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Design and evaluation of a one-operation shallow up-cut tillage sowing method for soybean production

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ABSTRACT

Sowing using a rotary tiller rotating in reverse (up-cut) is a labor-saving technology for soybean production because it can perform tillage and sowing, make ridges, and bury winter crop residues in one operation. However, the power requirement of up-cut rotation is higher than of normal rotation (down-cut), resulting in lower working speeds. Shallow tillage sowing methods may be a solution to this problem. Here, we develop a shallow tillage sowing method using an up-cut rotary and a side-disk which could perform the aforementioned works in one operation and conducted field experiments in 2015 and 2016 to study the effect of our sowing method (up-cut shallow tillage; UST) on ridge shape, soil volumetric water content (VWC) and soybean growth and yield, compared to conventional sowing methods (up-cut conventional tillage; UCT, and down-cut conventional tillage; DCT). Ridge shape did not differ among sowing methods. The VWC at 10 and 20 cm depths in DCT was always higher than in UST and UCT, indicating poorer drainage. The VWC at 10 cm depth decreased quickly after rain in UST and UCT, indicating good surface-layer drainage, but at 20 cm depth in UCT, VWC was lower than in UST, especially during dry spells, indicating higher water-holding capacity in UST than in UCT. Shoot and root growth and seed yield did not differ among sowing methods, indicating that UST did not negatively affect soybean growth and yield. These results suggest that UST can be used for soybean production.

1. Introduction

Soybean [*Glycine max* (L.) Merr.] seeds contain abundant protein, oil, and nutrients and have long been processed for traditional Japanese foods, such as tofu, miso, natto, and soy sauce. Soybean yields in Japan are low and have not increased in the past 30 years: the 30-year (1987–2016) average soybean yield is 1.65 t ha^{-1} FOASTAT (1987–2016). However, soybean yields have been steadily increased from 2.28 t ha^{-1} in 1987 to 3.50 t ha^{-1} in 2016 in the United States and from 1.86 t ha^{-1} in 1987 to 2.90 t ha^{-1} in 2016 in Brazil FOASTAT (1987–2016). To increase Japanese soybean production, it is necessary to develop new agricultural technologies or breed new higher yielding cultivars.

In southwestern Japan, the double-cropping system is widely practiced, making use of the warm climate. Rice (*Oryza sativa* L.) or soybean is grown in summer and wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) is cultivated in winter in the same paddy fields. In the double-cropping system, the summer crop operations are as follows: winter crops are harvested until early June, then rice is transplanted from mid- to late June, or soybean is planted in early to late July.

Optimum soybean planting date in southwestern Japan is thought to be around 10 July (Ohga, Miyoshi & Hirano, 1985; Uchikawa, Fukushima & Matsue, 2003). This is the middle or end of the rainy season in southwestern Japan, so unpredictable heavy rainfall frequently occurs. Furthermore, there is generally little rainfall after the rainy season. Therefore, producers are forced to plant soybean seeds in sunny spells during the rainy season or within several days of the end of the rainy season. If sowing is performed in sunny spells during the rainy season, flooding stress, which inhibits germination or early vegetative growth (Nakayama et al., 2004), may occur. Drought stress, which also inhibits germination and early seedling growth (Helms, Deckard, Goos & Enz, 1996), can occur if sowing is carried out after the rainy season. In this way, the soil water fluctuation from flooding to drought results in an unstable optimum planting date, leading to unstable and low soybean production in southwestern Japan.

A two-operation sowing method with down-cut rotary tillage is widely used for soybean production in southwestern Japan. The first operation plows and buries winter crops and weed residues into the soil with down-cut rotary tillage after harvesting winter crops (usually mid-June to early July). The second operation plows and sows seeds simultaneously with down-cut rotary tillage and seeding machinery (usually early to late July). Once the fields are plowed in the first operation, the plowed surface soil layer becomes soft and

porous. Thus, surface water after rainfall does not drain quickly. Furthermore, in southwestern Japan, more than 90% of soybeans are cultivated in converted rice paddy fields with poor drainage. Therefore, these problems make it difficult to perform the second operation within the optimum planting period if the two-operation sowing method is used.

To solve this problem, several one-operation sowing methods which carry out tillage, sowing, and ridging simultaneously, have been developed using both down-cut and up-cut rotaries. Previously developed methods include: all-in-one equipment for tillage, ridge formation, and seeding with up-cut rotary tillage (tillage depth; approx. 13 cm) (Hosokawa, 2005, 2006); shallow tillage seeder with down-cut rotary tillage and side-disk ditcher (tillage depth; 5 cm) (Fukami et al., 2009; Watanabe, 2006; Watanabe et al., 2009); inter-row strip tillage with both down-cut and up-cut rotaries (tillage depth; 4–5 cm) (Amaha, Yoshinaga & Koizumi, 2006; Yoshinaga, Kono, Shiratsuchi, Nagata & Fukuda, 2008); and partial shallow tillage and sowing with down-cut rotary tillage (tillage depth; 5–6 cm) (Kawamura, Odawara, Mitsuoka, Inoue & Okayasu, 2013).

The rate of soil pulverization (percentage of soil clod weight passing through a 20-mm sieve in the 0–5 cm soil layer) with an up-cut rotary tiller is higher than that with a down-cut rotary tiller (Kanatani & Kurata, 1989; Morimoto, Miura, Yagi & Karahashi, 1983). Kanatani and Kurata (1989) and Sun, Ito, Ataki and Yamashita (2004) showed that the germination rate of soybean decreased as the rate of soil pulverization decreased. Moreover, Morimoto et al. (1983) and Kanatani and Kurata (1989) reported that the percentage of culms and hills of preceding crops buried was higher with up-cut rotary tillage (tillage depth; approx. 11 cm) than with down-cut rotary tillage (tillage depth; approx. 11 cm). Thus, sowing with up-cut rotary tillage will lead to more stable germination of soybean than with down-cut. However, the power requirement of up-cut rotary tillage is larger than down-cut rotary tillage, because up-cut rotates against the tractor's running direction (Kanatani & Kurata, 1989; Morimoto et al., 1983), resulting in lower working speed with up-cut rotary tillers. Higher working speed is required to complete planting within optimum planting period because the optimum planting period in southwestern Japan is very short. Hosokawa, Adachi, Itoh and Matsuzaki (2001) studied the effect of tillage depth with up-cut rotary tillers on power requirement and reported that the power requirement for shallow (11–12 cm) tillage

Figure 1. Sowing with one-operation shallow tillage with up-cut rotary tiller and side-disk (up-cut shallow tillage: UST) (a, b), one-operation conventional tillage with up-cut rotary tiller (up-cut conventional tillage: UCT) (c, d) and two-operation conventional tillage with down-cut rotary tiller (down-cut conventional tillage: DCT) (e, f). Pictures are from the side of (a, c, e) and behind (b, d, f) rotaries. The upward arrow in Figure 1(a) indicates side-disk attached to up-cut rotary tiller. Downward arrows in Figure 1(a,c) indicate the difference in the space between the side-board and the soil surface in UST and UCT.

was approximately 40% lower than for standard or deep (14–15 cm) tillage. Their result indicated that shallow tillage with up-cut rotary tillers could increase tractor working speed. Although some researchers have developed one-operation shallow tillage sowing methods, they all use down-cut rotaries (Kawamura et al., 2013; Watanabe, 2006). One-operation shallow tillage sowing methods with up-cut rotary tillers have not been developed, despite the many benefits of up-cut rotary.

In the present study, we developed a one-operation shallow tillage sowing method with up-cut rotary tillage to perform tillage and sowing, making drainage ditches simultaneously. To make drainage ditches efficiently, a side-disk with structure was similar to that used by Watanabe (2006) was attached to the up-cut rotary tiller. We studied the effect of our novel sowing method on ridge shape, soil penetration resistance, soil

volumetric water content (VWC), and growth and yield of soybean compared to conventional sowing methods using the same tractor speeds.

2. Materials and methods

2.1. Site description and plant materials

Field experiments were conducted in 2015 and 2016 on a fine-loamy, thermic Typic Endoaquept (clay, 37.8%; silt, 37.4; sand, 24.8%) at the Kyushu Okinawa Agricultural Research Center (KARC), Chikugo, Fukuoka, Japan (33° 12′ N, 130° 30′ E, 10 m elevation). The volumetric solid content, porosity, and VWC at permanent wilting point (−1.5 MPa) of the soil were 30.6%, 69.4%, and 11.7%, respectively. The winter crop for both growing seasons was barley (*Hordeum vulgare*). The soybean cultivar used was Fukuyutaka, which is a leading cultivar in this region.

2.2. Sowing methods

In this study, three sowing methods were tested: one-operation shallow tillage sowing with up-cut rotary tiller and side-disk (up-cut rotary tiller with shallow tillage: up-cut shallow tillage (UST), tillage depth: 10 cm) (Figure 1(a,b), one-operation conventional tillage sowing with up-cut rotary tiller (up-cut rotary tiller with conventional tillage: up-cut conventional tillage (UCT), tillage depth: 15 cm) (Figure 1(c,d)), and two-operation conventional tillage sowing with down-cut rotary tiller (down-cut rotary tiller with conventional tillage: down-cut conventional tillage (DCT), tillage depth: 15 cm) (Figure 1(e,f)). In UST, side-disks (NSD-401; MATSUYAMA PLOW MFG Co., Ltd., Nagano, Japan) were modified and attached to the front side of an up-cut rotary tiller (APU1510H-0S; MATSUYAMA PLOW MFG Co., Ltd.) (Figure 1(a)). The bottom of the side-disks was lower than the rotary pawls. The side-disks dig drainage ditches and sufficiently dug soil is carried to the front side of the up-cut rotary tiller. The rotary pawls then plow the dug soil and the soil surface layer. The bottom of the sideboard of the up-cut rotary tiller in UCT (a downward arrow in Figure 1(c)) was lower (just above the soil surface) than in UST (a downward arrow in Figure 1(a)). The power of the tractor used in UST and UCT was 39.0 kW. In DCT, a down-cut rotary tiller (RL15K; Kubota Co., Osaka, Japan) was used, and a two-operation sowing method was carried out as in conventional cultivation in southwestern Japan. First plowing was performed to enhance working efficiency by burying winter crop residues without sowing, and then sowing was carried out at the same time as second plowing. The power of the tractor used in DCT was 30.1 kW. Regardless of sowing method, wheat and weed residues were incorporated into the soil (Figure 1(b, d and f)).

2.3. Crop management

Soybean seeds were treated with insecticide and fungicides that contained 22.6% thiamethoxam, 1.7% mefenoxam, and 1.1% fludioxonil (Cruiser MAXX, Syngenta, Tokyo, Japan) at a rate of 8 ml per 1 kg seed before sowing. The planting dates were 10 July and 7 July in the 2015 and 2016 growing seasons, respectively. All sowing methods were carried out in a single day. The field remained untilled, and after harvesting barley, the residues were in the field until the sowing of soybean. Two seeds per hill were planted with a seeding machine (ADRG-U, AGRITECNO YAZAKI Co., Ltd., Hyogo, Japan) with 75 cm row spacing by 20 cm hill spacing on a 150 cm ridge (13.3 plants m^{-2}) for all sowing methods. Tractor working speed was constant and set at approximately 2 km h^{-1} for all sowing methods. The area of each plot was 90 m^2 (3 ridges or 6 rows wide and 20 m long). A pre-emergence herbicide, which contained 8% thiobencarb, 0.8% pendimethalin, and 1.2% linuron (KUMIAI CHEMICAL INDUSTRY Co., Ltd., Tokyo, Japan), was applied at a rate of 5 g m^{-2} immediately after sowing. Inter-tillage and ridging, which are conventional agricultural practices in Japan for controlling weeds and lodging, were carried out on 30 July 2015 and 25 July 2016 and then hand weeding was performed as needed. Insecticides and pesticides
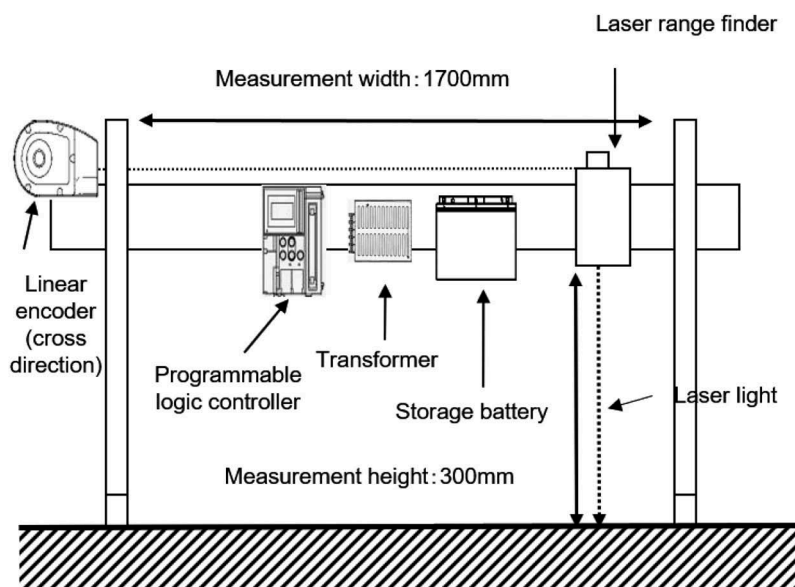

Figure 2. Details of hand-made profiler used for measurements of soil ridge shapes.

were equally applied to all plots as necessary to maximize the yield.

2.4. Measurements

Air temperature, hours of sunlight, solar radiation, and rainfall were measured at the KARC meteorological station, located about 100 m away from the experimental field. The soil VWC (v/v) was monitored with soil moisture sensors (EC5, METER Group, Inc., Pullman, WA, USA) at depths of 10 and 20 cm throughout the growth period. The VWC was measured and recorded every 60 min using dataloggers (Em5b, METER Group, Inc., Pullman, WA, USA). Due to a limited number of sensors and dataloggers, VWC was measured for one replication (central plot) per sowing method.

Immediately after sowing in 2015, the soil penetration resistance (SPR, MPa) was measured with a soil penetrometer (DIK-5521, Daiki Rika Kogyo Co., Ltd., Saitama, Japan). SPR measurement was performed from the soil surface down to 40 cm depth, and the SPR of three positions per plot was measured.

Soil pulverization rate of the tilled layer was measured for each sowing method after the SPR measurement. Soil samples of approx. 3 kg were collected and sieved with a 20 mm mesh, and then the weight of soil samples with bore diameter less than 20 mm were measured. On average, soil moisture content of the sampled soil was 29.7%.

The ridge shape was measured in 2015 with a hand-made profiler (Figure 2) as described by Tsuchiya, Tasaka and Sasaki (2009). Briefly, the profiler consisted of a laser range finder (Z4W-LD250, OMRON Co., Kyoto, Japan), linear encoder (D-1000Z, MUTOH INDUSTRIES Ltd., Tokyo, Japan), programmable logic controller (KV-1000, KEYENCE Co., Osaka, Japan), transformer (NVD24SC12-U1, ETA Electric Industry Co., Ltd., Tokyo, Japan), and a storage battery (GSYUASA PE12V7.2, GS Yuasa International Ltd., Kyoto, Japan). The laser range finder was attached to the linear encoder. Ridge height (longitudinal direction) was measured by moving the laser range finder across the ridge, and the migration length of the laser range finder (cross direction) was measured by linear encoder. An SD memory card inside programmable logic controller recoded the data measured by both laser range finder and linear encoder. The height of the untilled soil surface between ridges was assumed to be 0 cm (baseline). For UST, ridge shape was measured first, then the tilled soil layer was carefully removed, and the shapes of the untilled layer and drainage ditch were measured. For UCT and DCT, only ridge shape was measured, because it

Figure 3. Soil sampler modified and used in this study (a). Hand-made carrier used to move sampler inside the field (b). A soil sample perpendicular to the ground could be collected by pushing soil sampler along a guide into the soil (c).

could be assumed that the shape just below the tilled layer was flat in UCT and DCT. We checked the actual shape just below the tilled layer and confirmed that the shape was almost flat.

At R2 (22 August 22 2015 and 17 August 2016) and R5 (14 September 2015 and 2016) growth stages (according to Fehr, Caviness, Burmood & Pennington, 1971), the aboveground parts in

a 1.5 m^2 area were collected. At each sampling, the leaves were separated from whole plants, and the leaf area was determined with a leaf area meter (LI-3000C, LI-COR Inc., Lincoln, NE, USA). The leaf area index (LAI; m^2 m^{-2}) was calculated by dividing the measured leaf area by the sampling area. The aboveground parts were then dried at 80°C in a ventilated oven for at least 72 h to determine the shoot dry weight (SDW; g m^{-2}). The crop growth rate (CGR; g m^{-2} d^{-1}) from R2 to R5 stages was calculated by subtracting the SDW at the R2 stage from the SDW at the R5 stage and dividing this value by the number of days from R2 to R5.

To analyze the root length density (RLD; cm cm−3), soil samples between hills were collected at the R2 and R5 stages with a modified soil sampler (Figure 3(a)). A steel spiral (outer diameter: 125 mm, inner diameter: 105 mm, pitch: 100 mm, thickness: 3.2 mm) (Kyoto Spire Co., Ltd. Kyoto, Japan) was welded to the soil sampler (length: 30 cm, inner diameter: 9.5 cm, HS-30L; Fujiwara Scientific Co., Ltd., Tokyo, Japan) to facilitate its insertion into the soil and the soil sampler, then this modified sampler was connected to an engine drive type auger (AG531, Zenoah, Saitama, Japan). These implements were attached to the hand-made carrier to move it easily inside the field (Figure 3(b)) and could collect soil samples with being attached to the carrier (Figure 3(c)). Ridge shapes and the position of the soil surface at sowing time were changed by inter-tillage and ridging, so the soils heaped up by inter-tillage and ridging were carefully removed before soil sampling. Two soil samples were collected per replicate. The soil samples were further divided into depth sections of 0–15 cm and 15–30 cm. The soil was carefully removed from roots with tap water and root nodules were completely removed. For root length measurement, each root sample was spread on a transparent plastic sheet with minimal overlapping. By using an image scanner (EPSON Expression 11000XL, Epson America, Inc., Long Beach, CA, USA), we obtained digital tiff files at a resolution of 400 dpi. The root length of scanned images was measured with WinRHIZO Pro ver. 2016a (Regent Instruments Inc., Quebec, Canada). The RLD was calculated by dividing the image root length by the sample volume.

At harvest, the aboveground parts in a 3.0 m^2 area were collected to determine the number of harvested plants, the plant height, the number of main stem nodes, the yield and yield components [i.e., number of pods m^{-2} (pods m^{-2}), the number of seeds pod^{-1} (seeds pod^{-1}), and the 100-seed weight]. The yield was adjusted to moisture content of 140 g kg^{-1}.

2.5. Experimental design and statistical analysis

The experimental design was a randomized complete block design with three replications. Statistical analyses were carried out using SPSS Advanced Statistics ver. 25 (SPSS Inc., IBM, Chicago, IL, USA), and a linear mixed model was used for this analysis. Sowing method, experimental year, and their interactions were considered fixed effects, and replication (nested within year) was considered a random effect. Analysis of variance (ANOVA) was conducted to test the effect of sowing methods, year, and their interactions on shoot growth parameters (SDW, LAI, and CGR), the RLD, and agronomical traits at harvest (number of harvested plants, plant height, number of main stem nodes, number of branches, yield and yield components). Differences between means were tested using Fisher's protected least significant

Table 1. Air temperature, sunshine hours, solar radiation, and rainfall at the experimental fields in 2015, 2016, and the 30-year average.

| Month	Stage of month	Air temperature (°C)			Sunshine hours (h)			Solar radiation (MJ m^{-2})			Rainfall (mm)		
		2015	2016	30-year	2015	2016	30-year	2015	2016	30-year	2015	2016	30-year
July	Early	24.7	27.9	25.6	3.1	6.0	4.6	13.8	19.2	15.7	98	80	169
	Middle	26.4	27.4	27.0	3.7	5.0	5.9	14.7	17.0	17.8	91	186	120
	Late	27.8	29.3	28.1	6.2	9.5	7.5	19.1	24.1	19.6	45	1	60
August	Early	29.9	29.4	28.2	10.1	8.8	7.2	24.6	22.4	19.0	0	58	58
	Middle	27.0	30.6	27.9	4.6	9.9	6.5	15.9	23.9	17.8	119	6	70
	Late	25.4	27.8	27.1	3.5	7.6	6.4	13.4	20.5	17.1	162	30	75
September	Early	23.9	26.1	26.0	4.2	4.0	6.4	14.7	14.3	16.3	97	41	68
	Middle	22.3	24.9	24.5	6.1	2.8	6.1	17.1	12.1	15.6	23	199	41
	Late	23.9	25.0	22.3	6.2	4.6	5.7	15.7	14.1	13.8	30	218	45
October	Early	19.1	24.7	20.5	6.8	5.1	6.1	15.0	15.0	13.4	58	63	22
	Middle	18.1	20.7	18.7	8.4	3.3	6.4	16.2	12.9	13.2	5	24	28
	Late	17.4	18.5	16.5	7.6	2.9	5.8	13.7	9.1	11.6	7	59	22
November	Early	16.8	13.1	14.8	4.7	7.3	5.3	10.4	13.9	10.1	12	21	30
	Middle	17.3	15.5	12.4	2.7	3.9	4.7	7.5	10.3	9.0	99	69	22
	Late	12.5	11.3	10.9	3.2	3.6	4.8	8.5	9.5	8.6	7	34	24
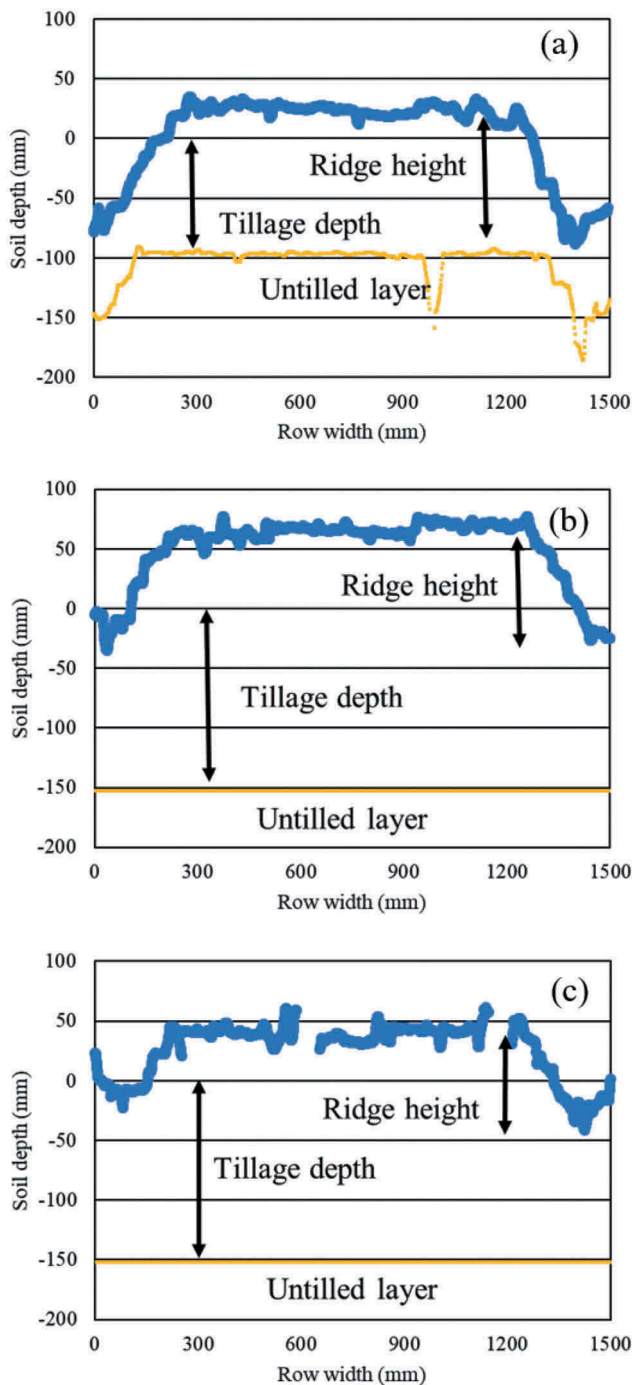
Figure 4. Sectional views of the ridges in UST (a), UCT (b) and DCT (c) in 2015. Up-cut shallow tillage, UST; up-cut conventional tillage, UCT; down-cut conventional tillage, DCT. The data for soil pulverization rate of the tilled layer in each sowing method are also shown.
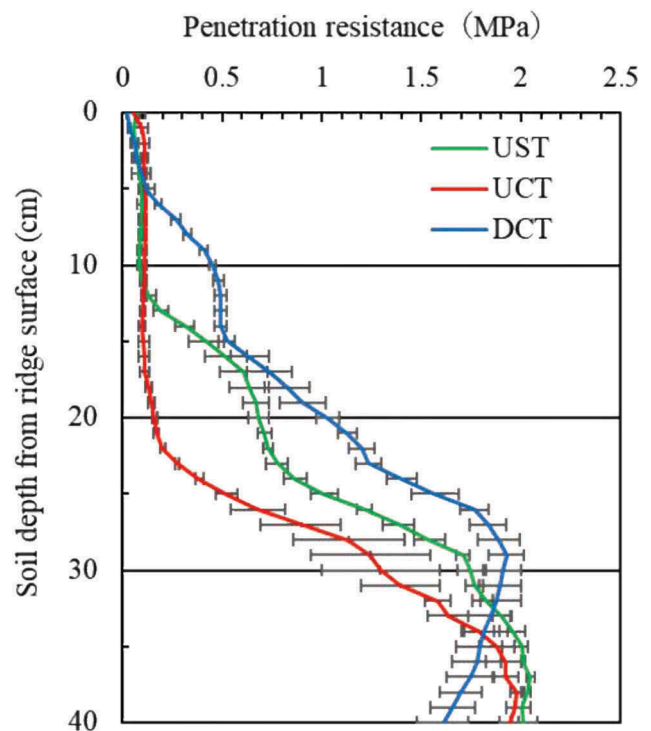

Figure 5. Penetration resistance of UST, UCT, and DCT measured just after sowing in 2015. Up-cut shallow tillage, UST; up-cut conventional tillage, UCT; down-cut conventional tillage, DCT. Values are mean ± SE (n = 3).

3. Results

3.1. Weather

The monthly mean air temperature, sunshine hours, solar radiation, and rainfall in 2015, 2016, and the 30-year average from 1985 to 2014 are presented in Table 1. Weather in 2015 included cool air temperatures, especially from mid-August to mid-September, few sunshine hours, low solar radiation from mid-August to early September, and low rainfall except in late August, when a typhoon hit the experimental field on 25 August, causing heavy rainfall. In 2016, the weather included high air temperatures and low rainfall from July to August, and high temperatures with few sunshine hours and high rainfall from September to October.

3.2. Ridge shape and soil pulverization rate

The ridge shape of each sowing method in 2015 is shown in Figure 4. Although the tillage depth (the height of tilled layer) was 5 cm shallower in UST than in UCT and DCT, drainage ditches of 5 cm were created by the side-disks in UST (Figure 4(a)). The ridge height of UST was similar to those of UCT and DCT. Soil
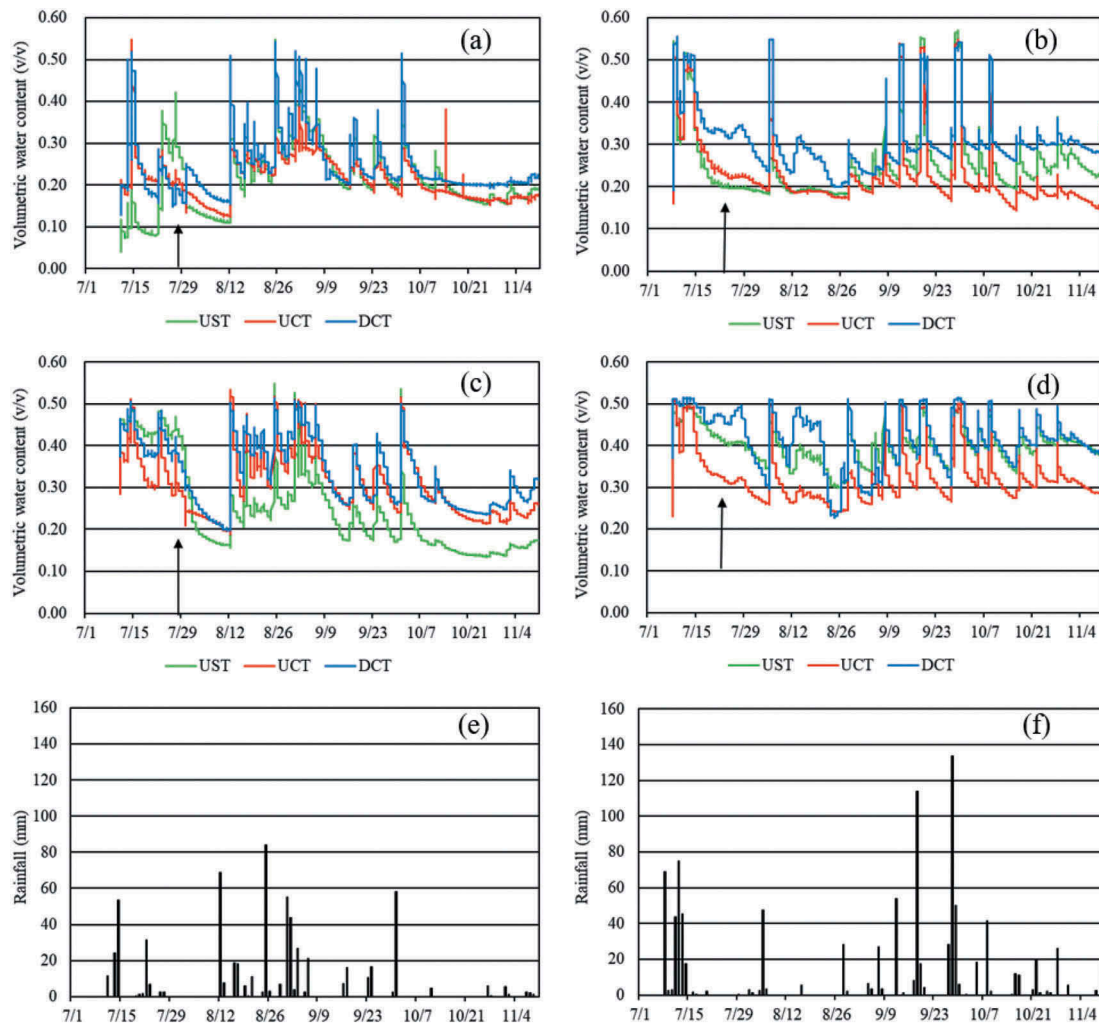
difference (LSD) if the F test of ANOVA exceeded the 0.05 probability level. Pearson's correlation coefficients were computed to evaluate the relationships between seed yield and the agronomical traits measured.

Figure 6. Volumetric water content of the soil at a depth of 0–15 cm (a, b) and 15–30 cm (c, d), and rainfall (e, f) in 2015 (a, c, e) and 2016 (b, d, f). Up-cut shallow tillage, UST; up-cut conventional tillage, UCT; down-cut conventional tillage, DCT.

Table 2. Effects of experimental year and sowing method on leaf area index (LAI) and shoot dry weight (SDW) at R2 and R5 soybean growth stage, and crop growth rate (CGR) from R2 to R5 stage.

Year	Sowing method	Harvest no. (plants m^{-2}) R2	R5	LAI (m^2 m^{-2}) R2	R5	SDW (g m^{-2}) R2	R5	CGR (g m^{-2} day^{-1})
2015		11.8	11.5 a	2.7	3.5 b	153	382 b	9.9 a
2016		10.4	9.7 b	3.0	4.8 a	186	542 a	12.7 b
	UST	11.0	11.1	2.6	4.3	159	478	12.5
	UCT	11.3	9.8	3.1	4.2	184	466	10.7
	DCT	11.0	10.9	2.8	4.0	165	443	10.8
2015	UST	11.8	12.4	2.3	3.7	136	419	12.3
	UCT	12.2	10.4	3.1	3.3	178	346	7.3
	DCT	11.3	11.6	2.6	3.6	146	380	10.2
2016	UST	10.2	9.8	2.9	4.9	182	536	12.6
	UCT	10.4	9.1	3.1	5.1	191	585	14.1
	DCT	10.7	10.2	2.9	4.5	185	505	11.5
ANOVA								
Year (Y)		0.121	0.005	0.330	0.035	0.078	0.009	0.042
Sowing method (S)		0.806	0.117	0.089	0.724	0.185	0.652	0.441
Y × S		0.614	0.493	0.341	0.387	0.433	0.251	0.109

Values followed by different letters differ significantly ($p < 0.05$).

Table 3. Effect of experimental year and sowing method on root length density (RLD) at the R2 and R5 soybean growth stage.

Year	Sowing method	RLD at R2 (cm cm^{-3})		RLD at R5 (cm cm^{-3})	
		0–15 cm	15–30 cm	0–15 cm	15–30 cm
2015		0.617	0.136 b	0.585	0.348
2016		0.763	0.358 a	0.593	0.196
	UST	0.754	0.273	0.577	0.262 b
	UCT	0.617	0.242	0.398	0.239 b
	DCT	0.699	0.227	0.791	0.315 a
2015	UST	0.706	0.122	0.687	0.330
	UCT	0.661	0.162	0.366	0.297
	DCT	0.483	0.125	0.701	0.418
2016	UST	0.802	0.425	0.466	0.195
	UCT	0.573	0.322	0.431	0.181
	DCT	0.914	0.328	0.881	0.211
ANOVA					
Year (Y)		0.568	0.004	0.971	0.107
Sowing method (S)		0.645	0.830	0.210	0.020
Y × S		0.243	0.646	0.610	0.131

Values within a column followed by different letters differ significantly ($p < 0.05$).

pulverization rates of the tilled layer were more than 80% and similar among sowing methods.

3.3. Soil penetration resistance

The SPR of each sowing method in 2015 is shown in Figure 5. The SPR in UCT was below 0.2 MPa up to 22 cm below the ridge surface, but it increased as soil depth increased beyond 22 cm. In UST, the SPR was below 0.2 MPa up to 13 cm below the ridge surface, then increased gradually to 0.7 MPa at a depth of 17 cm, stayed at approximately 0.5 to 0.7 MPa between 17 and 22 cm deep, and increased as soil depth increased below 22 cm. In DCT, the SPR was low between 0 and 5 cm deep, increased gradually up to 10 cm, stayed at

approximately 0.5 MPa between 10 and 15 cm deep, and increased as soil depth increased below 15 cm.

3.4. Soil VWC and rainfall pattern

The VWC at depths of 10 and 20 cm from the soil surface and rainfall in 2015 and 2016 are shown in Figure 6. In 2015, the VWC at 10 cm depth in UST differed in comparison to UCT and DCT until 30 July (Figure 5(a)); the VWC in UST was lower than in UCT and DCT until 22 July, but thereafter it increased rapidly and was higher than in UCT and DCT until 29 July. The VWC in 2015 at 20 cm depth was lower in UST than in UCT and DCT throughout the growth period after 30 July (Figure 6(c)). The VWC at depths of 10 and 20 cm in UCT was lower than that in DCT almost throughout the entire growth period (Figure 6(a,b)).

The 2016 VWC at 10 cm depth in UST and UCT decreased more rapidly than in DCT after rainfall throughout the growth period (Figure 6(b,f)). In UCT, the VWC at 20 cm depth in 2016 decreased more rapidly than in UST and DCT after rainfall, as at 10 cm deep (Figure 6(b, d and f)). Especially during the summer dry spells (i.e., from 14 July to 5 Augustand from 7 August to 26 August), the VWC at 20 cm depth in UCT was much lower than in UST and DCT. In DCT, the VWC at 20 cm depth stayed high after the rain (i.e., from 17 July to 29 July and from 12 August to 21 August). The VWC at 20 cm depth in UST showed intermediate values between DCT and UCT (Figure 6(d)).

3.5. Shoot and root growth

There were no significant main effects of year, sowing method, or their interaction on the number of harvested plants, LAI, and SDW at the R2 stage (Table 2).

Table 4. Effect of experimental year and sowing method on the number of harvested plants, plant height, the number of main stem nodes, yield components, and yield of soybean.

Year	Sowing method	Harvest no. (plants m^{-2})	Plant height (cm)	Main stem node no. (no. plant^{-1})	Pods m^{-2} (no. m^{-2})	Seeds pod^{-1} (no. pod^{-1})	100-seed weight (g)	Yield (g m^{-2})
2015		11.4 a	55.0 b	15.1	551	1.84 a	29.3 a	296 a
2016		9.5 b	63.7 a	15.7	602	1.57 b	26.4 b	251 b
	UST	9.9 b	58.3	15.4	571	1.68	28.3	269
	UCT	10.7 a	60.2	15.7	550	1.74	27.6	264
	DCT	10.8 a	59.6	15.2	609	1.69	27.8	288
2015	UST	10.5	53.6	15.1	507 bB[a]	1.83	29.5	273
	UCT	11.7	56.7	15.6	517 b	1.91	29.2	289
	DCT	12.0	54.8	14.7	630 a	1.77	29.3	326
2016	UST	9.2	63.1	15.7	635 aA	1.53	27.0	265
	UCT	9.7	63.7	15.8	584 a	1.57	26.0	239
	DCT	9.6	64.4	15.7	588 a	1.61	26.3	249
ANOVA								
Year (Y)		0.003	0.016	0.221	0.081	0.000	0.001	0.010
Sowing method (S)		0.041	0.680	0.452	0.111	0.400	0.710	0.398
Y × S		0.250	0.782	0.656	0.024	0.179	0.908	0.194

[a]Values within a column followed by different lowercase letters differ significantly ($p < 0.05$) among sowing methods for a given year and values within a column followed by different uppercase letters differ significantly ($p < 0.05$) between years for a given sowing method.

Table 5. Correlation coefficients of seed yield with yield components and shoot and root growth parameters of soybean in 2015 and 2016 (n = 9). Leaf area index, LAI; shoot dry weight, SDW; crop growth rate from R2 to R5, CGR; root length density, RLD.

Variables	2015		2016	
	r	p-value	r	p-value
Yield components				
Pods m^{-2}	0.887	0.001	0.861	0.003
Seeds pod^{-1}	0.278	0.468	0.394	0.294
100-seed weight	−0.227	0.556	0.770	0.015
Shoot traits				
LAI at R2	0.123	0.753	−0.232	0.547
LAI at R5	−0.319	0.403	−0.263	0.495
SDW at R2	0.048	0.903	−0.228	0.555
SDW at R5	−0.142	0.715	−0.417	0.264
CGR	−0.135	0.728	−0.329	0.387
Root traits				
RLD 0–15 cm at R2	−0.203	0.600	0.236	0.541
RLD 15–30 cm at R2	−0.010	0.980	0.477	0.194
RLD 0–15 cm at R5	−0.038	0.923	−0.349	0.357
RLD 15–30 cm at R5	0.354	0.350	−0.481	0.190

For the number of harvested plants, LAI and SDW at the R5 stage and CGR from R2 to R5 stage, only a significant main effect of year was found and these parameters except the number of harvested plants in 2016 were significantly greater than in 2015.

There were no significant main effects of year, sowing method, or their interaction on RLD at 0–15 cm depth at both the R2 and R5 stages (Table 3). A significant main effect of year was detected for RLD at 15–30 depth at the R2 stage, and the RLD in 2016 was higher than in 2015. At the R5 stage, the RLD at 15–30 cm depth cm was significantly higher in DCT than in UST and UCT.

3.6. Agronomic traits at harvest, yield, and yield components

There were significant main effects of year and sowing method on the number of harvested plants (Table 4); the number harvested in 2015 was higher than in 2016 and the number harvested in UST was smaller than in UCT and DCT. Plant height in 2016 was significantly higher than in 2015.

There was a significant year × sowing method interaction on pods m^{-2} (Table 4). In 2015, DCT produced significantly greater pods m^{-2} than UST and UCT, although no significant difference between sowing methods for pods m^{-2} was found in 2016. The pods m^{-2} of UST in 2016 was greater than in 2015, although pods m^{-2} of UCT and DCT did not differ significantly between experimental years. The seeds pod^{-1} and 100-seed weight were only significantly affected by year (Table 4). Both parameters were

greater in 2015 than in 2016. There was a significant main effect of year on yield, but no significant main effect of sowing method or year × sowing method interaction on the yield was found (Table 4). The yield in 2015 was greater than in 2016. The seed yield was significantly and positively correlated with pods m^{-2} both in 2015 and 2016 (Table 5). A significant positive correlation was detected between seed yield and 100-seed weight only in 2016. There were no significant correlations of the seed yield with shoot or root growth parameters in both years.

4. Discussion

In the present study, a one-operation shallow tillage sowing method with up-cut rotary tiller and side-disk was developed (UST). Ridge appearance in UST was similar to that in UCT (Figure 1(b,d)). It can be observed that there is a larger gap between the sideboard of up-cut rotary tiller and the soil surface in UST (Figure 1(a)) than in UCT (Figure 1(c)). When there is a large amount of winter crop or weed residues, the sideboard or chain case of the up-cut rotary tiller in UCT can get clogged up with residues, because these residues have not been buried into the soil before sowing in UCT. Once the sideboard or chain case is clogged up with residues, operators must stop sowing to remove the residues. In contrast, UST may escape up-cut rotary residue clogging to its higher ground clearance, leading to a smoother sowing operation. However, it should be noted that the combine type (head-feeding or multi-purpose) processing method of wheat or barley straws and the amount of residues of winter crops or weeds will affect the soil pulverization rate and ridge shape.

In the present study, we did not evaluate the effect of the one-operation shallow tillage sowing method with the down-cut rotary tiller on soybean growth and yield. It was reported that one-operation shallow tillage (depth: 5 cm) sowing method with down-cut rotary tiller and side-disk ditcher, which was a concept similar to our developed method, produced greater yield than the conventional tillage (depth: 12 cm) sowing method with down-cut rotary tiller (Watanabe et al., 2009). However, their sowing method required several modifications for the reinforcement for the side-disk, sideboard of the rotary tiller, and moldboard. In contrast, the structure of our developed sowing method was much simpler than that of Watanabe et al. (2009). Furthermore, weed damage is of concern when one-operation shallow tillage sowing method with down-cut rotary tiller is performed, because weeds which emerge after the harvest of winter crops (early June) and until the sowing of soybean (mid-July) cannot be buried into the soil

completely by this sowing method. Morimoto et al. (1983) and Kanatani and Kurata (1989) reported that the percentage of culms and hills of preceding crops buried was higher with up-cut rotary tillage than with down-cut rotary tillage. Thus, it is expected that the shallow tillage sowing method with up-cut rotary tiller developed in this study can bury more weeds than that with down-cut rotary tiller even if sowing was performed in one operation, resulting in less damage by weeds.

In 2015, the VWC in UST was different from those in UCT and DCT (Figure 6(a,c)). At 10 cm depth, the VWC in UST was lower than in the other sowing methods between 11 and 22 July, but it was higher between 22 and 30 July. This result might have been caused by contact failure between a sensor and the soil, potentially caused by barley residues. At 20 cm depth, the VWC in UST was lower than in UCT and DCT after 30 July, when inter-tillage and ridging were performed. Furthermore, the VWC at 20 cm depth was sometimes lower than that at 10 cm depth. Inter-tillage and ridging might have exposed the sensor to conditions that promoted drying at 20 cm depth.

After seeing the VWC results in 2015, we carefully installed sensors into the soil and performed inter-tillage and ridging in 2016. The amount and frequency of rainfall were both high after mid-September in 2016 (Table 1; Figure 6(f)), so we discuss the differences in VWC among the sowing methods until August hereafter. At 10 cm depth, the VWC in DCT was the highest among sowing methods (Figure 6(b)). Although SPR was not measured in 2016, it is possible to discuss the relationship between SPR in 2015 and VWC in 2016, with the assumption that SPR in 2016 was similar to that in 2015, because tilling operations were the same in both years. The SPR in DCT at 10 cm depths was higher than in UST and UCT, and SPR values in UST and UCT were almost zero. This result indicates higher soil density at this depth in DCT. Moriizumi and Hayashi (1995) measured clod size distribution after down-cut or up-cut rotary tillage and reported that relatively larger clods were distributed equally on the entire (upper, middle, and lower) tilled layer after down-cut rotary tillage, while, after up-cut rotary tillage, smaller clods were distributed on the tilled upper layer and clod size became larger as tillage depth deepened. The difference in clod distribution between down-cut and up-cut rotary tillage might result in different soil density between them. Higher soil density resulted in higher water-holding capacity. Therefore, high moisture conditions were maintained for a longer time in DCT than in UST and UCT after rainfall. It is preferable for soybean cultivation that excess surface soil water, which causes flooding stress to soybean plants, is

drained quickly after heavy or continual rainfall. Thus, from the viewpoint of shallow soil drainage, UST and UCT may be suitable for soybean plants.

At 20 cm depth, VWC in DCT was highest, followed by UST and UCT (Figure 6(d)). The SPR at 20 cm depth in DCT was the highest, followed by UST and UCT (Figure 5). VWC was related to the SPR; generally, the higher the SPR, the higher the VWC. The higher VWC at 20 cm depth in DCT indicates that the drainage ability in DCT was poorer than in UST and UCT, even in deeper soil. The VWC in UCT decreased most quickly after rainfall, indicating lower water-holding capacity even at 20 cm depth. Rainfall is generally limited after the rainy season (mid-July to late August, depending on year) in southwestern Japan. Soybean plants grow from early vegetative stage to flowering from mid-July to late August. Therefore, if there is a longer dry spell during early vegetative stages, the lower water-holding capacity of UCT soil across soil layers may reduce vegetative growth.

In this study, the amount of rainfall was small from mid-July to late August in 2016 (Figure 6(f)), but 47.5 mm of rainfall on 5 August might have relieved soybean plants from drought stress to some extent in UCT. The VWC at 20 cm depth was higher in UST than in UCT even during dry spells (Figure 6(d,f)). The 20 cm deep VWC measurement position was inside the untilled layer in UST and the tilled layer in UCT (Figure 4(a,b)). Kawamura et al. (2013), who developed a partially shallow tilling and sowing method with down-cut rotary tiller, reported that VWC at 5 to 10 cm depth was higher in their sowing method than in conventional tillage method during dry spells, because the soil at this depth was untilled in their sowing method, but tilled in the conventional tillage method. Similarly, Yoshinaga et al. (2008), who developed an inter-row strip tillage sowing method with down-cut rotary tiller, reported that the VWC of the untilled layer at a depth of 8–16 cm was significantly higher than that of the tilled layer at the same depth using conventional tillage during dry spells. Our finding that the VWC of the untilled layer in UST was higher than the tilled layer in UCT at 20 cm depth corresponds with their results.

Yoshinaga et al. (2008) also showed that solid phase rate and gas phase rate of the untilled layer were higher and lower than those of the tilled layer, respectively. They suggested that the reason for the higher VWC of untilled layers was that: (1) the soil water which was contained in the subsoil was absorbed by the untilled layer even during drought periods, because the untilled layer is connected to the subsoil and (2) the soil water in the untilled layer was slow to evaporate, because the

soil pores in untilled layers were small (low gas phase rate). Although the three soil phases were not measured in this study, a similar phenomenon might occur in UST as reported by Yoshinaga et al. (2008). From the viewpoint of water supply at deeper soil depths, especially during dry spells, UST may be suitable for soybean plants.

Although the ridge shape, SPR, and VWC differed among sowing methods, soybean growth and yield did not significantly differ among sowing methods in this study (Table 2, 3, 4). Although the harvest number in UST was significantly lower than in UCT and DCT (Table 4), the harvest numbers at the R2 and R5 stage did not differ significantly among sowing methods (Tables 2 and 3). Therefore, the lower harvest number in UST at harvest was unclear, but it did not significantly influence the seed yield. Kawamura et al. (2013) also reported that there was no significant difference in seed yield between a partially shallow tilling and sowing method and the conventional tillage sowing method. However, because their sowing method could be performed in one operation, total operation time in their sowing method was 50% less than that in conventional two-operation sowing method. In this study, the operation times of UST and UCT might be 50% less than that of DCT, because of the same tractor working speed (2 km h^{-1}) for all sowing methods and the difference in process (one- vs. two-operation). It was shown that the power requirement of up-cut rotary tillage reduced as tillage depth became shallower (Hosokawa et al., 2001). Thus, it may be possible that UST sows seeds at a faster working speed than UCT because the power requirement of UST is smaller than UCT. If seed yields are not different among sowing methods, production cost of UST will be the lowest, because of the shorter operation time due to faster working speed. In the future, we will attempt to investigate actual power requirements at different working speeds and to what extent UST can increase working speed.

It was expected that sowing methods would influence root growth, due to the difference in SPR among sowing methods. Before the measurement of RLD, we expected that RLD at 0–15 cm depth in DCT would be lower than in UST and UCT and that RLD at 15–30 cm depth in UCT would be higher than in UST and DCT. Contrary to our expectations, averaged across the experimental year, the RLD at depths of 0–15 and 15–30 cm did not differ among sowing methods at the R2 and R5 stages, except at 15–30 cm depth at the R5 stage (Table 3). Although the reason that significant differences in RLD among sowing methods were detected only at 15–30 cm depth at the R5

stage is unclear, the difference in SPR among sowing methods could not explain the difference in RLD. The SPR, which was thought to affect root growth, was measured only once just after sowing in this study; however, it would fluctuate with time, probably owing to rainfall events. Therefore, the measurement of changes in the SPR throughout the growing season is required to clarify the relationship between root growth and the SPR. Kawamura et al. (2013) observed that root growth was greater in a partially shallow tilling and sowing method than in a conventional tilling and sowing method, but their data were not shown. Yoshinaga et al. (2008) found a significantly larger root weight plant^{-1} in an inter-row strip tillage sowing method than in a conventional tillage sowing method in one of two experimental years. Although the effect of sowing method on root growth may be dependent on several environmental factors, such as cultivation year or soil type, there was no significant relationship between yield and RLD (Table 5) indicating that root growth did not greatly affect yield in this study.

Finally, we discuss the differences in soybean growth and yield between experimental years. The rainfall between mid-August and early September was high in 2015, causing cooler air temperatures, fewer sunshine hours, and lower solar radiation during this period (Table 1, Figure 6(d)). On the other hand, in 2016, air temperature was comparable to the 30-year average, rainfall was adequate, there were many sunshine hours, and solar radiation was high between mid-August and early September. Better weather conditions from the R2 to R5 stage in 2016 might have led to greater LAI and SDW at the R5 stage compared to 2015. The greater CGR between R2 and R5 stage in 2016 over 2015 supports this interpretation

RLD at 15–30 cm depth at the R2 stage was greater in 2016 than in 2015 (Table 3), although no significant differences of the RLD at 0–15 depth were observed between experimental years. Hoogenboom, Huck and Peterson (1987) demonstrated that drought stress during early vegetative growth stages (V1 to V4) or early reproductive stages (R1 to R2) promotes root growth and that the root systems of drought-stressed plants penetrate deeper soil layers than those of non-stressed plants. The rainfall amount from 15 July to 20 August in 2016 was lower than in 2015 (Figure 6(c,f)). Over 10 mm of rainfall in one day was observed only once (5 August) in 2016, but four times in 2015. Therefore, it is possible that the drier weather conditions in 2016 might have promoted root growth in deeper soil. The greater root growth at the R2 stage in 2016 might have contributed to the greater CGR from R2 to R5 stage compared with that in 2015.

Contrary to the fact that shoot growth at the R5 stage was greater in 2016 than in 2015, the seed yield in 2016 was lower than in 2015 (Table 6). In 2016, the rainfall amount was five times greater than the 30-year average (479 mm vs. 94 mm) during the seed filling period, resulting in fewer sunshine hours than in 2015 (Table 1). The much higher rainfall during the seed filling period in 2016 might have caused flooding stress to soybean plants. Rhine, Stevebs, Shannon, Wrather and Sleper (2010) reported that flooding treatment of 8 d at the R5 stage resulted in the greatest yield loss compared to non-flooded control. Linkermer, Board and Musgrave (1998) revealed that flooding treatment at the R5 stage for 7 d reduced seed yield by 66% compared to the non-flooded control through decreased seeds pod^{-1} and 100-seed weight. In the present study, seeds pod^{-1} and 100-seed weight in 2016 were lower than in 2015 (Table 4), resulting in lower seed yield in 2016 than in 2015. Our result was consistent with the results of Linkermer et al. (1998).

The fewer sunshine hours in 2016 might have also negatively influenced seed filling. Nakamura and Yokoo (1987) showed a positive relationship between 100-seed weight of the soybean cultivar Fukuyutaka and sunshine hours from 26 to 30 September (middle of seed filling). Kokubun (1988) reported that shading treatment at the middle of the pod filling stage significantly reduced 100-seed weight compared with non-shaded control. Their report is consistent with our results that 100-seed weight in 2016 was smaller than in 2015.

5. Conclusion

In the present study, a one-operation shallow tillage sowing method with up-cut rotary tiller and side-disk (UST) was developed. Sowing methods with up-cut rotary tillage (UCT and UST) can reduce the pre-plowing workload after harvesting winter crops in comparison to the two-operation conventional tillage sowing method with down-cut rotary tillage (DCT), leading to a labor-saving sowing method. Power requirements reduce as tillage depth becomes shallower, so the power requirement of UST should be lower than that of UCT, leading to faster sowing. Compared with conventional sowing methods with both up-cut and down-cut rotary tillage (UCT and DCT), UST did not significantly affect soybean growth and yield. Therefore, if the seed yields with UST are similar to those with UCT or DCT, UST can reduce total production cost. In the present study, tractor working speed was kept at 2 km h^{-1} for all sowing methods, and thus it was unclear to what extent UST could increase working speed. Furthermore, the differences of power requirements among sowing

methods and the effect of sowing speed on soybean growth and yield were not studied. Future studies will be needed to clarify the impact of these factors on working speed and production cost.

Disclosure statement

No potential conflict of interest was reported by the authors.

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