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To cite this article: Yoshiya Shinoto, Toshinori Matsunami, Ryuji Otani & Sachio Maruyama (2020) Effects of tillage on growth, yield and root lodging of six maize hybrids in upland fields converted from paddy fields in Andosol, *Plant Production Science*, 23:1, 39-47, DOI: [10.1080/1343943X.2019.1693277](https://doi.org/10.1080/1343943X.2019.1693277)

To link to this article: <https://doi.org/10.1080/1343943X.2019.1693277>



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Published online: 25 Nov 2019.



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Effects of tillage on growth, yield and root lodging of six maize hybrids in upland fields converted from paddy fields in Andosol

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ABSTRACT

We investigated the effects of tillage on growth, grain yield and root lodging of maize hybrids in upland fields converted from paddy fields in Andosol of northern Tohoku. Six hybrids were grown with rotary tilling or plowing (chisel plowing plus power harrow) in 2016 and 2017. Soil penetration resistance was higher in plowing than in rotary tilling under a soil depth of 5 cm. There were no significant interactions between hybrid and tillage method in plant height, SPAD value, grain yield, and yield components, indicating that growth and grain yield of the six hybrids were unaffected by tillage method. Maize hybrids had similar culm length and ear height, while horizontal pulling resistance was higher in plowing than in rotary tilling. In addition, root lodged plants caused by typhoons were fewer in plowing than in rotary tilling in 2017. There was a negative correlation between horizontal pulling resistance and the number of root lodged plants. The highest horizontal pulling resistance and the least number of root lodged plants were found in a maize hybrid KD641 grown by plowing. The results suggest that root lodging can be alleviated by growing root-lodging-resistant maize hybrids such as KD641 with plowing.

ARTICLE HISTORY

Received 14 March 2019
Revised 7 October 2019
Accepted 5 November 2019

KEYWORDS

Horizontal pulling resistance; maize hybrids; plowing; root lodging; rotary tilling; upland field converted from paddy field



1. Introduction

Farmland consolidation is progressing, and paddy fields larger than 1 ha account for 9.3% of the total paddy area in Japan (Ministry of Agriculture, Forestry and Fisheries [MAFF], 2016), while the number of core farmers is decreasing (MAFF, 2018). Therefore, core farmers need to manage large-scale farms with small numbers of workers. Rotary tilling, a conventional tillage method in paddy fields after the 1960s (Naka, 1981), operates at speeds of 2–3 km h⁻¹. Higher work efficiency is thus required for large-scale farm management. A tillage system of chisel plowing plus power harrowing offers

a higher speed tillage method (Otani, Sekiya, Kanmuri, Nakayama & Saito, 2013), and the system is expected to be introduced in upland fields converted from paddy fields (Matsunami et al., 2017; Otani, 2015; Shinoto, Matsunami, Otani & Maruyama, 2019).

Carter and Barnett (1987) and Wall and Stobbe (1983) reported on the different performance of maize hybrids grown with conventional and no-tillage systems. Carter and Barnett (1987) reported that some hybrids differed in yield according to tillage method; yield of some hybrids ranked lower under conventional tillage among hybrids, whereas ranked middle in no tillage

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among hybrids. Herrera, Verhulst, Trethowan, Stamp and Govaerts (2013) noted that there is a need to evaluate genotypes developed under no tillage and extend the research on genotype performance under no tillage. Therefore, grain yield might be different according to tillage methods. On the other hand, other investigations failed to detect a difference in maize hybrid performance among several tillage methods (Duiker, Haldeman & Johnson, 2006; Hallauer & Colvin, 1985; Imholte & Carter, 1987; Karlen & Sojka, 1985; Kaspar et al., 1987; Mock & Erbach, 1977). This discrepancy suggests that the maize hybrid response to tillage method is affected by environmental factors such as weather conditions and soil types. There have been few reports, however, investigating the maize hybrid response to tillage systems in upland fields converted from paddy fields in northern Tohoku. In addition, maize hybrids are provided by private companies in Japan, and so the replacement of maize hybrids is faster when compared with other major crops such as rice and wheat. It is thus important to investigate the interaction between hybrid and tillage methods in order to extend the plowing method in upland fields converted from paddy fields.

Maize root system tends to be longer and shallower with plowing than in rotary tilling in upland fields converted from paddy fields (Shinoto, Matsunami, Otani, Kanmuri & Maruyama, 2017, 2018b). Maize root system tends to develop in surface layers under no-tillage (Harada, Kobayashi, Miyazono, Takenouchi & Kuwamizu, 2009; Sakai, Sunohara, Yonekawa & Tsunoda, 1988), which contributes to higher root lodging resistance in no-tillage than in tillage systems (Harada et al., 2009; Inoue, Ito & Saigusa, 2000). Therefore, it is possible that maize grown with plowing differs in root lodging resistance when compared with rotary tilling.

The objective of this study was to evaluate plant growth, grain yield and root lodging of maize hybrids grown with rotary tilling and plowing in upland fields converted from paddy fields in Andosol of northern Tohoku. Six cultivars were selected from major seed companies that are widely used in the northern Tohoku region.

2. Materials and methods

2.1. Plants and growth conditions

Field experiments were conducted in upland fields converted from paddy fields (Andosol) at the National Agriculture and Food Research Organization (NARO) Tohoku Agricultural Research Center, Morioka, Japan (141°08'E, 39°45'N) in 2016 and 2017. Previous fields were paddy fields. The soil was Andosol. Maize was

grown under rain-fed conditions in this experiment. Three early (relative maturity (RM) 100–108) maize hybrids (34N84, DuPont Pioneer, Johnston, IA, USA; TX1241, Takii & Co., Ltd, Kyoto, Japan; Kimimaru, Snow Brand Seed Co., Ltd., Hokkaido, Japan) and three medium (RM114–120) maize hybrids (P2088, DuPont Pioneer, Johnston, IA, USA; SH3786, Snow Brand Seed Co., Ltd., Hokkaido, Japan; KD641, Kaneko Seeds Co., Ltd., Gunma, Japan) were selected to reach maturity early in November when sown in late May or early June in the northern Tohoku area.

The experiment design was a strip plot design with three blocks. Each block was divided into six subplots. The two tillage systems were used on the main plots, and the hybrids comprised the subplots. The area of each subplot was 24 m² (3 m × 8 m) in 2016 and 48 m² (6 m × 8 m) in 2017. Conventional tillage was rotary tilling (RT) to a depth of 20 cm using a 2.6 m-wide rotary tiller (LXR2610, Matsuyama Plow MFG. Co., Ltd, Nagano, Japan) with 75–80 horsepower tractors. Plowing tillage (PT) was conducted to a depth of 20 cm using a 1.9 m-wide chisel plow (MSC6PSQLK, Sugano Farm Machinery MFG., Co., Ltd., Ibaraki, Japan) with a 75–85 horsepower tractor and harrowing was to a depth of 5 cm using a 2.0 m-wide power harrow (BETA230P, Sugano Farm Machinery MFG., Co., Ltd, Ibaraki, Japan) with 75–80 horsepower tractors. Experiment fields were different in 2016 and 2017, because of crop rotation.

Two to three seeds per hill were planted on 2 June 2016, and on 6 June 2017, with 75 cm row spacing and 18 cm hill spacing with a seeder (TDR, Agritecno YAZAKI Co., Ltd., Hyogo, Japan). Plants were thinned to one plant per hill around V2 stage. Basal dressing of N, P₂O₅, and K₂O at the rates of 15, 20, and 15 g m⁻² (150, 200, and 150 kg ha⁻¹), respectively, was applied as a blended fertilizer (N: P₂O₅: K₂O = 15:20:15). For weed management, herbicides were applied at just after sowing (Dimethenamid-Linuron) and at the V6 stage (Topramezone). Pesticide was not applied.

2.2. Measurements

Penetration resistance of soil was measured at the seeded row with a cone penetrometer (DIK-5521 or DIK-5532, Daiki Rika Kogyo Co., Ltd., Saitama, Japan) on 3 June 2016, and 27 June 2017.

Plant height and leaf color were measured for five continuous plants in each replication in each field at about 10-day intervals. Leaf color was measured at the middle part of the topmost fully expanded leaves with a chlorophyll meter (SPAD-502 Plus, Konica Minolta Inc., Tokyo, Japan), and at top ear leaves at 74 days after sowing (DAS) at the silking stage.

At harvest, only ears were obtained from a 3-m² (2 rows × 2 m) area in each replication. After measuring ear length, the ears were shelled. After shelling, the kernels were equalized to 300–400 g, and then counted. After counting kernel number, 100 grain weight was calculated and grain yield were determined. Grain moisture was measured with a moisture meter (PM650, Kett Electric Laboratory, Tokyo, Japan). Grain yield and 100 grain weight were calculated as 15% moisture content.

Traits of root lodging were measured with 10 continuous plants in the same row in each replication, except for plants that could not be measured for culm length. An iron tool was attached to bottom of plants. A digital force gauge (DS2-50N, Imada Co., Ltd., Aichi, Japan) was attached to the iron tool, and then the part of iron tool at 1 m-height from the soil surface was pulled until it was 30° from vertical (Koinuma, Ikegaya & Ito, 1998). The value of the digital force gauge was regarded as horizontal pulling resistance (HPR). HPR measurements were conducted 25 days after silking in 2016 and 25–32 days after silking in 2017. Culm length and ear height were also measured after measurements of HPR in 2016 or 12 days before the measurement of HPR in 2017. Horizontal pulling resistance-value (HPR-value) was calculated using the following formula (Koinuma et al., 1998).

$$\text{HPR - value} = \frac{\sqrt{\text{Culm length(cm)} \times \text{Ear height (cm)}}}{\text{Horizontal pulling resistance (N)}}$$

The lower HPR-value, the higher root lodging resistance. Ishige, Yamada and Shiga (1983) evaluated resistance to lodging of maize by using discriminant function, in which three parameters were adopted; pulling resistance, plant weight and center of gravity. Tani (1963) showed that the moment of above-ground weight was calculated by the product of plant weight and the center of gravity. Koinuma et al. (1998) defined the moment of above-ground weight as the product of culm length and ear height, which correlates with above-ground weight and center of gravity, respectively. They defined HPR-value as the square root of product of culm length and ear height divided by horizontal pulling resistance.

In 2017, root lodging and stalk lodging occurred due to typhoons on September 18 and on October 23. Root lodging and stalk lodging were determined in 10 plants, which were used for the measurement of HPR at 160 DAS. Plants inclining more than 30° toward ground level were regarded as root lodging, and plants bending sharply under a node, including just above the node bearing the uppermost ear, were regarded as stalk lodging (Yoshimura, 2004). Plants regarded as both root lodging and stalk lodging were categorized as stalk lodging (Yoshimura, 2004). Plants that were damaged while measuring HPR were not included in root lodging and stalk lodging results.

2.3. Weather data

Meteorological data was obtained from the weather station at the Tohoku Agricultural Research Center and from the Morioka Meteorological Observatory of the Japan Meteorological Agency. The normal values for daily mean temperature and precipitation were averaged from 1981 to 2010. The normal values for the duration of sunshine were averaged from 1997 to 2010.

2.4. Statistical analysis

Analysis of variance was computed for data from each year. Statistical analysis was carried out using analysis software (JMP 11.2.0, SAS Institute Inc., Cary, NC, USA).

3. Results

3.1 Meteorological conditions and soil penetration resistance

Table 1 shows the meteorological data for 2016 and 2017 during the experiments. Precipitation in June and August 2016 was greater than normal levels. Daily mean temperature in 2016 was comparable to normal values. The duration of sunshine in 2016 was 87% when compared with normal values for June, which is the early

Table 1. Meteorological data for 2016 and 2017 during experiments.

Month	Precipitation (mm)			Daily mean temperature (°C)			Duration of sunshine (h)		
	2016	2017	Normal value	2016	2017	Normal value	2016 ^a	2017	Normal value
June	160	123	108	18.0	17.2	17.8	135	179	156
July	131	387	196	21.6	23.6	21.3	144	181	120
August	259	217	182	24.1	21.6	22.9	212	99	138
September	161	194	156	20.3	17.5	18.2	116	167	117
October	185	206	93	11.2	11.4	11.5	177	86	141

Notes: Duration of normal values; 1981–2010 (precipitation, daily mean temperature), 1997–2010 (duration of sunshine). ^aDuration of sunshine in 2016 was obtained from Morioka meteorological observatory of Japan Meteorological Agency because of broken equipment at the NARO Tohoku Agricultural Research Center.

growth stage; however, it was 153% when compared with normal values for August. Precipitation in 2017 was greater than normal values during experiments from June to October. Daily mean temperature as 1.3°C lower in August. The duration of sunshine was 151% in July, but was 61–72% in August and October when compared with normal values. In 2017, typhoons passed the area on September 18 (Talim) and October 23 (Lan). The maximum wind speed was 12.3 m s⁻¹ on September 18.

Figure 1 shows the soil penetration resistance. Soil penetration resistance in RT was 0.1–0.3 MPa at a soil depth of 1 to 20 cm. Soil penetration resistance in PT

was slightly higher than that in RT at the surface soil, but it rapidly increased to more than 0.4 MPa at a soil depth of 5 to 20 cm.

3.2 Plant growth and grain yield

Figure 2 shows changes in plant height and SPAD value. The effect of tillage on plant height was not significant during the experiment in 2016 and 2017. SPAD values in RT (32) were lower than those in PT (33) at 28 DAS in 2016. SPAD values obtained in RT (46) were higher than those in PT (43) at 36 DAS in 2017. The interaction between hybrid and tillage was not significant for plant height and SPAD value during the experiments in 2016 and 2017.

Table 2 shows the effects of hybrid and tillage on silking day, grain yield and yield components. Silking in PT was 1 day earlier than that in RT in 2016. The interactions between hybrid and tillage for grain yield and yield components were not significant in 2016. Tillage and the interactions between hybrid and tillage for all traits were not significant in 2017.

3.3. Root lodging traits

Table 3 shows root lodging traits. There were significant differences among hybrids for all the traits in 2 years. SH3786 had the lowest, and KD641 had the highest HPR among hybrids. HPR was higher in PT than in RT ($p < 0.1$). There were significant differences in ear height between tillage treatments in 2016. The interaction between hybrid and tillage for HPR was significant in 2016; however, no significant interaction was found in any traits in 2017. HPR-values did not have normal distribution according to Shapiro–Wilk test (2016: $p = 0.0004$, 2017: $p = 0.0087$), therefore, statistical analysis was not carried out. In 2017, the number of root lodged plants was significantly different among hybrids; SH3786 had the most root lodged plants, and KD641 had the least root lodged plants. Tillage had a significant effect on the number of root lodged plants; the number of root lodged plants was smaller in PT than in RT. The interaction between hybrid and tillage was significant in root lodging; among hybrids, the number of root lodged plants was reduced more for P2088 and KD641 and less for SH3786 in PT than in RT. In contrast, the number of stalk lodged plants was larger in PT than in RT.

Figure 3 shows relationships between the number of root lodged plants and HPR or HPR-value in 2017. There was a significant negative relationship between HPR and the number of root lodged plants. A significant positive relationship was also observed between HPR-value and

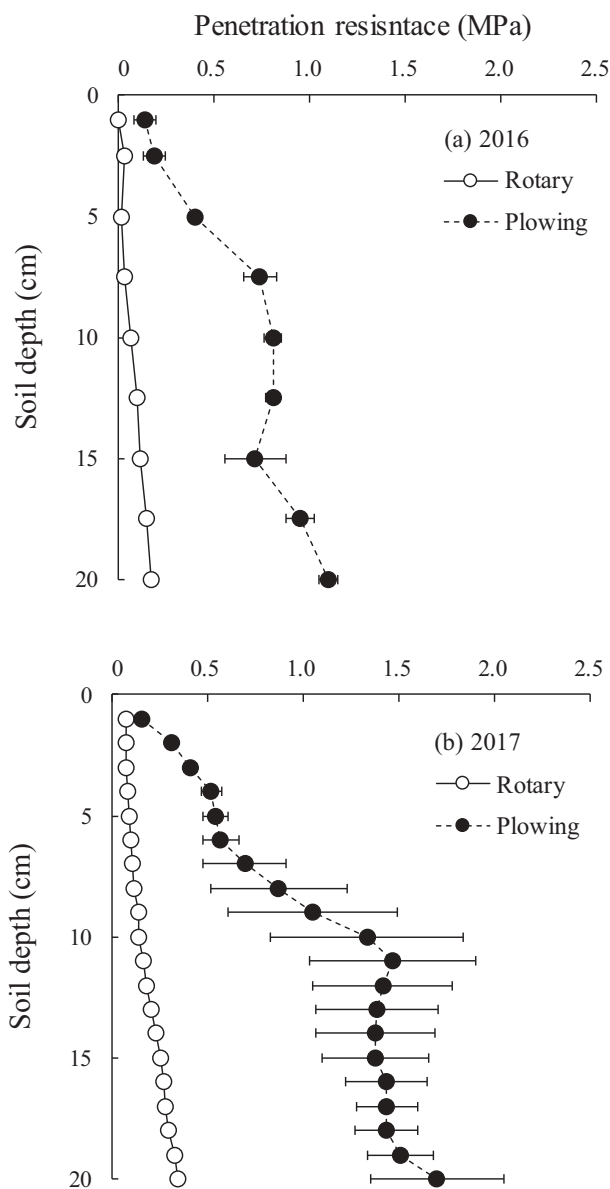


Figure 1. Soil penetration resistance of two tillage methods (a: 2016; b: 2017).

Notes: Bars represent standard error ($n = 3$). Rotary: Rotary tilling.

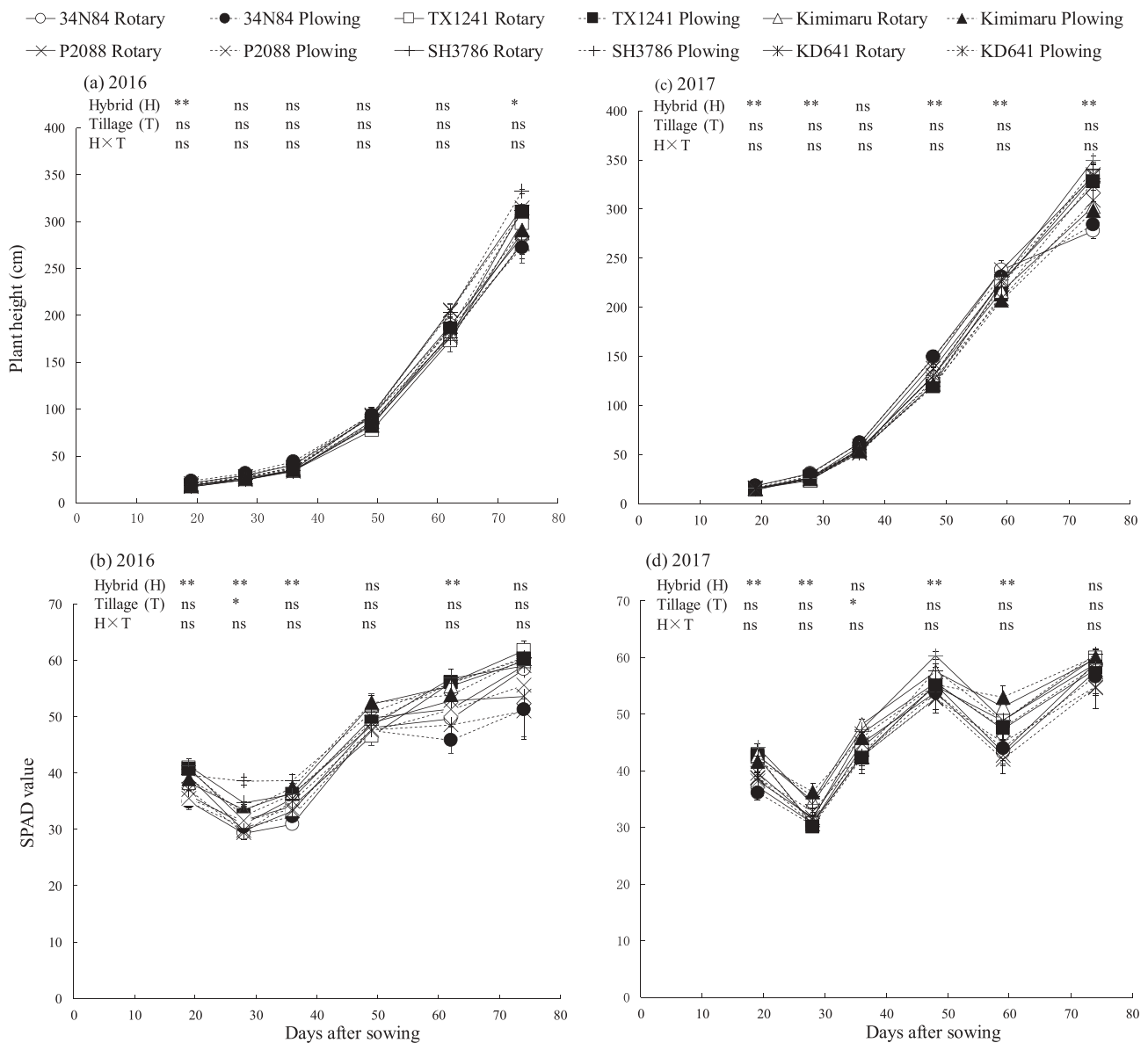


Figure 2. Changes in plant height and SPAD value of maize hybrids grown by two tillage methods.

Notes: Bars represent standard error ($n = 3$). ** and *, significant difference at $p < 0.01$ and $p < 0.05$, respectively. ns: not significant ($p < 0.05$). Rotary: Rotary tilling.

the number of root lodged plants. Plants with higher HPR and lower HPR-value had less root lodged plants than those with lower HPR and higher HPR value, respectively.

4. Discussion

Maize growth was largely unaffected by tillage methods in the present investigation. Although there were significant differences in the early stages of growth between RT and PT, the differences were not significant in other stages (Figure 2). The results agreed with the previous report (Shinoto et al., 2017). It is possible that tillage method affects soil temperatures, as soil temperature in

no-tillage is lower than that in conventional tillage due to covering the soil surface with crop residue (Carter & Barnett, 1987; Wall & Stobbe, 1983). A previous report (Shinoto, Maruyama, Matsunami & Otani, 2018a) indicates that there is no significant difference in soil temperature between RT and PT at a soil depth from 15 to 30 cm, as both methods remove crop residue from the soil surface. Silking day was earlier in PT than in RT (Table 2) due to the accelerated early growth by PT, which was similar to the previous report (Shinoto et al., 2017).

The tassel and final ear primordia are formed after the final leaf primordium is formed (Nielson, 2002), which is after V6 stage. The interactions between hybrid and tillage were not significant for SPAD values from V6 stage (36 DAS)

Table 2. Silking day, grain yield and yield components of maize hybrids grown by two tillage methods.

Year	Hybrid (RM) ^a	Tillage	Silking day (Days after sowing)	Ear length (cm)	Kernel number (m ⁻²)	100-grain weight (g)	Grain yield (g m ⁻²)
2016	34N84	Rotary	69	16.6	3391	29.9	1015
	(108)	Plowing	68	15.7	2772	27.9	781
	TX1241	Rotary	72	16.9	3429	29.5	1013
	(110)	Plowing	70	16.9	3241	30.9	1003
	kimimaru	Rotary	70	17.1	2984	34.8	1037
	(110)	Plowing	69	17.1	2954	34.7	1027
	P2088	Rotary	72	16.5	3207	32.4	1042
	(118)	Plowing	71	16.7	3060	31.8	998
	SH3786	Rotary	71	17.1	3089	29.5	922
	(118)	Plowing	69	18.2	3318	30.7	1018
	KD641	Rotary	74	17.4	4128	23.7	978
	(114)	Plowing	73	15.7	3704	23.7	895
	Average	Rotary	71	16.9	3371	30.0	1001
		Plowing	70	16.7	3175	30.0	954
	ANOVA	Hybrid (H)	**	ns	*	ns	ns
		Tillage (T)	*	ns	ns	ns	ns
		H × T	ns	ns	ns	ns	ns
2017	34N84	Rotary	66	16.2	3450	28.5	978
	(108)	Plowing	66	16.2	3660	26.7	976
	TX1241	Rotary	68	16.3	3713	28.1	1042
	(110)	Plowing	68	16.3	3553	28.0	995
	kimimaru	Rotary	67	16.0	2910	33.2	968
	(110)	Plowing	67	15.5	2621	33.3	873
	P2088	Rotary	68	15.5	3263	31.2	1022
	(118)	Plowing	68	15.4	3519	31.3	1100
	SH3786	Rotary	68	16.0	3373	28.4	959
	(118)	Plowing	69	15.3	3233	28.5	925
	KD641	Rotary	71	15.9	3918	22.9	896
	(114)	Plowing	71	15.6	4157	24.0	1000
	Average	Rotary	68	16.0	3438	28.7	978
		Plowing	68	15.7	3457	28.6	978
	ANOVA	Hybrid (H)	**	ns	**	**	ns
		Tillage (T)	ns	ns	ns	ns	ns
		H × T	ns	ns	ns	ns	ns

Notes: **Significant at the 0.01 probability level. *Significant at the 0.05 probability level. ns, nonsignificant at the 0.05 probability level.

^aRelative maturity. Rotary: Rotary tilling.

to the silking stage (75 DAS) (Figure 2). Therefore, responses of tassel and ear formations to tillage treatments were similar among hybrids. The interactions between hybrid and tillage were not significant for plant height until the silking stage (Figure 2). This result suggested that vegetative growth among hybrids did not differ between tillage treatments. Final kernel number and grain weight are associated with crop growth around bracketing silking (Cirilo & Andrade, 1994; Jones, Schreiber & Roessler, 1996). There were no significant differences in the interaction between hybrid and tillage in plant height and SPAD value at silking (Figure 2). Therefore, the potentiality of kernel number and grain weight of RT might be similar to that of PT. Furthermore, grain yield was not significantly affected by hybrid or tillage (Table 2), indicating that hybrid performance was similar in RT and PT in upland fields converted from paddy fields in northern Tohoku. These results will enable farmers to apply the plowing method to grow new maize hybrids in these fields. Nevertheless, further experiments with hybrids and tillage methods are needed, when PT is applied to the other soil types.

PT improved root lodging resistance of maize as compared with RT. Although maize hybrids had similar

culm length and ear height in both the tillage treatments, HPR was higher ($P < 0.1$) and HPR-value tended to be lower in PT than in RT in 2016 and 2017 (Table 3). In 2017, two typhoons caused root lodging in maize hybrids in the present investigation. The number of root lodged plants was lower in PT than in RT. Harada et al. (2009) suggest that root anchorage in no-tillage plants is stronger than in RT, because roots elongate in the hard soil surface. Soil penetration resistance at 5 to 20 cm was higher in PT than in RT (Figure 1). The root system is shallower in PT than in RT (Shinoto et al., 2018a). Therefore, it is likely that root lodging was alleviated in PT due to the root system distributed in hard soil. Root lodging tended to be more severe in RT than in PT due to heavy rain and strong winds, because root anchorage was inferior in RT than in PT. Stalk lodging was more delete in PT than in RT, after root lodging was alleviated by the strong root anchorage in PT. The previous report (Shinoto et al., 2019) indicates that root lodging is less in PT than in RT in upland fields converted from paddy fields both in Andosol and Gleysol.

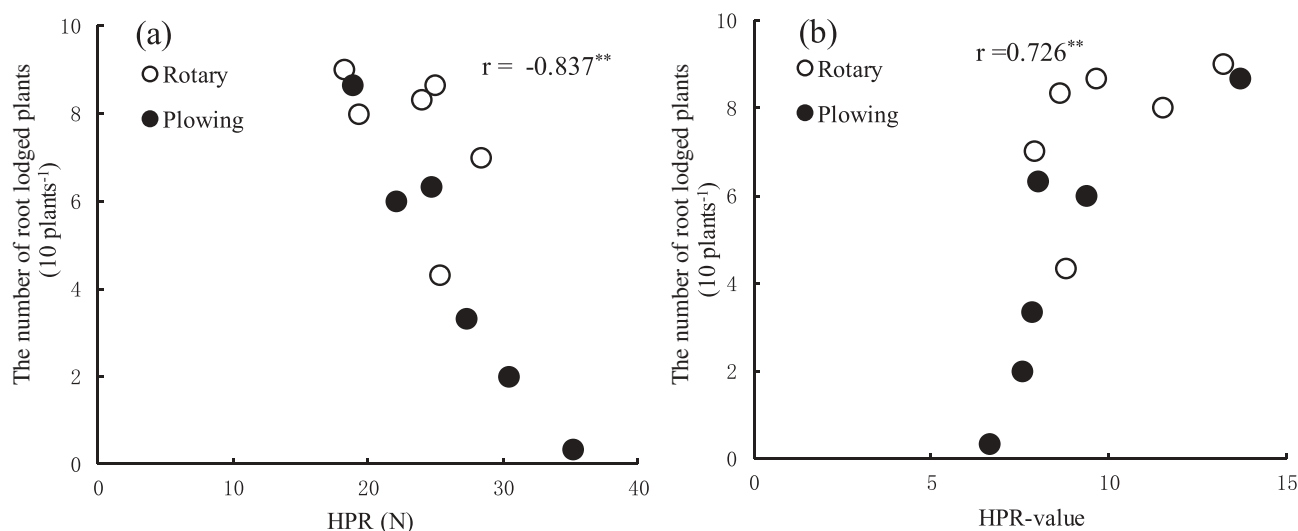
Among hybrids, KD641 had the highest HPR in 2016 and 2017 and the lowest number of root lodged plants

Table 3. Traits of root lodging of maize hybrids grown by two tillage methods.

Year	Hybrid (RM) ^a	Tillage	HPR ^b (N)	Culm length (cm)	Ear height (cm)	HPR-value	Root lodging (10 plants ⁻¹)	Stalk lodging (10 plants ⁻¹)	
2016	34N84 (108)	Rotary	27.5	248	103	6.2 ± 0.5	-	-	
		Plowing	28.9	250	102	6.1 ± 0.3	-	-	
	TX1241 (110)	Rotary	22.5	276	120	9.4 ± 1.3	-	-	
		Plowing	31.7	280	125	6.5 ± 0.8	-	-	
	kimimaru (110)	Rotary	26.8	268	133	7.3 ± 0.6	-	-	
		Plowing	29.8	272	138	6.9 ± 0.1	-	-	
	P2088 (118)	Rotary	24.5	289	128	8.3 ± 0.3	-	-	
		Plowing	34.4	297	131	6.3 ± 0.7	-	-	
	SH3786 (118)	Rotary	18.3	300	135	11.5 ± 0.6	-	-	
		Plowing	32.6	312	135	6.5 ± 0.1	-	-	
	KD641 (114)	Rotary	32.4	270	117	5.8 ± 0.2	-	-	
		Plowing	34.2	265	116	5.9 ± 0.8	-	-	
	Average	Rotary	25.3	275	122	8.1 ± 0.5	-	-	
		Plowing	31.9	279	124	6.4 ± 0.2	-	-	
	ANOVA	Hybrid (H)	**	**	**	-	-	-	-
		Tillage (T)	†	ns	*	-	-	-	-
		H × T	*	ns	ns	-	-	-	-
2017	34N84 (108)	Rotary	24.0	257	126	8.6 ± 0.4	8.3	0.7	
		Plowing	24.7	256	128	8.0 ± 0.1	6.3	0.3	
	TX1241 (110)	Rotary	25.4	298	144	8.8 ± 1.2	4.3	1.0	
		Plowing	27.3	289	138	7.8 ± 0.3	3.3	2.0	
	kimimaru (110)	Rotary	19.4	269	133	11.5 ± 1.3	8.0	2.0	
		Plowing	22.1	270	131	9.4 ± 0.4	6.0	2.7	
	P2088 (118)	Rotary	25.0	302	142	9.7 ± 0.9	8.7	1.0	
		Plowing	30.5	294	140	7.6 ± 0.9	2.0	2.0	
	SH3786 (118)	Rotary	18.3	321	151	13.2 ± 1.0	9.0	0.7	
		Plowing	18.9	319	151	13.7 ± 1.2	8.7	1.0	
	KD641 (114)	Rotary	28.5	294	144	7.9 ± 0.8	7.0	0.7	
		Plowing	35.2	290	141	6.7 ± 0.4	0.3	4.3	
	Average	Rotary	23.4	290	140	10.0 ± 0.6	7.6	1.0	
		Plowing	26.5	286	138	8.9 ± 0.6	4.4	2.1	
	ANOVA	Hybrid (H)	**	**	**	-	*	ns	ns
		Tillage (T)	†	ns	ns	-	*	*	*
		H × T	ns	ns	ns	-	-	*	ns

Notes: **Significant at the 0.01 probability level. *Significant at the 0.05 probability level. †Significant at the 0.1 probability level. ns, nonsignificant at the 0.1 probability level.

^aRelative maturity, ^bhorizontal pulling resistance. HPR-value indicated data ± standard error. Rotary: Rotary tilling.

**Figure 3.** Relationships between number of root lodged plants and HPR (a) or HPR-value (b) in 2017.

Notes: ** significant difference at $p < 0.01$. Rotary: Rotary tilling; HPR: horizontal pulling resistance.

in 2017 (Table 3). On the other hand, SH3786 had the lowest HPR in 2016 and 2017 and the highest number of root lodged plants in 2017. These results suggest that KD641 has the highest root lodging resistance, while

SH3786 has the lowest root lodging resistance among the six hybrids in the present investigation. In KD641, HPR was higher and the number of root lodged plants was fewer in PT than in RT. Maize plants with higher HPR

and lower HPR-value had lower numbers of root lodged plants (Figure 3). These results indicate that maize hybrids having high root lodging resistance grown by the plowing method are more resistant to heavy rain and strong winds, such as in typhoons, in upland fields converted from paddy fields.

The interactions between hybrid and tillage in plant growth and grain yield were not significant in the present investigation. Maize hybrids grown by plowing showed similar characteristics as those grown by rotary tilling in upland fields converted from paddy fields in northern Tohoku. Nevertheless, the present investigation confirmed that root lodging resistance of maize was higher in plowing than in rotary tilling. In addition, there were differences in root lodging resistance among maize hybrids. The results suggest that growing maize hybrids with high root lodging resistance by the plowing method alleviates root lodging under heavy rain and strong winds.

Acknowledgments

We would like to thank Mr. Hisashi Sato for technical advice on the measurement of root lodging resistance. We would also like to thank Mr. Soichi Nakayama, Mr. Akito Kubota and Dr. Hiroshi Uchino for statistical analysis. We are grateful to Mr. Akio Yoshida, Mr. Yukihiro Miura, Mr. Daisuke Kato, Mr. Atsushi Ogasawara, Mr. Hiroki Takahashi, Mr. Eiko Takahashi, Mr. Kazuhiro Kudo, and Mr. Nobuyuki Yoshizawa for field management and data collection in the study. Finally, we would like to thank Ms. Kumi Sakaki for data collection.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by a grant from the commissioned project study on 'Research for low-cost production and utilization of self-sufficient forage crops with high yield and high nutritional value', of the Ministry of Agriculture, Forestry and Fisheries, Japan.

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