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No-Tillage Enhanced the Dependence on Surface Irrigation Water in Wheat and Soybean

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Abstract : No-tillage often affects crop root development due to the higher mechanical impedance to root elongation, resulting in yield reduction under an unfavorable rainfall pattern, such as drought. In this study, we analyzed the changes in water source of wheat and soybean under drought stress in a continuous no-tillage field. Deuterium-labeled irrigation water was applied at different growth stages of crops to analyze their water uptake pattern. Mechanical impedance of the surface soil was 3.5 and 4.4 times higher in the no-tillage than in the conventional tillage under wet and drought conditions, respectively. Root length density and root branching index (the length of lateral roots per unit axile root length) of soybean in the surface soil layer were higher in the no-tillage field. This indicates that the increased branching by the higher mechanical impedance of undisturbed surface soil causes roots to accumulate in the surface soil layer. The deuterium concentration in the xylem sap of both crops was significantly higher in the no-tillage than in the tillage under a drought condition. This indicates that the crops in the no-tillage field depend highly on the newly supplied easily accessible water (irrigation water and/or rainfall) as compared with those in the conventional tillage field under a limited water supply. In conclusion, enhanced surface root growth in the no-tillage condition would result in higher dependence on surface supplied irrigation water than in the conventional tillage under drought.

Key words : Deep root, Heavy water, Soil mechanical impedance, Stable isotope, Sustainable agriculture, Water source, Water uptake.

No-tillage is an effective sustainable cropping system to prevent soil erosion (Iijima et al., 1999, 2003, 2004; Izumi et al., 2004b), and to reduce the production costs through reduced labor and machinery usage for the tillage practice. Although no-tillage is advantageous for crop production, it often affects crop root development due to the higher mechanical impedance to root elongation (Izumi et al., 2004a, b), and causes yield reduction under unfavorable conditions, such as drought. Soil water conditions under no-tillage have been mostly studied in the regions where the water shortage limits crop growth and/or yield. The crop residue in the no-tillage fields is often used as the mulching materials (in situ mulching) because they are mixed into the soil by the tillage. The water use of plants under mulching and no-tillage conditions has been reported previously in these regions. For example, the in situ mulching together with the no-tillage would reduce evaporation from the soil surface in the semi-arid regions (Unger, 1984; Norwood, 1994; Bonfil et al., 1999), and would increase the infiltration rate of rain water into the surface soil (Roth et al., 1988; Meek et al., 1990; Waddell and Weil, 1996; Shukla et al., 2003). In no-tillage, available soil water in the deep soil layer seem to be increased due to the less water consumption as compared with the conventional tillage practice, resulting in much more water stored in the no-tillage soil (Gantzer and Blake, 1978; Smika, 1990; Dao, 1993; Chan and Heenan, 1996; Hussain et al., 1999; Norwood, 2000).

Soil water status in the no-tillage field is usually monitored by the tensiometer and neutron probe methods (Webber III et al., 1987; Merrill et al., 1996), and the value is sometimes used as an index of the water uptake by crops. These methods, however, cannot always properly indicate the actual water uptake by the crop. Without detailed analysis of soil water movement, one cannot discriminate the water movement to different soil layers from the water uptake by the plant. In contrast, the source of water taken up by the crops can be accurately evaluated by measuring the abundance of deuterium in xylem sap of plants relative to that in the soil. The comparison of the hydrogen isotope signatures in xylem sap with those in a simulated rainfall event (recently irrigated water) and existing (stored) soil water can be used to reveal the source of water used by the plants. Recently, this technique has been used to reveal the water sources of annual crops species (Zegada-Lizarazu and Iijima, 2004; Araki and Iijima, 2005; Iijima et al., 2005;

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Abbreviations: ANOVA, analysis of variance; DAS, days after sowing.

Zegada-Lizarazu and Iijima, 2005; Zegada-Lizarazu et al., 2005; Zegada-Lizarazu et al., 2006a, b; Zegada-Lizarazu et al., 2007).

The water uptake by crops from no-tillage fields has not been fully investigated due to the experimental difficulties of the estimation of water uptake in the field-grown crops. Moreover, the water source of the crops grown in a no-tillage field has not been analyzed except for a report on rice-wheat intercropping experiment (Iijima et al., 2005). The question arising is whether no-tillage changes the plant water source or not, because the rooting pattern of the crops is modified under the higher mechanical impedance in the no-tillage field. The objective of the present study was to determine the water sources of crops grown in no-tillage fields under different soil water conditions in continuous wheat-soybean crop rotation in Japan.

Materials and Methods

1. Study site

Wheat-soybean rotation with no-tillage has been continuously practiced since 1999 in the field at the experimental farm of the University of Shiga Prefecture (latitude 35° 5' N, longitude 136° 13' E, altitude 87 m.a.s.l.). The yield and root development in the first three years have been reported previously (Izumi et al., 2004a). The topsoil in the field was light clay with a pH (H_2O) of 7.02; total N, 1.75 g kg^{-1}; total C, 20.9 g kg^{-1}; CEC, 15.15 cmol kg^{-1}. In the present paper, the water source of crops in the no-tillage field was analyzed in the fourth wheat-soybean cropping season in the 2002/ 2003 winter and summer season.

2. Treatments and field management

We set up water treatment (Wet and Dry) as the main plot and tillage treatment (Tillage and No-tillage) as the sub plot with three replications following the split-plot design arrangement. The size of each plot was 5.5 m × 3.5 m (19.25 m^2), and in total 25 m × 12 m (300 m^2) field. For the dry treatment, a vinyl shade of polyethylene transparent film (thickness 0.075 mm, 2.5 m high) was placed over the plots to keep the plants from receiving rainfall. The prefabricated framework on which the vinyl shade was placed had a semicircular shape with a height at the center point of 2.5 m and high sidewall clearance for maximum vertical plant growth. The front and back were completely open when the sidewalls were open up to a 0.8 m height from the soil surface, allowing the air to flow freely inside the vinyl shade and minimize the effect of any other environmental factors (especially air temperature) other than soil water content. By contrast, the wet treatment received natural rainfall during the experimental period (Fig. 1). In the tillage treatment, rotary tilling (0.24 m deep) was performed twice immediately before sowing. In the no-tillage treatment, the soil was undisturbed except for making

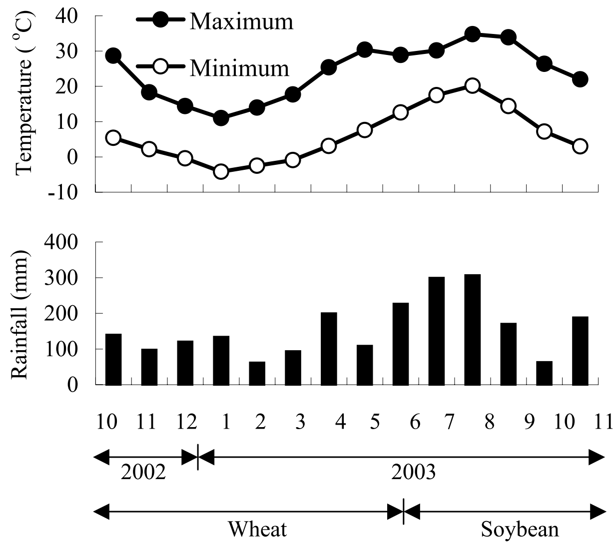

Fig. 1. Monthly maximum and minimum temperature, and rainfall during the experimental period (Source; Hikone Local Meteorological Observatory).

planting holes and surface scraping for weeding.

The wheat cultivar, Norin 61, and the soybean cultivar, Tamahomare, were used for the experiment. Wheat was sown on 17 Nov 2002, and harvested on 5 June 2003. After the wheat cropping, soybean was planted on 20 June, and harvested on 22 October in the wet treatment and on 31 October in the dry treatment due to the delay of maturing in the dry treatment. In both fields, plant residue was removed to reduce the effects of mulching on the water usage of the crop (Iijima et al., 2004).

Wheat seeds were sown manually with 0.3 m row spacing (line planting), and soybean seeds with 0.6 m row spacing and 0.2 m hill spacing, two seeds in each hill (hill planting). The seedlings were thinned to adjust planting density to 17 and 8.3 plants m^{-2} in wheat and soybean, respectively. For wheat, synthetic fertilizer with 6 g m^{-2} each of N, P_2O_5 and K_2O was applied as a basal dressing, and 7 g m^{-2} each of N and K_2O was top-dressed by three times split application. For soybean, 2, 6 and 8 g m^{-2} of N, P_2O_5 and K_2O, respectively, were applied as a basal dressing without topdressing. The fertilizers for topdressing were broadcasted on the soil surface.

Pest management was conducted for soybean on demand, but not for wheat. Fig. 1 shows the monthly precipitation and average of daily maximum and minimum temperature during the experiment. For the wet treatment, the field was irrigated sufficiently when a slight drought symptom was observed in soybean. The dry treatment was started at 142 and 37 days after sowing (DAS) in wheat and soybean, respectively, and continued until harvest in both crops. For soybean under dry treatment, 10 to 20 mm irrigation was applied on 8 August, 6 September, and 9 September when severe drought symptom was observed. The average temperature during the growing period of wheat (October 2002 - June 2003) was 12°C with a total rainfall of 1185 mm (Fig. 1). The average temperature during the soybean-growing period (July-November 2003) was 21°C with a total rainfall of 1029 mm.

3. Soil physics

At 67 DAS in soybean cropping, soil penetration resistance was measured with a cone penetrometer (DIK-5521, Daiki Rika Kogyo Co., Ltd., Japan) in the top 5 cm of the surface soil (0-5 cm depth), but not in deeper layers because the soil was very hard in no-tillage dry treatment. A tensiometer was inserted into the soil at a 5-12 cm depth and 25-32 cm depth at two positions for each soil layer to analyze the change in soil water status during the experiment. The tensiometer reading was recorded from 171 to 193 DAS in the field with wheat. Saturated hydraulic conductivity of the surface 0-5 cm soil layer was measured by the Falling-Head Method (Klute and Dirksen, 1986) at 45 DAS in the field with soybean.

4. Water source analysis, crop physiology, and root development

Water source analysis was conducted at heading (179 DAS) in the field with wheat, and at early flowering (42 DAS), late flowing (67 DAS), and pod filling (84 DAS) in the field with soybean to evaluate the water acquisition pattern. In wheat at heading and soybean at early flowering, the photosynthetic and transpiration rates were measured one day prior to water source analysis with a portable photosynthesis analyzer (LI-6400, LI-COR, USA) using the first fully expanded leaf from the top. After the measurement, 100 mL of deuterated water (1.0 and 0.5 atom % D_2O for wheat and soybean, respectively) was applied at 5 cm from the plant base. The heavy water application was regarded as the recent rainfall or recently irrigated water. About 15 h 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). The root system was sampled just after the xylem sap collection and either the root length density or root weight density was measured following the method described in detail by Izumi et al. (2004a). Briefly, the root system was sampled with a square-shaped soil sampler (0.04 m in width, 0.05 m in length and 0.4 m in height) from the wheat and soybean just below the plant axis. In soybean at the pod filling stage, the branching index, which is the length of lateral roots per unit axile root length, was also determined to express the extent of root branching in the surface soil layer (Morita and Collins, 1990). The dry weight of the root was measured after oven-drying at 80°C for 72 hours.

Table 1. Penetration resistance (MPa) and saturated hydraulic conductivity (Falling-Head Method; 10^{-4} cm s^{-1}). **, statistically significant at $P < 0.01$. ns, not statistically significant at $P \geq 0.01$.

	Water treatment (W)	Tillage treatment (T)	
		No-tillage	Tillage
Penetration resistance (0-5 cm depth)	Wet	1.64	0.47
	Dry	2.41	0.55
	W	ns	
	T	**	
	W*T	ns	
Hydraulic conductivity (0-5 cm depth)	Wet	9.2	10.6
	Dry	5.4	8.5
	W	ns	
	T	ns	
	W*T	ns	

5. Statistical analysis

Differences among the treatments were subjected to 2-way analysis of variance (2-way ANOVA).

Results

1. Soil physical properties

Soil penetration resistance in the top 5 cm from the soil surface was significantly higher in the no-tillage condition than in the tillage condition; no-tillage resulted in 3.5 and 4.4 times higher penetration resistance under wet and drought conditions, respectively (Table 1). Although no significant differences were found in the soil hydraulic conductivity between any treatments, the value in no-tillage dry was lower than other treatments; it was 36 - 49 % lower than the other treatments, indicating that the water movement in the no-tillage field becomes significantly lower under drought conditions. The soil water potential was measured only at two replicates in the field, therefore, the average value of the tensiometer reading without the statistical evaluation was presented here for reference value; The values at top soil layer (5-10 cm) were −19.8 and −80.2 kPa for wet and dry treatment, respectively. Those at subsoil layer (30-35 cm) were −11.5 and −79.5 kPa for wet and dry treatment, respectively. The values were consistently lower in the dry treatment than in the wet treatment, but the difference was not observed between the tillage treatments.

2. Root growth

No-tillage tended to reduce the root length density in wheat, but tended to increase root weight density in soybean (Table 2). The root growth in topsoil (0-15 cm depth) in the dry treatment, however, responded to no-tillage similarly in both crops. Namely, no-tillage

Table 2. Root length density[#] ($cm\ cm^{-3}$), root weight density[$] ($g\ cm^{-3}$) and root branching index[!] ($cm\ cm^{-1}$). †, * and **, statistically significant at $P < 0.1$, $P < 0.05$ and $P < 0.01$. ns, not statistically significant at $P \geq 0.1$.

		Water treatment	Tillage treatment (T) No-tillage	Tillage
Wheat	0-15 cm[#] depth	Wet	10.3	21.1
		Dry	11.8	10.2
		W	*	
		T	*	
		W*T	ns	
	15-30 cm[#] depth	Wet	4.0	3.8
		Dry	1.6	3.1
		W	*	
		T	ns	
		W*T	ns	
Soybean early flowering stage	0-15 cm[$] depth	Wet	0.099	0.052
		Dry	0.212	0.066
		W	†	
		T	†	
		W*T	ns	
	15-30 cm[$] depth	Wet	0.017	0.021
		Dry	0.004	0.046
		W	ns	
		T	ns	
		W*T	ns	
Soybean pod filling stage	0-5 cm[#] depth	Wet	4.2	3.0
		Dry	4.4	2.4
		W	ns	
		T	*	
		W*T	ns	
	0-5 cm[!] depth	Wet	33.0	15.2
		Dry	53.4	17.0
		W	**	
		T	**	
		W*T	ns	

tended to increase the root growth of both crops at early flowering stage, 1.16 and 3.20 times, respectively. In soybean at the pod filling stage, root length density and root branching index in the surface soil layer (0-5 cm) were 1.8 and 3.1 times, respectively, higher in no-tillage than in tillage. The root branching index is the parameter of branching in a root system (Morita and Collins, 1990). Thus, the higher root branching index in no-tillage indicates the promoted lateral root growth in the no-tilled surface soil layer in the dry treatment. On the other hand, the root growth of wheat and soybean in subsoil (15-30 cm layer) in the dry treatment were 1.9 and 11.5 times higher, respectively, in the tillage field than in the no-tillage field. Thus, drought stress under the no-tillage condition tended to increase the root growth in topsoil, but decrease that in subsoil layer in both crops.

3. Photosynthetic and transpiration rates

In this study, the photosynthetic and transpiration rates of uppermost fully expanded leaf, which would exhibit the highest photosynthetic activity in the canopy, was regarded as the physiological index of plants in water source analysis. The photosynthetic rate in wheat was similar in the two tillage treatments although the dry conditions significantly reduced the values (Table 3). In soybean, however, the photosynthetic rate was higher in the no-tillage field than in the tillage field under a wet condition, and the opposite was the case under a dry condition. The responses of the transpiration rate to water treatment and tillage treatment were similar to those of photosynthetic rate. Under such physiological conditions, the water source was analyzed.

4. Water source

Table 4 shows the concentration of deuterium in xylem sap measured 15 h after the application of deuterated water. The deuterium concentration indicates the relative dependence of the crops on the recently supplied irrigation water or rainfall. A significant interaction between the effects of tillage and water treatments was observed in most of the cases except soybean at the pod filling stage. In general, the crops in the no-tillage plot under drought treatment contained the largest amount of deuterium in xylem sap, indicating the highest dependence on surface supplied irrigation water. The deuterium concentration in xylem sap was significantly higher in the no-tillage plot than in the tillage plot. This trend, however, was not clearly observed in soybean at the late flowering stage. Heavy rainfall (76 mm) was observed on the day before the analysis, which might have affected the deuterium analysis due to the excess soil moisture. The deuterium concentration in xylem sap was higher in the crops under dry than under wet condition, except for soybean at early flowering stage in tillage and at pod filling stage in both tillage treatments. At both stages, long dry span before the analysis might have affected the treatment effect of adequate water levels in the wet treatment. In soybean the deuterium concentration in xylem sap was the highest at the late flowering stage especially under the dry conditions, which imply the higher dependence on the irrigation water at this stage.

Table 3. Photosynthetic rate (μmol m^{-2} s^{-1}) and transpiration rate (mmol m^{-2} s^{-1}). †, * and **, statistically significant at $P < 0.1$, $P < 0.05$ and $P < 0.01$. ns, not statistically significant at $P \geq 0.1$.

	Water treatment (W)	Tillage treatment (T)					
		Wheat		Soybean			
				Early flowering stage		Pod filling stage	
		No-tillage	Tillage	No-tillage	Tillage	No-tillage	Tillage
Photosynthetic rate	Wet	28.4	28.6	20.9	20.0	10.8	9.3
	Dry	14.6	14.7	12.5	18.3	7.0	9.6
	W	**		†		*	
	T	ns		ns		ns	
	W*T	ns		†		ns	
Transpiration rate	Wet	5.20	5.03	4.9	4.9	13.6	9.6
	Dry	1.77	1.93	3.0	5.5	9.5	10.3
	W	**		†		ns	
	T	ns		**		†	
	W*T	ns		**		*	

Table 4. Deuterium concentration in xylem sap (atom % excess) measured 15 h after application of deuterated water; 1.0 and 0.5 atom % for wheat and soybean, respectively. * and **, statistically significant at $P < 0.05$ and $P < 0.01$. ns, not statistically significant at $P \geq 0.05$.

Water treatment (W)	Tillage treatment (T)							
	Wheat		Soybean					
			Early flowering stage		Late flowering stage		Pod filling stage	
	No-tillage	Tillage	No-tillage	Tillage	No-tillage	Tillage	No-tillage	Tillage
Wet	0.033	0.012	0.027	0.018	0.030	0.024	0.034	0.024
Dry	0.177	0.078	0.046	0.019	0.091	0.047	0.032	0.026
W	*		*		**		ns	
T	**		**		**		ns	
W*T	*		*		**		ns	

Discussion

In this study, the change in water source of wheat and soybean grown in a continuous no-tillage field was investigated as a trial for establishment of no-tillage upland crop rotation system in Japan. The results confirmed that no-tillage caused higher dependence on the surface supplied irrigation water in both wheat and soybean (Table 4). This agreed with our previous findings in no-tillage wheat - rice intercropping experiments in a small experimental paddy field (Iijima et al., 2005). This phenomenon could be mainly attributed to the accumulation of roots in the surface soil layer under the no-tillage condition (Table 2). The no-tillage treatment increased mechanical impedance to root penetration to 3.5 - 4.4 times that with tillage (Table 1). The higher impedance reduces the root elongation rate causing a shallow root system (Iijima and Kono, 1991; Iijima et al., 1991), and in the no-tillage field, roots often accumulate at the surface soil layer (Izumi et al., 2004a, b). In fact, under the drought condition, the root density in the subsoil layer (15－30 cm) in the no-tillage field was declined to 52 % and 9 % of that in the tillage field with wheat and soybean, respectively (Table 2). The deep rooting of crops (Araki and Iijima, 1998; Araki et al., 2000; Araki and Iijima, 2001; Araki et al., 2002) must be very important for the water acquisition from the limited water source especially under drought stress condition. The reduced root growth in the deep soil layer of no-tillage field will cause the water shortage under prolonged drought condition. By contrast, the roots of soybean in the pod filling stage showed enhanced lateral root branching in the no-tillage field, especially under dry condition. The dense branching of lateral roots in the surface soil layer, which is the compensatory growth for the reduced deep-root development, would be effective in absorbing the rainfall and/or irrigation water.

The deuterium analysis also revealed that both crops showed higher dependence on the irrigation water under a dry condition than a wet condition (Table 4). This agreed with our previous findings in the experiments with drought-stressed pearl millet - cowpea intercropping experiments in the Namibian field (Zegada-Lizarazu et al., 2006b) and Japanese field (Zegada-Lizarazu et al., 2006a) and simulated pot experiments (Zegada-Lizarazu and Iijima, 2005). Under a drought condition, the use of available soil water is relatively difficult due to a lower water potential. Under such circumstances, newly supplied irrigation water, which shows the highest water potential just after the application to the soil, may be easily absorbed by the crops under drought stress. This may be why the crops in dry treatment rely much on the newly supplied water. Further study is necessary to find out the range of soil water potential, which shows the higher accessibility for plants as a dominant water source.

In conclusion, the no-tillage treatment caused the higher dependence of wheat and soybean on the supplied irrigation water. This is most probably attributed to the densely accumulated shallow root system due to the high mechanical impedance to root penetration of the soil in no-tillage.

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