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Effects of Different Seeding Patterns on the Yield of Rice Directly Sown in a Well-drained Paddy Field Using Plowing and Compaction

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Abstract

This study aimed to experimentally determine the effectiveness of hill seeding in a well-drained paddy field using plowing and compaction systems by comparing the yield, quality, and lodging resistance under high-fertilizer conditions, to those of direct sowing in rows. The degree of lodging was found to be higher with hill seeding than with row sowing. There was a significant reduction in yield with row seeding. This was related to the lower percentage of ripened grain on the primary and secondary rachis branches of the panicle. Therefore, under high-fertilizer conditions, which promote lodging in rice directly sown in a well-drained paddy field using plowing and compaction systems, hill seeding has superior lodging resistance. This was due to the presence of shorter and thicker lower internodes in hill seeding compared to row seeding. Ripening capability was also maintained, which resulted in a higher yield and improved quality. Therefore, hill seeding is effective in obtaining stable and high yields of rice directly sown in well-drained paddy fields using plowing and compaction systems and of rice directly sown in flooded paddy fields.

Discipline: Crop Science
Additional key words: hill seeding, lodging, multi-crops direct seeder

Introduction

With rice consumption decreasing and rice prices falling, it has become increasingly important for farmers to introduce cultivation techniques that help in lowering production costs and securing their income. Many Japanese farmers quit the industry because of these pressures, and there is currently a growing shortage of farmers (MAFF 2017). However, although the number of farms with an area less than 5 ha is decreasing, the number of large farms with an area over 10 ha has increased substantially, and the overall scale of farming is increasing. Large 1 ha plots have seen a higher rate of infrastructure development. The operation of these large fields requires a high number of farmers. Thus, technologies to reduce the labor requirements, such as direct seeding, have been introduced. In cultivation by transplanting, rearing and puddling are the most time-consuming components, and direct seeding in well-drained paddy fields avoids these activities. Thus, direct seeding could be an effective technology for expanding the scale of rice cultivation by avoiding labor competition in early spring. In particular, plowing and compaction systems in well-drained paddy fields performed at a high speed of 5 to 10 km h^{-1} are considered suitable for large fields (Otani et al. 2013). These techniques are rapidly spreading in the Tohoku region of Japan, where the scale of farming operations is

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expanding (MAFF 2022, Tohoku Agricultural Research Center, NARO 2022). The increased use of agricultural implements and machinery is expected to reduce labor and costs in large paddy field crop rotations, and because of versatility, they can be used for different crops and are not limited by rice culture (Matsunami et al. 2017, Otani et al. 2013, Shinoto et al. 2017). However, in terms of yield, direct seeding in well-drained paddy fields with leading varieties is inferior to transplanting (Shinoto et al. 2021, Yukawa et al. 2003). Therefore, to obtain yields comparable to those of transplanted cultivars, the number of seedlings and the use of fertilizers have to be increased. The use of varieties with superior lodging resistance increases the leaf color during the growing season (He et al. 2017, Morikawa & Otani 2009, Shinoto et al. 2021). In general, direct seeding in flooded paddy fields can result in a low yield due to excess of seedlings establishing and overgrowth of rice plants from excessive fertilization, which leads to lodging. With the recent development of lowland crop rotation, rice plants in restored rice paddies become overgrown and fall over because of high levels of nitrogen mineralization from the early stages (Kaneda et al. 1986, Watanabe 1982). Furthermore, row seeding and broad seeding result in inferior lodging resistance compared to hill seeding, resulting in an unstable yield and quality (Ogata & Matsue 1998, Yoshinaga et al. 2001). These benefits have made hill seeding the most popular method for achieving stable high yields in direct seeding in flooded paddy fields, leading to the development of hill seeding machines (MAFF 2022, Togashi et al. 2001). Hill seeding is also effective for a stable high yield in well-drained paddy fields using plowing and compaction. However, currently, there have been no reports on the yield, quality, and lodging resistance resulting from direct seeding in well-drained paddy fields using plowing and compaction. To understand the hill seeding effects, we set up an experiment using a multicrop direct seeder (Tachibana et al. 2014). To stimulate crop rotation, soil with a high fertilizer content was used, and then, yield, quality, and lodging resistance were analyzed.

Materials and methods

The experiments were conducted in 2016 and 2017 in the paddy fields of the National Agriculture and Food Research Organization, Morioka, Iwate, Japan (141°08′E, 39°45′N). The soil type at the site was Andisol. Soybeans were the crop that had been cultivated at the site in the last two years. The soil chemical properties are shown in Table 1. An experimental plot (50 m × 15 m) was set up for each seeding machine within a field, with one replication in 2016 and two replications in 2017. In each experimental plot, four subplots were equally located diagonally. Two subplots were set up as survey sample plots (4.0 m × 3.0 m) to determine the average number of seedlings. The data from the two survey sample plots were averaged to obtain a replicate value.

Rice seeds [*Oryza sativa* (L.) cv. ‘Akitakomachi’] were coated with thiuram. Sowing was conducted on April 27, 2016 and on April 25, 2017, at a seeding rate of 50 kg ha^{-1} using a high-speed multicrop direct seeder (NTP-8AF, Agri-Techno Research, Co., Ltd., Hyogo, Japan). The interrow space for hill seeding was 30 cm, performed by a high-speed multicrops direct seeder. An interrow space of 25 cm was set for row seeding, performed by a pneumatic seeder (NG plus 4, Monosem Co., Ltd., Largeasse, France) (Fig. 1). Before seeding, a chisel plow (HS250, Kongskilde Co., Ltd., Albertslund, Denmark) was used for plowing at a depth of 20 to 25 cm and harrowing the topsoil (5 cm). After harrowing, the topsoil was leveled using a laser leveling machine (LLT3200B, Sugano Farm Machinery Co., Ltd., Ibaraki, Japan). Then, 1,000 kg ha^{-1} of silicate magnesium lime was applied, and 180 kg N ha^{-1} of CU fertilizer was applied, which contained three types of slow-release fertilizer, differing in the rate and pattern of N release with a bulk blend of P and K fertilizers (Chokuha senyou 211, Kumiai Hiryou Co. Ltd., Iwate, Japan). These fertilizers were applied as a basal fertilizer 1 week before seeding. Soil was crushed and leveled using a power harrow (KE3000 Special, AMAZONE Co., Ltd., Hasbergen, Germany) and compacted using a Cambridge roller (MAXIROLL 530, Dalbo Co., Ltd., Bindeballevej,

Table 1. Physicochemical properties of soil in the experimental field

Year	pH	CEC	Available P	Exchangeable cation			Available N	Total N	Total C
				K_2O	MgO	CaO			
	(H_2O)	(me/100g)	(mg/100g)	(mg/100g)	(mg/100g)	(mg/100g)	(mg/100g)	(%)	(%)
2016	6.2	29.7	5.4	30	42.2	304	5.1	0.50	6.4
2017	6.0	34.2	6.2	22	44.4	432	8.4	0.57	6.7

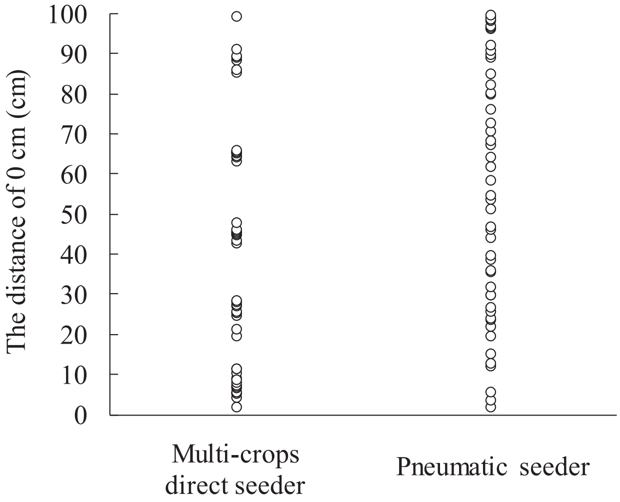

Fig. 1. Seeding pattern of each seeder used in the experiment
White circles in the figure represent rice seedling stands.

Denmark).

The number of established seedlings in 1 m of three adjacent rows was surveyed on May 30, 2016 and on June 01, 2017. Seedlings within 1 m of one row that showed the average number of seedlings in the adjacent locations were then sampled. The samples were examined to determine the length, whitened stem length, and age of the seedlings. In this context, the next leaf after the incomplete leaf was considered the first leaf. After the survey, the seedlings were air-dried at 90°C for at least 3 days, and the aboveground dry matter was weighed. At maturity, panicles within 1 m in length, including those from the seedling establishment survey plots, were counted, and the degree of lodging was determined. After that, 50-cm long rows in the survey plots were sampled. The harvest was allowed to dry naturally for 10 days in an indoor facility with open windows. We surveyed the internode length and internode width of the top eight longest stems. They were then cut off at the neck node of the panicle, the ears were dehulled for each rachis branch, and the ripening rate and thousand grain weight were determined. The total harvest yield was defined as the yield of polished brown rice with a grain thickness of 1.9 mm over harvested from each experimental plot using a combine harvester. The lodging score was determined by dividing the angle of inclination for a straight line connecting the base of the root and the neck node of the panicle from the ground into six levels. The degree of lodging was expressed as the percentage of the area of lodging. The appearance quality survey for the brown rice was conducted by the Tohoku Branch of the Japan Grain Inspection Association, and the rice was evaluated at nine levels from 1 to 9 (1st to 3rd grades). The percentage of whole grains was based on the Agricultural Product Inspection Standard (Ministry of Agriculture, Forestry and Fisheries 2018). This was expressed as a percentage of the number of high-quality grains, excluding immature, damaged, dead, and colored grains. Three soil subsamples were obtained from the topsoil of the experimental field from a depth of 12 cm. The subsamples were then mixed, and the following chemical properties were analyzed: pH (H_2O) (glass electrode); available P (Truog method); K, Mg, and Ca (Schollenberger and Simon method); hot water extractable N (autoclave method); and total N and C (Dumas method) according to the Hokkaido Research Organization, Agricultural Research Department (2012). T-tests were conducted for the data from each seeding pattern from 2017. Statistical analysis was performed via software (JMP 11.2.0, SAS Institute Inc., Cary, NC, USA). Percentage data were analyzed after angular transformation.

Results

The seeding patterns analyzed in this study were hill seeding performed using a high-speed multicrop direct seeder and row seeding performed using a pneumatic seeder (Table 2). The number of established seedlings ranged from 141 to 148 m^{-2} for hill seeding and from 172 to 180 m^{-2} for row seeding. There were no clear differences in whitened stem length, seedling length, seedling age, and top dry matter.

The total plant length at maturity was longer in 2017 than in 2016 and did not differ between seeding patterns in both years (Table 3). The degree of lodging had a higher level of significance in 2017 than in 2016, with a trend toward higher lodging for row seeding than for hill seeding. There were a higher number of panicles in 2017 than in 2016. The percentage of ripened grains was lower in 2017 than in 2016 and significantly lower in row seeding than in hill seeding. The 1,000-unhulled rice weight did not differ among seeding patterns in 2016 but tended to be lighter in 2017 for row seeding than for hill seeding. The yield was lower in 2017 than in 2016 and significantly lower in 2017 for row seeding than for hill seeding. The appearance quality and percentage of whole grains were lower in 2017 than in 2016 and tended to be lower in row seeding than in hill seeding. The yield was significantly correlated with the percentage of ripened grains rather than with the panicle number (Fig. 2).

No differences were observed in the rachis branch number and number of grains per rachis branch according to the seeding pattern. However, the percentage of ripened grain and 1,000-unhulled rice weight tended to be lower for row seeding than for hill seeding (Table 4). Hill seeding tended to have longer internodes I and II, and row seeding tended to have longer internode IV (Table 5). The width of Internode V was greater with hill seeding than with row seeding.

Discussion

The optimum number of seedlings established from direct seeding in a well-drained paddy field was 150-200 m^{-2} (Nara 1967). The number of seedlings established in this study ranged from 141 to 180 m^{-2} (Table 2). This indicated that this study was conducted under optimum seedling establishment conditions. The experimental field had a more abundant soil nutrient environment in 2017 than in 2016. The total plant length was higher in 2017 than in 2016 (Table 1), and panicle number was higher in 2017 than in 2016. These results indicate that the 2017 seedlings were established under high-soil-fertility conditions (Table 1). In this study, no differences in seedling quality and total plant length were observed between the seeding patterns. However, the degree of lodging tended to be greater in row-seeded plants (Tables 2, 3). When the lower internodes of plants were very long, the internodes broke during the ripening period, resulting in lodging. In hill seeding, the distance between the first and second internodes tended to be larger, and in row seeding, the distance between the fourth and fifth internodes tended to be larger (Table 5). In no-till direct seeding in well-drained paddy fields, where field conditions were similar to those after plowing and compaction, row seeding resulted in vigorous early growth and longer lower internodes compared to hill seeding (Kobayashi & Washio 1977). The lower internodes of rice plants were significantly longer as a result of reduced light availability at the stem base. This was caused by overgrowth due to increased LAI at the lower internode elongation stage (30 days before heading), resulting in lodging (Kamiji et al. 1993, Sasaki et al. 2001). These results suggest that the light intensity at the stem base of row-seeded plants deteriorated owing to overgrowth during the early development stages. This resulted in longer lower

Table 2. Effect of different seeding patterns on establishment of seedlings

Year	Seeding pattern	Number of seedling (m^{-2})	Whitened stem length (cm)	Seedling length (cm)	Seedling age (leaf number)	Top dry matter weight (mg $plant^{-1}$)
2016	Hill seedng	141	2.0	11.0	1.3	17.9
	Row seeding	172	2.0	11.5	1.5	20.4
2017	Hill seedng	148	2.1	8.9	1.9	8.6
	Row seeding	180 **	2.0	8.6	1.7	8.8
Average	Hill seedng	145	2.0	10.0	1.6	13.2
	Row seeding	176	2.0	10.0	1.6	14.6

Statistically significant effects are indicated. **: $P < 0.01$

Table 3. Effect of different seeding patterns on total plant length, lodging score, yield, yield component and quality

Year	Seeding pattern	Total plant length (cm)	Lodging score (0-5)	Panicle number (m^{-2})	Percentage of ripened grains (%)	1,000-unhulled rice weight (g)	Brown rice yield (g m^{-2})	Whole grain ratio (%)	Appearance quality (1-9)
2016	Hill seeding	102.6	0.2	490	92.5	25.4	584	83.3	1.0
	Row seeding	104.6	3.7	561	87.8	25.4	576	81.8	1.0
2017	Hill seeding	118.1	3.0	665	75.2	26.0	558	64.1	2.5
	Row seeding	114.7	3.3	654	55.8 †	24.5	455 †	58.7	4.5
Average	Hill seeding	110.4	1.6	578	83.9	25.7	571	73.7	1.8
	Row seeding	109.7	3.3	608	71.8	25.0	516	70.3	2.8

Statistically significant effects are indicated. †: $P < 0.10$

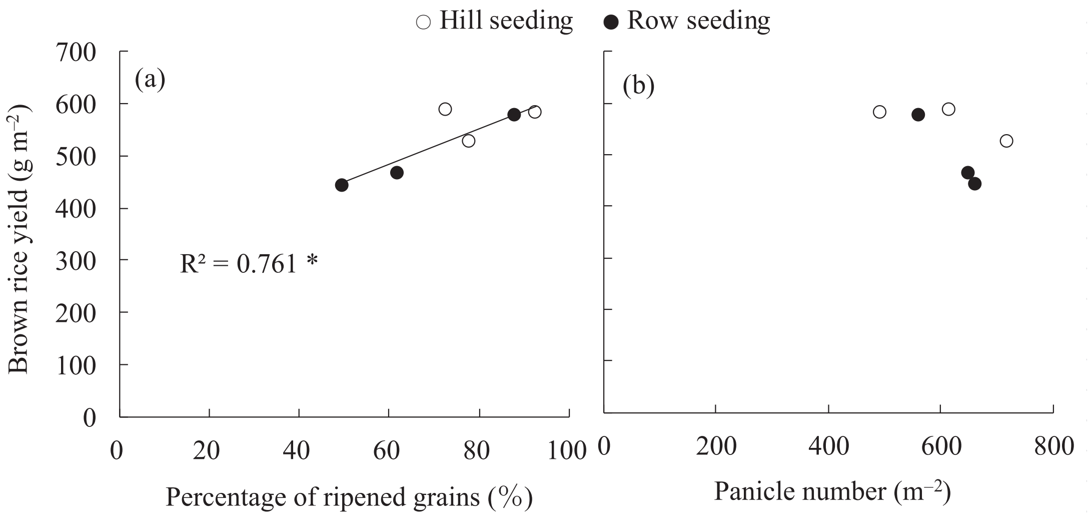

Fig. 2. Relationship of yield and percentage of ripened grains (a) and panicle number (b)
Statistically significant effects are indicated by *: $P < 0.05$.

Table 4. Effect of different seeding patterns on ear characteristics and percentage of ripened grain and 1,000-unhulled rice weight per rachis branch

Seeding pattern	Rachis branch number		Number of grains		Percentage of ripened grain		1,000-unhulled rice weight	
	Primary	Secondary	Primary	Secondary	Primary	Secondary	Primary	Secondary
	(panicle^{-1})		(grain panicle^{-1})		(%)		(g)	
Hill seeding	9.7	13.9	53.7	38.8	86.3	54.2	27.0	23.7
Row seeding	9.8	14.0	53.8	38.4	76.2	38.5	26.2	22.8
t-test	ns	ns	ns	ns	†	ns	ns	†

Statistically significant effects are indicated. †: $P < 0.10$, ns: not significant

Table 5. Effect of different seeding patterns on internode length and internode width

Seeding pattern	Internodes length					Internodes width		
	I	II	III	IV	V	III	IV	V
			(cm)				(mm)	
Hill seeding	30.0	23.3	23.2	13.3	5.4	3.7	4.4	4.8
Row seeding	28.8	21.8	23.3	15.0	5.7	3.9	4.5	4.4
t-test	ns	*	ns	†	ns	ns	ns	*

Statistically significant effects are indicated. *: $P < 0.05$, †: $P < 0.10$, ns: not significant

internodes in 2017, larger total plant length, and increased panicle number. The width of internode V in row seeding was smaller than that in hill seeding. Kobayashi & Washio (1977) reported that the stem base was thinner and the degree of lodging was higher in row seeding than in hill seeding. Among direct seeding techniques in flooded paddy fields, hill seeding has higher pushing and lodging resistance than row seeding (Ogata & Matsue 1998, Taguchi & Maruyama 2012). Hozyo & Oda (1967) suggested that seeding patterns that produce a canopy of a low-intensity light environment, such as the excess number of stems of barley, increase the risk of lodging due to the weak stem base caused by the thinning of the culm. The same phenomenon was observed in the present study. However, the mechanism by which the lower internode width becomes thicker in hill seeding compared to row seeding remains unclear and needs to be clarified by future research.

In 2017, when the total plant length and panicle number were higher than those in 2016, the percentage of ripened grains and yield in row seeding were lower (Table 3). In this study, a close correlation was observed between the yield and percentage of ripened grains (Fig. 2). Therefore, the high grain filling is important for obtaining a high yield with direct seeding in well-drained paddy fields using plowing and compaction systems, even under lodging conditions. Kobayashi & Hitaka (1968) concluded that the photosynthetic activity and translocation of photosynthetic products from the leaf to the grain of rice lodged by breaking were prevented externally and internally. By contrast, rice lodged by bending was recovered to a limited extent from both of their photosynthetic disturbance and translocation hindrance of photosynthetic products. In 2017, rice plants in both row and hill seeding were lodged in late September. Then, rice plants in row seeding were heavily bent and some were broken. Rice plants in hill seeding were only bent. This can result in reduced grain filling capacity and photosynthetic translocation in primary and secondary rachis branches and a significant decrease in yield (Endo et al. 1990, Hane et al. 1984). In this study, the ripening rate of the primary and secondary row seeding was lower and the grain weight from those with row seeding tended to be lighter than that of hill seeding (Table 4). This suggests that the yield reduction from row seeding was caused by a decrease in ripening ability due to lodging.

In general, hill seeding has a higher lodging resistance than row seeding under the same row spacing. In this study, row spacing was 30 cm for hill seeding and 25 cm for row seeding. The number of established seedlings was higher in row seeding. It was presumed that the space per plant for row seeding is smaller than that for hill seeding. In direct seeding of a flooded paddy field, there is no difference in the degree of lodging between 20 and 30 cm rows in the range of 240 m^{-2} - 287 m^{-2} (Tanno et al. 2007). In direct seeding in a well-drained paddy field, the space per plant is almost the same for 20 and 33 cm rows in the range of 150 m^{-2} - 180 m^{-2} (Nara 1967). Therefore, it was assumed that the effect of the different row spacing and the number of seedlings on the experimental outcome was small. However, because these reports were conducted under standard fertilization conditions, it is necessary to confirm the reproducibility of future trials under high-fertilizer conditions and using the same row spacing.

Under high-fertilizer conditions, which promoted lodging with direct seeding in well-drained paddy fields using plowing and compaction systems, hill seeding resulted in superior yield and quality. This is explained by the shorter and thicker lower internodes of hill-seeded plants than, resulting in higher ripening ability and lodging resistance. Therefore, hill seeding is effective for obtaining stable and high yields in direct seeding in well-drained paddy fields using plowing and compaction systems and in direct seeding in flooded paddy fields.

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