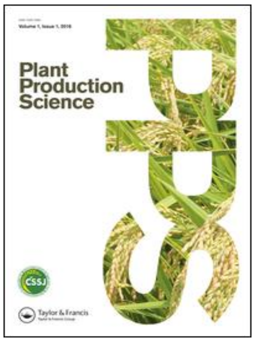

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Productivity and Water Source of Intercropped Wheat and Rice in a Direct-sown Sequential Cropping System: The Effects of No-tillage and Drought

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Abstract : In Japan, wheat-rice crop rotation with the practice of rice transplanting has been quite popular in the past. Mechanized direct-planted wheat-rice sequential cropping was developed at the Aichi Prefecture Agricultural Research Center by intercropping them for two months in spring. An objective of this study was to evaluate the introduction of continuous no-tillage to the cropping system with emphasis on water stress. The water source of intercropped wheat was also elucidated using deuterated heavy water to analyze water competition between crops. Continuous no-tillage of wheat-rice direct planting was performed for six seasons (three years) in an experimental small paddy field. No-tillage resulted in a doubled soil penetration resistance in the surface layer of soil, indicating the risk of suppressing root development. The higher yield of wheat in the dry plot suggested that excess-moisture stress occurs in the field. In the no-tillage plot, light transmission to intercropped rice seedlings increased significantly due to the reduced wheat biomass production. Wheat and rice yields were not statistically lowered by the no-tillage practice. This indicated that it is possible to introduce continuous no-tillage to the cropping system. The no-tillage significantly increased the deuterium concentrations in the xylem sap in wheat after the application of simulated rainfall with deuterated water. This indicated that the water uptake dependency of wheat shifted from stored soil water to recently applied water, which suggested the higher competition between the crops may occur under no-tillage conditions.

Key words : Competition, Crop rotation, Deuterium, Direct sowing, Hydrogen stable isotope, Intercropping, No-tillage, Water use.

Rice-wheat crop rotation has been widely practiced as a traditional agricultural technique in Japan. Rice is transplanted and grown in paddy fields from spring to autumn, and wheat is cultivated in the field as an upland winter crop. In the Tokai district in central Japan, however, this cultivation system was discontinued after the introduction of the rice transplanter. One reason is that it is necessary to transplant younger rice seedlings in mechanical transplanting than those used in hand transplanting. When a rice transplanter is used after wheat harvesting under the mechanized transplanting system, the period of vegetative growth of rice is shorter, and rice yield may become lower. On the other hand, establishment of the direct-sowing cultivation method in rice has been expected to save labor force and production cost. Under these circumstances, the Aichi Prefecture Agricultural Research Center conducted experiments to evaluate the rice-wheat no-tillage direct sowing system to transform the traditional cropping system into a mechanized rice-wheat cropping system to reduce labor (Hamada et al., 2000).

With this cropping system, rice and wheat are planted directly in a field. The growth period of crops must be overlapped for about two months because the growing season of rice is too short when the rice is seeded directly into the field after harvest of wheat. The characteristic of the cropping is that the rice is line planted by a machine under no-tillage condition in February, which is mid-winter in Japan, between the wheat rows. As it is mid-winter, internode elongation of the wheat has not started; thus, machine planting of rice does not cause a reduction in wheat yield by stamping down the wheat leaves. Rice germinates in mid-April and emerges from the soil surface at the end of April, when the wheat heading starts. The wheat is machine-harvested in mid-June, just before the rainy season. At this time the plant height of rice is from 0.1 to 0.2 m, but, the shoot apical meristem is still underground because the seeds were sown at a depth of 0.05 m. Thus, most of the rice plants will later recover, and no yield reduction will result from the plants being stamped down by the harvester.

Direct-sowing sequential cropping provides the opportunity for continuous rice-wheat cropping; however, there are also associated problems to be solved. For example, excess moisture stress for wheat occurs during the rainy year; in contrast, early growth

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of rice under wheat is sometimes restricted during the dry years, most probably due to the water competition between crops. Moreover, land preparation by tilling must be done between rice harvesting in mid-October and wheat planting in mid-November, within less than one month. If a system of continuous no-tillage can be introduced, more labor savings and safety would be achieved.

The practice of no-tillage has been extensively researched in many cropping systems (Lal, 1989; Oyanagi et al., 1989; Iijima et al., 2003; Izumi et al., 2004a and b) however, it has not yet been tested for direct-sowing rice-wheat sequential cropping. Basic information on the effects of no-tillage on the cropping system is required to solve the above-mentioned problems. The primary objective of this study was to evaluate the introduction of continuous no-tillage to a cropping system with emphasis on water stress.

As stated above, water competition between rice and wheat at the rice seedling stage occurs in dry years. Evaluation of water competition between intercrops has been traditionally done by direct observations of root distribution, water-uptake capacity, and water use efficiency of component crops (Nambiar and Sands, 1993; Casper and Jackson, 1997). A more agile way to determine the water sources and root activity in competitive environments is to measure the variation in the relative abundance of deuterium in the xylem water of plants. Hydrogen stable-isotopes have been extensively used to determine the source of water taken up by plants (Ehleringer et al., 1991; Dawson, 1993; Lin et al., 1996; Sekiya and Yano, 2003; Araki and Iijima, 2004; Zegada-Lizarazu and Iijima, 2004). We used this technique for the evaluation of the water use in wheat-rice intercropping system. The secondary purpose of this paper was to determine the water source of intercropped wheat using deuterated heavy water to analyze water competition between crops.

Materials and Methods

1. Experimental paddy field, tillage and water treatments

An experiment was conducted for three years in an experimental paddy field made with a concrete frame at Nagoya University, Japan (N 35˚9'47, E 136˚56'57). Eight 2.3×2.3 m (5.29 m^2) plots were prepared, and were subjected to tillage and no-tillage treatments with four replications randomly arranged. The wheat cultivar, Norin 61, and the paddy rice cultivar, Aoinokaze, both are recommended cultivars in Aichi Prefecture, were used for the experiment. Wheat and rice were grown under upland and paddy conditions, respectively, by draining the excess water through a channel between the plots. The crops were grown for six successive cropping seasons from 2000/2001 to 2002/2003. In the second and third years, half of the replicates were covered with transparent vinyl sheets from April to June to protect the field from rainfall (dry treatment). The other half of the replicates were under natural rainfall (wet treatment). During the growth period in 2001/2002, the wet plots, however, were irrigated occasionally to avoid drought. The vinyl shade was removed after wheat harvesting.

2. Field management

In May 2000, the field was hand-ploughed twice and then leveled using a rake. From June to October 2000, rice was cultivated as the preparatory cropping before the experiment began. In the tillage treatment, hand-tilling (0.10−0.15 m deep) was performed immediately before wheat sowing. In the no-tillage plots, the soil was undisturbed except for the planting holes and surface scraping for weeding. The topsoil in the field was heavy clay (sand 22.3%, silt 47.6%, clay 30.2%). Wheat was sown between mid-November and the beginning of December, and rice between mid and late February. Both crops were sown manually in a V-shape planting ditch (0.05 m deep) with row spacing of 0.2 m in the row planting. Ten g and 15 g of dry seeds per m^2 were sown for wheat and rice, respectively. For wheat, the basal fertilizer was mixed with soil during tilling, and applied on the soil surface for the no-tillage treatment. For rice, the basal fertilizer was applied to the planting holes together with the seeds. Topdressing was broadcast on the soil surface in all treatment and crops. Fertilization was done according to the prefecture guidelines as follows. For wheat, 6, 4, and 6 g/m^2 of N, P_2O_5 and K_2O, respectively, were applied as a basal dressing using a compound synthetic fertilizer (N, 0.14 g g^{-1}; P_2O_5, 0.10 g g^{-1}; K_2O, 0.14 g g^{-1}). An additional application was conducted by one- to two-time split dressing to supply 6 g/m^2 of N using ammonium sulfate. When the rice was sown, a slowly-dissolving (controlled release) nitrogen fertilizer (LP-S100: LP-S120＝4:6) at the rate of 13.3 g N/m^2 was applied to the planting ridge. No other elements or topdressing were applied to rice because rice plants can utilize additional fertilizer applied to wheat. Pest management was not conducted for either crop.

3. Soil physical properties, harvesting and light transmission

The penetration resistance of the soil was measured with a cone penetrometer (DIK-5521, Daiki Rika Kogyo Co., Ltd., Japan) in the second year, six weeks after planting of wheat. The soil-water content (volume %) was measured with a profile probe (Delta-T Devices Ltd., UK) at the maturing stage of wheat, about one month after the drying treatment was initiated in the second year. The profile probe was inserted in the center point of each plot. For each treatment, eight and four replicates were taken for measurement of penetrometer resistance and soil-water content, respectively. Three to five lines (0.3 m each) of wheat and rice were harvested in mid-June and October, respectively, from each plot, and shoot dry weight and yield were measured. However, the shoot dry weight in the 1st year and the yield of wheat and rice in the 3rd year were not measured. Light transmission to the top of the rice leaf was measured with a photometer (CONMIC-100B, Koito Industries Ltd., Japan) in the second year in May 2001, at the wheat maturing stage, to evaluate the light competition between crops. Light transmission (LT) to the rice leaf was evaluated as LT (%) = (Lr/Lo), where Lr is the light intensity at the top of the rice leaf and Lo is that outside the plant canopy.

4. Deuterium analysis

In the final year, only deuterium analysis was conducted to evaluate the water acquisition pattern of wheat. The water uptake pattern of wheat was examined at the heading stage in the third year by the stable-isotope method, which is used widely in natural forest ecosystems. Schwinning et al., (2002) determined dependability on simulated recent rainfall using deuterated irrigation in a desert shrub-grass community. We used a similar technique for field-grown wheat at the heading stage. One hundred mL of heavy water (1 atom % D_2O) was applied between the wheat and rice rows just before sunset on the day before xylem sap collection. The heavy water application was regarded as the recent rainfall or recently irrigated water. The xylem samples were collected from the cut end of the stems, placing cotton puffs on the cut end of the stumps of wheat and wrapping them in thin polyethylene film for three hours. Due to the small diameter of the rice seedlings, we could not collect a sufficient amount of xylem sap for deuterium analysis. The samples were then placed in plastic bags. The stored soil water, which existed in the soil before application of labeled water, was also collected. The samples were stored at −20˚C before the analysis of δD by mass spectrometry (DELTA^{plus}, Finnigan Mat Instruments, Inc., Germany). The δD values were expressed as $\delta D = [(R_{sample}/R_{V\text{-}SMOW})-1]*1000‰$, where R is the molar ratio of heavy to light isotope (D/H), with D being deuterium and H hydrogen. These values were converted into the concentration of deuterated water (atom %) and used to calculate the atom % excess in plant xylem sap after an enriched irrigation event.

5. Replications and statistical analysis

For the analysis of wheat yield in the first-year and that of rice in the first- and second-years, and for the analysis of penetrometer resistance, the number of replications was four, which are the average values of individual plots. Data from four to six samplings were used as the replications for other analysis because only two replicate plots, which offer an insufficient degree of freedom for analyses of variance (ANOVA), were available due to the limitations of the construction for dry treatments. A two-way ANOVA was used to compare the effects of two tillage and two soil moisture conditions. To compare the two tillage treatments, we used a one-way ANOVA.

Results and Discussion

1. Climate and soil physical conditions

Fig. 1 shows the monthly hours of sunshine, amount of rainfall, and average temperature during the experiment. Wheat heading was observed from April 20 to 30 in the first and third years; however, it began on April 4 in the second year because of the warmer temperature in March. The total rainfall during the wheat cultivation from mid-November to mid-June was 200 and 180 mm less than the average of 670 mm in the first and second years, respectively. In the third year, however, significantly less sunshine (only 2/3 of the average from 1992 to 2002) was recorded in summer from June to August due to very wet climate (1.78 times of the average rainfall).

Soil penetration resistance, at a depth between 0.25 and 0.1 m from the soil surface, was significantly higher in the no-tillage than in the tillage plot (Fig. 2). No-tillage resulted in twice as much soil penetration resistance at the soil surface; this indicates that the no-tillage results in the high risk of suppressing root development. There was no significant difference in the soil-water content (volume %) between the no-tillage and tillage plots near the soil surface layer, but a significant difference was observed at a depth of 0.15 m (Table 1). Under the wet treatment, the soil water content of tillage plot was 16% higher than that of the no-tillage plot in this soil layer. This trend was similar under the dry treatment, although there was no significant difference. These results indicate that the drainage at this depth was slightly better in the no-tillage plot; the outcome was attributed to the formation of biopore under continuous no-tillage. Because there was no disturbance resulting from plowing, continuous no-tillage contributed to the maintenance of biopores, which are formed by the activities of soil organisms such as earthworms and the decay of plant roots. The biopores can provide a favorable condition for root growth by the improvement of permeability of air and water in soil (Wuest, 2001). Although the no-tillage practice caused higher soil resistance to root growth in the soil surface layer, the favorable soil structural condition at a slightly deeper level can be expected in a paddy field under the continuous no-tillage.

2. Growth, shading effects, and yield

The growth of wheat was slower under no-tillage. At the maximum tillering stage, the number of stems per

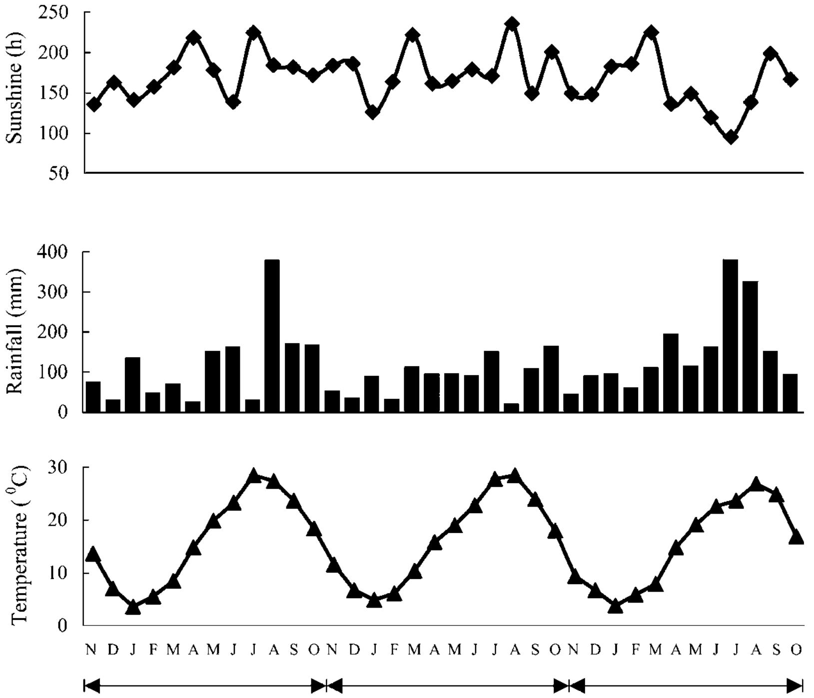

Fig. 1. Monthly sunshine and rainfall, and average temperatures near the experimental site during the three-year experiment (Source; Nagoya local meteorological observatory).

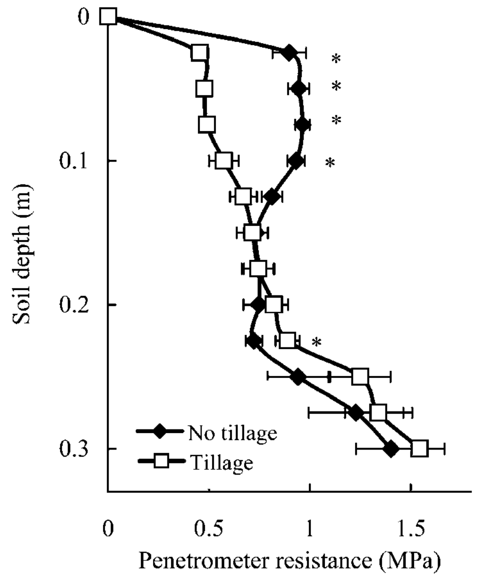

Fig. 2. Penetrometer resistance of the field under tillage and no-tillage conditions. The tillage field was cultivated up to 0.10 – 0.15 m deep using a hoe. Error bars show standard error (n=4). *, significant difference at the 5% level. Data was taken on December 2001, the second year of the experiment.

Table 1. Soil water content (volume %) in a field with different tillage and water treatments. *, significant difference at 5% level (n=4). The two-factor interaction was not significant. Data was taken on May 2002, the second year of the experiment.

	Water treatment	Tillage treatment No-tillage	Tillage	Mean
0.05 m depth	Wet	52.4	51.6	52.1
	Dry	47.3	42.1	44.7 *
	Mean	49.8	46.8 ns	
0.15 m depth	Wet	46.1	53.3	49.7
	Dry	50.4	53.8	52.1 ns
	Mean	48.3	53.5 *	

Table 2. Light transmission and shoot dry weight of rice seedlings with different tillage and water treatments. **, significant difference at 1% level (n=6). The two-factor interaction was not significant. Data was taken on June 2002, the second year of the experiment.

	Water treatment	Tillage treatment No-tillage	Tillage	Mean
Light transmission (%)	Wet	56.8	16.2	36.5
	Dry	56.2	19.5	37.8 ns
	Mean	56.5	17.8 **	
Shoot dry weight (mg plant^{-1})	Wet	47.5	19.0	33.2
	Dry	33.4	18.4	25.9 ns
	Mean	40.5	18.7 **	

unit area was 1.5 times greater in the tillage than in the no-tillage plot. Plant height was significantly lower in the no-tillage plot than in the tillage plot (data not shown). The reduced wheat shoot growth allowed greater light transmission to the intercropped rice seedlings. Light transmission in the no-tillage plot was more than three times higher than that in the tillage plot (Table 2). This enhancement of light transmission to the rice canopy, together with the reduced wheat growth, resulted in promoted shoot growth (more than twice) of the rice seedlings in the no-tillage plot. The dry treatment did not affect the light transmission or the shoot dry weight, as shown in the two-way ANOVA. The shoot dry weight in the no-tillage plot, however, was about 30% lower under the dry treatment than under the wet treatment. This would be caused by the shortage of surface soil water for intercropped rice seedlings.

Although the wheat shoot growth was significantly lower in the no-tillage plot (Table 3), the productive tiller ratio was higher (91%) in the no-tillage than in the tillage plot (64%). As a result, the number of productive tillers was not significantly different between the two tillage plots (data not shown). Finally,

Table 3. Yield and shoot dry weight of wheat in the 2000/2001 and 2001/2002 seasons. * and **, significant difference at the 5 and 1% level {n=4 (first year) and 6 (second year)}. The two-factor interaction was not significant.

			Tillage treatment		
		Water treatment	No-tillage	Tillage	Mean
2000/2001	Yield (g m^{-2})	Wet	506	531	519 ns
2001/2002	Yield (g m^{-2})	Wet	344	369	357
		Dry	437	429	433 *
		Mean	391	399 ns	
	Shoot dry weight (g m^{-2})	Wet	1151	1826	1488
		Dry	1221	1688	1454 ns
		Mean	1186	1757 **	
	Harvest index	Wet	0.30	0.20	0.25
		Dry	0.36	0.25	0.31 *
		Mean	0.33	0.23 **	

Table 4. Yield, shoot dry weight, and harvest index of rice at the 2001 and 2002 seasons. NS, not significant difference (n=4).

	Yield (g m^{-2})		Shoot dry weight (g m^{-2})		Harvest index	
	No-tillage	Tillage	No-tillage	Tillage	No-tillage	Tillage
2001	640	575 ns	2043	2392 ns	0.31	0.24 ns
2002	700	762 ns	1780	1863 ns	0.39	0.41 ns

the wheat yields in the first and second years were not significantly decreased by no-tillage (Table 3). Although the shoot growth was reduced, harvest index in the no-tillage plot was 1.4 times greater than that in the tillage plot. As for the water treatments, the yield under the dry treatment was 1.2 times greater than that under the wet treatment. As the shoot growth was not affected by the water treatments, the harvest index was 1.2 times greater under the dry treatment. The higher yield of wheat under the dry treatment suggested that excess moisture stress occurred in the field. The wheat yield was the highest in the no-tillage plot with dry treatment, although they were not statistically significant. There were no significant differences in seed and shoot biomass production for rice between the two tillage treatments, although the no-tillage treatment tended to cause a reduction in the shoot dry weight (Table 4).

The production of intercropped wheat and rice was not significantly lowered by the practice of no-tillage. Therefore, the application of continuous no-tillage to the direct seeding wheat-rice intercropping is basically possible. In the present cropping system, tillage should be done between rice harvesting and wheat planting during a lapse of less than one month. In a rainy year, farmers occasionally can not afford enough time to conduct land preparation under dry-field condition, because of the labor requirements after harvesting of rice and preparations for wheat planting. Introduction of continuous no-tillage into the cropping system should be effective for saving labor and increasing safety. Practical examination in a farm field should be further conducted to search for any disadvantages in applying the continuous no-tillage to the direct seeding wheat-rice intercropping system.

Table 5. Shoot dry weight, xylem sap exudation, and deuterium concentration in xylem sap of wheat after the application of deuterated water to the soil surface. Significant difference at 1% (**), 5% (*), and 10% (†) levels (n=6). The two-factor interaction was not significant. Data was taken on May 2003, the third year of the experiment.

		Tillage treatment		
	Water treatment	No-tillage	Tillage	Mean
Shoot dry weight (g)	Wet	1.2	1.8	1.5
	Dry	1.1	1.7	1.4 ns
	Mean	1.2	1.8 **	
Xylem sap exudation/shoot dry weight (mg g^{-1})	Wet	13.4	35.3	24.3
	Dry	12.6	25.1	18.9 ns
	Mean	13.0	30.2 **	
Deuterium concentration in xylem sap (atom % excess)	Wet	0.089	0.073	0.081
	Dry	0.076	0.050	0.062 †
	Mean	0.084	0.063 *	

3. Deuterium analysis

The results of the analysis of water source of wheat at the heading stage are summarized in Table 5. The no-tillage treatment significantly increased the deuterium concentration in xylem sap. This indicated that the water source of wheat was shifted to the deuterium-labeled simulated rainfall by the practice of no-tillage. Therefore, it is assumed that wheat grown under no-tillage conditions would have a higher water-uptake dependency on rainfall than on stored soil water. This would be attributed to the root activities, root distribution, and root branching near the surface soil layer. No-tillage and/or associated higher soil penetration resistance cause root accumulation in the surface soil layer (Lal, 1989; Iijima et al., 1991; Izumi et al., 2004a and b). Roots that accumulate in a limited volume of surface soil often consist of densely branched higher-order laterals (Iijima and Kono, 1991). These roots may absorb recently irrigated and/or rained water more quickly than stored soil water. This would most likely be the main reason for the modified water uptake pattern in the no-tillage condition. Because rice seedling roots mainly would accumulate in the surface soil layer at this growth stage, higher competition for stored soil water may occur between wheat and rice under no-tillage conditions.

The practice of no-tillage significantly decreased the xylem sap exudation rate, which is the indication of total root mass and root activities (Morita and Abe, 1999), showing that total root mass and/or root activities were reduced by the no-tillage treatment. In the present study, the deuterium concentration in xylem sap was significantly reduced by the dry treatment. That is, the wet soil caused increased dependency on simulated rainfall (significant at $P < 0.10$). This is probably due to the lower water-uptake ability of deeper roots in wheat subjected to excess moisture stress (wet treatment); the absorption of stored soil water under the wet soil condition would be much slower than that in the dry non-stressed roots. Root distribution to the deeper layers may also be restricted due to the excess moisture condition under the wet treatment.

The root system in a mechanically impeded soil often develops near the surface of the soil with densely proliferated branching roots (Iijima and Kono, 1991; Iijima et al., 1991). Under such conditions, rice seedlings with a relatively small root system (smaller than that of matured wheat) will require sufficient water in the shallow soil layer accessible by the rice roots in order to sustain optimum growth. If the water on the surface layer of the soil is limited as a result of a prolonged drought, the practice of no-tillage will cause the water shortage to the intercropped rice seedlings. Wheat growth would also rely on the water in the surface soil, as its water uptake activities in the deeper soil would be reduced as a result of excess moisture stress. If this were the case, the water competition between young rice seedlings and mature wheat would increase. Rice seedling growth in the no-tillage plot was restricted by the dry treatment (Table 2). This phenomenon can be explained more clearly by the water-uptake competition between the two crops. The dependence of rice seedlings on deuterium-labeled rain water should also be examined further to demonstrate the water competition between the two crops.

Conclusion

In this study, the effects of continuous no-tillage on the wheat-rice direct sowing cropping was examined. The results led to the conclusion that the practice of no-tillage can be introduced into the wheat-rice intercropping system. The no-tillage practice enhanced the dependence of wheat on simulated rainfall. The water competition for the limited water in surface soil between young rice seedlings and matured wheat may increase due to the practice of no-tillage.

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* In Japanese with English summary

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