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Waxy Barley Yield and Grain β-Glucan Content Affected by Heterogeneous Soil Properties in Differently Managed Fields

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Abstract

Soils are heterogeneous at a spatial scale because of variability in soil nutrients and physical factors. The present study was conducted to investigate the heterogeneity of soil physicochemical properties in differently managed fields to determine the key factors influencing the grain yield and β-glucan content of naked waxy barley. Two fields were compared—one upland field converted from a paddy (converted upland) and one conventional upland field (normal upland). In each field, the relationships between variables were examined using correlation analyses. The results showed that the converted upland had lower yield and β-glucan content than that of the normal upland. Soil water content was a significant factor in both fields, but greater effect was observed in the converted upland. The β-glucan content was negatively correlated with soil water content in the converted upland. Electrical conductivity or mineral N was positively correlated, whereas soil penetration resistance at the depth of 20 cm-30 cm was negatively correlated with the β-glucan content in the normal upland. Comprehensive analyses indicated that avoiding water damage is the priority for increasing the yield and grain β-glucan content of naked waxy barley.

Discipline: Agricultural Environment
Additional key words: plow pan, soil penetration resistance, soil water content, spatial variability, upland field converted from a paddy

Introduction

Barley (*Hordeum vulgare* L.) is one of the world's most important crops and has a higher β-glucan concentration than other cereals (Aman & Graham 1987). Because of this high dietary fiber content (β-glucan), the use of barley as a human food source is becoming very important. β-glucan is one of the minor constituents in barley kernels, and waxy barley is known to have high β-glucan content. Moreover, waxy barley has a similar texture to glutinous rice, meaning that Japanese people are more likely to accept rice–waxy barley mixtures compared with rice and nonwaxy barley mixtures in Japan. Because consumption of a high dietary fiber diet is recommended for health, waxy barley has attracted attention as a high-fiber crop. In Japan, the recent production area of naked barley is 4,970 ha (MAFF 2018).

Barley, despite it being susceptible to waterlogging (de San Celedonio et al. 2014), is often rotated with rice in Japan and is often exposed to excess soil water conditions under heavy rainfall because of subsoil compaction to optimize flooding conditions for rice. Nitrogen is one of the most important elements for cultivating barley, and it greatly affects the yield (Cantero-Martınez et al. 2003). Additionally, the extent of the soil compaction affects crop yield; excessive compaction reduces plant emergence in the seedbed and impedes root growth (Dürr & Aubertot 2000, Gemtos & Lellis 1997). A plow pan, which is formed under plowing to the same depth because of extremely high pressure in the contact zone between the plow blade and soil, is supposed to be the factor influencing the grain yield because a plow pan is known to inhibit the root growth (Chan et al. 2006).

Generally, soil properties are heterogeneously distributed in arable fields. Presently, the effects of soil heterogeneity on waxy barley yield and β-glucan content

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are poorly understood. de San Celedonio et al. (2014) studied the effects of waterlogging in various growth periods on grain yield of barley and concluded that the growth period from stem elongation to anthesis is the most susceptible period to waterlogging. Thus, to increase the yield and grain quality of naked waxy barley, how physicochemical soil properties at the stem elongation stage vary in heterogeneous soil should be comprehensively understood. In the present study, the within-field spatial variability in soil properties with the potential to affect the growth of naked waxy barley was evaluated. In this study, two differently managed fields were compared—one upland field converted from a paddy (converted upland) and one conventional upland field (normal upland). In each field, factors that explained within-field spatial variability in yield, yield components, and β-glucan content of naked waxy barley were identified via correlation analyses.

Materials and methods

1. Sites and cropping management

The study was conducted on two flatland-agricultural fields—one upland field converted from a paddy (converted upland) and one conventional upland field (normal upland). Both fields had gray lowland soil within the experimental farm of Osaka Prefecture University, Osaka, Japan (34.5°N, 135.5°E). During the experiment, naked waxy barley was rotated with rice in the converted upland and soybean in the normal upland. The initial soil properties of the converted upland and normal upland were as follows: pH of 1:5 soil water extracts of 6.6 and 6.7, electrical conductivity (EC) of 1:5 soil water extracts of 61 and 62 μS cm^{-1}, total C of 12.8 and 13.0 g kg^{-1}, total N of 1.3 and 1.3 g kg^{-1}, mineral N (NO_3^-–N + NH_4^+–N) of 7.9 and 5.0 mg kg^{-1}, and available P (Truog-P) of 111 and 144 P_2O_5 mg kg^{-1}. Soil sand, silt, and clay contents were 14.6%, 50.3%, and 35.1% in the converted upland and 20.8%, 50.6%, and 28.6% in the normal upland, respectively. Experimental plots were 9.0 m × 10.9 m in size, and surface drainage ditches (0.45 m wide) were established around and at the center of the plots, as shown in Figure 1. In the converted field, an underdrain system was not constructed, and one drainage outlet was established on the left side, as shown in Figure 1. Soil surface in the front area was topographically lower than that in the other areas, probably because of agricultural vehicle passage in the converted field. Data about rainfall and temperature during the experimental period were obtained from AMeDAS in Sakai City, Osaka (Fig. 2).

The experiment was conducted during two growing seasons, namely, the 2016-2017 season (from November 1, 2016 to May 17, 2017) and the 2017-2018 season (from November 29, 2017 to May 22, 2018). Eight grams per square meter each of the N, P_2O_5, and K_2O basal

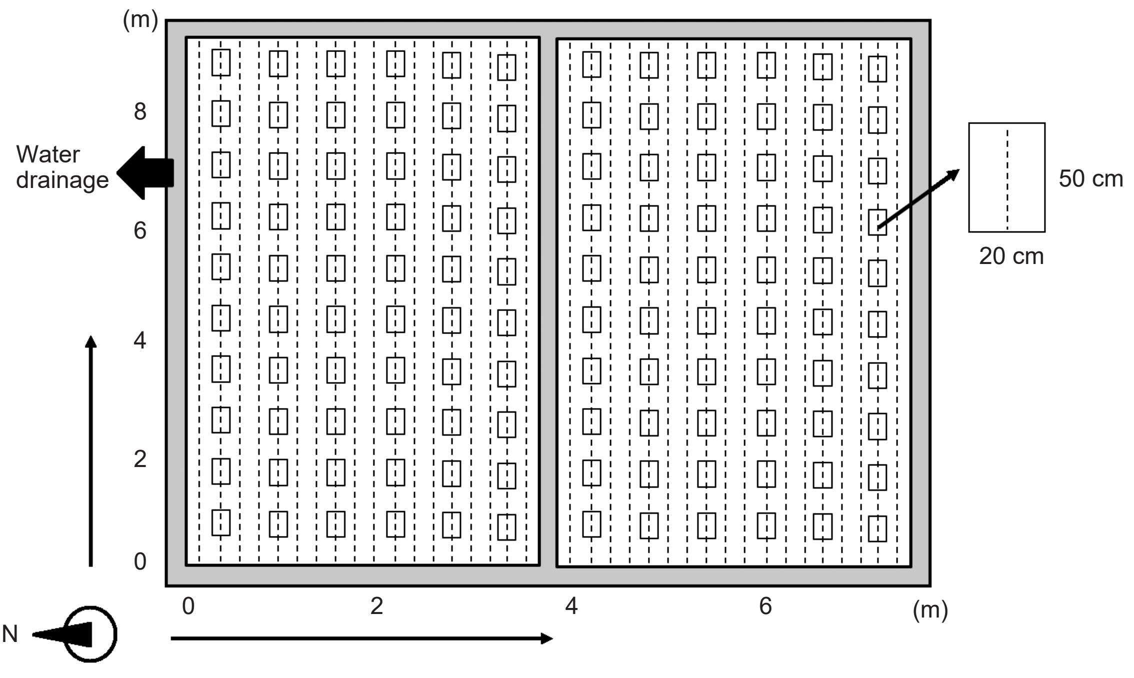

Fig. 1. Experimental setup illustrating sampling area design
Each block (20 cm × 50 cm) comprises 120 sampling areas. Gray area indicates surface drainage ditch.
A water drainage outlet was established only in converted upland.

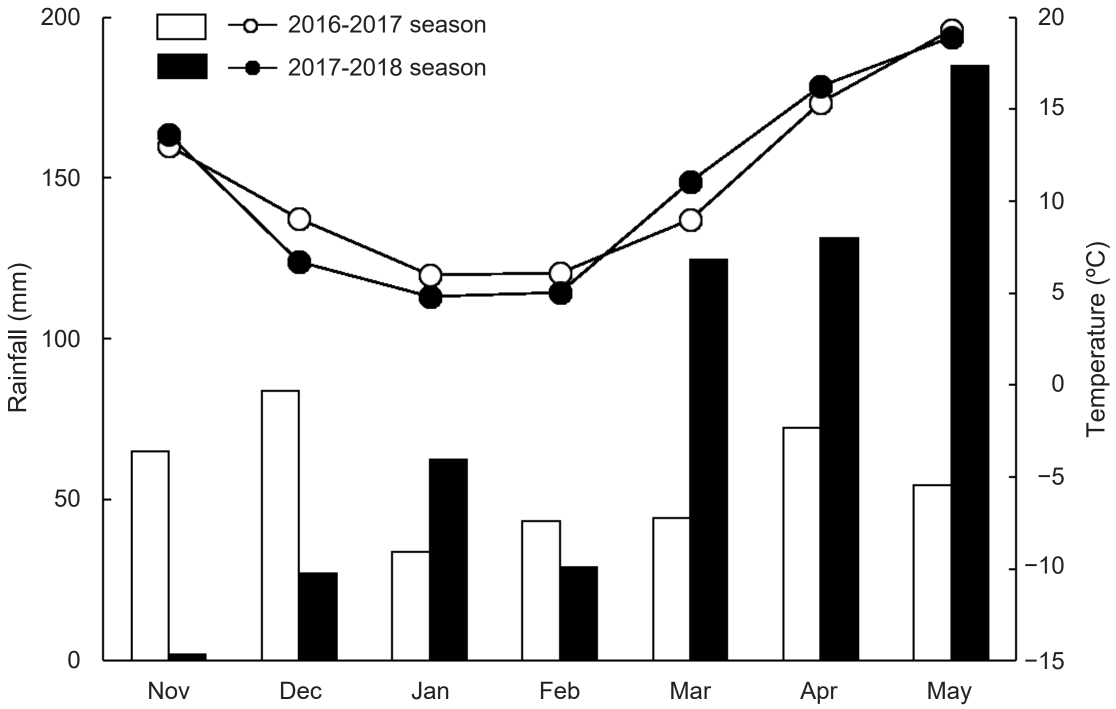

Fig. 2. Rainfall and average temperature during the experiment conducted from November to May
Experiment during the 2016-2017 season was conducted from November 1, 2016 to May 17, 2017.
Experiment during the 2017-2018 season was conducted from November 29, 2017 to May 22, 2018.

chemical fertilizers, as well as N top-dressing (2 g m^{-2}) with ammonia sulfate at the tillering stage (January 26 and February15), was applied during the 2016-2017 season. Fertilizer management was changed in the 2017-2018 season; 6 g m^{-2} each of the N, P_2O_5, and K_2O basal fertilizers, as well as N top-dressing (2 g m^{-2}) with ammonia sulfate at the tillering stage (February 8, 2018) and stem growth stage (March 28, 2018), were applied. To improve soil pH, 180 g m^{-2} magnesium lime was applied to each field during the 2017-2018 season. Naked waxy barley, cv Daishimochi, was sown by hand at 8 g m^{-2} in 36 rows, with an inter-row distance of 20 cm, on November 1, 2016 (2016-2017 season) and November 29, 2017 (2017-2018 season), respectively. Every effort was made during the 2017-2018 season to sow during the same period as in the 2016-2017 season, but irregular rainfall prevented the preparation of the experimental field and sowing (Fig. 2). Ultimately, sowing was delayed by approximately 30 days. Finally, the cultivation period of the 2017-2018 season was 23 days shorter than that of the 2016-2017 season.

2. Sampling and analytical methods

A total of 120 soil sampling sites per plot were selected as shown in Figure 1. The soil samples were collected during the stem elongation stage of naked waxy barley on March 14, 2017 during the 2016-2017 season and March 27, 2018 during the 2017-2018 season. Soil samples were air-dried and ground to pass through a 2-mm mesh. During the 2016-2017 season, soil EC was measured. During the 2017-2018 season, the concentrations of mineral N (NH_4–N and NO_3–N) were determined besides soil EC. Volumetric soil water content (m^3 m^{-3}) at the depth of 0 cm -10 cm was determined 51 days after sowing (DAS; December 21, 2016) during the 2016-2017 season, and at 119 DAS (stem elongation stage; March 27, 2018) during the 2017-2018 season, using a soil moisture meter (DIK-311F, Daiki). To evaluate soil compaction at each sampling site during the 2017-2018 season, soil penetration resistance, which indicates soil compaction (Hemmat & Adamchuk 2008), up to the depth of approximately 40 cm was measured with a digital cone penetrometer (DIK-5532, Daiki) at the stem elongation stage.

At harvest, the yield components including the number of spikes, number of grains per spike, 1,000-grain weight, and grain yield in each sampling site (total 120 points) were recorded. The 1,000-grain weight and grain yield (g m^{-2}) were corrected at 12.5% moisture content. The β-glucan content of the grains was determined during the 2017-2018 season using a β-glucan assay kit for mixed linkage β-glucan (β-glucan Assay Kit, Megazyme, Ireland).

3. Data analysis

All statistical analyses were performed using SPSS (IBM SPSS Statistics 26). Data obtained from each sampling site were used to develop heat maps, which were based on a grid to harmonize the resolution of all maps in S-PLUS software 8. Correlations were statistically evaluated using Pearson's correlation coefficient after outliers were removed. Single regression (2016-2017 season) and stepwise multiple regression (2017-2018 season) analyses were applied to detect the factors influencing yield, yield components, and β-glucan content of naked waxy barley. Regarding soil penetration resistance, average values of soil penetration resistance at the soil depth of every 10-cm were used for the stepwise multiple regression analyses.

Results

1. Spatial variability and comparisons of soil properties

During the 2016-2017 season, soil water content measured at the initial growth stage (51 DAS) was higher in the converted upland than in the normal upland (Table 1). Visualization of the spatial variability of soil water content showed that the converted upland had relatively higher soil water content in the frontal and near drainage ditches (Fig. 3A). Coefficients of variation

Table 1. Means and coefficients of variation (CV) of soil properties at the stem elongation stage of naked waxy barley cultivated in the converted upland and normal upland during the 2016-2017 and 2017-2018 seasons

Soil properties	2016-2017 season			2017-2018 season		
	Date	Converted upland	Normal upland	Date	Converted upland	Normal upland
SWC (m^3 m^{-3})	21 Dec 2016	0.37 (0.18)	0.33 (0.13)	27 Mar 2018	0.26 (0.27)	0.21 (0.18)
EC (μS cm^{-1})	14 Mar 2017	107.10 (0.21)	96.50 (0.30)	27 Mar 2018	87.80 (0.25)	88.90 (0.26)
Mineral N (mg 100g $soil^{-1}$)	14 Mar 2017	0.69 (0.49)	1.48 (0.42)	27 Mar 2018	0.90 (0.54)	1.30 (0.44)

Values in parentheses indicate the coefficient of variation. SWC: soil water content, EC: electrical conductivity

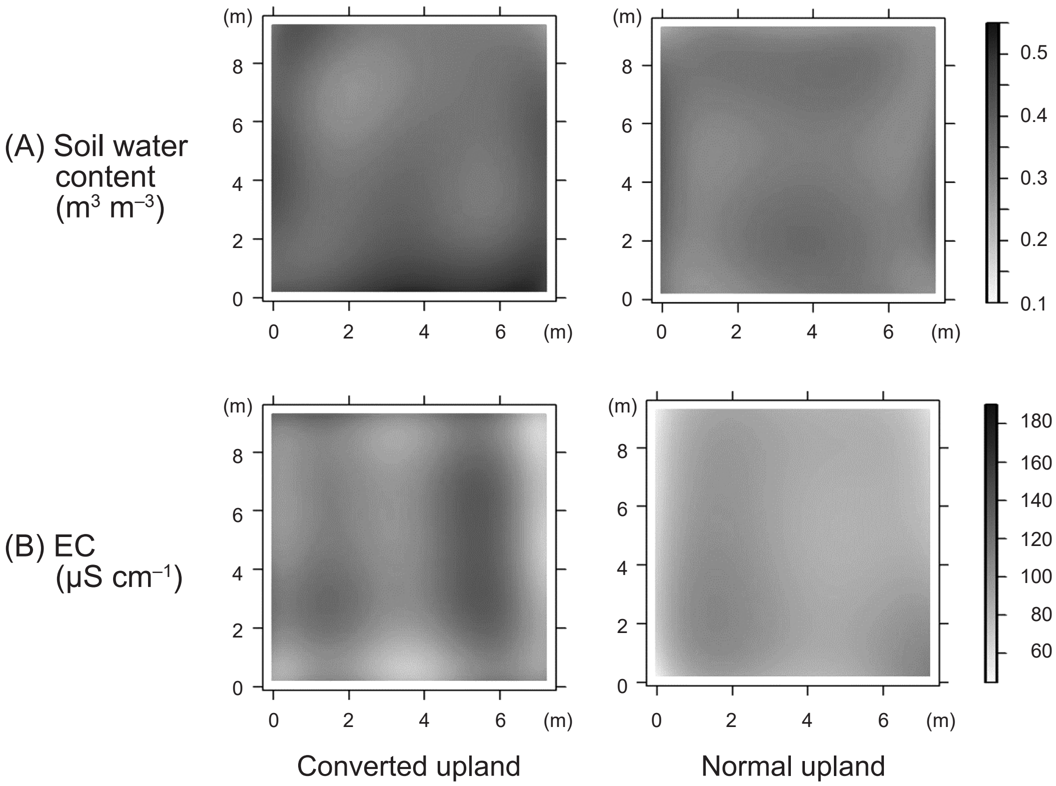

Fig. 3. Heat maps of soil water content (A) and EC (B) in the converted upland and normal upland during the 2016-2017 season
EC: electrical conductivity

(CVs) of soil water content were also higher in the converted upland. A higher EC value was observed in the converted upland soils than in the normal upland soils. The converted upland showed clear difference in EC by location, i.e., lower EC was observed near surface drainage ditches (Fig. 3 B).

During the 2017-2018 season, the converted upland also had higher soil water content than that of the normal upland as in the 2016-2017 season (Table 1). From the visualization of soil water content, normal upland showed a relatively uniform distribution, whereas higher water content was observed on the right side of the converted upland (Fig. 4 A). The EC value and soil mineral N content were higher in the normal upland than in the converted upland. The spatial variability of EC and mineral N showed similar tendencies that were observed between EC and mineral N content in the normal upland but not in the converted upland (Figs. 4 B, C). The converted upland exhibited higher values for soil penetration resistance up to the soil depth of 15 cm, but values at deeper depths were higher in the normal upland because the plow pan layer was observed at the soil depth of approximately 20 cm in the normal upland (Fig. 5).

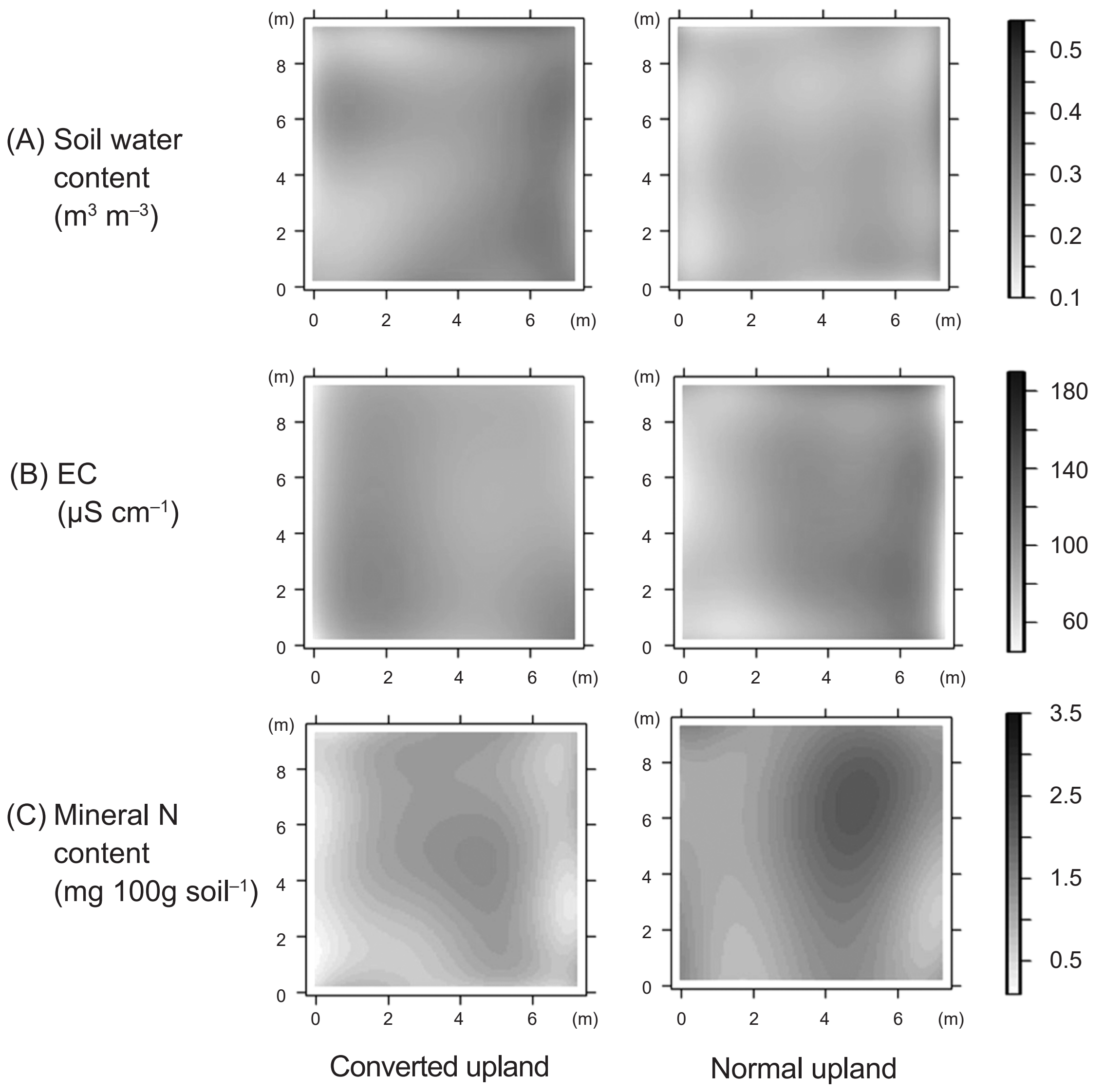

Fig. 4. Heat maps of soil water content (A), EC (B), and soil mineral N (C) in the converted upland and normal upland during the 2017-2018 season
EC: electrical conductivity

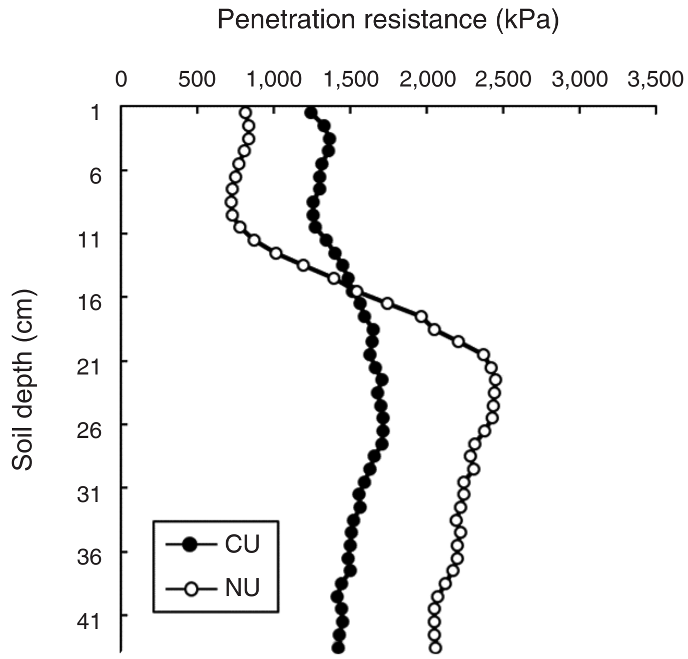

Fig. 5. Average soil penetration resistance in the converted upland and normal upland during the 2017-2018 season
Data were collected from 120 sampling points in each upland.
CU: converted upland, NU: normal upland

2. Yield, yield components, and β-glucan content

Table 2 shows barley yield and yield components during the 2016-2017 and 2017-2018 seasons. During the 2016-2017 season, the grain yields of the converted upland and normal upland were 377.1 and 420.8 g m^{-2}, respectively. The grain number per spike and 1,000-grain weight were higher in the normal upland than in the converted upland. During the 2017-2018 season, yield, all yield components, and the β-glucan content were greater in the normal upland than in the converted upland. The converted upland produced higher CV% values for the yield and yield components during both the cropping seasons. In addition to the delay in sowing, heavy rain during stem elongation to anthesis (from March to May) led to stagnant water in the experimental field (Fig. 2), resulting in a reduction in yield during 2017-2018 season compared with that of the 2016-2017 season.

The variability in yield and the β-glucan content within fields were visualized as maps of the kriged predictions. During the 2016-2017 season, lower yields were observed near drainage ditches in both fields (Fig. 6 A). During the 2017-2018 season, the yield on the right half of the converted upland was clearly low

Table 2. Means and coefficients of variation (CV) of yield, yield components, and β-glucan content of waxy barley cultivated in converted and normal fields during the 2016-2017 and 2017-2018 seasons

	2016-2017 season		2017-2018 season	
	Converted upland	Normal upland	Converted upland	Normal upland
Yield (g m^{-2})	377.1 (0.58)	420.8 (0.44)	125.4 (1.01)	279.2 (0.67)
Number of spikes (m^{-2})	327.6 (0.50)	332.5 (0.43)	112.5 (0.87)	169.7 (0.64)
Grain number ($spike^{-1}$)	36.5 (0.27)	42.5 (0.13)	32.8 (0.35)	49.3 (0.27)
1,000-grain weight (g)	29.1 (0.08)	29.9 (0.06)	28.7 (0.07)	31.2 (0.05)
β-glucan content (%)	-	-	4.8 (0.13)	5.1 (0.14)

Values in parentheses indicate the coefficient of variation

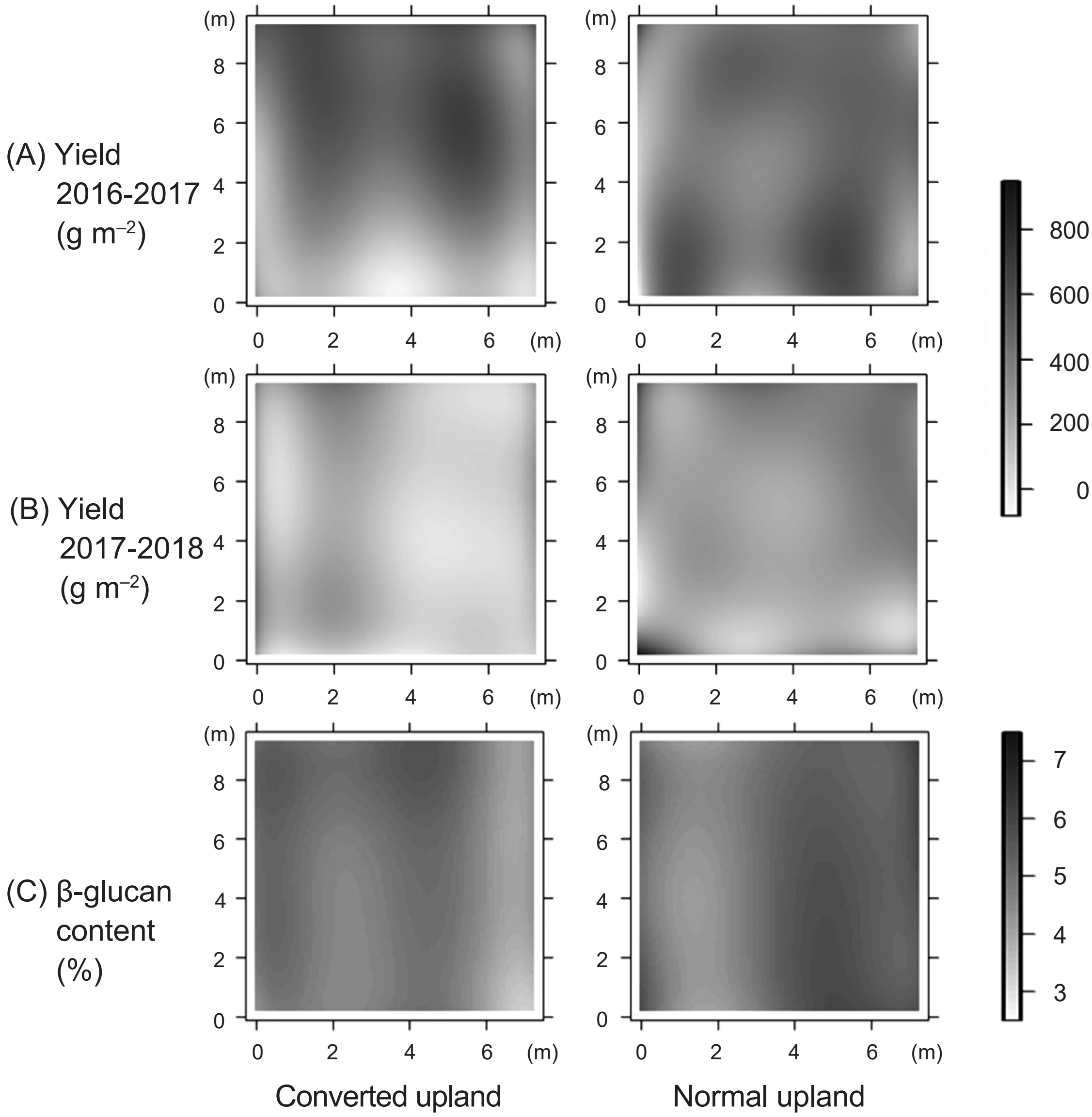

Fig. 6. Heat maps of yield and β-glucan content for naked waxy barley cultivated in the converted upland and normal upland during the 2016-2017 (A) and 2017-2018 seasons (B, C)

(Fig. 6 B). Different spatial distribution patterns were observed between yield and β-glucan content during the 2017-2018 season. Parallel maps of β-glucan content and soil properties showed opposite tendencies with soil water content in the converted upland, but showed similar patterns with EC and mineral N content in the normal upland (Fig. 3, Fig. 6 C).

3. Regression analysis of soil properties and waxy barley yield, yield components, and β-glucan content of waxy barley

During the 2016-2017 season, soil water content and EC had significant effects on grain yield in both fields, with soil water content having a negative impact and EC having a positive impact (Table 3). Spike number was affected by soil water content and EC similarly to grain yield. In the converted upland, grain number and 1,000-grain weight were negatively influenced by soil water content. During the 2017-2018 season, regression analysis of the measured soil properties showed that yield and β-glucan content were negatively influenced by soil water content in the converted upland (Table 4). Yield in the converted upland was also positively influenced by soil penetration resistance at a depth of 20 cm-30 cm. In the normal upland, the yield was negatively correlated with soil water content. The

Table 3. Simple regression of waxy barley yield and yield components cultivated in the converted upland and normal upland fields and soil properties during the 2016-2017 seasons

Site	Explanatory variable	Yield	Number of spikes	Grain number	1,000-grain weight
Converted upland	SWC	−0.58**	−0.56**	−0.52**	−0.36**
	EC	0.40**	0.46**	0.22*	0.18
Normal upland	SWC	−0.23*	−0.26**	0.05	−0.07
	EC	0.35**	0.39**	−0.04	−0.15

Asterisks (*, **) indicate statistical significance at $P < 0.05$ and $P < 0.01$, respectively. SWC: soil water content, EC: electrical conductivity

Table 4. Stepwise regression of waxy barley yield and yield components cultivated in the converted upland and normal upland and soil properties during the 2017-2018 season

Site	Dependent variable	Explanatory variable	γ	β	R^2
Converted upland	Yield	Soil water content	−0.46**	−0.36**	0.28**
		EC	0.08		
		Mineral N	−0.02		
		Soil compaction (0 cm-10 cm)	0.20*		
		Soil compaction (10 cm-20 cm)	0.27**		
		Soil compaction (20 cm-30 cm)	0.36**	0.29**	
		Soil compaction (30 cm-40 cm)	0.18		
	β-glucan	Soil water content	−0.33**	−0.33**	0.16*
		EC	−0.07		
		Mineral N	0.08		
		Soil compaction (0 cm-10 cm)	0.21*		
		Soil compaction (10 cm-20 cm)	0.05		
		Soil compaction (20 cm-30 cm)	−0.01		
		Soil compaction (30 cm-40 cm)	0.06		
Normal upland	Yield	Soil water content	−0.20*	−0.20*	0.03*
		EC	0.00		
		Mineral N	0.01		
		Soil compaction (0 cm-10 cm)	0.05		
		Soil compaction (10 cm-20 cm)	−0.08		
		Soil compaction (20 cm-30 cm)	0.09		
		Soil compaction (30 cm-40 cm)	0.08		
	β-glucan	Soil water content	0.12		
		EC	0.28**	0.25**	0.19**
		Mineral N	0.26**	0.26*	
		Soil compaction (0 cm-10 cm)	0.07		
		Soil compaction (10 cm-20 cm)	−0.15		
		Soil compaction (20 cm-30 cm)	−0.24*	−0.30**	
		Soil compaction (30 cm-40 cm)	−0.11		

Asterisks (*, **) indicate statistical significance at $P < 0.05$ and $P < 0.01$, respectively. γ: simple regression coefficient, β: standardized partial regression coefficient selected by stepwise multiple regression analysis, R^2: coefficient of determination by stepwise multiple regression analysis. SWC: soil water content, EC: electrical conductivity

Table 5. Simple regression of soil water content (SWC) and soil compactions at each soil depth in the converted upland and normal upland fields during the 2017-2018 season

	Soil compaction			
	0 cm ~ 10 cm	10 cm ~ 20 cm	20 cm ~ 30 cm	30 cm ~ 40 cm
SWC in converted upland	−0.38*	−0.23*	−0.35*	−0.08
SWC in normal upland	−0.24*	−0.10	0.08	0.10

Asterisks (*) indicate statistical significance at $P < 0.05$.

β-glucan content in the normal upland was positively correlated with EC and mineral N content but negatively correlated with soil penetration resistance at a depth of 20 cm-30 cm. An additional correlation analysis between soil water content and soil compaction showed that soil water content was negatively correlated with most soil compaction at all soil depths in the converted upland but negatively correlated with the soil compaction from 0 to 10 cm in the normal upland (Table 5).

Discussion

Soil is heterogeneous at a spatial scale because of variability in soil nutrients and physical factors. The heterogeneity in soil properties, plant growth, and yield has been reported previously (Nakamoto et al. 2002, Yanai et al. 2001). The present study focused on the soil heterogeneity in two waxy barley fields where different cropping systems were followed. The present study showed that the converted upland lacked the stability of naked waxy barley production as shown in the spatial variability and higher CV% for the yield. Furthermore, the β-glucan content was lower in the converted upland. According to our results, the soil properties in the normal upland were suitable for the cultivation of naked waxy barley.

Visualization of soil water content showed the hotspot existence of soil water even within the small fields. In the converted upland, higher soil water contents were observed in the region near the surface drainage ditch, in the frontal region where soil surface was topographically lower, in the upper left-hand region where water drainage was established, and in the right-hand region that was far from water drainage (Fig. 3 A, Fig. 4 A). The CV% for soil water content was also higher in the converted upland than in the normal upland. In the present study, both fields were tilled with the same rotary tillage implemented on a suitable day, but the trends of soil heterogeneity were different between converted upland and normal upland. This could be due to the differences in clay content and drainage. Although both field soils possessed relatively higher clay content, the proportion was higher in the converted upland (35.1%) than in the normal upland field (28.6%). The rate of soil pulverization is likely to have differed between the fields because the clay content influences soil pulverization (Hosokawa et al. 2001). In drainage, the converted upland, which possessed impermeable soil to reduce percolation losses, had a lower ground soil surface to establish waterlogged conditions for rice cultivation.

Soil water content was identified as negatively affecting the yield during both the cropping seasons. Simple correlation analysis of the 2016-2017 season data showed that soil water content was significantly negatively correlated with yield and number of spikes in both experimental fields. Stepwise regression analysis of the 2017-2018 season data also showed that soil water content was the key factor affecting the yield and yield components. The reduction in yield was likely due to the decrease in spike number, as the same correlation analysis results were obtained between yield and spike number (data not shown). Abeledo et al. (2003) reported that the number of spikes per plant is the main component explaining the variations in grain number per square meter. In most studies focusing on the subject, it has been suggested that biomass reductions occurring when barley is waterlogged during the stem elongation phase could be due to reductions in plant growth rate as well as to increases in tiller mortality (de San Celedonio et al. 2014). In the present study, the development of naked waxy barley spikes would suffer under high soil water conditions at the stem elongation stage, resulting in the observed reduction in yield. Soil penetration resistance at the depth of 20 cm-30 cm in the converted upland positively influenced the yield during the 2017-2018 season. Soil penetration resistance is influenced by soil water content, as reported by Medvedev (2009). Positive correlations between yield and soil compaction observed in the converted upland are possibly due to low soil water conditions because soil water content was negatively correlated with soil penetration resistance as shown in Table 5. Thus, it can be argued that soil water content was the most important determinant of yield components in the present study.

Soil water content was negatively correlated with the β-glucan content in the converted upland. Güler (2003) evaluated β-glucan content under different levels of irrigation and reported that an increase in irrigation level significantly decreased grain β-glucan content in barley. Güler (2003) also reported that nitrogen levels in the soil and nitrogen fertilization are major factors that affect the β-glucan content. In normal upland, the β-glucan content in the normal upland was positively impacted by EC and mineral N content. Our results obtained by correlation analysis are similar to a previous study (Güler 2003). Furthermore, soil compaction at the depth of 20 cm-30 cm was extracted to be a negative factor to β-glucan content in the present study. According to the results of the soil penetration resistance survey, this depth is consistent with the plow pan area (Fig. 5). Because the growth of roots is inhibited in a plow pan (Chan et al. 2006), breaking the plow pan would increase the β-glucan content by increasing the growth of deep roots.

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