Analysis of the shallow root system of maize grown by plowing upland fields converted from paddy fields: effects of soil hardness and fertilization

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\section*{ABSTRACT}
The root system of maize tends to be shallower with plowing tillage than with rotary tilling in upland fields converted from paddy fields. Soil hardness and fertilizer distribution differ between plowing tillage and rotary tilling; thus, we investigated the maize root system at different growth stages with or without fertilizer application in both of these tillage methods. We evaluated the effect of soil hardness on the root system by comparing plowing tillage and rotary tilling in unfertilized plots, and the effect of fertilization by comparing responses to fertilizer application with plowing tillage and rotary tilling since the effects of tillage and fertilization cannot be separated in each tillage method. Root depth index (RDI), which indicates average root depth, was about 20\% smaller with plowing tillage than with rotary tilling after the 7th leaf growth stage (V7) in unfertilized plots. Although RDI in fertilized plots was similar or slightly smaller than that in unfertilized plots, the interaction between fertilization and tillage was not significant, except at the tassel formation stage in 2016. Analysis of root distribution indicated that root length density at soil depths of 0–5 cm tended to be higher with plowing tillage than with rotary tillage after V7, but the effect of the interaction between fertilization and tillage was not significant. These results suggest that the root system of maize becomes shallower after V7 with plowing tillage than with rotary tillage mainly due to higher soil penetration resistance in upland fields converted from paddy fields.

\section*{1. Introduction}
While rotary tilling is widely used as conventional tillage in paddy fields in Japan, plowing tillage was recently introduced as an alternative. Rotary tilling can be used for tillage and harrowing at the same time and can also be used for puddling (Goto, 1997). Therefore, it was the main tillage method in Japan after the 1960s. Although the number of farmers is decreasing in Japan, the number of farms larger than 100 ha in prefectures other than Hokkaido increased by 34.8\% from 2010 to 2015 according to a 2015 census of agriculture and forestry (Ministry of Agriculture, Forestry and Fisheries, 2017). Large-scale farms require a faster tillage method. The speed of plowing tillage is about 5–8 km h\textsuperscript{-1}, whereas that of rotary tilling is about 2–3 km h\textsuperscript{-1}. Shinoto et al. (2019b) reported that the operating efficiency of tillage in a farmer’s fields was higher with plowing tillage (5.1 hr ha\textsuperscript{-1}) than with rotary tillage (13.0 hr ha\textsuperscript{-1}). In Japanese paddy fields, cultivation of rice, soybean and maize with plowing tillage is spreading (Matsunami et al., 2017; Otani et al., 2013; Shinoto et al., 2019b).

In upland fields converted from paddy fields, growth, grain yield, and nitrogen absorption of maize are not significantly different between rotary tilling and plowing tillage; however, the root system of maize does differ between plowing tillage and rotary tilling (Shinoto et al., 2018a, 2017, 2018b). The root system at maturity or at the milk stage tends to be shallower with plowing tillage than with rotary tilling.
than with rotary tilling (Shinoto et al., 2019a, 2018a). Others have also reported that the root system of maize becomes shallower in untilled or shallowly cultivated soils because the root length in the surface layers is longer (Ball-Coelho et al., 1998; Barber, 1971; Bauder et al., 1985). However, these reports focused on later growth stages and there have been few studies investigating the growth stage of changing root systems of maize due to tillage treatments.

A previous report (Shinoto et al., 2018b) indicated the differences of soil hardness and fertilizer distribution between rotary tilling and plowing tillage. Soil penetration resistance is higher at soil depths of 5–20 cm with plowing tillage than with rotary tilling. In addition, 95% of fertilizer distributes at soil depths of 0–10 cm with plowing tillage, while fertilizer distribution is uniform at 0–20 cm depths with rotary tilling. The root system of maize becomes shallower when soil bulk density and soil hardness are higher in the surface layers (Ball-Coelho et al., 1998; Pidgeon & Soane, 1977). Furthermore, the root length of maize increases in the fertilized soil zone (Anderson, 1987; Duncan & Ohlrogge, 1958; Kaspar et al., 1991). Both soil hardness and fertilizer distribution could be the reason for the shallower root system of maize grown with plowing tillage. There are few studies, however, investigating whether soil hardness or fertilization affects the depths of root systems of maize in different tillage methods.

The objectives of this study were to investigate the development of the root system of maize with plowing tillage and rotary tilling, to identify the growth stages when the root system of maize becomes shallower with plowing tillage than with rotary tilling, and to clarify whether soil hardness or fertilization affects the shallower root system of maize grown with plowing tillage. We evaluated the effect of soil hardness on the root system by comparing plowing tillage and rotary tilling without fertilization and the effect of fertilization by comparing responses to fertilizer application with plowing tillage and rotary tilling, since the effects of soil hardness and fertilization cannot be separated in each tillage method.

2. Materials and methods

2.1. Cultivation and tillage

Field experiments were conducted in 2016 and 2017 in upland fields converted from paddy fields (Andosol) at Tohoku Agricultural Research Center, National Agriculture and Food Research Organization, Morioka, Iwate, Japan (141°08′E, 39°45′N). The previous crop was rice. The rice cultivation methods were transplanting after puddling in 2016 and direct seeding on well-drained paddy fields without puddling in 2017. Maize (Zea mays L.) cv. 34N84 (DuPont Pioneer, Johnson, IA, USA) was selected to reach maturity early in November when sown in early June in the northern Tohoku area for this study.

The experimental design was a strip plot with three blocks. The horizontal treatment plots were an unfertilized plot (U) and a fertilized plot (F). The vertical treatment plots were rotary tilling (RT) and plowing tillage (PT). There were three replications for each treatment. The area of each replication was 304 m² (8 m × 38 m) in 2016 and 184 m² (8 m × 23 m) in 2017. Fertilization treatments consisted of an unfertilized plot and a fertilized plot. In the fertilized plot, a basal dressing of N, P₂O₅, and K₂O at rates of 22, 22, 22 g m⁻², respectively, was applied as a blended fertilizer (N₂P₂O₅·K₂O, O = 15:20:15). Fertilizer was applied using a backpack-type fertilizer spreader on 29 and 30 May, 2016, and 30 May 2017. Conventional tillage was RT to a depth of 20 cm with a rotary tiller (LXR2610, Matsuyama Plow Mfg. Co., Ltd., Nagano, Japan) with 75–80 horsepower tractors (2016: AF880UQZ, Yanmar Co., Ltd., Osaka, Japan; 2017: T750FBCY01, Iseki & Co., Ltd., Ehime, Japan) on 30 May 2016 and on 6 June 2017. PT was conducted to a depth of 20 cm with a chisel plow (MSC6PQLK, Sugano Farm Machinery Mfg., Co., Ltd., Ibaraki, Japan) with 75–85 horsepower tractors (2016: TJ85CF51GQCY, Iseki & Co., Ltd.; 2017: GM75-HPC, Kubota Corporation, Osaka, Japan) on 30 May 2016 and on 31 May 2017. Harrowing was to a depth of 5 cm with a power harrow (BETA230SP; Ortolan Zappatrici S.n.c., Vicenza, Italy) with 75–80 horsepower tractors (2016: T750FBCY01, Iseki & Co., Ltd.; 2017: F880UQZ, Yanmar Co., Ltd.) on 30 May 2016 and on 6 June 2017.

Two to three seeds per hill were seeded on 2 June 2016, and on 6 June 2017, with 75-cm row spacing and 21-cm hill spacing with a seeder (TDR; Agritecno YAZAKI Co., Ltd., Hyogo, Japan). Plants were thinned to one plant per hill 13 days after sowing (DAS). For weed management, herbicides were applied after sowing (Dimethenamid-Linuron) and at the 6th leaf stage (V6) (Topramezone). For pest management, a pesticide was applied just after sowing (Diazinon).

2.2. Measurements

Penetration resistance of soil was measured between hills in seeded rows with a cone penetrometer (DIK5521 or DIK5532, Daiki Rika Kogyo Co., Ltd., Saitama, Japan) at 1 DAS in 2016 and 21 DAS in 2017.

Five soil sub-samples in each plot were obtained from topsoil at V6 (36 DAS in 2016 and 2017). The sub-
samples in each plot were mixed and nitrate nitrogen was analyzed according to Nakatsu et al. (2012).

The maize root system is at its maximum at around the silking stage, based on a previous report (Shinoto et al., 2017); therefore, this study was conducted until the silking stage. One plant was randomly sampled from each replication at the 3rd leaf stage (V3: 2016, 25 DAS; 2017, 27 DAS), V6 (2016, 33 DAS; 2017, 34 DAS), the 7th leaf stage (V7: 2016, 43 DAS; 2017, 44 DAS), tassel formation stage (2016, 57 DAS; 2017, 58 DAS) and silking stage (71 DAS in 2016 and 2017), respectively, following the soil sample collection method of Murakami and Izawa (2008). The soil monolith (5 cm (length) × 40 cm (width) × 20 cm (depth)) was sampled, with the width running perpendicular to the row and with a hill at the center. The soil was cut out to depths of 0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, respectively, and stored in chucked vinyl bags at 5°C. The stored soil samples were separated into soil, plant residue and roots following the boiling method (Murakami et al., 1999), and the roots were collected and stored at −25°C until the analysis was performed. Root images were obtained using a scanner (Epson Perfection V700 Photo; Seiko Epson Corporation, Nagano, Japan) with a resolution of 1000 dpi. The root images were analyzed using computer software (WinRHIZO; Regent Instruments Inc., Quebec, Canada). Root dry weight was determined after drying.

Root depth index (RDI) was calculated using the following formula (Oyanagi et al., 1993):

$$RDI \ (cm) = \Sigma \{ (\text{Median depth of the layer, cm}) \times \ (\text{Percentage of root length contained in the layer, %}) \}.$$  

Aboveground dry matter was measured using the same plants as for root measurements. Dry matter was measured after drying in an oven for 48 h at 80°C.

2.3. 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). Percentage data were analyzed after angular transformation.

3. Results

3.1. Soil penetration resistance and nitrate nitrogen at V6

Figure 1 shows soil penetration resistance at different soil depths in 2016 and 2017. Soil penetration resistance was 0.1–0.3 MPa in RT, whereas it rapidly increased from 5–20 cm in 2016 and 8–20 cm in 2017 in PT, to more than 0.6 MPa.

Figure 2 shows nitrate nitrogen at different soil depth in V6 in 2016 and 2017. The effect of fertilization was significant at all soil depths in 2016 and 2017 except 5–10 cm in 2016. The effect of tillage was significant at soil depths of 0–5 cm in 2016 and 15–20 cm in 2017. The interaction between fertilization and tillage was significant at soil depths of 0–5 cm in 2016 and 15-20 cm in 2017. In F, nitrate nitrogen at soil depths of 0–5 cm was higher or tended to be higher in PT than in RT in 2016 and 2017. In F, nitrate nitrogen at soil depths of 15–20 cm was lower or tended to be lower in PT than in RT in 2016 and 2017.

3.2. Total root length at soil depths of 0-20 cm

Table 1 shows changes in root length at soil depths of 0–20 cm in 2016 and 2017. The effect of fertilization was only significant at 43 DAS in 2016. The effect of tillage and the interactions between fertilization and tillage for total root length were not significant in 2016 and 2017. However, total root length tended to be shorter in PT than in RT from 33 to 71 DAS in 2016, and from 34 to 71 DAS (except 44 DAS) in 2017.

3.3. Aboveground dry weight

Figure 3 shows changes in aboveground dry weight during experiments. The effect of fertilization was significant, except at 33 DAS in 2016; aboveground dry weight was larger in F than in U. The effect of tillage on aboveground dry weight was significant only at 25 and 33 DAS in 2016. The effect of tillage on aboveground dry weight was not significant during the growth stage in 2017. The interactions between fertilization and tillage were not significant during experiments in 2016 and 2017.

3.4. Root length density at different growth stages and root depth index

Figure 4 shows root length density at different growth stages in 2016. The root length density at soil depths of 10–20 cm was lower in U than in F at 33 DAS. The root length density at soil depths of 0–10 cm was lower in U than in F at 43 DAS. The root length density at soil depths of 5–20 cm was lower in PT than in RT at 57 DAS. The interaction between fertilization and tillage was not significant at any growth stages and any soil depths.

Figure 5 shows root length density at different growth stages in 2017. The root length density at soil depths of 10–15 cm was lower in F than in U at 71 DAS. No significant effect of fertilization was, however, found at the other soil depths or growth stages. The
root length density at soil depths of 15–20 cm was lower in PT than in RT at 27, 34 and 71 DAS. In addition, the root length density at soil depths of 10–15 cm was lower in PT than in RT at 34 and 58 DAS. The root length density at soil depths of 10–20 cm tended to be lower in PT than in RT at the other growth stages. In contrast, the root length density at soil depths of 0–5 cm was higher in PT than in RT at 44, 58 and 71 DAS. The interactions between fertilization and tillage at soil depths of 15–20 cm was significant at 27 and 71 DAS, but no significant interaction was found at the other soil depths or at any growth stages.

Figure 6 shows changes in RDI. The effect of fertilization on RDI was significant only at 25 DAS in 2016, and at 58 and 71 DAS in 2017; RDI was smaller in F than in U. The effect of tillage on RDI was significant from 43 to 71 DAS in 2016, and from 34 to 71 DAS in 2017. RDI was smaller in PT than in RT by 11–23% in U and by 15–29% in F from V7 (43–44 DAS) to silking. The interactions between fertilization and tillage for RDI were not significant, except at 57 DAS in 2016.

4. Discussion

Previous reports (Shinoto et al., 2019a, 2018a) indicate that the root system is shallower in PT than in RT under fertilized conditions. Furthermore, soil hardness at soil depths of 5–20 cm is higher in PT than in RT, and a higher proportion of fertilizer is distributed in the surface layer in PT than in RT (Shinoto et al., 2018b). In the present study, maize was grown with or without fertilizer application in PT and RT, and root systems were investigated at different growth stages to examine whether soil
hardness or fertilizer distribution affects shallow root systems in PT.

In the present investigation, the soil penetration resistance below soil depths of 5 cm was higher in PT than RT (Figure 1), and nitrate nitrogen contents at soil depths of 0–5 cm was higher or tended to be higher in PT than in RT under fertilized conditions (Figure 2). Nitrate nitrogen at soil depths of 15–20 cm was lower or tended to be lower in PT than in RT (Figure 2). Although fertilizer distribution was not directly determined in the present investigation, the results suggest that fertilizer was distributed more in the surface and less in the deep soil in PT than RT. These observations confirm the differences in soil hardness and fertilizer distribution between PT and RT in our previous investigations (Shinoto et al., 2018b).

Shinoto et al. (2018b) reported that there is little difference in aboveground dry weight between RT and PT in fertilized plots. Although aboveground dry weight was smaller in U than in F, there was also little difference between PT and RT in U (Figure 3). Similarly, no significant difference was found in total root length density between RT and PT (Table 1). In addition, there was no significant difference in total root length density between U and F, except the V7 (43 DAS) stage in 2016 (Table 1). Aboveground dry weight was larger and total root length density was higher in 2017 than in 2016 (Figure 3, Table 1), probably because nitrogen nutrition was superior in 2017 than in 2016. In preceding cropping, the paddy field was puddled and rice was transplanted in 2016, but rice was direct seeded on well-drained paddy fields without puddling in 2017. Harada et al. (1964) reported that physical pretreatment of soil promotes mineralization of native organic nitrogen. Nitrogen mineralization might be higher with puddling than without puddling and more nitrogen probably remained without puddling than with puddling. In addition, more nitrogen was applied for direct-seeded rice than for transplanted rice. Furthermore, yield was normally about 10% higher with puddling than without puddling in research fields. As a result, higher levels of nitrogen remained in paddy soil in 2017 which was after without puddling than in 2016 which was after puddling (Figure 2). However, the effect of tillage on root systems was similar between 2016 and 2017 despite previous rice cultivation methods (Figures 4–6).

Tillage method affected root distribution in the present investigation. Root length density was higher in PT

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Table 1. Changes in root length density at soil depths of 0–20 cm in 2016 and 2017.

| Year | Fertilization | Tillage | Root length density (cm cm⁻²) |
|------|--------------|---------|------------------------------|
|      |              |         | Days after sowing (2016/2017) |
|      |              |         | 25/ | 33/ | 43/ | 57/ | 71/ |
|      |              |         | 27 | 34 | 44 | 58 | 71 |
| 2016 | U            | RT      | 0.3 | 0.3 | 0.6 | 1.5 | 1.5 |
|      |              | PT      | 0.3 | 0.3 | 0.4 | 1.2 | 1.0 |
|      | F            | RT      | 0.3 | 0.5 | 1.0 | 1.9 | 1.9 |
|      |              | PT      | 0.3 | 0.5 | 1.0 | 1.6 | 1.7 |
|      | ANOVA        | Fertilization | ns | ns | * | ns | ns |
|      |              | Tillage | ns | ns | ns | ns | ns |
|      |              | A × B   | ns | ns | ns | ns | ns |
| 2017 | U            | RT      | 0.3 | 0.7 | 0.9 | 2.4 | 4.4 |
|      |              | PT      | 0.3 | 0.4 | 1.1 | 2.3 | 3.8 |
|      | F            | RT      | 0.3 | 0.6 | 1.1 | 2.6 | 3.4 |
|      |              | PT      | 0.3 | 0.6 | 1.0 | 2.2 | 3.3 |
|      | ANOVA        | Fertilization | ns | ns | ns | ns | ns |
|      |              | Tillage | ns | ns | ns | ns | ns |
|      |              | A × B   | ns | ns | ns | ns | ns |

U: unfertilized plot, F: fertilized plot, RT: rotary tilling, PT: plowing tillage.

Growth stages (2016/2017): V3: 25/27 days after sowing (DAS), V6: 33/34 DAS, V7: 43/44 DAS, tassel formation stage: 57/58 DAS, silking stage: 71/71 DAS. * Significant at the 0.05 probability level.

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Figure 3. Changes in aboveground dry weight during experiments in 2016 (a) and 2017 (b). Vertical bars indicate standard error. U: unfertilized plot, F: fertilized plot, RT: rotary tilling, PT: plowing tillage. Growth stages (2016/2017): V3: 25/27 DAS, V6: 33/34 DAS, V7: 43/44 DAS, tassel formation stage: 57/58 DAS, silking stage: 71/71 DAS. †, *, ** Significant at the 0.1, 0.05, and 0.01 probability levels, respectively.
than RT at soil depths of 0–5 cm from V7 (44 DAS) to the silking stage (71 DAS) in 2017 (Figure 5), and a similar tendency was observed at V7 (43 DAS) and the tassel formation stage (57 DAS) in 2016 (Figure 4). In addition, root length density was lower in PT than in RT at soil depths of 5–20 cm at the tassel formation stage (57 DAS) in 2016 (Figure 4). Furthermore, root length density tended to be lower in PT than in RT at soil depths of 10–20 cm at all growth stages in 2016 and 2017 (Figures 4 and 5). Since the interactions between tillage and fertilization were significant only at soil depths of 15–20 cm at V3 (27 DAS) and at the silking stage (71 DAS) in 2017 (Figure 5), tillage is regarded as having an effect on soil hardness. Among gramineous crops, root penetration of maize into hard soil is weak (Arima & Tanaka, 1988; Tanakamaru et al., 1998), and roots have little ability to reduce their diameter to pass through pores smaller than their own diameter (Goss, 1977;
These results suggest that root elongation below depths of 10 cm in soil tended to be suppressed in PT regardless of growth stage, and enhanced root elongation occurred in the surface layers of soil at V7 and at the tassel formation stage, compared with RT.

Fertilization had limited effects on root distribution. The effect of fertilization on root length density was significant at soil depths of 0–5 cm at V7 (43 DAS) in 2016 (Figure 4). The interaction between fertilization and tillage was not significant at depths of 0–5 cm at all growth stages in 2016 and 2017 (Figures 4 and 5). In particular, the root length density between F and U at soil depths of 0–5 cm did not differ much between RT and PT. However, the interaction between fertilization and tillage was significant at soil depths of 15–20 cm at V3 (27 DAS) and the silking stage (71 DAS) in 2017 (Figure 5). Comparing the root length density of U and F, decreased root length density due to fertilization was smaller in PT than in RT. These results suggest that the difference of fertilizer distribution between PT and RT hardly affects root elongation in the surface layers of soil; however, fertilization in PT maintains root elongation in the deep layers of soil better than in RT.

RDI was smaller in PT than in RT after V7 (43 DAS) in 2016, and after V6 (34 DAS) in 2017 (Figure 6). Ball-Coelho et al. (1998) revealed that maize roots distribute more horizontally with no-tillage than with conventional tillage. An important factor affecting the root system of cereal crops is the direction of growth of individual nodal roots (Nakamoto et al., 1991). The root length density of maize
factor of the shallower root system of maize grown in PT than in RT is higher soil hardness at depths of 5–20 cm. Furthermore, fertilization has a limited role in controlling the depth of the root system.

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