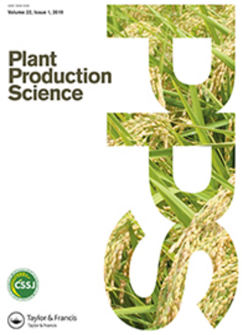

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Growth and yield of maize using two tillage systems in crop rotation of paddy fields

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ABSTRACT

Plowing is a more efficient tillage method than conventional rotary tilling in paddy fields. We thus investigated growth, grain yield, and quality of maize (*Zea mays* L.) using two tillage systems in crop rotation of paddy fields at Morioka (Andosol) and Hanamaki (Gleysol). Maize was grown with rotary tilling after growing transplanted rice with puddling and leveling, and alternatively, with plowing (chisel plowing plus power harrow) after direct seeding of rice with plowing and compaction. There was no significant difference in seedling establishment between the two tillage treatments. Although silking was slightly earlier and root lodging was less severe in plowing than in rotary tilling, there was no significant difference in plant height, SPAD value, dry weight at maturity, Kernel number, grain weight, grain yield, starch content, crude protein content, or mycotoxin accumulation, irrespective of soil type. These results indicate that growth and yield of maize were similar for the plowing system and the rotary tilling system. Thus, the plowing system could improve work efficiency for maize cultivation in crop rotation of paddy fields for large-scale farm management.

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Crop rotation; maize; paddy field; plowing; rotary tilling; soil type

1. Introduction

Transplanting is widely used in rice cultivation in Japan. Labor-saving and low-cost cultivation are required because the number of farmers is decreasing, and the price of rice is declining. Therefore, the area used in direct seeded rice is increasing (Ministry of Agriculture, Forestry and Fisheries [MAFF], 2018b). Farmland consolidation is progressing, and paddy fields larger than 1 ha are 9% of the total paddy fields (MAFF, 2016). According to a 2015 census of agriculture and forestry in Japan, the number of farms larger than 100 ha increased by 34.8% from 2010 to 2015. In large-scale farm management, crop rotation of paddy fields has involved direct seeding of rice for cultivation by plowing and compaction and introduction of field crops (Matsunami et al., 2017; Otani, Sekiya, Kanmuri, Nakayama, & Saito, 2013).

Plowing or chisel plowing with a power harrow is used in the system of rotating three crops in two years in paddy fields including direct-seeded rice using plowing and compaction (Otani et al., 2013). A 120 horsepower class tractor in this system operates at speeds faster than 12 km hr^{-1} from preparation of the seed bed to compaction. With a 2.5 m-wide chisel plow attached to a 126 horsepower tractor, work efficiency can be as high as 1.2 ha hr^{-1} (Otani, 2015), while that of rotary tilling (RT) is typically around 0.5–0.6 ha hr^{-1} with a 2.0 m-wide rotary tiller (Gotoh et al., 2004). Although fair comparisons between a chisel plow and rotary tiller are difficult from the literature because the work width of the tools is different, the work efficiency of plowing is more than two times faster than that of RT. The Japanese government aims to consolidate 80% of agricultural land for core farmers (MAFF, 2015). It is expected that high-speed machinery systems will be widely used for large-scale farm management. When field crops are planted in upland fields converted from paddy fields after rice cultivation with puddling, the conventional tillage method is RT. There is much knowledge about field crop cultivation techniques using RT in upland fields converted from paddy fields (Hoshi, 2013; Ikenaga et al., 2012; Kawamura, Nakano, Mitsuoka, Inoue, & Okayasu, 2013; Sakamoto & Oshita, 2008). However, there are few reports on growth and grain yield of field crops in crop rotation systems of paddy fields that include direct seeding for rice cultivation with plowing and compaction.

Some farmers who cultivate rice by direct seeding with plowing and compaction grow maize for grain. The use of self-sufficient concentrated feed is quite low at 14%, and the aim is to improve use to 20% by

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2025 (MAFF, 2018a). Growing maize for grain in upland fields converted from paddy fields in Japan makes it possible to improve production of domestic concentrated feed. Furthermore, maize for grain is considered a labor-saving crop because less cultivation management is necessary compared with rice and soybean. Therefore, maize for grain is considered a suitable crop for large fields after direct seeding of rice with plowing and compaction.

In a previous report (Shinoto, Matsunami, Otani, Kanmuri, & Maruyama, 2017), maize was sown in RT plots and plowing plots after transplanted rice with puddling and leveling in the same Andosol field, revealing differences in growth and grain yield between RT and plowing after the same rice cultivation method. However, there are few reports on the effects of tillage for growth and grain yield of maize in a crop rotation system. To extend the crop rotation system to include plowing, it is necessary to compare growth and grain yield of maize between plowing and RT, which is a conventional tillage method in paddy fields in Japan.

The objective of this study was to compare the growth, grain yield, and quality of maize under a crop rotation system in paddy fields between RT and plowing. This study was conducted in two different soil types, Andosol and Gleysol. Maize was sown in RT plots after transplanted rice with puddling and plowing after direct seeded rice without puddling.

2. Materials and methods

2.1. Experiment 1 in Andosol (Morioka, Iwate)

Field experiments were conducted in 2016 and 2017 in upland fields converted from paddy fields (Andosol) at the National Agricultural and Food Research Organization (NARO) Tohoku Agriculture Research Center, Morioka, Iwate, Japan (141°08´E, 39°45´N). Maize (*Zea mays* L.) cv. TX1241 (Takii Seed Co., Ltd., Kyoto, Japan) was used in 2016 and cv. 34N84 (DuPont Pioneer, Johnston, IA, USA) was used in 2017 because TX1241 had been discontinued. Relative maturity (RM) was 110 in TX1241 and 108 in 34N84. These hybrids were selected to reach maturity early in November when sown in late May to early June in the northern Tohoku area.

Conventional tillage was RT to a depth of 12–15 cm by a 2.4 m-wide rotary tiller (LXR2408, Matsuyama Plow Mfg. Co., Ltd., Nagano, Japan) with a 85 horsepower tractor. Previous cropping was transplanted rice with puddling. RT was conducted with an all-in-one operation for seeding maize in a no-tillage field where rice stubble remained. Plowing tillage (PT) was conducted to a depth of 15 cm by a 2.5 m-wide chisel plow (HS250, Kongskilde Agriculture, Albertslund, Denmark) and harrowing was to a depth of 5 cm by a 3.0 m-wide power harrow (KE3000, Amazone Ltd., Hasbergen, Germany) with a 152 horsepower tractor. Previous cropping was direct seeded rice without puddling. The chisel plow was used as the means of plowing and the width of chisel was 50 cm. A total of five chisels were used, and all chisels were arranged in a staggered shape. There were no other parts within the operating width of the chisel plow without tillage; therefore, all fields were tilled entirely by chisel plowing. The experimental fields were different in 2016 and 2017 due to crop rotation.

Maize seeds were sown at a rate of 63,000 seeds ha^{-1} on 31 May 2016 and 78,000 seeds ha^{-1} on 30 May 2017 with 75 cm row spacing. Seeding was conducted with a seeder (TDRT, Agritecno Yazaki Co., Ltd., Hyogo, Japan) attached to a rotary tiller in RT, and with a pneumatic seeder (NG plus 4, Monosem, Largeasse, France) in PT. The operating width of both seeders was 3.0 m. Basal dressing of N, P_2O_5, and K_2O at rates of 150, 200, and 150 kg ha^{-1}, respectively, was applied as a blended fertilizer (N:P_2O_5:K_2O = 15:20:15), and cow manure (2016, Total N:P_2O_5:K_2O = 2.2:2.3:2.1 DM%; 2017, Total N:P_2O_5:K_2O = 2.7:2.1:4.0 DM%) was applied at a rate of 10 t ha^{-1}. Weed and pest management followed conventional practices. Meteorological data were 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 calculated from 1981 to 2010. The normal values for duration of sunshine were calculated from 1997 to 2010.

Soil properties and crop growth traits were measured at three locations in each field (hereafter, plots). 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. Soil pulverization rate was calculated as the proportion by weight of clod (< 1.9 mm) after taking three samples from a depth of 5 cm at each field. The sampling of soil pulverization rate was done before seeding.

Plant height and leaf color were measured for five contiguous plants in three plots 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 (SPAD502 Plus, Konica Minolta Inc., Tokyo, Japan), and at top ear leaves at 76 days after seeding (DAS).

Aboveground dry matter was measured approximately 3 wk before silking (49 DAS in 2016; 42 DAS in 2017), 2 wk after silking (85 DAS in 2016; 83 DAS in

2017), and at maturity stage (140 DAS in 2016; 147 DAS in 2017) by taking samples of five plants from three plots in each field. The samples were separated into stems, leaves and ears (when visible). Dry matter was measured after drying in an oven for 48 hr at 80°C. For one plant per plot, the leaves were separated from whole plants, and the leaf area was determined with a leaf area meter (LI3100C, Li-cor Inc., Lincoln, NE, USA) at 3 wk before silking and 2 wk after silking. Specific leaf area (SLA) was calculated from the leaf area and dry matter, and leaf area of other plants was calculated as the product of leaf dry weight and SLA. We calculated the crop growth rate (CGR) for the period between 3 wk before silking and 2 wk after silking (hereafter, bracketing silking period) by dividing the increase in dry matter by the number of days during the bracketing silking period.

At harvest, samples were obtained from a 3 m^2 area in each of three plots. After measuring ear length, the ears were polished, and the kernel number, 100 grain weight and grain yield were measured. Grain moisture was measured with a moisture meter (PM650, Kett Electric Laboratory, Tokyo, Japan) and grain yield was calculated as 15% moisture content.

In 2017, root lodging and stalk lodging occurred due to typhoons on 18 September and on 23 October. Root lodging and stalk lodging per unit area of yield survey was determined at 147 DAS. Plants inclining over 30° toward ground level were regarded as showing root lodging, and plants showing lodging under a node, including just above the node bearing the uppermost ear, were regarded as showing stalk lodging (Yoshimura, 2004). Plants regarded as showing both root lodging and stalk lodging were categorized as showing stalk lodging (Yoshimura, 2004).

Five soil sub-samples in each plot were obtained from topsoil before application of basal dressing. The sub-samples in each plot were mixed and the following chemical properties were analyzed: pH (H_2O) (glass electrode), available phosphorus (P-a, Truog method), exchangeable potassium (K-e, Schollenberger and Simon method), hot water extractable nitrogen (N-h, autoclave method), nitrate nitrogen (N-n, hydrazine reduction method), and ammonium nitrogen (N-a, indophenol method) according to the Hokkaido Research Organization, Agricultural Research Department (2012).

To evaluate feed composition, starch and crude protein (CP) were measured by conventional methods (Enishi, 2009). Contamination by the following mycotoxins was measured by an LC/MS/MS method: deoxynivalenol (DON), nivalenol (NIV), zearalenone (ZEA), and fumonisin B_1, B_2, and B_3 (FUM). The samples for determination of feed composition were obtained from three plots in each field. Three sub-samples for determination of mycotoxin contamination in each field were mixed well and then analyzed.

2.2. Experiment 2 in Gleysol (Hanamaki, Iwate)

A field experiment was conducted in 2017 at upland fields converted from paddy fields (Gleysol) of a farmer in Hanamaki, Iwate, Japan (141°10′E, 39°28′N). Experimental fields were 0.6 ha for each tillage treatment, RT and PT. RT was conducted to a depth of 12–13 cm three times: twice before seeding by a 2.4 m-wide rotary tiller (LXR2408, Matsuyama Plow Mfg. Co., Ltd., Nagano, Japan) with a 55 horsepower tractor, and once when seeding by the same rotary (LXR2408, Matsuyama Plow Mfg. Co., Ltd., Nagano, Japan) attached to an 88 horsepower tractor. A 2.5 m-wide chisel plow (SC8PYL, Sugano Farm Machinery Mfg., Co., Ltd., Ibaraki, Japan) was used for soil incorporation because it was necessary to deodorize as soon as possible after application of pig manure. PT was conducted to a depth of 15 cm by the same chisel plow and harrowing was to a depth of 5 cm by a 3.0 m-wide power harrow (HRB302D, Kuhn S.A., Saverne, France) with an 88 horsepower tractor. The width of the chisel was 31 cm. A total of eight chisels were used, and all chisels were arranged in a staggered shape. There were no other parts within the operating width of chisel plowing without tillage; therefore, all fields were tilled entirely by chisel plowing.

Maize seeds were sown at a rate of 75,000 seeds ha^{-1} on 29 May 2017 with 75 cm row spacing in RT and 70 cm row spacing in PT. Seeding was conducted with the same seeders used in Experiment 1. Basal dressing of N, P_2O_5, and K_2O at rates of 112, 112, and 112 kg ha^{-1}, respectively, was applied with compound fertilizer (N:P_2O_5:K_2O = 14:14:14), and pig manure (Total N:P_2O_5:K_2O = 3.1:5.7:1.6 DM%) was applied at 20 t ha^{-1}. The following drainage measures were conducted: subsoiler on 21 November 2016 and open ditch drainage of marginal zone of fields on 22 May 2017. Weed and pest management followed conventional practices. Meteorological data were obtained from the weather station at the Shiwa Meteorological Observatory of the Japan Meteorological Agency.

Penetration resistance was measured with a cone penetrometer (DIK-5532, Daiki Rika Kogyo Co., Ltd., Saitama, Japan) at three locations randomly selected from the whole plot on 30 May 2017. Analysis of soil chemical properties, soil pulverization rate, plant growth (plant height, SPAD value), plant samples (3 wk before silking; 45 DAS, 2 wk after silking; 75 DAS), yield survey, root lodging survey, feed composition, and mycotoxin contamination survey were conducted with the same methods as Experiment 1. At harvest, samples were obtained from three plots with 3 m^2 in RT 130 DAS and 2.8 m^2 in PT 142 DAS.

2.3. Statistical analysis

A pairwise t-test was conducted to test the difference in crop traits between RT and PT. Three pairs across two sites (two in Morioka and one in Hanamaki) were provided for the test. The t-test was carried out using analysis software (JMP 11.2.0, SAS Institute Inc., Cary, NC, USA). Percentage data were analyzed after angular transformation.

3. Results

3.1. Meteorological conditions, soil chemical properties, soil penetration resistance, and operating efficiency

Figure 1 shows meteorological data for 2016 and 2017 during experiments in Morioka. In 2016, daily mean temperature was similar to normal until the late part of July and was higher after the middle of July; duration of sunshine was shorter than normal from the middle of June to the early part of July, and longer than normal from the middle of July to the early part of September; precipitation was higher than normal from the middle of June to the early part of July, from the middle of August to the early part of September, and in the early part of October. In 2017, daily mean temperature was 1.1–3.9°C higher than normal from the late part of June to the middle of July, and was 0.6–2.2°C lower than normal from the early part of August to the early part of September; the duration of sunshine was longer than normal from the middle of June to the middle of July, and shorter than normal in August; precipitation was higher than normal in the late part of July, in August, and in the middle of September.

Figure 2 shows meteorological data for 2017 in Shiwa for Hanamaki. Daily mean temperature was higher than normal from the late part of June to the middle of July, and similar to normal after the late part of July. Duration of sunshine was longer than normal from the middle of June to the middle of July, and shorter than normal from the late part of July to the late part of August. Precipitation was higher than normal in the late part of July, in August, and in the middle of September.

Table 1 shows soil chemical properties before cropping. In Morioka and Hanamaki, pH, P-a, K-e, N-h, N-n,

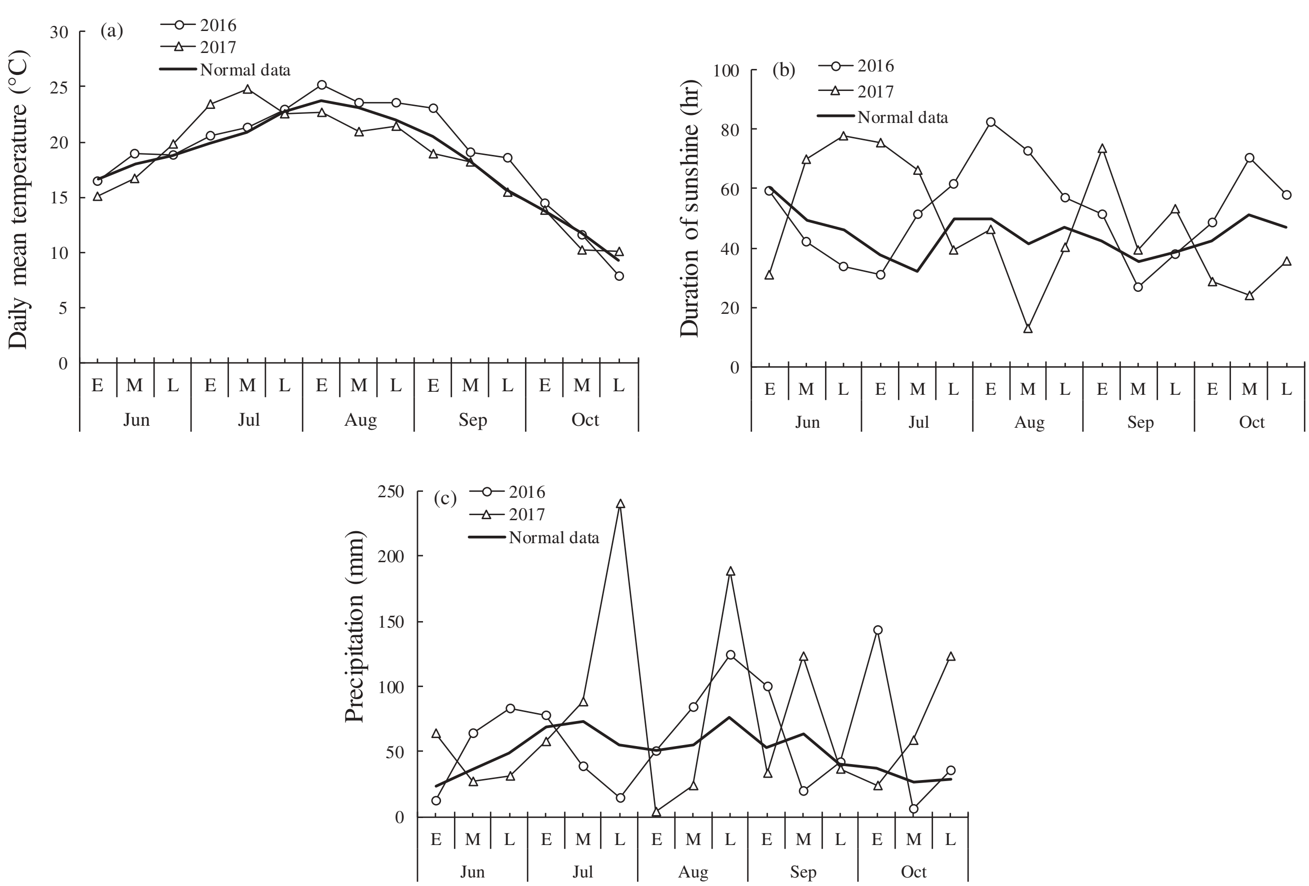

Figure 1. Changes in daily mean temperature (a), duration of sunshine (b), and precipitation (c) during the growing season (Morioka, Iwate).

Notes: E: Early part of the month; M: Middle of the month; L: Late part of the month.

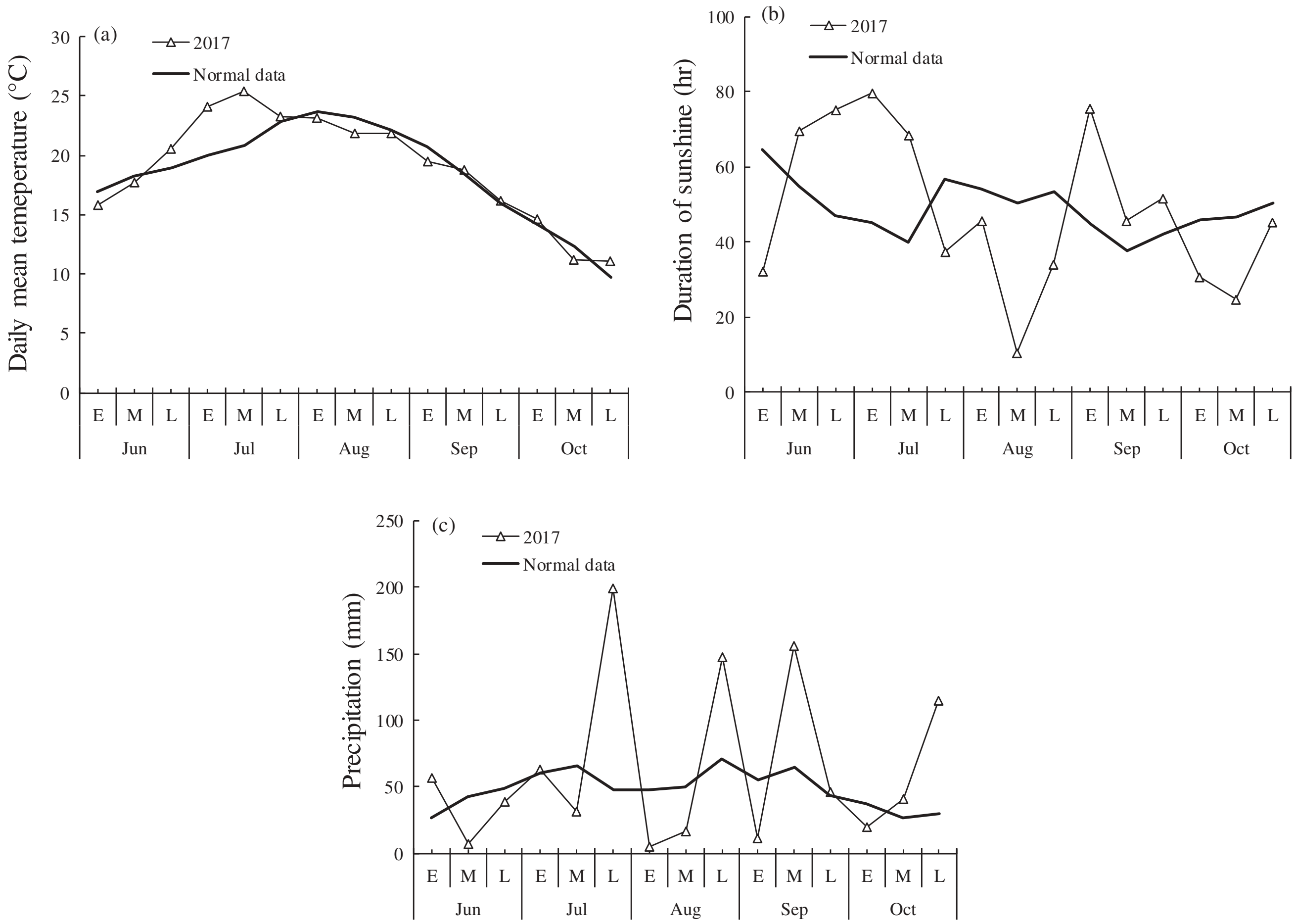

Figure 2. Changes in daily mean temperature(a), duration of sunshine (b), and precipitation (c) during the growing season (Shiwa, Iwate).

Notes: E: Early part of the month; M: Middle of the month; L: Late part of the month.

Table 1. Soil chemical properties before cropping.

Year	Location	Tillage	pH	P-a[a] (mg 100 g^{-1})	K-e[b] (mg 100 g^{-1})	N-h[c] (mg 100 g^{-1})	N-n[d] (mg 100 g^{-1})	N-a[e] (mg 100 g^{-1})
2016	Morioka	RT	6.4	3.2	20.6	6.0	0.5	1.2
		PT	6.3	3.0	20.5	5.7	0.2	1.6
2017	Morioka	RT	6.3	1.8	14.5	7.6	0.4	3.1
		PT	6.4	2.1	15.6	7.8	0.3	2.2
	Hanamaki	RT	5.5	19.6	19.4	6.4	0.3	1.0
		PT	5.6	15.7	19.6	7.1	0.4	1.1

Notes: [a]Available phosphorus, [b]exchangeable potassium, [c]hot water-extractable nitrogen, [d]nitrate nitrogen, [e]ammonium nitrogen.
RT: Rotary tilling; PT: Plowing tillage.

and N-a were not greatly different between the tillage treatments.

Figure 3 shows soil penetration resistance. Soil penetration resistance in Morioka and Hanamaki was 0.1–0.2 MPa in RT up to a 13-cm depth, whereas it rapidly increased from 5–20 cm in PT, to more than 0.6 MPa.

Table 2 shows soil pulverization rate. In Morioka, the soil pulverization rate was higher in PT than in RT by 14–16 points in both years. In Hanamaki, the soil pulverization rate was not significantly different between the tillage treatments.

The operating efficiency of tillage in Hanamaki was 13.0 hr ha^{-1} in RT and 5.1 hr ha^{-1} in PT. The operating efficiency of seeding was 3.4 hr ha^{-1} in RT and 1.5 hr ha^{-1} in PT.

3.2. *Plant growth and grain yield*

Table 2 shows the rate of seedling establishment and days to silking stage. The number and the percentage of seedlings established were not significantly different

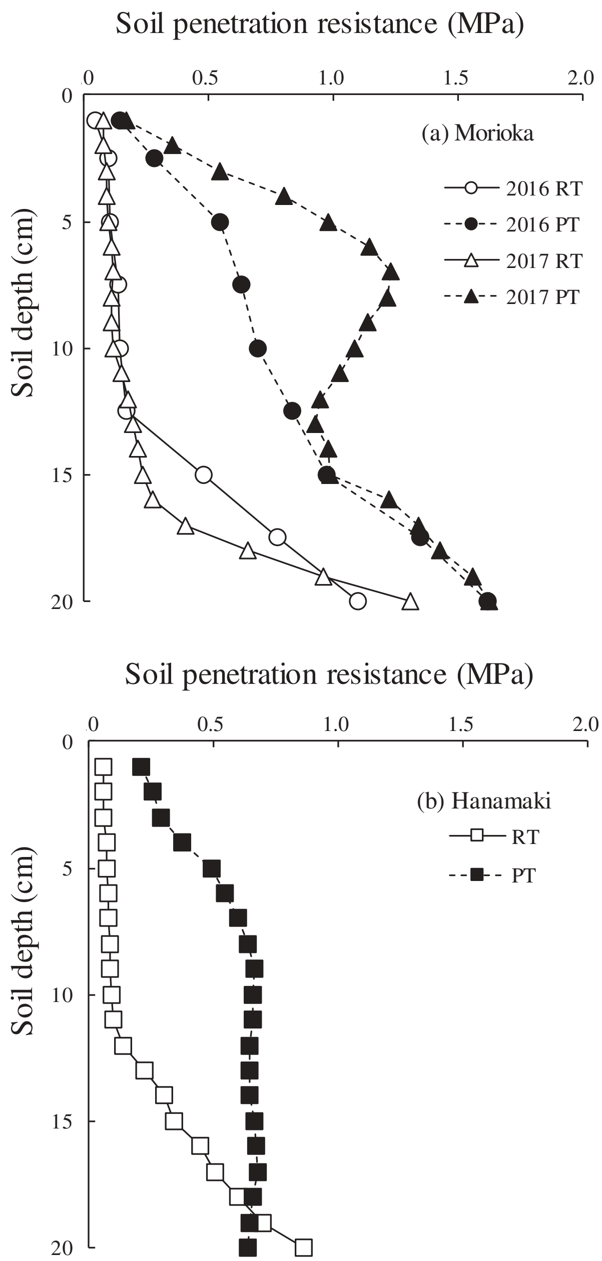

Figure 3. Soil penetration resistance in Morioka, Iwate (a) and Hanamaki, Iwate (b).

Notes: RT: Rotary tilling; PT: Plowing tillage.

between the tillage treatments. Silking stage was reached 2 days earlier in PT than in RT, although the difference was not significant ($P = 0.074$).

Figure 4 shows growth and chlorophyll measurements. Plant height was significantly taller in PT than in RT at 29–30 and 38–40 DAS ($P < 0.01$ and 0.05, respectively), but was not significantly different at other stages. Means of tillage did not have any significant effect on SPAD value.

Table 3 shows growth analysis during bracketing silking. CGR, net assimilation rate (NAR), and mean leaf area index (LAI) were not significantly different between the tillage treatments.

Table 2. Soil pulverization rate, seedling establishment rate, and time to silking stage.

Year	Location	Tillage	Soil pulverization rate (%)	Seedling establishment: Number of plants (plants m^{-2})	Rate (%)	Silking stage (DAS[a])
2016	Morioka	RT	68	5.9	82	71
		PT	84	6.1	93	68
2017	Morioka	RT	65	6.6	90	69
		PT	79	7.1	95	68
	Hanamaki	RT	76	6.3	92	63
		PT	79	6.2	85	61
	Average	RT	70	6.2	88	70
		PT	81	6.3	91	68
		t-test	ns	ns	ns	ns

Notes: *Significant at the 0.05 probability level. ns, nonsignificant at the 0.05 probability level. *t*-test of soil pulverization and seedling establishment rate was conducted after angular transformation.
[a]Days after sowing.
RT: Rotary tilling; PT: Plowing tillage.

Table 4 shows agronomical traits at harvest. Aboveground dry matter in PT at harvest was significantly greater than in RT. Grain yield and yield components were not significantly different between the tillage treatments. Grain yield of Morioka was 14% lower in 2017 than in 2016. The incidence of root lodging tended to be higher in RT than in PT, although stalk lodging tended to be higher in PT than in RT at both locations.

3.3. Feed components and mycotoxin accumulation

Table 5 shows feed components and mycotoxin accumulation. CP was significantly lower in PT than in RT ($P < 0.05$). Starch content, DON, NIV, ZEA, and FUM content did not differ significantly between the tillage treatments at either location. FUM in 2017 was higher in RT than in PT.

4. Discussion

The climatic conditions during the early growth stage from the early part of June to the late part of July (seeding-silking) and in August (silking-milk stage) in 2016 were different from those in 2017. During early growth, daily mean temperature and duration of sunshine in 2016 were similar to normal, whereas they were higher than normal in 2017 (Figure 1). From silking to the milk stage, which is the critical period for kernel set (Cirilo & Andrade, 1994; Jones, Schreiber, & Roessler, 1996), climate conditions were better for maize growth in 2016 than in 2017; daily mean temperature was higher and duration of sunshine was longer than normal in 2016, but inferior to normal in 2017.

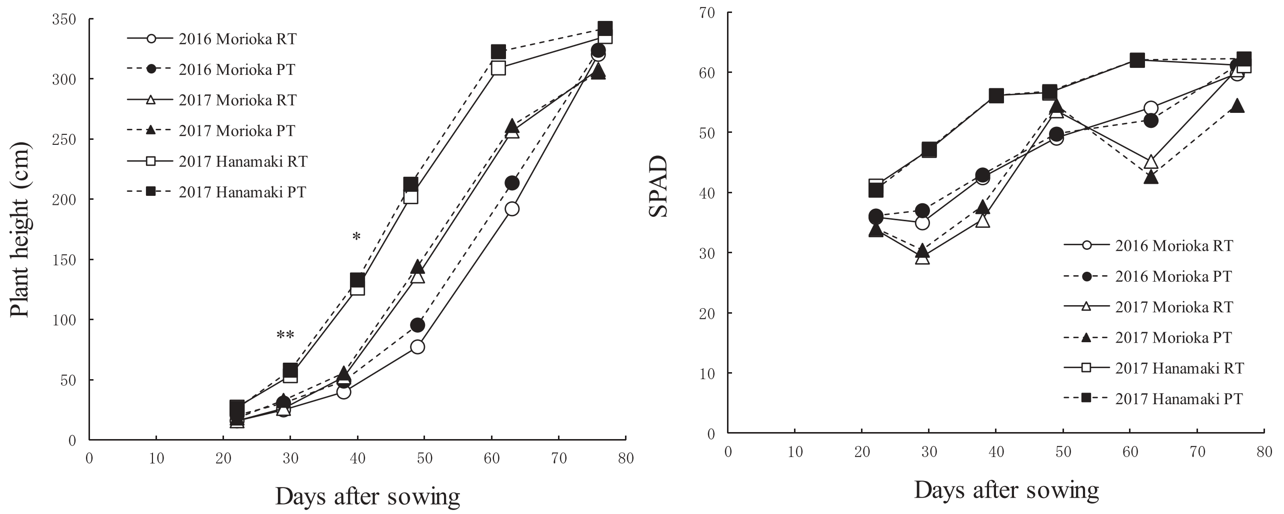

Figure 4. Changes in plant height and SPAD value.

Notes: **significant at the 0.01 probability level at tillage treatment; *significant at the 0.05 probability level between tillage systems.RT: Rotary tilling; PT: Plowing tillage.

Table 3. Crop growth rate (CGR), net assimilation rate (NAR), and mean leaf area index (LAI) during bracketing silking period.

Year	Location	Tillage	CGR (g m^{-2} d^{-1})	NAR (g m^{-2} d^{-1})	LAI (m^2 m^{-2})
2016	Morioka	RT	28.6	10.3	2.8
		PT	32.0	9.5	3.4
2017	Morioka	RT	31.0	6.5	4.7
		PT	36.5	7.3	5.0
	Hanamaki	RT	31.6	6.4	5.0
		PT	29.8	5.9	5.0
	Average	RT	30.4	7.8	4.2
		PT	32.7	7.6	4.4
		t-test	ns	ns	ns

Notes: ns, nonsignificant at the 0.05 probability level.
RT: Rotary tilling; PT: Plowing tillage.

Table 4. Aboveground dry weight at maturity, grain yield, and yield components.

Year	Location	Tillage	Dry weight (g m^{-2})	Ear length (cm)	Kernel number (m^{-2})	100 grain weight (g)	Grain yield (g m^{-2})	Root lodging (%)	Stalk lodging (%)
2016	Morioka	RT	2025	18	3172	30.4	966	–	–
		PT	2172	17	3616	29.6	1071	–	–
2017	Morioka	RT	2003	15	3412	26.5	909	59	6
		PT	2073	15	3060	27.4	842	19	20
	Hanamaki	RT	2302	19	3500	32.3	1124	98	0
		PT	2409	18	3288	35.7	1170	12	11
	Average	RT	2110	17	3361	29.8	1000	79	3
		PT	2218	17	3321	30.9	1028	15	15
		t-test	*	ns	ns	ns	ns	ns	ns

Notes: *Significant at the 0.05 probability level. ns, nonsignificant at the 0.05 probability level.
RT: Rotary tilling; PT: Plowing tillage.

Therefore, this study was conducted in two years under different climate conditions. Furthermore, the normal daily mean temperature during the growth stage was similar between Morioka and Shiwa for Hanamaki (Figures 1 and 2). However, the normal duration of sunshine was longer in Shiwa for Hanamaki than in Morioka, and the normal precipitation was slightly higher in Morioka than Shiwa for Hanamaki (Figures 1 and 2). In particular, the duration of sunshine during August, which is the silking to milk stage, was 15% longer in Shiwa for Hanamaki than in Morioka. Therefore, the climatic conditions were better in Shiwa for Hanamaki than Morioka. This was thought to be one of the reasons that grain yield was higher in Hanamaki than in Morioka. There was no great locational difference in soil

Table 5. Starch, CP, and mycotoxin contamination.

Year	Location	Tillage	Starch (DM[f]%)	CP[a] (DM[f]%)	DON[b] (ppm)	NIV[c] (ppm)	ZEA[d] (ppm)	FUM[e] (ppm)
2016	Morioka	RT	69	9.0	0.8	n.d.[g]	0.63	1.74
		PT	69	8.7	0.2	n.d.[g]	0.01	2.42
2017	Morioka	RT	67	7.9	1.6	n.d.[g]	0.09	11.54
		PT	68	7.7	2.5	0.1	0.08	6.42
	Hanamaki	RT	67	9.6	1.8	0.6	0.41	15.90
		PT	67	9.0	1.3	0.5	0.11	8.30
	Average	RT	68	8.9	1.4	n.d.[g]	0.38	9.7
		PT	68	8.4	1.3	0.3	0.07	5.7
		t-test	ns	*	ns	-	ns	ns

Notes: *Significant at the 0.05 probability level. ns, nonsignificant at the 0.05 probability level. *t*-test of starch and crude protein was conducted after angular transformation.
[a]Crude protein, [b]deoxynivalenol, [c]nivalenol, [d]zearalenone, [e]fumonisin, [f]dry matter, [g]not detected.
RT: Rotary tilling; PT: Plowing tillage.

chemical properties before cropping except for phosphorus, and soil chemical properties were similar between the tillage treatments (Table 1).

As previous reports (Shinoto et al., 2017, Shinoto, Matsunami, Otani, Kanmuri, & Maruyama, 2018) indicated, soil penetration resistance increased at depths greater than 5 cm in PT, but was low and stable from 1 to 13 cm in RT (Figure 3). The soil penetration pattern was similar in Morioka and Hanamaki despite the different soil types. These results showed that soil penetration resistance for PT was higher at depths greater than 5 cm regardless of soil type. Harada, Kobayashi, Miyazono, Takenouchi, and Kuwamizu (2009) suggested that root anchorage is improved in no-tillage over RT after plowing because roots in no-tillage are elongated in the soil surface, which has high soil penetration resistance. Inoue, Ito., and Saigusa (2000) also showed that root lodging resistance was higher in no-tillage than in RT. Therefore, root lodging was alleviated in PT in 2017 probably because the higher penetration resistance at 5–20 cm depth in PT affected root distribution and improved root lodging resistance.

Soil pulverization rate tended to be higher in PT than in RT (Table 2). In PT, a power harrow was used after chisel plowing. Therefore, pulverization by a power harrow after chisel plowing in upland fields converted from non-puddling paddy fields might be same or better than RT. Otani, Nishizaki, and Shibata (1996) and Ota, Masuya, Murakami, Fujii, and Kobayashi (2001) showed that soil pulverization was higher in paddy fields with non-puddling than with puddling. Our results do not allow fair comparisons between the tillage methods used because the number of tillage operations differed between treatments. However, they did indicate that the soil pulverization rate after direct seeding of rice using plowing and compaction was higher than with RT after transplanting rice with puddling.

There was no significant difference in seedling establishment, which was more than 85% regardless of treatment or location, or in plant growth between the tillage treatments (Table 2). Except for plant height at 29–40 DAS, neither plant height nor SPAD value was significantly different between treatments (Figure 4). CGR during bracketing silking, which is closely related to the kernel number of maize (Andrade, Echarte, Rizzalli, Maggiora, & Casanovas, 2002, Andrade et al., 1999), was not significantly different between treatments either (Table 3). These observations all indicated that plant growth did not differ between RT and PT aside from the silking stage being reached two days earlier in PT than in RT (Table 2). Shinoto et al. (2017) also reported that silking was earlier in PT than in RT, suggesting that the mechanism of early silking in PT should be investigated.

Aboveground dry matter at maturity was consistently larger in PT than in RT across sites and years ($P < 0.05$, Table 4). The advantage of PT over RT for biomass did not translate to grain yield, suggesting that grain yield of maize with the plowing system is comparable to that with the RT system. Feed quality was also not different between PT and RT except CP, which was lower in PT than in RT by 0.5 points (Table 5). The reason for the difference in CP is not clear, but CP in PT averaged 8.4% (Table 5), which was similar to that of imported American grains, which averaged 8.4% in 2014–2016 (U.S. Grains Council, 2017). Therefore, even if CP in PT is lower than in RT, feed quality can be secured in comparison to that of grains imported from the United States.

Starch content was not different between PT and RT (Table 5), but was slightly lower than that of grains imported from the United States, which averaged 73% in 2014–2016 (U.S. Grains Council, 2017). Nakatsu et al. (2015) reported that starch of grains grown in Hokkaido located in Japan was about 65%. These reported differences in starch content between Japanese and American grains might be due to a different means of analysis, suggesting the need to analyze grains using the same method. Although there was little difference in mycotoxin accumulation between treatments, the FUM content in 2017 was higher in RT than in PT (Table 5). Kernels infected by FUM appear 4–5 weeks after pollination, at the milk stage of kernel development (Bush, Carson, Cubeta, Hagler, & Payne, 2004), and fusarium ear rot is most severe when hot weather occurs at and after flowering (Payne, 1999). Thus, the FUM content could have been higher in RT because ears were exposed to high temperatures due to flattened crops on the soil surface by root lodging 6–7 weeks after pollination. However, FUM, which was 12–16 ppm in 2017, was lower than the cap of 30 ppm for levels in human food and animal feed in the United States (United States Food and Drug Administration, 2001). Although PT may alleviate the risk of FUM contamination by decreasing root lodging, the relationship between FUM content of grains and root lodging must be clarified.

PT had an apparent advantage over RT in terms of work efficiency. In this study, we found that plant growth, grain yield or quality of maize grown in two different soil types was not different between use of a rotary tilling system after puddling cultivation of rice and use of a plowing system after direct seeding of rice with plowing and compaction. We therefore conclude that the plowing system can improve work efficiency without decreasing grain yield or quality of maize, and can be a useful option for large-scale farm management involving maize cultivation in the paddy rotation system.

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Disclosure statement

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