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REVIEW

Stabilization of Yield and Quality of Winter Wheat for Bread in Sand Dune Fields in Niigata Prefecture in Japan

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Abstract

Winter wheat for bread cropping began in 2012 in the sand dunes of Niigata Prefecture, Japan. Winter wheat for bread grown there requires frequent topdressing to compensate for the soil's low fertilizer-holding capacity. We developed a cropping method that maintains yield and quality while reducing the number of fertilizer applications to save labor. We compared the growth of a new winter wheat for bread cultivar, 'Natsukogane,' with good bread-making quality, and a winter wheat for bread cultivar, 'Yukichikara,' under sand dune conditions. Ensuring the number of grains per ear promoted the yield stability of 'Natsukogane.' The grain ash content in farmers' fields on sand dunes during four cropping seasons was greater in years when the soil water potential during the grain-filling period in May was low, and the 1,000-grain weight was low.

Discipline: Crop Science

Additional key words: grain ash content, grain protein content, nitrogen topdressing, *Triticum aestivum* L.

Introduction

The restoration of cropping is required to control soil loss on the many abandoned tobacco fields on the sand dunes along the Sea of Japan (East Sea) coast in Niigata Prefecture. Winter wheat for bread cropping began there in 2012 to meet the growing need for locally grown wheat. The dunes feature immature dune soil, either sandy or loamy sand, with good drainage. The CEC of the dune soils (Sand dune regosol) was 2.5 to 3.8, lower than the CEC of 31.8 to 36.9 of the converted paddy field soils (Gley lowland soil) (Shibukawa et al. 2020). Although the soils' water- and fertilizer-holding capacities are very low, the good drainage makes agricultural work less susceptible to rain. Niigata has less sunshine, more rain, and more snow from autumn to winter than other parts of Japan, and winter wheat for bread is not grown under such conditions elsewhere in Japan. We conducted experiments to establish high-quality, high-yield cultivation of winter wheat for bread on sand dune fields. This report reviews the results.

Creation of a system for winter wheat for bread cropping in sand dune fields

With the goal of devising a system for growing wheat in the sand dune fields in Niigata Prefecture, we grew 'Yukichikara' winter wheat for bread, which has strong resistance to cold and snow (Yoshikawa et al. 2009). Insufficient fertilizer is the most important concern when growing wheat on sandy soil. Therefore, we initially assumed that frequent topdressings would be necessary and tested the effect of applying a pre-wintering topdressing, which increases pre-winter growth, ear number, and yield (Shimazaki et al. 2017). We applied basal N fertilizer at 6 g m^{-2} and topdressings of 2 g m^{-2} before winter, 3 g m^{-2} after winter, 2 g m^{-2} at jointing, and 6 g m^{-2} at full heading (a total of 19 g m^{-2}).

The pre-wintering topdressing increased the number of stems both before and after winter (Shimazaki et al.

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2017), increasing the maximum number by 50% to 1,365 stems m^{-2}, the final ear number by 17% to 489 ears m^{-2}, and yield by 11.5% to 4.335 t ha^{-1}.

At the same time, we tested the effects of "topsoiling" and "trampling," which are widely conducted in western and eastern Japan. Topsoiling improves drainage between ridges, suppresses denitrification of the fertilizer, and increases fertilizer use efficiency (Ikeda et al. 1957). Trampling involves rolling the wheat plants before jointing, which reduces lodging (Ohtani 1950, Tanio et al. 2019), prevents frost damage (Ohtani 1950, Nakatsukasa et al. 2002, Mizumoto et al. 2022), increases the number of panicles (Ohtani 1950), and increases the number of grains per ear (Nakatsukasa et al. 2002).

The effect of topsoiling was not clear in our experiments. However, trampling before winter delayed ripening and increased the grain protein content. Trampling improves drought resistance by allowing the roots to reach deeper and maintaining the water supply from the deeper parts by capillary action (Ohtani 1950). In the test year, there was little rainfall during the latter stage of spikelet differentiation (late March rainfall was 23.1% of normal), the booting stage (late April rainfall was 21.1% of normal), and the middle-ripening stage (late May rainfall was 13.0% of normal) of wheat. In the trampling plot, plant moisture content was well maintained, likely delaying leaf senescence during ripening and thus increasing the grain protein content.

We also attempted to reduce the number of operations to save labor (Shimazaki et al. 2019): we applied urea dissolved in water at the same time as Fusarium head blight control at the flowering stage, reduced the number of topdressings to reduce costs, and redistributed the amount of fertilizer applied to create a higher topdressing-to-basal fertilizer ratio.

In winter wheat for bread cropping, N fertilizer is applied around flowering to increase the grain protein content. Applying fertilizer at the same time as Fusarium head blight control during flowering has already proven effective at minimizing costs in other regions (Nakatsukasa & Kimura 2011, Takeuchi et al. 2006, Sato et al. 2009). Plots where urea dissolved in water were applied by 1 or 2 foliar sprays during flowering, and the plot where ammonium sulfate was applied to the soil surface during flowering had noticeably higher grain protein content than the plot where no fertilizer was applied at flowering (Fig. 1). There were no differences in the occurrence of Fusarium head blight between the plots.

A topdressing-to-basal fertilizer ratio that increased the percentage of N applied after jointing increased yield by 12% to 50% (Watanabe et al. 2016). This increase was due to an increase in the number of ears, grains per ear,

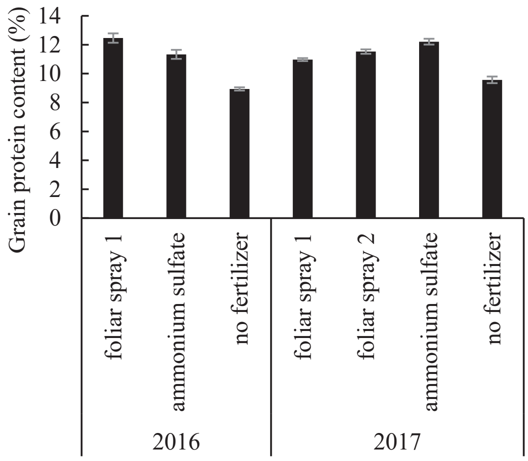

Fig. 1. Effect of fertilization technique at flowering on protein content of grains

Foliar spray 1 was applied twice, a week apart, at 2.5 g of N m^{-2} of urea in 1 kL ha^{-1}.
Foliar spray 2 was applied once at 5 g of N m^{-2} of urea in 1 kL ha^{-1}.
Ammonium sulfate equivalent to 5 g of N m^{-2} was applied to the soil surface.
The no-fertilizer area received no N fertilizer at flowering.
The bars in the figure indicate standard errors.
Tests were conducted in 2016 and 2017 with the variety 'Yukichikara.'
This figure was plotted from Shimazaki et al. (2017).

and the 1,000-grain weight. To reduce labor, we reduced the number of fertilizer applications to 'Yukichikara' from six to five, moving one to the late flowering stage (Table 1) (Shimazaki et al. 2019). The higher fertilizer allocation in the second half of growth relative to the total N in the labor-saving plot than in the standard plot increased yields by 12% to 65% (Table 2). The grain protein content was up to 0.6 percentage points lower in the labor-saving plot (Table 2). The aboveground N content at maturity was higher in the labor-saving plot (Table 2). The higher yield explains the lower grain protein content in the labor-saving plot.

Comparison of winter wheat for bread cultivars 'Natsukogane' and 'Yukichikara'

We compared the cold-tolerant cultivar 'Yukichikara,' which was registered in 2005, with the new 'Natsukogane,' which was registered in 2019, at 10 sites, including dune field sites, over three years in Niigata Prefecture (Shimazaki 2021).

'Natsukogane' is an autumn-sown hard wheat grown for bread and Chinese noodles bred at the Tohoku Agricultural Research Center of the National Agricultural

Table 1. Nitrogen amount of fertilizer (g m^{-2}) and fertilizer application date

Plot	Basal	Before winter	After winter	Jointing stage	Flag leaf extraction	Flowering stage		Total amount
	5-Oct	8-Nov	8-Mar	27-Mar	12-Apr	1-May	8-May	
Labor-saving	6	0	6	0	3	4*	0	19
							2*	21
							4*	23
Standard	6	2	3	2	2	4	0	19
						6	0	21
						8	0	23

Basal fertilizer: N-P_2O_5-K_2O = 14-8-8
Other fertilizers (except that applied at flowering in the labor-saving plot): ammonium sulfate
*Fertilizer was applied during flowering in the labor-saving plot by foliar spraying of urea mixed with fungicide.
Tests were conducted in 2018 with the variety 'Yukichikara.'
This table was modified from Shimazaki et al. (2019).

Table 2. Effect of fertilization method on yield, ear number, grain protein content, and above-ground nitrogen content at maturity

Plot	Nitrogen amount at flowering	Yield (g m^{-2})	Number of ears (m^{-2})	Grain protein content (%)	Above-ground nitrogen content at maturity (g m^{-2})
Labor-saving	4 (4-0)	620	494	9.9	15.3
	6 (4-2)	620	462	10.7	16.4
	8 (4-4)	652	491	11.7	19.7
Standard	4	375	323	9.9	9.3
	6	481	381	11.1	14.0
	8	582	413	12.3	16.1

Tests were conducted in 2018 with the variety 'Yukichikara.'
This table was modified from Shimazaki et al. (2019).

Research Organization (Ikenaga et al. 2018). At the breeding site, 'Natsukogane' matures one day earlier than 'Yukichikara;' has a shorter culm length than 'Yukichikara;' and has a similar yield, 1,000-grain weight, and bulk density as 'Yukichikara.' Its medium resistance to red mold and its strong resistance to preharvest sprouting are stronger than those of 'Yukichikara.' With the glutenin subunit gene *Glu-B3g*, 'Natsukogane' has better baking qualities than 'Yukichikara' (Ikenaga et al. 2018).

The mean heading, flowering, and maturity dates of 'Natsukogane' in Niigata were one to two days earlier than those of 'Yukichikara' (Table 3). The culm length of 'Natsukogane' was significantly shorter (Table 3). The yield did not differ significantly, but its greater coefficient of yield variation in 'Natsukogane' (Table 3) suggests that its yield has greater inter-annual and inter-regional variation. Its greater coefficients of variation of the yield of 'Natsukogane' (Table 3) suggest that ensuring the number of grains per ear would effectively stabilize a high yield of 'Natsukogane.'

The grain protein content ranged from 10.8% to 14.6% in 'Yukichikara' and from 10.7% to 13.5% in 'Natsukogane,' with no significant differences between the two (Table 3). However, five out of ten tests of 'Yukichikara' did not include the standard content of 11.5% to 14.0%, established by the Ministry of Agriculture, Forestry and Fisheries of Japan as high-quality wheat for bread. In comparison, only one out of ten tests of 'Natsukogane' did not, and the coefficient of variation of 'Natsukogane' was smaller than that of 'Yukichikara.' These results point to higher stability of grain protein content in 'Natsukogane' than in 'Yukichikara.'

High ash content of 'Yukichikara' grown in a sand dune field

When the grain protein content of 'Yukichikara' grown in sand dune fields reached the standard value, the number of cases in which the grain ash content exceeded the allowable limit of 1.80% became a problem (Shibukawa et al. 2020). Grain ash content is an important factor in wheat quality and is used in the evaluation of wheat quality: the quality classification standard for grain ash content in wheat for bread is ≤ 1.75%, established by the Ministry of Agriculture, Forestry and Fisheries of Japan. The excess content was related to N topdressing at flowering to increase the grain protein content, but the response differed depending on the soil type (Shibukawa et al. 2018): the content increased with flowering-stage N fertilization in sand dune soils (Sand dune regosol) and regular fields (Andosol), but not in an upland field converted from paddy field (Gley lowland soil).

The main components of grain ash are P and K (Sato et al. 1996). To clarify the components contributing to the increase in grain ash due to N topdressing at flowering, we investigated the relationship between N topdressing at flowering, grain protein content, and grain ash content in sand dune fields and converted paddy fields (Shibukawa et al. 2020). The grain protein content increased with increasing N topdressing at flowering in the dune fields but not in the converted paddy fields (Table 4). The grain ash content increased significantly with increasing N fertilizer application (Table 4). Among the major minerals in grains—P, K, Mg, and Ca—grain P content increased significantly with increasing N fertilizer application

Table 3. Characteristics of “Yukichikara” and “Natsukogane” grown in Niigata Prefecture

	Cultivar	Heading date	Flowering date	Maturity date	Culm length (cm)	Yield (g m^{-2})	Number of ears (ears m^{-2})	Whole grain percentage (%)	Grain number per ear	1,000-grain weight (g)	Grain protein content (%)
Average	Yukichikara	29-Apr	9-May	11-Jun	90.0	439	376	94.6	29.8	39.7	12.1
	Natsukogane	28-Apr	7-May	10-Jun	85.0	433	379	96.2	29.1	39.5	12.3
Coefficient of variation	Yukichikara	0.00	0.00	0.00	0.07	0.17	0.21	0.05	0.10	0.04	0.10
	Natsukogane	0.00	0.00	0.00	0.08	0.23	0.19	0.03	0.16	0.04	0.06
	paired *t*-test	***	**	***	*	NS	NS	NS	NS	NS	NS

Average values for ten plots in three cropping seasons are shown.
Significance of difference: *5%, **1%, ***0.1%; NS, not significant at $P < 0.05$ by paired t-test.
“Whole grain percentage” means the percentage of the harvest that remains on the 2.4 mm sieve.
Yield, whole grain percentage, and 1,000-grain weight are applied to grain retained on a 2.4 mm sieve.
Yield and 1,000-grain weight are corrected for 12.5% moisture. Grain protein content is corrected for 13.5% moisture. Grain number per ear was calculated from yield, 1,000-grain weight, and number of ears.
Tests were conducted in 2018, 2019, and 2020, with the variety ‘Yukichikara’ and ‘Natsukogane.’
This table was modified from Shimazaki (2021).

Table 4. Grain ash content, grain protein content, and grain mineral content

		Nitrogen topdressing at flowering (g m^{-2})	Ash content (%)	Protein content (%)	P content (%)	K content (%)	Mg content (%)	Ca content (%)
Sand dune fields	Average	0	1.56	8.5	0.41	0.48	0.14	0.029
		6	1.65	11.5	0.45	0.43	0.15	0.030
		12	1.68	15.2	0.47	0.42	0.15	0.031
	ANOVA	Nitrogen topdressing	**	**	**	**	NS	**
		Field	**	NS	**	**	**	**
		Interaction	*	**	NS	NS	NS	NS
Paddy field conversion fields	Average	0	1.58	9.6	0.40	0.43	0.16	0.027
		5 ~ 6	1.60	12.6	0.41	0.40	0.18	0.027
	ANOVA	Nitrogen topdressing	NS	**	NS	*	NS	NS
		Field	NS	**	NS	**	NS	**
		Interaction	*	NS	*	NS	NS	**

Grain ash and protein contents on a 13.5% moisture basis. Grain mineral content on a dry matter basis.
Significance of difference: *5%, **1%; NS, not significant at $P < 0.05$.
Tests were conducted in 2017, 2018, and 2019 with the variety ‘Yukichikara.’
This table was taken from Shibukawa et al. (2020).

during flowering in the dune fields (Table 4). This indicates that P contributed to the increase in grain ash content.

The available Truog phosphoric acid content was 314-530 mg kg^{-1} in the sand dune fields and 44-106 mg kg^{-1} in the converted paddy fields (Shibukawa et al. 2020). The former met Niigata Prefecture's target value for improvement of available phosphoric acid (200 to 600 mg kg^{-1}, Niigata Prefecture Department of Agriculture, Forestry and Fisheries, 2007), but the latter fell short of the target. The high levels of available phosphate in the dune fields were most likely due to the addition of available phosphate to the soil associated with earlier plantings of tobacco, potato, and other crops.

Although the increase in grain ash content in dune fields is related to soil-available phosphate (Shibukawa et al. 2020), the actual relationships between grain ash and grain P contents and between grain ash and soil-available phosphate contents in farmers' fields are not well understood. Therefore, we analyzed the grain ash content of wheat over 4 cropping seasons in 11 farmers' fields on sand dune fields in Niigata (Shibukawa et al. 2022).

There was no clear relationship between the soil-available phosphoric acid content and grain P content (data not shown). In two of the four cropping seasons, there was a significant relationship between grain P content and grain ash content (Fig. 2). At all 11 sites, no irrigation was performed, and the soil-available phosphoric acid content was within or above the Niigata Prefecture target values for improvement of content. Therefore, it was impossible to determine the relationship between the available phosphoric acid content and grain P content under intermediate soil P fertility. In the two seasons when there was a correlation between grain P content and grain ash content, there was also a positive correlation between grain protein content and grain ash content (Fig. 3). On the other hand, there was a significant positive correlation between grain protein content and 1,000-grain weight in two of the four cropping seasons (Fig. 4). The reason for the difference in the relationship

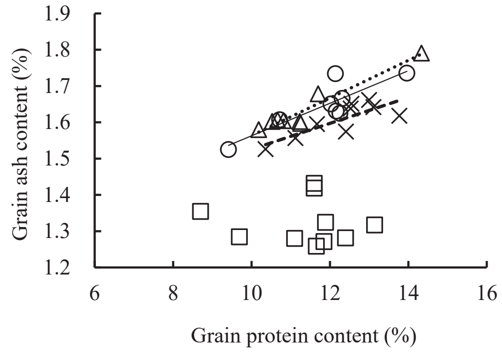

Fig. 3. Relationship between grain protein and ash contents (both 13.5% moisture basis)
○2016: $y = 0.045x + 1.11$ ($r = 0.865$**)
△2017: $y = 0.052x + 1.04$ ($r = 0.964$**)
□2018: $y = 0.004x + 1.37$ ($r = 0.079$)
×2019: $y = 0.036x + 1.17$ ($r = 0.809$**)
Significance: **1%.
Tests were conducted in 2016, 2017, 2018, and 2019 with the variety 'Yukichikara.'
This figure was modified from Shibukawa et al. (2022).

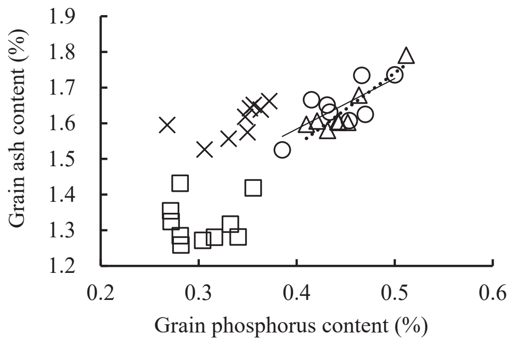

Fig. 2. Relationship between grain P (dry-matter basis) and ash contents (13.5% moisture basis)
○2016: $y = 1.42x + 1.02$ ($r = 0.738$*)
△2017: $y = 2.04x + 0.73$ ($r = 0.908$**)
□2018: $y = 0.17x + 1.27$ ($r = 0.087$)
×2019: $y = 0.87x + 1.31$ ($r = 0.610$)
Significance: *5%, **1%.
Tests were conducted in 2016, 2017, 2018, and 2019 with the variety 'Yukichikara.'
This figure was modified from Shibukawa et al. (2022).

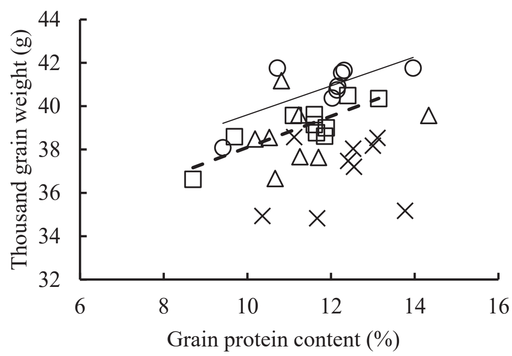

Fig. 4. Relationship between grain protein content (13.5% moisture basis) and 1,000-grain weight (12.5% moisture basis)
○2016: $y = 0.67x + 32.9$ ($r = 0.716$*)
△2017: $y = 0.22x + 36.1$ ($r = 0.205$)
□2018: $y = 0.72x + 30.9$ ($r = 0.849$**)
×2019: $y = 0.36x + 32.6$ ($r = 0.242$)
Significance: *5%, **1%.
Tests were conducted in 2016, 2017, 2018, and 2019 with the variety 'Yukichikara.'
This figure was modified from Shibukawa et al. (2022).

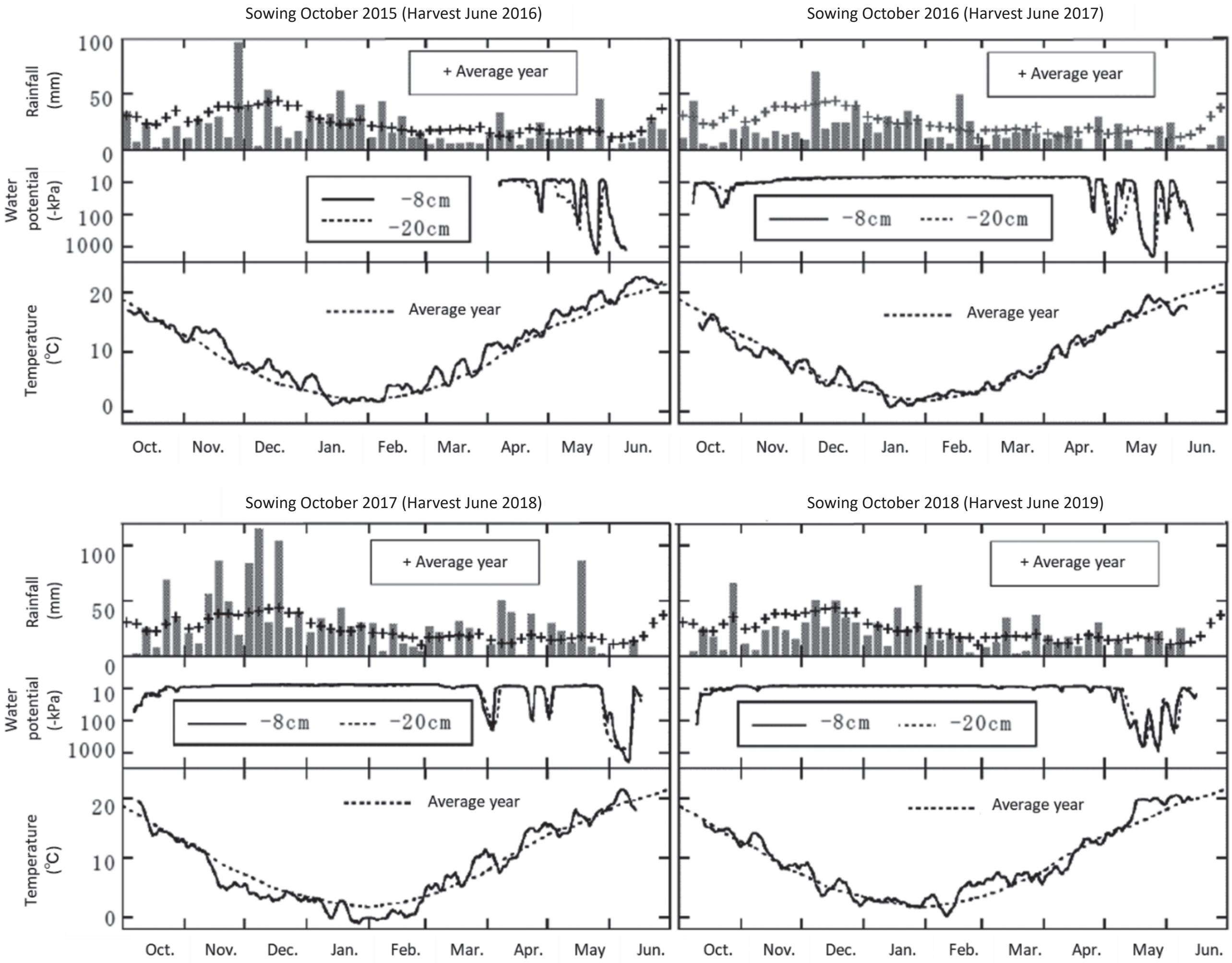

Fig. 5. Rainfall, soil water potential, and temperature during the wheat growing season (2016-2019)
Rainfall was divided into 6 parts per month and summed over that period.
Soil water potential was measured at depths of 8 cm and 20 cm below the surface and averaged daily.
Temperatures were shown as 7-day moving averages.
Values for rainfall and temperature averages during the 2016 growing season were from the Agro-Meteorological Grid Square Data, NARO. Other data were collected in the field.
This figure was taken from Shibukawa et al. (2022).

between grain protein content and 1,000-grain weight in different years may be the effect of soil moisture during the grain-filling period: in the seasons with severe drought stress during grain filling in May in 2017 and 2019 (Fig. 5), there was no correlation between grain protein content and 1,000-grain weight, while in the season when soil moisture was adequate in May in 2018 (Fig. 5), 1,000-grain weight increased with an increase in grain protein content. In the season when there was no relationship between grain protein content and grain ash content, there was a strong positive correlation between grain protein content and 1,000-grain weight. Under conditions of severe soil moisture deficiency during the grain-filling period, the increase in grain N and ash contents increased as the effect of N topdressing at flowering increased, but the increase in 1,000-grain weight was relatively small. This suggests that the relationship between grain ash content and 1,000-grain weight due to N topdressing at flowering may have affected grain ash content. Thus, grain ash content is likely to increase in sand dune fields where low precipitation during ripening tends to cause soil moisture deficiency.

Conclusion

The weather in Niigata Prefecture is characterized by low sunlight from autumn to winter, excessive rainfall, and a lot of snow. The sand dune fields have the disadvantages of low water and fertilizer retention, but they also have the advantages of good drainage. In Niigata Prefecture, where there is a lot of precipitation from autumn to winter, poor soil drainage is often a problem in wheat cultivation. Good soil drainage of the sand dune fields allows tractors to enter the field immediately after rainfall for tillage, etc. By taking advantage of these characteristics to grow wheat that prefers dry conditions, it has become possible to grow winter wheat for bread, which is in high demand, on sand dune fields.

While winter wheat for bread on dune fields has good drainage, the grain ash content tended to be high when little rain fell during the grain filling period. Since many dune fields have irrigation facilities, irrigation could limit the grain ash content when there is little rainfall during grain filling. The trampling technique effectively improves drought resistance by allowing roots to reach deeper into the soil and maintaining a deeper water supply by capillary action (Ohtani 1950). Although trampling was not used in most studies (Shibukawa et al. 2018, Shimazaki et al. 2019, Shibukawa et al. 2020, Shimazaki et al. 2021, Shibukawa et al. 2022) because of its labor-intensive aspects, it may be an effective technique for limiting high grain ash content.

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