

Crop Production in Successive Wheat-Soybean Rotation with No-Tillage Practice in Relation to the Root System Development

Yasuhiro Izumi, Kazuhito Uchida and Morio Iijima*

(School of Environmental Science, The University of Shiga Prefecture, 2500 Hassaka, Hikone, Shiga 522-8533, Japan;

*Graduate School of Bioagricultural Sciences, Nagoya University, Nagoya 464-8601, Japan)

Abstract : To elucidate the effect of no-tillage practice on the root system development and productivity in a wheat-soybean rotation system in Japan, we continuously cultivated these crops under tilled and non-tilled field conditions and compared the growth and yield for three years. Effect of presence or absence of tillage on the root growth was evaluated by the quantitative analysis for the root systems obtained by the core sampling method. The total shoot biomass and yield of wheat were significantly higher in the tilled field than in the non-tilled field in the first and second seasons, whereas, they were significantly higher in the non-tilled field in the third season. On the other hand, no significant difference between the tilled and non-tilled field was found in the soybean yield for the three seasons. Root length per unit area had a significant positive correlation with both the total shoot biomass and yield in wheat but not in soybean. The continuous no-tillage practice improved the soil condition for root development and resulted in an enhancement of the shoot growth and yield of wheat. In soybean, on the other hand, the root system development greatly fluctuated from season to season, especially, in the non-tilled field, but the productivity in the non-tilled field was relatively stable equivalent to that in the tilled field. Thus, stable production equivalent to that obtained by conventional tillage can be achieved by the no-tillage practice in a typical Japanese climate regardless of the fluctuation in root system development.

Key words : *Glycine max* (L.) Merr., No-tillage, Root length density, Root distribution, Soybean, *Triticum aestivum* L., Wheat.

The no-tillage practice is widely conducted worldwide for erosion control and to maintain soil fertility. In Japan, however, it is conducted mainly to save labor cost, which is indispensable to improve food self-supply ratio of rice and other field crops. Especially, for crop rotation of wheat (*Triticum aestivum* L.) and soybean (*Glycine max* (L.) Merr.), both of which are expected as alternative crops for paddy rice field in this country, the no-tillage cultivation system may be desirable and may become widespread.

Because the plow layer is not disturbed, a field with continuous no-tillage will certainly have different soil physical, chemical and biological properties from that with conventional tillage. Attention is currently being given to the effects of no-tillage on the formation and retention of biopore, which is formed by the activities of soil organisms such as earthworms and the decay of plant roots. The biopore may provide a favorable condition for root growth by improving the permeability of air and water in soil (Wuest, 2001). It is clear that changes in the root system development affect shoot growth and has a potential to affect crop yields.

Lal (1989) reported that the root system distribution was shallow in upland fields without tillage. This would be attributed to the soil mechanical impedance

associated with the no-tillage practice because higher mechanical impedance often causes shallow root systems in cereal crops (Iijima and Kono, 1991; Iijima et al., 1991). Similarly, Oyanagi et al. (1998) found a shallower root distribution in soybean but not in wheat grown in an upland field converted from a paddy field. However, little information is currently available on the development of root systems in wheat-soybean rotation with no-tillage practice. Furthermore, it is probable that the effect of no-tillage practice differs with the duration of practice. Nevertheless, there have been no studies on the root growth in this crop rotation system under soil conditions with and without tillage practice during plural years.

In this study, we cultivated both wheat and soybean under tilled and non-tilled field conditions and compared the growth and yield for three years. Effect of presence or absence of tillage on the root growth was evaluated by the quantitative analysis for the root systems obtained by the core sampling method. The objective of this study is to elucidate how the continuation of no-tillage practice affects the crop production via root system development.

Materials and Methods

An experiment was conducted for three successive

Table 1. Dates of sowing, root sampling and harvesting.

Season (year)	Crop	Date		
		Sowing	Root sampling	Harvesting
1st (1999/2000)	Wheat	Nov. 17	May 2	Jun. 12
	Soybean	Jun. 18	Sep. 9	Nov. 10
2nd (2000/2001)	Wheat	Nov. 16	May 3	Jun. 12
	Soybean	Jun. 18	Aug. 31 - Sep. 1	Nov. 7
3rd (2001/2002)	Wheat	Nov. 14	May 3	Jun. 12
	Soybean	Jun. 19	Sep. 7	Oct. 28

years in a field (24×12 m=288 m²) at the University of Shiga Prefecture, Hikone, Shiga, Japan (N 35°15', E 136°13'). Twelve 5.5×3.5 m (19.25 m²) plots were prepared, and tilled and no-tilled plots each with six replications were randomly arranged. In the tilled plots, rotary tilling (0.24 m deep) was performed twice immediately before sowing. No molding was done. In the non-tilled plots, the soil was undisturbed except for making planting holes and surface scraping for weeding. The top soil in the field was light clay, and its chemical property was as follows: pH (H₂O), 7.02; total N, 1.75 g kg⁻¹; total C, 20.9 g kg⁻¹; CEC, 15.15 cmol kg⁻¹.

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. The schedule of the experiment is summarized in Table 1. On May 1999, the entire field was ploughed for the previous cropping before the no-tillage experiment began. From June to November, 1999, soybean was cultivated under the condition described below for both treatments. Sowing was conducted manually with row spacing 0.3 m for wheat (line planting) and in hill sowing (two seeds in a hill) with row spacing 0.6 m and hill spacing 0.2 m for soybean. At the seedling stage, planting density was thinned to 167 and 8.3 plants/m² for wheat and soybean, respectively. All the fertilizers were broadcasted on the soil surface. The prefectural guidelines for fertilization regarding the amount and timing were as follows. For wheat, 6 g/m² each of N, P₂O₅ and K₂O were applied as a basal dressing using compound synthetic fertilizer (0.14 g g⁻¹, N; 0.14 g g⁻¹, P₂O₅; 0.14 g g⁻¹, K₂O). An additional application was conducted by three-time split dressing to supply 7 g/m² each of N and K₂O using ammonium sulfate and potassium chloride, respectively. When the soybean was sown, 2, 6 and 8 g/m² of three major elements were applied using a compound synthetic fertilizer (0.05 g g⁻¹, N; 0.15 g g⁻¹, P₂O₅; 0.2 g g⁻¹, K₂O), and without additional application. Pest management was conducted for soybean on demand, but was not conducted for wheat. The monthly precipitation and average of daily maximum and minimum temperature during the experiment are shown in Fig. 1. During

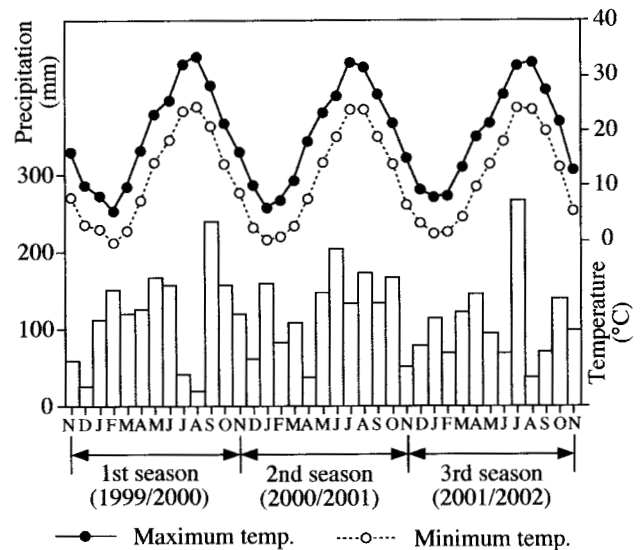


Fig. 1. Monthly precipitation and average values of daily maximum and minimum temperature at the experimental site (Hikone, Shiga prefecture, Japan) during the experiment.

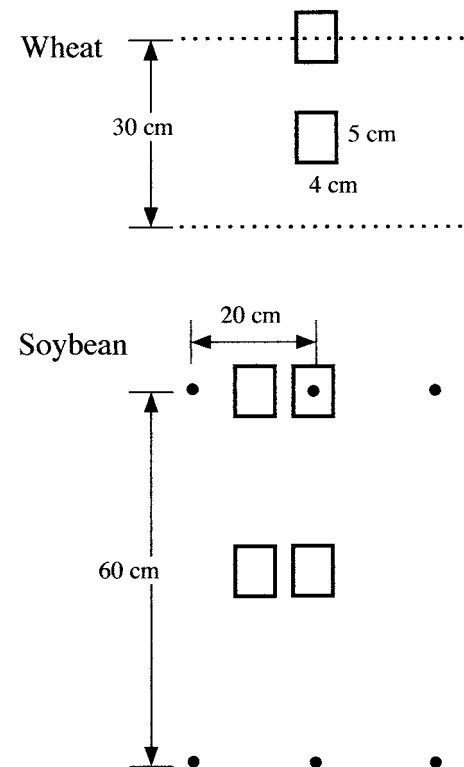


Fig. 2. Soil sampling points for wheat and soybean in the experiment. See the text for the detail.

the soybean growth period in 2000 and 2002, the plots were irrigated when a severe drought symptom was observed.

The roots were sampled at the ripening stage for wheat and at the late flowering stage (young pod stage) for soybean. For the root sampling, two adjacent plots showing average shoot growth of wheat in both

Table 2. Total shoot biomass and yield of crops in consecutive wheat-soybean rotation as affected by the no-tillage. The no-tillage practice was started from May 1999, and continued for three successive years.

Crop	Treatment	Total shoot biomass (g m ⁻²)			Yield (g m ⁻²)		
		1st	2nd	3rd	1st	2nd	3rd
Wheat	Tillage	15.46	10.52	9.85	5.91	4.45	4.27
	No-tillage	13.77	9.27	11.25	5.08	3.80	4.82
		*	*	*	*	**	†
Soybean	Tillage	6.16	6.94	6.68	2.65	3.55	2.98
	No-tillage	5.68	6.09	5.85	2.50	3.08	2.88
			†				

** , * and †; significantly different at P < 0.01, 0.05 and 0.1 level, respectively by student t-test.

tilled and non-tilled plots were selected in each season. Eight and six of root samples were obtained from both tilled and non-tilled plots for wheat and soybean, respectively. After cutting the shoots at the soil surface, the soil was sampled 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 intra-row space, and in the center of four plants in the intra-row space, as shown in Fig. 2. A stainless steel core sampler whose inner size was 0.04 m in width, 0.05 m in length and 0.4 m in height was used. The soil was separated into six blocks of 5-cm depth each from the soil surface for wheat and into four blocks at depths of 0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm for soybean. Soil deeper than 30 cm was not included for samples because root penetration was scarcely observed in either crop. Soil samples were carefully washed with a root washer (Gillison's Variety Fabrication Inc., GVF 13050) to collect roots. After removing the debris, the roots were stained with a 0.01 % aqueous solution of methyl violet and arranged on water at a depth of 5 mm in a transparent plastic tray. They were then converted to a digitized image with 256 gray levels and 300 dots per inch (DPI) using a desktop image scanner. Image analysis was done by NIH Image (ver.1.62) with a Macintosh™ computer, and length of the roots was determined by the macro program created by Kimura (1999). The dry weights of the shoot and root were measured after oven-drying at 80°C for 72 hours. 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. From the RLD of all the soil layers, the root depth index (RDI), which indicates an average rooting depth (Oyanagi et al., 1993), was also calculated. Furthermore, by assuming that the mean value of the two points for wheat and the four points for soybean was equivalent to an average amount of roots distributed in a field, the root length and

weight per unit area were estimated. The penetration resistance of the field was measured with a cone penetrometer (DAIKI Co., LTD., DIK-5521) during the wheat growth period near the root-sampling day. In both tilled and non-tilled plots, data of penetration resistance were taken from five points in the same plots as those for the root sampling.

For the yield research, plots where the roots were sampled once were excluded, therefore; the plants in the first, second and third season were sampled with five, four and three replications, respectively. From each plot, wheat on five 1-m-long and 16 soybean plants showing average growth were harvested and air-dried, and the total shoot biomass including the leaves before defoliation and the yield (economical yield) were determined. All the plant residuals (leaf, stem and pod) were removed from the field during harvest for both treatments.

Results

1. Biomass production and yield

In the tilled and non-tilled plots, the total shoot biomass was higher in the first season than in later seasons for wheat (Table 2). In the first and second seasons the biomass was significantly higher in the tilled plot, whereas, in the third season, it was significantly higher in the non-tilled plot. A similar trend was observed for the yield. On the other hand, the total shoot biomass and yield of soybean were more constant than those of wheat. The total shoot biomass in the tillage treatment was significantly higher than that in the non-tilled plot in the second season, but no significant difference in the yield was observed. Indeed, the harvest index varied with the season, but no significant difference between the plots was found in any season (data not shown).

2. Root growth

(1) Vertical root distribution

In wheat, in all the soil layers each 5 cm in depth, the RLD was lower in the non-tilled plot than in the

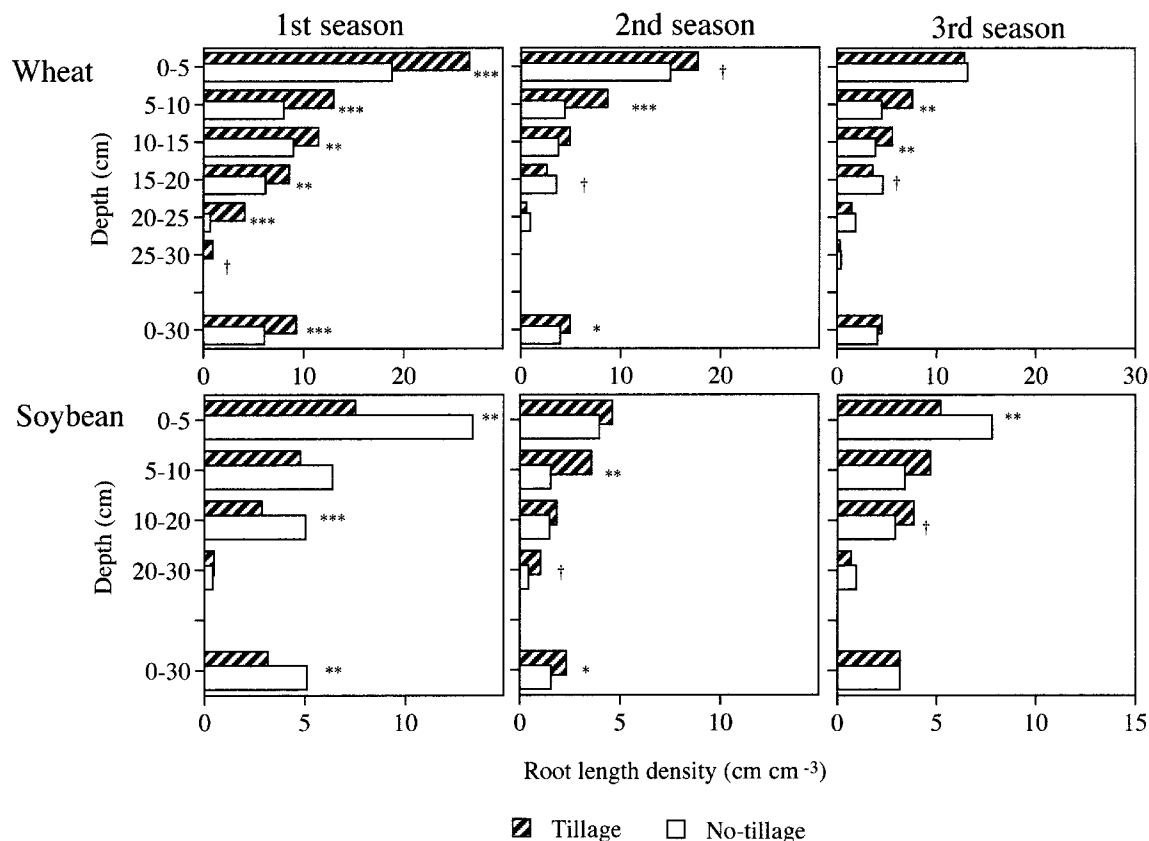


Fig. 3. Root length density of wheat (upper) and soybean (lower) at each soil depth in tilled and non-tilled plots in three successive years. ***, **, * and † indicate significant difference between the tilled and non-tilled plots at $P < 0.001$, 0.01, 0.05 and 0.1 level, respectively by student t-test.

Table 3. Estimated root length and weight per unit area within 30 cm soil depth, specific root length (SRL) and root depth index (RDI) in wheat and soybean cultivated by rotation in the tilled and non-tilled plots. The no-tillage practice was started in May 1999, and continued for three successive years.

Crop	Treatment	Root length (m m^{-2})			Root weight (g m^{-2}) [#]		SRL (m g^{-1}) [#]		RDI (cm)		
		1st	2nd	3rd	2nd	3rd	2nd	3rd	1st	2nd	3rd
Wheat	Tillage	32344	17240	15600	134	143	128	111	8.94	6.58	8.33
	No-tillage	21330	13777	14130	109	137	128	108	8.04	7.31	8.82
		***	*		*				†		
Soybean	Tillage	9499	6949	9481	332	191	21	51	8.77	10.45	10.46
	No-tillage	15332	4664	9447	396	243	12	40	8.35	9.88	9.51
		**	*			†	***	†	†	†	

[#] not examined in the first season.

***, **, * and †; significantly different at $P < 0.001$, 0.01, 0.05 and 0.1 level, respectively by Student's t-test.

tilled plot, and significant differences between the two treatments were found in the first season (Fig. 3). On the average, the RLD in the non-tilled plot was approximately two thirds of that in the tilled plot. In the second season, the RLD was also reduced by the no-tillage practice, but the ratio to that in the tilled plot was 0.80, indicating a moderate reduction in comparison with the previous season. In the third

season, the ratio increased to 0.91, and no significant difference was observed between the plots. In the second and the third seasons, significant differences between the plots were found only in some part of the soil layers, and the RLD in the 15-20 cm layer was significantly higher in the non-tilled plot than in the tilled plot. The root depth index (RDI) was significantly higher in the tilled plot than in the non-

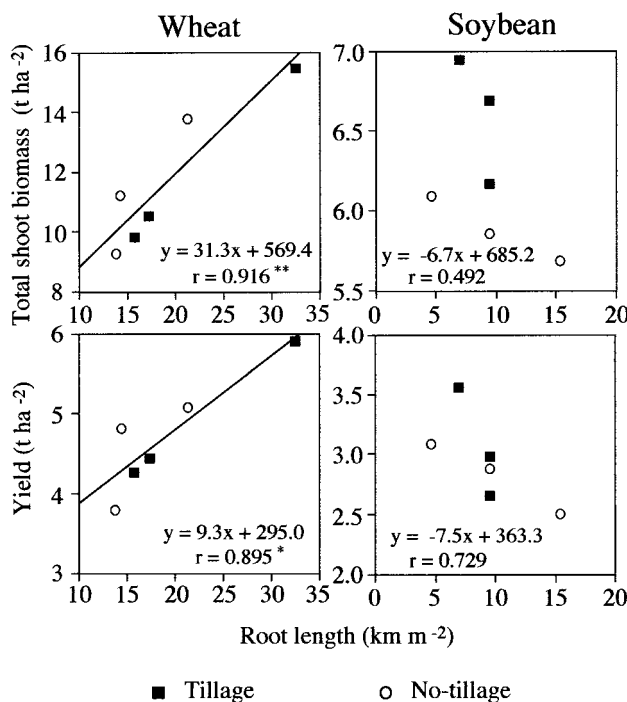


Fig. 4. Relation between estimated root length per unit area and total shoot biomass (upper) or yield (lower) in wheat (left) and soybean (right). Average values of two treatments x three seasons are plotted and linear regression line was drawn. ** and * indicate significant difference at $P < 0.01$ and 0.05 level ($n=6$), respectively for correlation coefficient (r).

tilled plot in the first season, however, the opposite was observed afterwards although the difference was not significant (Table 3).

In soybean, the total RLD was significantly higher (1.6 times) in the non-tilled plot than in the tilled plot in the first season (Fig. 3). However, the RLD in the second season in the non-tilled plot was two thirds of that in the tilled plot, and that in the third season was almost the same as that in the tilled plot. Thus, no consistent trend was observed for the three seasons. It was notable that the difference among the three seasons was greater in the non-tilled plot than in the tilled plot. A significant difference in RDI was observed in the second and third season, and the root distribution was nearly 1 cm deeper, on the average, in the tilled plot than in the non-tilled plot (Table 3). When observations were restricted to the area just below the plant, the RDI was approximately 2 and 3 cm larger in the tilled plot in the second and third season, respectively (data not shown). Concerning the vertical root distribution evaluated with the RWD, quite similar trends were found in both crops, although the difference between the treatments was less significant (data not shown).

(2) Root traits as a whole

As expected from the large fluctuation in RLD, estimated root length changed considerably during

Table 4. Coefficients of correlation of the root length density with soil depth and total shoot biomass or yield in wheat and soybean.

Soil Depth	Wheat		Depth	Soybean	
	Biomass	Yield		Biomass	Yield
0-5 cm	0.859*	0.811	0-5 cm	-0.702	-0.779
5-10 cm	0.758	0.769	5-10 cm	-0.192	-0.601
10-15 cm	0.933**	0.868*	10-20 cm	-0.402	-0.719
15-20 cm	0.943**	0.904*	20-30 cm	0.526	0.674
20-25 cm	0.659	0.752			
25-30 cm	0.630	0.755			

Average values of two treatments x three seasons are used for calculation.

** and *; statistically significant at $P < 0.01$ and 0.05 level ($n=6$), respectively.

the three seasons (Table 3). In wheat, the root length in the first season was larger than that in the other seasons. A similar trend of difference between the tilled and non-tilled plots in the root length was found in the second and third seasons, and no difference between the plots in the specific root length (SRL). In soybean, the root length in the second season was shorter than that in the other seasons, especially in the non-tilled plot, whereas the root weight in the second season was heavier than that in the third season in both plots. Therefore, the SRL was shorter in the second season than in the third one and shorter in the non-tilled plot than in the tilled plot, indicating that roots were thicker in the former than in the latter as a whole.

3. Correlation between root growth and productivity

The relationship between root growth and crop productivity was tested by plotting six average values (two treatments x three seasons). In wheat, the root length per unit area had a significant positive correlation with both the total shoot biomass and yield (Fig. 4). When root weight per unit area was plotted, the correlation coefficient against the total shoot biomass and yield were 0.632 and 0.766, respectively, and neither of them was significant (data not shown). In soybean, the coefficient of correlation between the root length and biomass was low and not significant because the extent of defoliation at harvest was inconsistent over the years. The coefficient of correlation between the root length and yield was slightly higher but not significant.

The relationship between the RLD in different soil layers and productivity was also tested (Table 4). The correlation coefficient was higher in the 10-15 and 15-20 cm layers than in the surface layer in wheat, where the root distribution was heaviest. Furthermore, in the 15-20 cm layer, which had the largest correlation coefficient, the RLD in the intra-row space had a closer

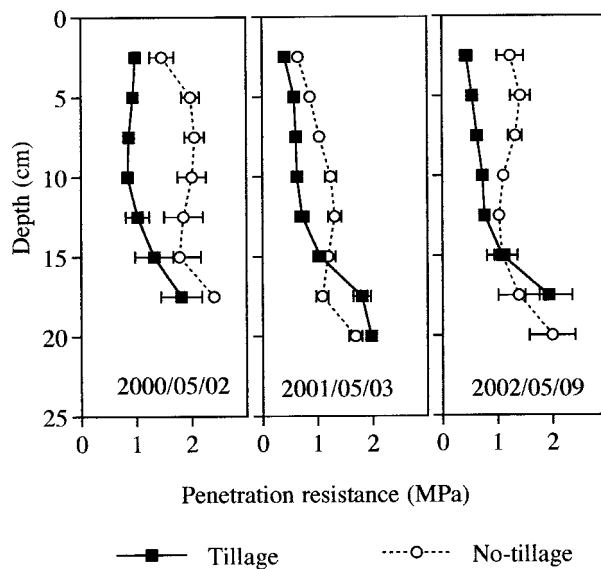


Fig. 5. Penetration resistance of the field under tillage and no-tillage condition during three-year wheat cultivation. Error bars show standard error ($n=5$).

correlation ($r=0.968$ and 0.908 with the total shoot biomass and yield, respectively) than the RLD just on the row ($r=0.889$ and 0.871 , respectively), though the former had a smaller amount of roots (data not shown). No significant correlation was observed between the RLD of any soil depth and productivity in soybean.

4. Penetration resistance

In the first season, the penetration resistance during the wheat growth period was higher at all depths in the non-tilled than in the tilled plot, whereas, in the later seasons, the opposite was observed at points deeper than 15 cm (Fig. 5). Furthermore, in the third season, the penetration resistance at 10 and 12.5 cm of depth was slightly weaker than that at 5 and 7.5 cm of depth in the plot without tillage.

Discussion

1. Root growth

The root growth in soybean and wheat rotation under tillage and no-tillage conditions were examined for three successive years. A considerable fluctuation in root growth was observed over the three years (Table 3 and Fig. 3). Yamaguchi and Tanaka (1990a) reported that cleaning procedures to separate roots from soil are important when quantifying roots. In our research, special attention was paid to all the processes to separate roots from soil. Moreover, the data obtained in this study were collected from the same field in the same growth stage, and identical procedures were used for sampling, cleaning, and measurements. Hence, we believe that only the difference in growth conditions produced such a large variation in root traits.

(1) Effects of precipitation

Soybean root length changed drastically over the three successive seasons, especially in the non-tilled plot (Table 3). The monthly precipitation during the soybean growth period was relatively constant in the second season, and it was quite small in July and August of the first season and in August and September of the third season (Fig. 1). Low soil moisture would have triggered the abundant lateral root emergence in the first and third seasons, while sufficient precipitation may have caused the relatively poor lateral root development in the second season. In fact, enhancement of lateral root development in soybean under low soil moisture has been reported previously (Kono et al., 1987; Turman et al., 1995). Further, in the non-tilled plot, in which more roots were concentrated in the surface layer than in the tilled plot (Fig. 3), soil moisture was probably variable and caused a larger fluctuation in root length. Such fluctuation in root length caused by the difference in precipitation was also reported in wheat cultivation by Merrill et al. (1996). Therefore, the relatively small amount of precipitation in the early growth period of wheat (November and December) might have enhanced root growth in the first season in our experiment (Fig. 3 and Table 3) as well.

(2) Effects of no-tillage

Although the large fluctuation masked the consistent effects of the no-tillage practice on the root growth, RDI of soybean in the non-tilled plot tended to be smaller than that in tilled plot, indicating that root distribution was shallower in the non-tilled plot (Table 3). However, the difference was not so apparent in wheat. This phenomenon coincided with the results obtained by Oyanagi et al. (1998). Similarly, the SRL of soybean in the non-tilled plot was smaller than that in tilled plot in the second and third seasons, indicating that the roots in the non-tilled plot were thicker on the average. This was not the case in wheat. Indeed soybean roots were thicker than wheat in average as shown in SRL (Table 3), but such a difference in root diameter was not directly related to the restriction of root growth in hard soils (Clark et al., 2003; Iijima et al., 1991). It is rather assumed that soybean with a tap root system is more susceptible to the hardness of surface soil than wheat with a fibrous root system and tends to have a shallower and thicker root system when no-tillage is applied. In non-tilled fields in Paraguay, an inhibition of vertical elongation of soybean tap roots was observed in the deep soil profile (Seki et al., 2001). Therefore, further morphological study on the difference in the responses to no-tillage practice between the crops will be needed.

In wheat, which showed relatively small fluctuations in root growth, root growth was improved after three consecutive years of no-tillage practice (Fig. 3 and Table 3). Due to the improvement of the physical

properties of the soil as a result of continuous no-tillage practice, the penetration resistance became much favorable to the root growth in the non-tilled plot (Fig. 5). This would have caused a significantly larger RLD at 15-20 cm layer in the non-tilled plot (Fig. 3). Such effect of continuous no-tillage to lessen the penetration resistance in a deeper layer was also previously reported (Hammel, 1989). In this study, the sum of the monthly precipitation during wheat cultivation (November to June) in the first, second, and third season was 917.5, 925 and 743.5 mm, respectively. Hence, the reduction in precipitation may also contribute to the favorable root growth of the crops in the non-tilled plot in the third season. The relatively less rainfall may have caused the less waterlogged condition for the roots in the non-tilled field.

(3) Validity of the measurement of root traits

In this study, the maximum value in the RLD recorded was 26.6 cm cm⁻³ in wheat and 14.9 cm cm⁻³ in soybean, and the root length per unit area was 32.3 km m⁻² in wheat and 15.3 km m⁻² in soybean. Asseng et al. (1998) reported that the maximum wheat root length was 30 km m⁻², which was similar to the results obtained in the current study (Table 3), and comparable values in the RLD (El-Hafid et al., 1998; Steingrobe et al., 2001a) and root length (Merrill et al., 1996; Steingrobe et al., 2001b) were also reported. On the other hand, Oyanagi et al. (1998) reported a shorter root length than that obtained in our study, especially in soybean. In other studies, RLD values much lower than ours were reported by Moreno et al. (1997), Zubaidi et al. (1999), and Rahman et al. (2000) in wheat and by Hirasawa et al. (1998) in soybean. Such a difference among the studies is probably due to the difference in the measuring methods and/or growing conditions, as already mentioned.

It is notable that RLD values similar to ours were obtained by Yamaguchi and Tanaka (1990b). They measured crop root lengths at almost the same growth stage, i.e., shortly after full flowering in wheat and at the pod-filling stage in soybean. Furthermore, they applied core sampling and image analysis, as we did in our study. Therefore, our data are valid enough to discuss the fluctuation and effect of no-tillage practice on the root growth already described.

2. Relationship between root growth and productivity

In wheat, the reduction in productivity resulting from the no-tillage practice was improved (Table 2) by alleviating the restraint of root growth (Fig. 3 and Table 3). Furthermore, a significantly positive correlation between root length and yield (Fig. 4) implies that not only the amount but also the spatial enlargement of a root system, which is considered to be important for water and nutrient acquisition,

has a close relationship with productivity. A closer correlation between the productivity and RLD in the deeper layer (Table 4) may also indicate that a favorable soil condition for root system development in the vertical and horizontal directions is related with the high productivity in wheat.

As already discussed, soybean root growth responded sharply to soil moisture and hardness, but had no significant correlation with the productivity (Fig. 4). Furthermore, though the fluctuation in root growth was much greater in the non-tilled plot than tilled plot, both the biomass production and yield were relatively stable in the former. Yield responses to no-tillage practice different from those obtained in our results have often been reported. For example, Oyanagi et al. (1998) observed a reduction in the shoot biomass and yield in soybean as well as in wheat by no-tillage practice under a one-year successive cultivation of the two crops. Lal et al. (1989) also reported that soybean yield was greater in plots with plough tillage than without tillage. Turman et al. (1995) did not find any effects of three different tillage methods on soybean yield for two years, as in our study, and mentioned that none of the difference in yield could be explained by differences in root growth. The mechanism of such "buffer effect" in soybean is unclear at the moment, hence, further research will be needed concerning the relationship between soil moisture and root growth and that between root growth and productivity in soybean.

Conclusion

Relatively stable production equivalent to the conventional tillage can be achieved by the no-tillage practice in soybean in typical Japanese climates in spite of the large fluctuation in the root system. In wheat, on the other hand, continuous no-tillage practice gradually improves the soil condition for the root systems development and, furthermore, enhances the shoot growth and yield.

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