Effects of Subsoiling to the Non-tilled Field of Wheat-Soybean Rotation on the Root System Development, Water Uptake, and Yield

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Abstract: We introduced subsoiling to a field of wheat-soybean rotation where no-tillage practice had been conducted for five years and whose yield tended to decrease or stagnate. By subsoiling a half of each plot just before wheat sowing, treatments of tillage/no-tillage × subsoiling/no-subsoiling were established. Root distribution, shoot growth, water uptake and yield of both crops were examined to elucidate whether the subsoiling improves the productivity such as shoot biomass and yield through the modification of root system development, and how differ the effects of subsoiling between tilled and non-tilled fields. In wheat, roots were less concentrated in surface (0−5 cm) layer in no-tillage, and distributed more in deep (20−25 cm) layer of the soil. Deuterium labeled heavy water analysis revealed that the subsoiling enhanced water uptake from the deep soil layer in the no-tillage field. Both the no-tillage and subsoiling showed positive and significant effect on total biomass and yield. The effect of subsoiling must be related to water supply by deep roots in spring. In soybean no-tillage significantly increased the productivity, but subsoiling did not though distribution of the roots was modified by both practices. Soybean in non-tilled accumulated roots in the surface soil layer, but subsoiling did not significantly modify the root distribution especially in the deep soil layer. Water uptake trend and yield was thus not changed significantly by subsoiling. Subsoiling in the non-tilled field increased rooting depth and showed the possibility of braking yield stagnation in long-term no-tillage cultivation in wheat, but not in soybean.

Key words: Deuterium, Glycine max (L.) Merr., Heavy water, No-tillage, Stable isotope analysis, Subsoiling, Triticum aestivum L., Water source.

The no-tillage practice is nowadays recognized to be effective in the erosion control, which is essential to maintain soil fertility, and has been applied worldwide. The yield of a crop under the no-tillage condition is comparable to, or even higher than that in conventionally-tilled condition (Lal, 1974; Seki et al., 2001). The no-tillage practice does not result in substantially high soil strength to impede root growth with the effect of “biopore” formed by soil organisms and decayed plant roots (Cresswell and Kirkegaard, 1995; Williams and Weil, 2004).

However, if no-tillage continues for more than a few years, yield of the crops may decline year by year due to a deterioration of soil physical and chemical properties of soil. Hussain et al. (1998) reported that the loss of air porosity could fail to maintain macroporosity of soil and result in higher bulk density under continuous no-tillage for a longer time. Moreover, vertical stratification of nutrients in the profile, which is characterized in no-tillage as a consequence of surface-applied fertilizers without incorporation, may also lead to detrimental effects on root growth. Namely, nutrients accumulated near the surface may restrict the root distribution within a shallow soil layer (Holanda et al., 1998). Plants with shallower root systems have a disadvantage for water uptake and sensitive to drought in summer. Further, such plants are vulnerable to lodging. In any case, some solution to avoid root localization is required to maintain yield.

Subsoiling to break up and loosen compacted layer is known to be effective to improve soil physical condition and nutrient availability (Al-Adawi and Reeder, 1996; Diaz-Zorita, 2000). Bauer et al. (2002) reported that subsoiling increased nutrient removal by crops and mitigated the nutrient stratification. Furthermore, Ghosh et al. (2006) mentioned that this practice could improve infiltration and water storage in deep soil layer, and increase rooting depth.

From the year 1999 the authors continued a field experiment of successive no-tillage in wheat (Triticum aestivum L.) - soybean (Glycine max (L.) Merr.) rotation, both of which are expected as alternative crops for paddy rice field in Japan, aiming to elucidate how the different tillage practice affect root system development, shoot growth, water uptake, and yield (Izumi et al., 2004; Iijima et al., 2007). We found that
the continuous no-tillage practice improved the soil condition for root development and resulted in an enhancement of the shoot growth and yield in wheat, and comparable yield was acquired in soybean for three years, i.e., first to sixth cropping season (Izumi et al., 2004). However, through the next two years (the seventh to tenth cropping season) yield of wheat gradually decreased and that of soybean tended to stagnate (not published), and the water uptake from deep soil layer was limited under the no-tillage (Iijima et al., 2007). Therefore, we attempted to introduce subsoiling expecting its effect mentioned above.

In this study, we continued the wheat-soybean rotation under tilled or non-tilled field conditions as the sixth year (11th and 12th cropping season). Further, subsoiling treatment was conducted for a half of each plot just before the 11th cropping, when wheat was sown. Root distribution, shoot growth, water uptake estimated by deuterium labeled water application method, and yield were examined in tilled and non-tilled fields with subsoiling and non-subsoiling treatments. The objective of this study was to elucidate whether the subsoiling improves the crop productivity such as shoot biomass and yield through the modification of root system development, and how differ the effects of subsoiling between tilled and non-tilled fields.

Materials and Methods

Methods of cultivation, sampling and statistical procedure are basically the same as those we previously reported (Izumi et al., 2004; Iijima et al., 2007), hence here we describe an outline.

This study was conducted at the experimental field of the University of Shiga Prefecture, Hikone, Shiga, Japan (N 35°15', E 136°13'). Twelve 5.5 × 3.5 m² plots were prepared and tilled and non-tilled plots each with six replications randomly arranged in 1999. This assignment was maintained in this study. In the tilled plots, rotary tilling was performed twice immediately before sowing. In the non-tilled plots, the soil was undisturbed except for making planting holes. Intertillage was not conducted for both treatments except for scraping soil surface for weeding.

On 5 November 2004, all the twelve plots were duplicated by subsoiling for halves of the plots. Therefore, totally 24 plots, i.e., tillage/no-tiltillage × subsoiling/no-subsoiling ×6 replications set up. Subsoiling was practiced between the two rows of soybean harvested in the previous month. There existed nine interrow spaces with 0.6 m wide in each plot. By two-time passes of a subsoiler (SUGANO MS2A) with two tines 1.2 m apart, four successive interrows were subsoiled at 0.25 m deep on average. The penetration resistance of the field was measured at the center of each plot with a cone penetrometer (DAIKI Co., LTD., DIK-5521) on 13 May and 27 Oct. 2005.

The wheat cultivar, Norin 61, and the soybean cultivar, Tamahomare, both of which are the recommended cultivars of Shiga prefecture, were used for the experiment. Sowing was performed manually with 0.3 m row spacing for wheat (line planting) on 17 November 2004, and in hill sowing with 0.6 m row spacing and 0.2 m hill spacing (two seeds in a hill) for soybean on 22 June 2005. The amount of fertilizer for both crops followed the guideline of the prefecture and all the fertilizers were broadcasted on the soil surface. At the seedling stage, the plants were thinned to approximately 50 plants per 1 m row for wheat and one plant per hill for soybean. Pest management was conducted for soybean on demand, but was not necessary for wheat. The monthly precipitation and average of daily maximum and minimum temperature during the experiment are shown in Fig. 1. No irrigation was conducted for both crops.

The roots were sampled at the ripening stage for wheat and at the late flowering stage (young pod stage) for soybean from each plot (six replications). The soil was taken from two positions for wheat, i.e., on the row and in the middle of the intra-row space, and from four positions for soybean, i.e., just below a plant, between two plants in a row, between two plants in the inter-row space, and in the center of four plants in the inter-row space. Stainless tube named Liner Sampler (DIK-110B, Daiki Rika Kogyo Co., Ltd.) with 0.3 m long and 0.05 m diameter was used. We used this sampler because root penetration deeper than 30 cm was scarcely observed in either crop. The soil cylinder was separated into different depths from the surface as shown in Table 2. The reason for less discrimination in vertical direction in soybean was that the sampling points were twice of...
those in wheat as mentioned above. Soil samples were carefully washed to collect roots. After removing the debris, the roots were stained and arranged on water at a depth of 5 mm in a transparent plastic tray. They were then scanned to convert to a digitized image, and length was determined with the help of NIH Image ver. 1.62 and Root Length ver. 1.34 (Kimura, 1999).

The root length density (RLD) and root weight density (RWD), namely root length and root weight per unit soil volume, and the specific root length (SRL), namely the root length per unit root weight, were calculated. The ratio of roots distributed at each depth through 30-cm soil layer was also estimated. Further, from the RLD of all the soil layers, the root depth index (RDI), which indicates an average rooting depth (Oyanagi et al., 1998), was calculated.

Water uptake analysis was conducted a few days after rainfall when the soil moisture was at the field capacity. One hundred mL of deuterated water (1.0 and 0.5 atom % D₂O for wheat and soybean, respectively) was applied at 5 cm from the plant base just before the sun set. The heavy water application was regarded as the recent rainfall or recently irrigated water. About 15 hr after the application of the deuterated water, xylem sap was collected from the labeled plants and analyzed following the method of Iijima et al. (2005, 2007).

On 9 June and 14 October 2005, wheat and soybean, respectively, were harvested, respectively. For the yield research, from each plot five rows with 1 m long for wheat and 10 plants for soybean were sampled. After oven-drying at 80ºC for 72 hr, the total shoot biomass and the yield were determined. All the data were statistically analyzed by two way ANOVA using an add-in program for Excel (SSRI software). Values of root distribution ratio were subjected to arcsine conversion before analysis of variance.

**Results**

1. Penetration resistance

Because significant interactions of two factors were observed in many cases (data not shown), means of the penetration resistance of the four treatment combinations (tillage × subsoiling) are shown in one way (Fig. 2). During the wheat growth period (left) penetration resistance of top soil layer (up to 15 cm deep) in no-tillage with no-subsoiling plot was larger than the other three treatment combinations. After harvesting soybean (right), the value of subsoiling plot was smaller than that of no-subsoiling plot in each depth under the no-tillage condition as observed about 6 mo before, while such difference was relatively small or not clear under the tilled condition.

2. Root growth and distribution

The average RLD and RWD calculated from the data of all the sampling points, SRL, i.e., the ratio of the former to the latter, and RDI are shown in Table 1. In wheat, RLD in the no-tillage treatment was lower than that in the tillage treatment. Significant interaction by two way ANOVA shown in italic letters means that this effect was only observed under no-subsoiled condition. On RWD, main effect of tillage treatment was also significant (P < 0.1) but was independent of subsoiling treatment. Although no significant effect was found in total, there was a tendency that SRL in tillage plot was larger than in no-tillage plot in upper soil layer (upper to 10 cm), and larger in tillage and subsoiling plot in interrow position (data not shown). No significant effect was found on RDI. In soybean, significant main effect of tillage treatment was found for all the four parameters. However, contrary to wheat, RLD and RWD were higher in no-tillage than in tillage plot. The SRL in no-tillage was significantly larger than that in tillage plot indicating that roots were thinner. RDI in the no-tillage was approximately 2 cm smaller than in the tillage plot, which means that the root system was distributed in a shallow soil layer.

The RLD at different soil depth was summarized in Table 2. In wheat, RLD in the uppermost layer (0–5 cm) of the tillage plot was significantly larger than in no-tillage plot. Significant interaction means that the difference was only evident under no-subsoiled condition as observed in the RLD in a soil layer. In 20–25 cm layer the RLD was significantly larger in the subsoiling plot than in the no-subsoiling plot. In soybean, the RLD in the no-tillage was much larger than that in the tillage plot in 0–5 and 5–10 cm.
layer. Further, in the latter layer significant effect of subsoiling was observed with significant interaction of two factors, indicating that the difference was only evident under no-tillage condition. On the RWD similar and more evident trend was observed than in the RLD in wheat, while it was less clear in soybean (data not shown).

Table 1. Effect of tillage and subsoiling on the root length density (RLD), root weight density (RWD), specific root length (SRL) and root depth index (RDI) of wheat and soybean in 30-cm soil layer.

| Crop   | Treatment | RLD (cm cm$^{-3}$) | RWD (mg cm$^{-3}$) | SRL (m g$^{-1}$) | RDI (cm) |
|--------|-----------|--------------------|--------------------|------------------|----------|
| Wheat  | Tillage   | 5.53               | 0.49               | 115.07           | 8.71     |
|        | No-till.  | 4.94               | 0.41               | 115.88           | 8.91     |
|        | †         | †                  | †                  | ns               | ns       |
|        | Subsoiling| 5.32               | 0.47               | 112.23           | 8.87     |
|        | No-sub.   | 5.15               | 0.43               | 118.71           | 8.75     |
| Soybean| Tillage   | 2.15               | 0.75               | 30.08            | 10.30    |
|        | No-till.  | 3.15               | 0.85               | 38.42            | 8.08     |
|        | †         | †                  | †                  | ns               | ns       |
|        | Subsoiling| 2.77               | 0.77               | 37.29            | 9.42     |
|        | No-sub.   | 2.53               | 0.83               | 31.20            | 8.96     |

Values are shown in averages of each treatment. ns, not significantly different. *** and †; significantly different at P < 0.001 and 0.1 level, respectively. Italic letters mean a significant tillage × subsoiling interaction at P < 0.1 level by two way ANOVA.

Table 2. Effect of tillage and subsoiling on the root length density (cm cm$^{-3}$) of wheat and soybean at different soil depths.

| Crop   | Treatment | Depth in soil layer (cm) |
|--------|-----------|--------------------------|
|        |           | 0–5 | 5–10 | 10–15 | 15–20 | 20–25 | 25–30 |
| Wheat  | Tillage   | 14.66 | 6.44 | 4.83  | 4.63  | 2.15  | 0.49  |
|        | No-till.  | 11.37 | 6.82 | 4.95  | 4.81  | 1.40  | 0.28  |
|        | *         | ns   | ns   | ns    | ns    | ns    | ns    |
|        | Subsoiling| 13.03 | 7.07 | 4.47  | 4.88  | 2.20  | 0.25  |
|        | No-sub.   | 13.00 | 6.19 | 5.31  | 4.56  | 1.34  | 0.52  |
| Soybean| Tillage   | 3.92  | 2.73 | 2.74  | 2.41  | 0.39  |
|        | No-till.  | 8.43  | 4.35 | 2.52  | 0.53  |
|        | ***       | ns   | ns   | ns    | ns    |
|        | Subsoiling| 6.07  | 3.94 | 2.85  | 0.46  |
|        | No-sub.   | 6.27  | 3.14 | 2.41  | 0.46  |

Values are shown in averages of each treatment. ns, not significantly different. ***, **, * and †; significantly different at P < 0.001, 0.01, 0.05 and 0.1 level, respectively. Italic letters mean a significant tillage × subsoiling interaction by two way ANOVA (P < 0.05 level for wheat and P < 0.1 level for soybean).

layer. Further, in the latter layer significant effect of subsoiling was observed with significant interaction of two factors, indicating that the difference was only evident under no-tillage condition. On the RWD similar and more evident trend was observed than in the RLD in wheat, while it was less clear in soybean (data not shown).

Table 3 shows the relative root distribution in length. In wheat, the distribution ratio in the uppermost layer (0–5 cm) of the tillage plot was significantly higher than in no-tillage plot. The opposite trend was observed in the subsequent three layers. In the subsoiling plot the ratio was significantly lower in 10–15 and higher in 20–25 cm layer as compared with that in the no-subsoiling plot. In soybean, the ratio was significantly higher under no-tillage and no-subsoiled condition indicating a localized root growth near the soil surface. Contrary, the ratio was significantly increased by tillage practice in 10–20 cm and by subsoiling in 5–10 cm layer. It is obvious
that the tillage and/or subsoiling treatment affected vertical distribution pattern of roots in both crops. Furthermore, the effect of tillage treatment on the horizontal distribution was also observed. Namely, the ratio of roots existing in inter-row space was significantly higher (P<0.01) in the non-tilled plot (28%) than that in tilled plot (21%), whereas this ratio was significantly lower (P<0.1) in the non-tilled plot (37%) than in the tilled plot (40%) in soybean. The effect of subsoiling on the horizontal distribution was not clear (data not shown).

3. Water uptake

Fig. 3 shows the concentration of deuterium in xylem sap measured at 15 hr after the application of deuterated water to the soil surface. The deuterium concentration indicates the relative dependence of the crops on the recently supplied irrigation water or rainfall. In wheat, no-tillage showed significantly higher values than in tillage by 2 way ANOVA, indicating that the dependence of recently irrigated water is higher in no-tillage. Deuterium concentrations between the subsoiling and no subsoiling was not statistically significant, although the tillage × subsoiling interaction was significant at P<0.05. This indicates that the subsoiling effect was significant only in no-tillage and not in tillage treatments as clearly visible in Fig. 3 In contrast, soybean did not show any significant differences in the deuterium concentration between the tillage and subsoiling treatments or in their interaction. This indicates that water uptake trend was not modified by the treatments.

Table 3. Effects of tillage and subsoiling on the root distribution ratios of wheat and soybean in 30-cm soil layer.

| Crop | Treatment | Depth in soil layer (cm) |
|------|-----------|-------------------------|
|      |           | 0-5 | 5-10 | 10-15 | 15-20 | 20-25 | 25-30 |
| Wheat | Tillage | 0.44 | 0.19 | 0.14 | 0.14 | 0.07 | 0.02 |
|       | No-ill. | 0.39 | 0.23 | 0.17 | 0.17 | 0.04 | 0.01 |
|       |         | ** | * | † | * | ns | ns |
| Subsoiling | 0.41 | 0.22 | 0.14 | 0.15 | 0.07 | 0.01 |
| No-sub. | 0.42 | 0.20 | 0.17 | 0.15 | 0.04 | 0.02 |
|       |         | ns | ns | * | ns | † | ns |
| Soybean | Tillage | 0.31 | 0.21 | 0.43 |       | 0.05 |
|       | No-ill. | 0.45 | 0.23 | 0.27 |       | 0.05 |
|       |         | *** | ns | *** | ns |     |
| Subsoiling | 0.36 | 0.23 | 0.36 |       | 0.05 |
| No-sub. | 0.40 | 0.21 | 0.33 |       | 0.06 |
|       |         | † | * | ns | ns |     |

Values are shown in averages of each treatment. ns, not significantly different. ***, **, * and †; significantly different at P<0.001, 0.01, 0.05 and 0.1 level, respectively. Italic letters mean a significant tillage × subsoiling interaction at P<0.1 level by two way ANOVA.

Fig. 3. Deuterium concentration in xylem sap measured 15 hr after application of deuterated water; 1.0 and 0.5 atom % D2O for wheat and soybean, respectively. Vertical error bars indicate standard error of means (n=3−6). Two way ANOVA evaluation is indicated in the text.

4. Biomass production and yield

The main effects of tillage and subsoiling and their interaction on the total biomass of wheat were significant (Table 4). Biomass in the tillage with subsoiling, tillage with no-subsoiling, no-tillage with subsoiling, and no-tillage with no-subsoiling plots were
784, 750, 958, and 756 g m\(^{-2}\), respectively. This indicates that positive effect was only observed when both the no-tillage and subsoiling were combined. On the wheat yield, significant and independent effects of both no-tillage and subsoiling were observed. In soybean, a significant effect of no-tillage was found only for total biomass and yield. No significant effect of the treatments on harvest index was found (data not shown).

### Discussion

1. **Root growth and productivity**

   **(1) Wheat**

   Merrill et al. (1996) reported greater root length growth and higher yield in spring wheat under no-tillage condition than under conventional tillage. As well as the effect of no-tillage, that of subsoiling or deep tillage on wheat root growth was previously reported. Ishaq et al. (2001) mentioned that the subsoil compaction significantly decreased the nutrient uptake (N, P and K), and also showed the significant and negative correlation of RLD of wheat below 0.15 m at flowering with soil bulk density. Ishaq et al. (2003) described that the higher RLD was obtained by deep tillage and that the RLD positively correlated with nutrient uptake and yield of grain and straw. Holloway and Dexter (1991) and Zhang et al. (2004) also reported the enhancement of wheat root development into deep soil layer by deep tillage.

   Our results showed that both the no-tillage and subsoiling significantly and independently affected the yield of wheat (Table 4). Frederick and Bauer (1996) reported that the deep tillage with no-surface tillage was more effective than that with disc tillage on the yield of winter wheat, although such trend was not recognized in this study. The positive effect of no-tillage had been already observed from the third year of wheat-soybean rotation in the same field (Izumi et al., 2004). In this study, conducted at the sixth year, while the amount of root itself did not significantly differ (Table 2), distribution ratio of roots in the 5–20 cm layer was higher in no-tillage than in the tillage treatment (Table 3). This suggests that a suitable soil physical condition for root growth in this layer was maintained during six years of continuous no-tillage, even though it was not reflected in the penetration resistance, especially in the no-tillage with no-subsoiling plot (Fig. 2-left). Moreover, as mentioned above, a higher distribution ratio of roots in intra-row position in the no-tillage treatment indicates that the root system of wheat in the non-tilled field tends to develop more uniformly into not only vertical but also horizontal directions as compared with that in the tillage treatment.

   **(2) Soybean**

   Hussain et al. (1999) reported that the four-year average soybean yield with no-tillage was 15% higher than with the moldboard plough. Conversely, several researchers described that the yield was not improved, or even reduced by no-tillage practice (Lal et al., 1989; Oyanagi et al., 1998; Jug et al., 2006). Similarly, in our field no positive effect of no-tillage on soybean yield was found during the first three years of wheat-soybean rotation, and correlation between root traits and yield was not found (Izumi et al., 2004). However, in the present study soybean under the no-tillage condition, which developed greater roots both in length and weight, and thicker and shallower root system as compared with that under the tilled condition (Table 1), had significantly larger shoot biomass and yield (Table 4). Hussain et al. (1999) mentioned that the no-tillage system, which left more crop residue on the soil surface, performed better in dry years. In fact, root traits such as RLD and SRL were quite comparable to those in the second year when there was plenty rainfall in summer (Izumi et al., 2004). Therefore, depletion of soil moisture was probably not a critical limiting factor on yield, though no-tillage soybean roots tended to distribute near the surface as was prospected. Micucci and Taboada (2006) mentioned that subsoil property, and not the tillage systems, had the primary effect on root growth of soybean. Anyway, we could not find any relationship between the root growth and productivity within 6-year successive no-tillage cropping in soybean.

Barbosa et al. (1989) reported that improved soybean growth and yield in deep tillage treatment...
were attributed to the deeper rooting, which resulted in greater nutrient and moisture availability. Actually, their data showed that the rooting depth in soybean of subsoiling treatment was significantly and (9 cm) deeper than that of conventional one. Mohanty et al. (2007) also mentioned that RLD of soybean increased by subsoiling resulted in an improvement of water use efficiency and enhanced productivity. However, in this study the effect of subsoiling on RLD and RDI was not significant (Table 2) and neither biomass nor yield significantly differed between subsoiling and no-subsoiling treatments (Table 4). This was possibly because water supply was not serious problem for soybean growth in this season as already described.

Furthermore, the amount and distribution of roots were affected by subsoiling only in the surface 10 cm layer and no significant effect was observed in subsurface layer (Tables 2, 3). We firstly assumed that the effect of the subsoiling was canceled within approximately 7 months before soybean planting. However, the difference in the penetration resistance between subsoiling and no-subsoiling under the no-tillage conditions was retained for a longer period (Fig. 2-right, open circles). Mohanty et al. (2007) found that water use efficiency and yield of soybean under subsoiling every year and in alternate years were not different. Ghosh et al. (2006) concluded that there was no need of subsoiling every year to obtain the optimum yield of soybean. Al-Adawi and Reeder (1996) even described that soil properties were improved less by subsoiling twice than only once.

Moreover, Hunt et al. (2004) reported that subsoiling treatment was effective in improving yield of wheat and corn but not that of soybean. Busscher et al. (2006) also reported that lower cone index by deep tillage treatment of high strength soils led to higher yield in wheat but not in soybean. Therefore, some difference in responses of root growth to soil strength and/or less close relation between root growth and productivity in soybean may cause the smaller effect of subsoiling than in wheat.

2. Water uptake

This study also analyzed the water uptake trend using deuterated water (Fig. 3). By analyzing the deuterium concentration in xylem sap water, the source of water absorbed by the field grown crop species can be estimated (Iijima et al., 2005; Iijima et al., 2007). In wheat, water uptake trend in no-tillage indicated significantly higher dependence on recently supplied surface water, which agrees with our former findings (Iijima et al., 2007). This means that no-tillage caused the shallow root system, and therefore the plants depend highly on the surface supplied water. Subsoiling effect was significant only in no-tillage and not in tillage treatments as clearly visible in Fig. 3. Dependence of recently irrigated water of no-tillage wheat was lowered by the subsoiling treatment. This means that subsoiling of no-tillage field enhanced water uptake from deep soil layers. Therefore, the roots deeply developed roots by subsoiling (Tables 2 and 3) must contribute to enhanced water uptake from deep soil layer. Wheat growth in April where the precipitation was the least during the experiment (Fig. 1) was considered to be a critical period for yield formation before anthesis. Deep soil water in the subsoiled no-tillage field should contribute to the flowering of wheat plant during the drought condition, and thus, this would contribute to the higher yield of wheat in subsoiled no-tillage field. In contrast, water uptake trend in soybean was statistically influenced neither by no-tillage nor subsoiling (Fig. 3). This could be attributed to the root development in no-tillage soybean as discussed above (Tables 2, 3).

Dependence on surface-supplied water of soybean in the non-tilled field tended to be lower than that in the tilled field, which was the opposite trend of that in wheat. This means that no-tillage soybean shows higher dependence on the deep soil-stored water by the enhanced growth of deep roots in the continuous no-tillage field.

3. Effect of subsoiling on the continuous no-tillage

Very few studies were conducted previously on the root growth of crops in the same non-tilled fields for plural years. First, we examined RDI of both crops in this study during the first three years (from 2000 to 2002). RDI in length of wheat was nearly 9 and 8 cm in the tillage and no-tillage treatment, respectively, except the second year when precipitation at the early growth stage was plenty (Fig. 4-left). It is notable that the RDI of wheat in the no-tillage with subsoiling plot was almost the same as that under the tilled condition, which resulted from a larger amount of roots in 20−25 cm layer (Table 2). In soybean, the RDI in the no-tillage condition was constantly smaller than that in the conventional tillage and became shallower from the third to the sixth year (Fig. 4-right). Although we do not have RDI data for the fifth year (2004), higher RLD in the shallow layer caused by the higher mechanical impedance of undisturbed surface soil was observed in the non-tilled field (Iijima et al., 2007). However, this trend was moderate in the subsoiling treatment which mitigated the concentration of roots in the soil surface layer of soil (Tables 2, 3).

On the other hand, a trend of continuous decline in yield was observed in both crops (Fig. 5). Furthermore, relative yield in the no-tillage (yield relative to that in the conventional tillage) wheat, which exceeded 1 in 2002, decreased from 2003 to 2004 (Fig. 6). However, in the next year the ratio was recovered by subsoiling. In the no-tillage soybean that started to achieve a yield comparable to that in the tillage treatment from 2002, a positive effect of no-tillage on yield was evident.
only in the subsoiling treatment. Thus, we found a possibility of breaking or braking yield stagnation in long-term no-tillage practice by subsoiling. It is useful to enhance water uptake by deep roots in wheat, whereas it may not always be effective for soybean because the positive effect of continuous no-tillage on the root growth as a total is probably much larger. Moreover, such yield decline shows a possibility of continuous-cropping injury such as soil-borne diseases, although we did not observe any severe symptom in both crops. Subsoiling might have also contributed to suppression of diseases by improving drainage.

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References

Al-Adawi, S.S. and Reeder, R.C. 1996. Compaction and subsoiling effects on corn and soybean yields and soil physical properties. Am. Soc. Agric. Eng. 39 : 1641-1649.

Barbosa, L.R., Diaz, O. and Barber, R.G. 1989. Effects of deep tillage on soil properties, growth and yield of soya in a compacted Ustochrept in Santa Cruz, Bolivia. Soil Tillage Res. 15 : 51-63.

Bauer, P.J., Frederick, J.R. and Busscher, W.J. 2002. Tillage effect on nutrient stratification in narrow- and wide-row cropping systems. Soil Tillage Res. 66 : 175-182.

Busscher, W.J., Bauer, P.J. and Frederick, J.R. 2006. Deep tillage management for high strength southeastern USA coastal plain soils. Soil Tillage Res. 85 : 178-185.

Cresswell, H.P. and Kirkegaard, J.A. 1995. Subsoil amelioration by plant roots ? The process and the evidence. Aust. J. Soil Res. 33 : 221-239.

Diaz-Zorita, M. 2000. Effect of deep-tillage and nitrogen fertilization interactions on dryland corn (Zea mays L.) productivity. Soil Tillage Res. 54 : 11-19.

Frederick, J.R. and Bauer, P.J. 1996. Winter wheat responses to surface and deep tillage on the southeastern coastal plain. Agron. J. 88 : 829-833.

Holloway, R.E. and Dexter, A.R. 1991. Tillage and compaction effects on soil properties, root growth and yield of wheat during drought in a semi-arid environment. Soil Technol. 4 : 233-253.

Hunt, P.G., Bauer, P.J., Matheny, T.A. and Busscher, W.J. 2004. Crop yield and nitrogen accumulation response to tillage of a coastal plain soil. Crop Sci. 44 : 1673-1681.

Ishfaq, M., Ibrahim, M. and Hassan, A., Saeed, M. and Lal, R. 2001. Subsoil compaction effects on crops in Punjab, Pakistan : II. Root growth and nutrient uptake of wheat and sorghum. Soil Tillage Res. 60 : 153-161.

Ishfaq, M., Ibrahim, M. and Lal, R. 2003. Tillage and fertilizer effects on root growth of wheat and cotton on a sandy clay loam in Pakistan. J. Sustainable Agric. 22 : 43-57.

Izumi, Y., Uchida, K. and Iijima, M. 2004. Crop production in the successive wheat-soybean rotation with no-tillage practice in relation to the root system development. Plant Prod. Sci. 7 : 329-336.

Jug, D., Stipesevic, B. and Zugec, I. 2006. Effects of conventional and reduced tillage systems in winter wheat ? Soybean crop rotation on crops biomass development. Cereal Res. Commun. 34 : 1137-1143.

Kimura, K. 1999. Accurate root length measurement by image analysis. Plant Soil 216 : 117-127.

Lal, R. 1974. No-tillage effects on soil properties and maize (Zea mays L.) production in Western Nigeria. Plant Soil 40 : 321-331.

Lal, R., Logan, T. J. and Faussy, N. R. 1989. Long-term tillage and wheel traffic effects on a poorly drained Mollic Ochraqual in northwest Ohio. 1. Soil physical properties root distribution and grain yield of corn and soybean. Soil Tillage Res. 14 : 341-358.

Merrill, S. D., Black, A. L. and Bauer, A. 1996. Conservation tillage affects root growth of dryland spring wheat under drought. Soil Sci. Soc. Am. J. 60 : 575-583.

Micucci, F.G. and Taboada, M.A. 2006. Soil physical properties and soybean (Glycine max Merril) root abundance in conventionally- and zero-tilled soils in the humid Pampas of Argentina. Soil Tillage Res. 86 : 152-162.

Mohanty, M., Bandyopadhyay, K.K., Painuli, D.K. and Misra, A.K. 2006. Growth, competition, yield advantage and economics in soybean/pigeonpea intercropping system in semi-arid tropics of India. I. Effect of subsoiling. Field Crops Res. 96 : 80-89.

Oyanagi, A., Nanseki, T., Tsuchida, S. and Naganoma, H. 1998. Analyses of the vertical distribution of roots in wheat, soybean and rice in conventionally- and zero-tilled fields in Paraguay. Jpn. J. Crop Sci. 67 : 49-55*.

Oyanagi, A., Nanske, T., Tsuchida, S. and Naganoma, H. 1998. Analyses of the vertical distribution of roots in wheat, soybean and rice in conventionally- and zero-tilled fields in Paraguay. Jpn. J. Crop Sci. 67 : 49-55*

Williams, S.M. and Weil, R.R. 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68 : 1405-1409.

Zhang, X., Pei, D. and Chen, S. 2004. Root growth and soil water utilization of winter wheat in the north China plain. Hydrol. Process. 18 : 2275-2287.

*In Japanese with English abstract.