH_{21II-10III}$) at the critical sunshine period (Z3.1–3.2) (stem elongation stage). Wheat yield showed significant negative correlations to the mean temperatures at the

end of grain filling stage (\overline{OT}_{11-20V}) (Table 2), however, the affected grain filling period was considerably shorter compare to Hokkaido, Japan (Nishio et al., 2013).

The grain number per square meter significantly positively correlated to the PTQ for the critical sunshine period (Z3.1–3.2), at FARC ($r = 0.63$, $P \leq 0.01$, $n = 17$) and at SARC ($r = 0.61$, $P \leq 0.01$, $n = 17$) from 2000 to 2016. However, the PTQ from 30 days preceding heading (Z3.2–5.5) did not show significant correlation to grain number per square meter at FARC ($r = -0.15$, $P > 0.05$, $n = 17$) and SARC ($r = -0.12$, $P > 0.05$, $n = 17$) (Figure 5).

4. Discussion

In the present study, we analyzed the relationships between long-term wheat yield and meteorological data. We identified the critical precipitation period, 21 to 32 days after sowing with one- to two-leaf stage (Z1.1–1.2) (early seedling stage) brought the severe reduction in wheat growth and yield. Hara (2012) developed a long-term soil redox potential measuring device, and detected strong correlations between the precipitations and the soil redox potential reduction at the barley growing paddy field in the Chikushi Plains. Thus, we assume the excess precipitation during the critical

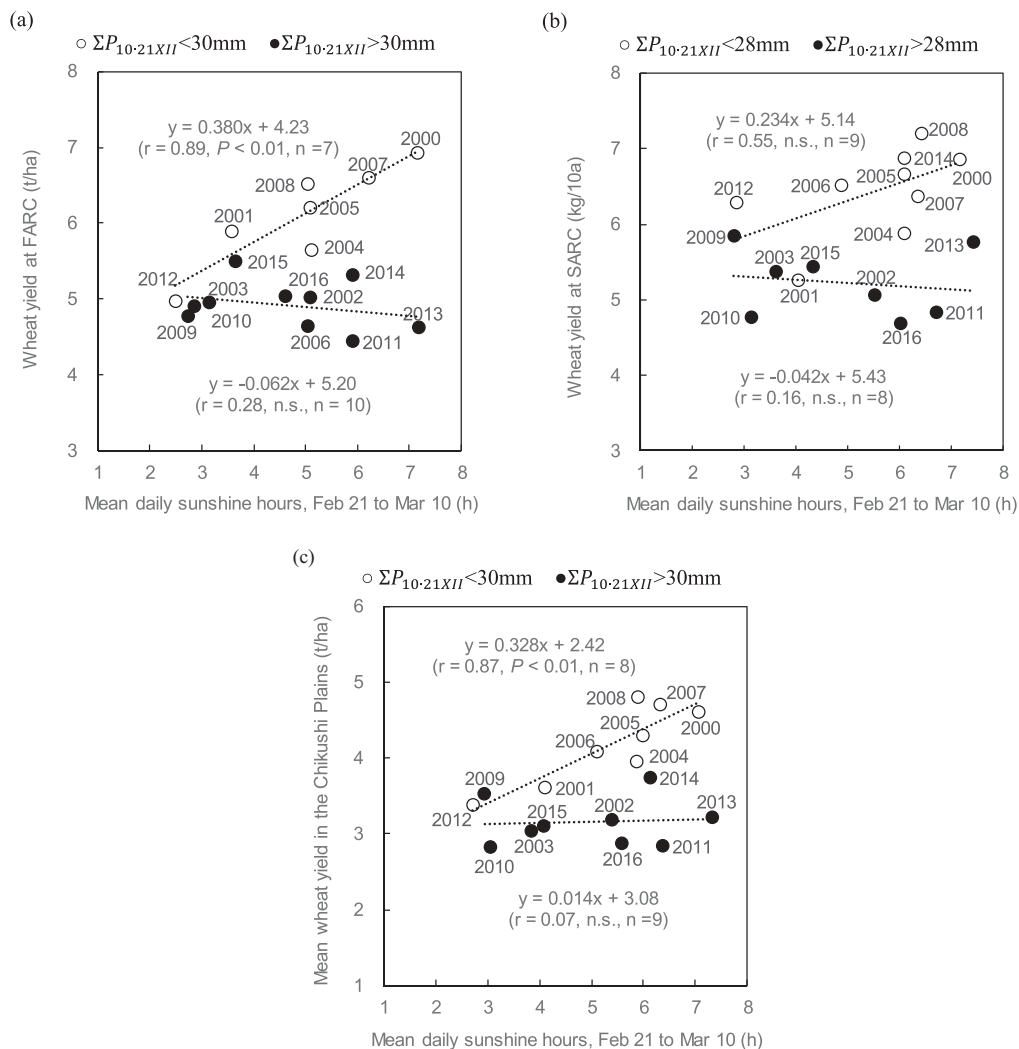


Figure 4. Relationships between mean daily sunshine hours during critical period of stem elongation stage from February 21 to March 10 ($\Sigma SH_{21II-10III}$) and mean wheat yield in Fukuoka prefectural Agriculture and Forestry Research Center (FARC), Chikushino, Fukuoka (a), Saga prefectural Agricultural Research Center (SARC), Kawasoe, Saga (b), and the Chikushi Plains (c), Northern Kyushu, Japan from 2000 to 2016. Open circles represent years where mean precipitation over the critical precipitation period, $\Sigma P_{10-21XII} < 30\text{mm}$ ($\Sigma SH_{21II-10III} < 28\text{mm}$ at SARC), and close circle are years where $\Sigma P_{10-21XII} > 30\text{mm}$ ($\Sigma P_{10-21XII} > 28\text{mm}$ at SARC) during the critical precipitation period.

precipitation period during early seedling stage is possible major determinants of waterlogging stress for wheat plants in paddy field.

Malik et al. (2002) showed that when 21-day-old wheat plants were subjected to 3 days of waterlogging, seminal root growth ceased and plants showed poor recovery upon removal of the stress. This indicates that even a short period of precipitation at early seedling stage can have considerable longer-term effects on wheat growth. The present results also imply that precipitation stress at the onset of tillering (vs. at other phenological stages) has the considerable negative impact on plant growth and crop maturation in paddy field. Alzueta et al. (2012) reported that the final tiller number is defined

during the early phase of the tillering process, while de San Celedonio et al. (2016) concluded waterlogging affects wheat yield through reduced tiller appearance rate and delayed flowering. Thus, precipitation stresses are inimical to the tiller growth of wheat seedlings, and poor drainage of paddy field would enhance this stress.

To examine the relationships between regional wheat yield and yield reduction by $\Sigma P_{10-21XII}$, we divided the 27 municipalities in the Chikushi Plains into three groups of 9 according to their mean wheat yield ranking between 2000 and 2016: high yield (mean of 3.81t/ha), moderate yield (3.63t/ha), and low yield (3.36t/ha). The slopes (26kg/ha at high yield vs. 30kg/ha at low yield reduction per 1mm increase of $\Sigma P_{10-21XII}$) of the

Table 4. Correlation coefficients between wheat phenology, yield components, precipitation over the critical precipitation period of Dec 10 to 21 ($\sum P_{10-21XII}$) (during early seedling stage), and cumulative sunshine hours during critical sunshine period of Feb 21 to Mar10 ($\sum SH_{21II-10III}$) (during stem elongation stage), grouped by precipitations ($\sum P_{10-21XII} < 30$ mm vs. $\sum P_{10-21XII} > 30$ mm) over the during critical precipitation period at FARC and SARC from 2000 to 2016.

Traits N	Zadoks growth stage	vs. Yield		vs. ($\sum P_{10-21XII}$)		vs. ($\sum SH_{21II-10III}$)			
						$\sum P_{10-21XII} < 30\text{mm}^{1)}$		$\sum P_{10-21XII} > 30\text{mm}^{1)}$	
		FARC	SARC	FARC	SARC	FARC	SARC	FARC	SARC
		17	17	17	17	7	9	10	8
Phenology									
First node detectable date	Z3.1	-0.49*	0.03	0.29	-0.22	-0.58	-0.53	0.85**	0.10
Heading date	Z5.5	-0.07	0.36	0.34	-0.20	-0.23	-0.13	0.14	0.36
Maturing date	Z9.2	-0.07	0.34	0.34	-0.36	0.16	-0.01	0.16	0.25
Grain filling duration	Z5.5-Z9.2	0.08	-0.13	-0.07	-0.15	0.56	0.21	-0.01	-0.21
Yield components									
No. of tillers									
Jan 20 (62 DAS)	Z1.3&Z2.1	0.66**	0.08	-0.46	-0.30	0.49	0.34	-0.68*	-0.19
Feb 10 (83 DAS)	Z1.4&Z2.2	0.52*	0.03	-0.60*	-0.55*	0.03	0.10	-0.63*	-0.75**
Mar 1 (102 DAS)	Z3.1-3.2	0.46	0.24	-0.54*	-0.62**	-0.06	-0.01	-0.37	-0.50
Mar 20 (121 DAS)	Z3.2-3.3	0.45	0.37	-0.53*	-0.53*	0.11	0.17	-0.18	-0.37
No. of spikes	-	0.75**	0.59*	-0.54*	-0.76**	0.60	0.31	-0.39	-0.53
Culm length	-	0.46	0.48*	-0.54*	-0.23	0.08	0.58	-0.48	-0.70
Spike length	-	0.37	0.25	-0.33	0.17	0.27	0.52	-0.67*	-0.21
1000 grain weight	-	0.10	0.61**	-0.04	-0.25	-0.41	-0.15	0.28	-0.03
No. grains/m ²	-	0.90**	0.93**	-0.54*	-0.72**	0.95**	0.69*	-0.45	-0.21
Mean yield of Chikushi Plains	-	0.81**	0.86**	-	-	-	-	-	-

FARC, Fukuoka prefectural Agriculture and Forestry Research Center; SARC, Saga prefectural Agricultural Research Center; DAS, days after sowing. * $P \leq 0.05$, ** $P \leq 0.01$

¹⁾28mm at SARC.

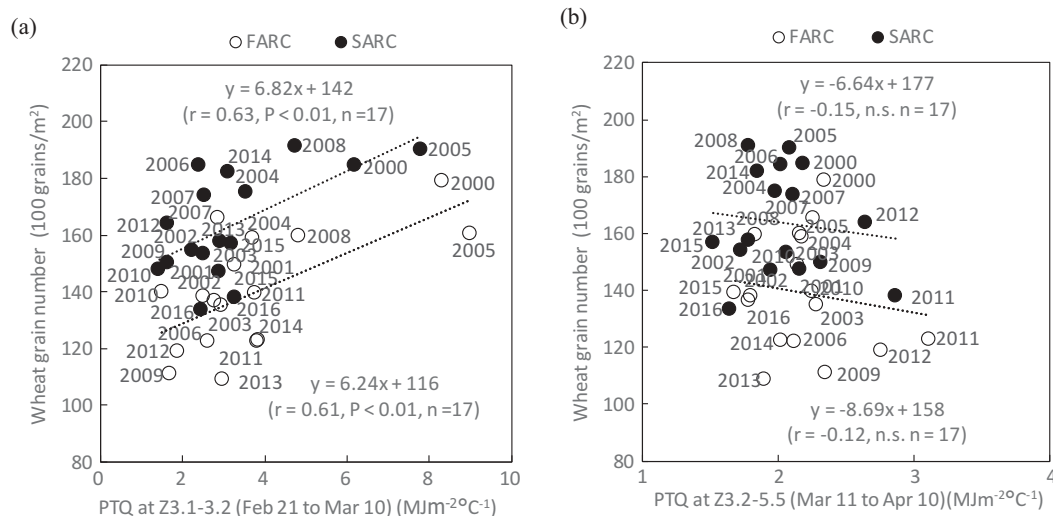


Figure 5. Relationships between wheat grain number per square meter and PTQ for the critical sunshine period of stem elongation stage (Z3.1-3.2) (a) from 30 days preceding heading (Z3.2-5.5) (b) from 2000 to 2016. Open circles represent the data at Fukuoka prefectural Agriculture and Forestry Research Center (FARC), Chikushino, Fukuoka, and close circle represent Saga prefectural Agricultural Research Center (SARC), Kawasoe, Saga.

different yield categories' regression curves were not significantly different ($P > 0.05$). Similarly, the slopes of FARC and SARC showed close values to the mean of the Chikushi Plains (24kg/ha and 28kg/ha vs. 27kg/ha) despite large difference of their mean yield for 17 years (5.41t/ha and 5.87t/ha vs. 3.64t/ha) (Figure 3). Thus, the rate of wheat yield reduction brought on by an increas-

ing $\sum P_{10-21XII}$ could be rather constant irrespective of its basal yield level.

From these results, drainage measures especially for early wheat growth stage are encouraged because of the critical precipitation period during early seedling stage for wheat yield in Northern Kyushu. To promote the drainage of paddy field prior to the wheat sowing, earlier drainage

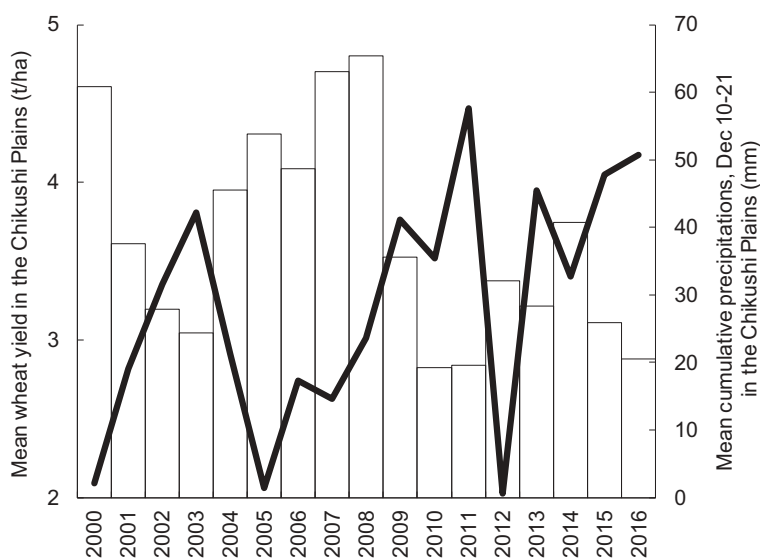


Figure 6. Mean precipitation during the critical precipitation period during early seedling stage (from Dec 10 to 21) (solid line) and mean wheat yields collected from crop statistics of Japanese Ministry of Agriculture, Forestry and Fisheries (bars) in the Chikushi Plains, Northern Kyushu, Japan from 2000 to 2016.

before rice harvest, and maintenance of underdrainage and open ditch drainage should be recommended to relieve the precipitation stresses of wheat. In addition, avoiding soil crusting and stickiness would ensure favorable wheat growing environment by reducing precipitation stresses. Increasing basal wheat yield level should also be accomplished by accumulating those essential techniques and soil fertility.

In this study, the PTQ of critical sunshine period during stem elongation stage (Z3.1–3.2) from 58 to 41 days preceding heading were significant ($r = 0.63$, $P \leq 0.01$, $n = 17$ at FARC; $r = 0.61$, $P \leq 0.01$, $n = 17$ at SARC), however, the PTQ of 30 days preceding heading were not significant ($r = -0.16$, $P > 0.05$, $n = 17$ at FARC; $r = -0.12$, $P > 0.05$, $n = 17$ at SARC) (Figure 5). Nalley et al. (2009) concluded PTQ of 31 days preceding and 1 day after anthesis was optimal to explain grain number at Yaqui Valley of Mexico. The Chikushi Plains and Yaqui Valley, Mexico (Nalley et al., 2009) showed different patterns of temperature and solar radiation increase (5.4–16.3°C vs. 17.6–21.7°C, and 10.7–16.5 MJm⁻²d⁻¹ vs. 17.7–26.2 MJm⁻²d⁻¹, monthly mean from February to April). In the Chikushi Plains, the critical sunshine period (Z3.1–3.2) overlaps the later terminal spikelet stage. Temperatures during this stage affects the duration of spike development in terms of differentiated florets number (Dawson & Wardlaw, 1989; Toyota et al., 2003). Those differences could bring different significant PTQ period.

We showed that precipitation stress at early seedling stage certainly negates the positive effect of sunshine hours at significant PTQ period. To our knowledge, no

previous report has shown such an interaction. Our results also indicated the importance of evaluating aftereffects of precipitation stress on plants. The mean temperature at the end of March (booting stage), $\bar{T}_{21-30/III}$, showed a significant positive correlation with yield in the Chikushi Plains ($r = 0.71$, $P \leq 0.05$, $n = 8$) and FARC ($r = 0.73$, $P \leq 0.05$, $n = 10$) when $\sum P_{10-21/XII} > 30$ mm (Table 3). We speculate the growth of young spike may have partially recovered under high temperature conditions during booting stage. However, we need further investigation to clarify this speculation.

The relationship between mean precipitations during the critical precipitation period and mean wheat yield collected from crop statistics of Japanese Ministry of Agriculture, Forestry and Fisheries in the Chikushi Plains between 2000 and 2016 is shown in Figure 6. Although the influence and mechanisms linking global warming and precipitation have not been well elucidated, mean precipitation during the critical precipitation period in Northern Kyushu region of Japan have increased throughout the 2010s. This rise is associated to the reduction of mean wheat yield in the Chikushi Plains, indicating that the risks of precipitation stress to wheat in paddy field have been rising. On the Chikushi Plains, wheat yield showed no significant correlation with precipitation for the period from sowing to first top-dressing in January ($r = -0.20$, $P > 0.05$, $n = 17$). The effect of nitrogen fertilizer lost in surface runoff is not a likely contributor to yield loss as the negative impact of precipitation was limited to the 12-day critical precipitation period.

The results suggest that our long-term approach in this study was effective in assessing the sensitivity of wheat

yield under branched meteorological conditions. Such datasets are indispensable for crop management modeling and the approach of our study could be useful for other crops or locations. Our approaches would also be useful in complementary analyses of plant physiological robustness to unfavorable weather conditions that constrain plant growth.

This is the first report that intensively documents the interactions between critical precipitation period at early seedling stages and critical sunshine period at stem elongation stage for wheat yield. The present results provide important clues to effectively increasing wheat yield in paddy field cropping systems. Further research should clarify the different genotypic reactions to achieve most effective genetic improvement to mitigate precipitation stress.

Disclosure statement

No potential conflict of interest was reported by the authors.

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