

REVIEW

Dry Direct-seeding Rice Cultivation Method Incorporating a Water-leakage Prevention Process Using a Vibratory Roller

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Abstract

Dry direct-seeding rice cultivation requires less labor than traditional transplanting cultivation, as there is no need for seedling production, the puddling process, and the transfer of seedling trays. In northern Kyushu, a double-cropping area in southern Japan, dry direct-seeding rice cultivation has generally not been adopted due to water leakage and the accompanying weed overgrowth. This situation prompted the authors to devise a water leakage prevention technique that can be rapidly implemented after winter cropping, with the aim of guaranteeing a reliable rice harvest. In this study, we use a vibratory roller to compact the soil, investigate the optimal conditions for effective compaction, and demonstrate the procedures for confirming these conditions on-site. This article provides an overview of the research process used to develop this water leakage prevention technique and an outline of our dry direct-seeding rice cultivation method for double-cropping areas, including weed control during the dry period.

Discipline: Agricultural Environment

Additional key words: double-cropping, on-site evaluation, pore size distribution, soil compaction, soil moisture condition

Introduction

Rice is one of the three major grains in the world. Its high production in Asia as a staple food is reflected by China and India accounting for 53% of the world's production (USDA 2020). In terms of global rice exports, the United States ranks in the top five (FAO 2017). Transplanting seedlings is the traditional method of cultivation in Asia, but direct sowing has always been the predominant method in South Asia, including India (Tanaka 1991). In the United States, direct sowing is conducted in large fields. In Japan, which is located in Northeast Asia, rice has been mainly grown by transplantation. As of 2017, direct seeding cultivation accounted for only 2.3% of the total area of cultivated paddy rice (Japan's Ministry of Agriculture, Forestry and

Fisheries 2017). However, more than 60% of agricultural workers are 65 years old or older, with only about 10% younger than 50 (Japan's Ministry of Agriculture, Forestry and Fisheries 2016). These numbers reflect an aging farming population that will soon face a severe manpower shortage. Both elderly farmers and leading farmers who consolidated the fields of retired farmers, require low-labor cultivation practices. Direct-seeding rice cultivation eliminates the traditional processes of preparing seedlings, transferring seedling trays from a nursery to paddy fields, and then loading the trays onto a rice planting machine, thereby allowing manpower to be reduced. There are two types of direct seeding: submerged direct seeding (in which sowing is done after puddling), and dry-direct seeding (in which sowing is done in dry fields that are later flooded after the shoots emerge).

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Received 6 March 2020; accepted 1 July 2020.

In the latter case, puddling can also be omitted. However, paddy fields are generally designed to hold water when flooded by low-permeability layers, assisted by puddling. Consequently, omitting the puddling process may lead to water leakage and a corresponding decrease in the effectiveness of herbicides and fertilizers. It is therefore necessary to add a leak prevention process to replace puddling. From the standpoint of saving labor, it is essential that the substitution process be simpler than the puddling process.

Two methods have been commonly used in Japan in recent years for reliable cultivation and water leakage prevention. One is the “V-furrow no-till direct seeding of rice” (Aichi Agricultural Research Center 2007), in which the sowing bed in a dry field is prepared by puddling. The other is “Dry direct-seeding rice cultivation using plowing and compaction” (NARO Tohoku Agricultural Research Center 2016), in which leveling is repeated using levelers and then Cambridge rollers. In both methods, water leakage controls are performed in the winter and/or early spring. The areas of dry direct-seeded rice are increasing in Tokai, Tohoku, and Hokkaido where these methods were developed, but no expansion has been seen in Kyushu, although some areas are being cultivated using these techniques (Fig. 1). Agricultural conditions are much the same in Kyushu as in other regions in Japan, so this stagnation suggests that other conditions in Kyushu are discouraging the adoption of dry direct-seeding. We therefore investigated the problems seen in northern Kyushu, the area where rice

cultivation is most common in the Kyushu region, and developed a work process for the direct seeding of rice in dry fields for double-cropping cultivation (Fig. 2). This article provides an overview of the series of research efforts made in the development of this dry direct-seeding rice cultivation method.

Development policy for dry direct-seeding rice in Northern Kyushu

1. The characteristics of paddy fields in northern Kyushu

The paddy fields in northern Kyushu are used for double-cropping. Soybean is sometimes planted in place of rice in summer, as in other regions, and wheat or barley is produced in winter. Northern Kyushu is also a habitat for the apple snail, which feeds on young rice sprouts. This species migrates into flooded fields and causes significant damage to young shoots in submerged direct seeding fields, but such damage does not occur in dry direct-seeded fields. The dry direct-seeding of rice not only saves labor but also offers this additional benefit. However, the potential introduction of dry direct-seeding cultivation in northern Kyushu has been stalled, as noted above.

The reasons often given for not adopting direct-seeding cultivation concern the difficulty of maintaining flooding and the problems regarding weed control. Fields used for double-cropping are often managed as upland, despite actually being paddy fields. The use of a paddy

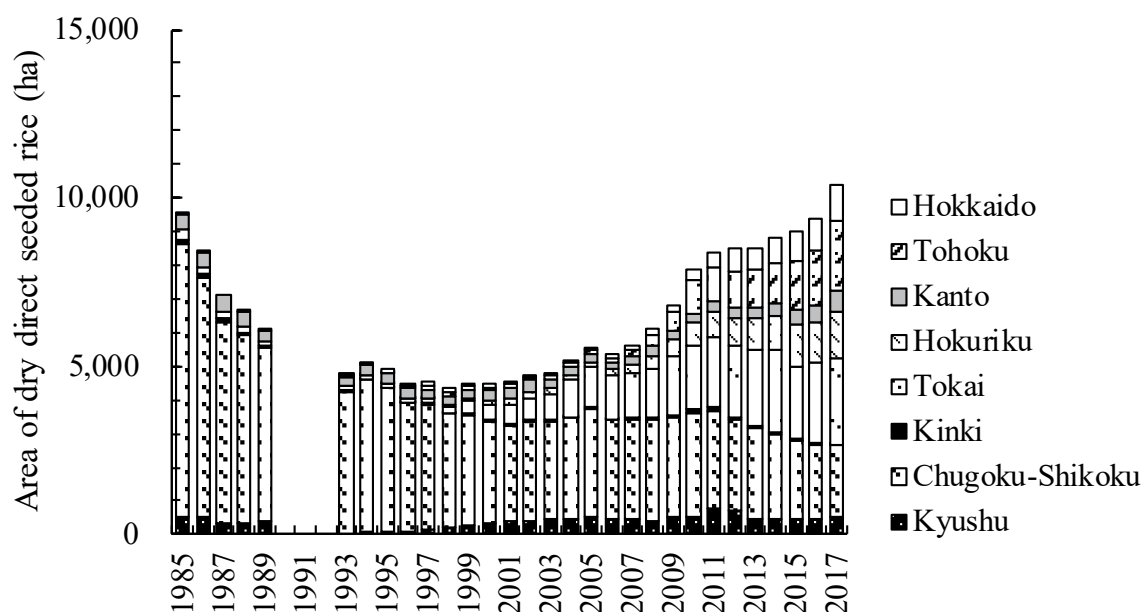


Fig. 1. Changes in dry-direct seeded rice areas in each region of Japan
Data from Japan's Ministry of Agriculture, Forestry and Fisheries, 2017

field as an upland field promotes root elongation that penetrates the subsoil, and root scars and cracks caused by shrinkage due to drying of the subsoil affect the number of macropores in the soil (e.g., Yamazaki et al. 1966, Inoue 1993). Consequently, the drainage characteristics of double-cropped fields are generally believed to differ from those of single-cropped rice fields. However, no extensive measurements have been made regarding the association between macropores and permeability across different cropping systems, independent of soil type and/or cultivator. Therefore, we investigated the permeability of the plow sole using a disk permeameter in the plains of the southern parts of Saga and Fukuoka prefectures in northern Kyushu, where many farmers practice double-cropping (Nakano et al. 2010). A disk permeameter can measure the hydraulic conductivity of the soil, excluding the contribution of macropores to water flow within the cross section used for the permeability measurement. Study areas with different soil textures and soil classifications were selected, and measurements were made in both double-cropped fields and single-cropped paddy fields. Figure 3 shows the results. The difference in hydraulic conductivity between the two sets of applied tension suggests that some pores were involved in hydraulic conductivity in the weaker set tension, but not in the stronger set. The farther the set tension is from zero, the more macropores are excluded from hydraulic conductivity. The hydraulic conductivity in each area at $h = 0$ cm in double-cropped fields was greater than the corresponding values in

single-cropped rice fields. This high hydraulic conductivity is likely attributable to macropores due to a steep decrease with increases in the applied tension. For coarse textured soil around the middle reaches of rivers and the volcanic ash-derived andosol, no differences by cropping system were found under tension, which could be due to the relative increase in the contribution of basic soil characteristics to hydraulic conductivity under stronger set tension. In any case, macropores significantly affected the saturated hydraulic conductivity of the plow sole in double-cropped fields. This study indicated that the prevention of water leakage during rice cultivation is more important in double-cropping fields than in single cropping fields.

2. Development of a water leakage prevention technique for double-cropping paddy fields

Based on the above data and interviews with farmers, when developing our water leakage prevention technique for double-cropping areas, we took the following factors into account.

- (1) A low-permeability plow sole generally supports flooding in paddies, but such function is weak in the plow sole in double-cropping fields. Thus, a process that replaces puddling is essential.
- (2) The high permeability of the plow sole should be maintained for use in upland cropping.
- (3) Given the frequent rainfall between the harvesting of wheat or barley and the sowing of rice, quick leakage-prevention operation is needed.

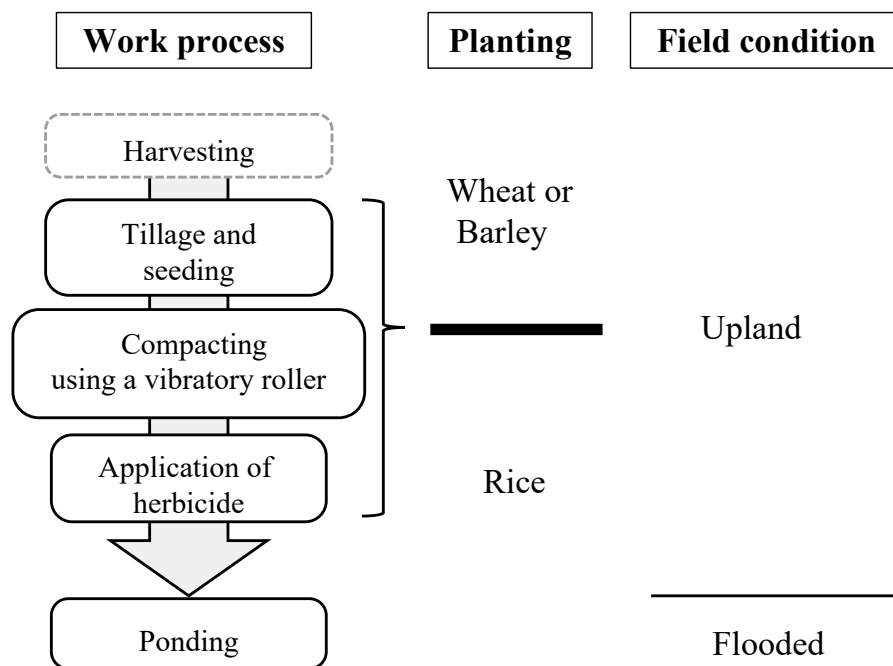


Fig. 2. Work process for direct seeding of rice in dry fields for double-cropping cultivation

The purpose of developing this technique was therefore intended “to create a water permeation suppressive layer in topsoil after harvesting a winter crop, using a short working process.” It was also decided to reduce the weight of the tools to maintain mobility between the fields, taking into account the type and size of machinery owned by the farmers, the size of the fields, and the distribution of individual fields.

The process of creating a water leakage barrier

1. Soil compaction using rollers

Surface compaction using rollers is often adopted to minimize water permeability. We decided to use this technique and studied a method that enables efficient and reliable water leakage prevention without interfering with other tasks, such as tillage, sowing, and weed control. Many studies on paddy soils have been conducted to determine the relationship between changes in soil properties and the soil moisture status at farming operations. Tillage should be done when the soil is reasonably dry for good crushing. For example, Kawasaki (1990) reported that soil crushing was good at water potential of 29.4 kPa–196 kPa (pF 2.5 – 3.3, the plastic limit of soil under test being equivalent to pF 2.9) for post-paddy tillage, and 39.2 kPa (pF 2.6) for post-wheat tillage. However, hydraulic conductivity decreases most when the water content is slightly higher than the optimum water content in the compaction test. It has been pointed out that in dry direct-seeding rice cultivation

using plowing and compaction, the effect of reduced permeability by compaction is higher when the conditions are slightly wetter than the plastic limit (Kanmuri et al. 2015). In addition, it should be noted that when the soil is slightly moist (with varying moisture content depending on the roller material, soil, etc.), it may easily stick to the roller and interfere with the compaction work. It was difficult to perform both tillage and compaction processes under optimum soil moisture conditions in terms of soil crushing, leakage prevention, and roller workability during a short planting changeover period. Therefore, we prioritized the stability of the tillage and seeding operations and the workability of the compaction operation to ensure smoothness of the entire process. That is, tillage and seeding were done after the winter crop harvest in dry soil conditions, followed by compacting (Fig. 2). In order to expand the suitable timing for leakage prevention, we explored the types of rollers, number of roller passes, and drier soil conditions for achieving a high leakage prevention effect.

Fukami et al. (2014a) developed a 960-kg roller shown in Photo 1 a) that can be directly mounted on a tractor’s three-point hitch and which uses oil drums filled with sand, taking into account the mobility inside and outside the field, and the manufacturing costs. Being directly attached to the three-point link, the roller could be lifted when turning in the field or moving between the fields, thus offering excellent mobility. When using this roller to perform five passes of compaction on sufficiently dry soil, the penetration resistance of the soil increased

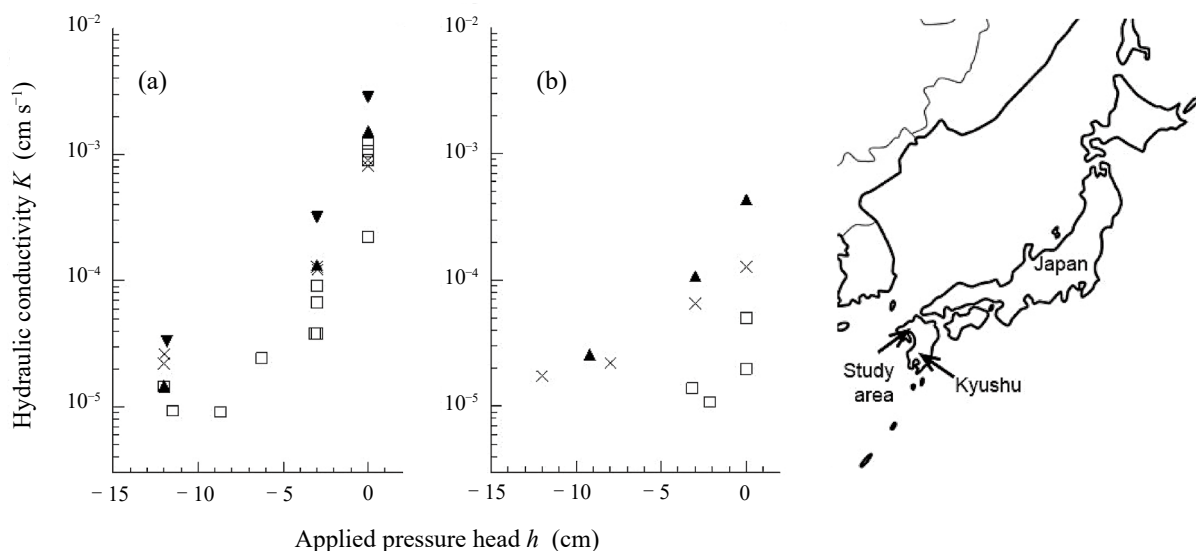


Fig. 3. Near saturated hydraulic conductivity in plow sole of (a) double-cropped fields and (b) single rice cropped fields (modified from Nakano et al. 2010)

- ×: Gray Lowland soil around the middle reaches of rivers
- : Gray Lowland soil around the lower reaches of rivers
- ▼: Andosol
- ▲: Brown Lowland soil

and the porosity decreased, resulting in water permeability approximating that of farmers' fields that have been used for dry-direct sowing cultivation in northern Kyushu (Table 1). As five passes would take too much time to make the work feasible during the short crop changeover period, there was still the need to increase the running speed and reduce the number of passes.

2. Structural changes in the soil required to prevent water leakage

Nakano & Fukami (2017) investigated the suppression of water infiltration by roller compaction and the changes in topsoil structure between the rollers and plow sole under dry conditions. The pore size distribution changed progressively with the higher number of

compaction roller passes. A decrease in total porosity was observed after one and three passes of the roller. After five passes of the roller, there was no further decrease, only a shift to a narrower pore size distribution (Fig. 4). The intake rate decreased as the number of roller passes increased, but was not low enough to suppress water leakage until after three passes. In short, water leakage was prevented when the porosity in the soil was sufficiently reduced and the macropores were deformed into smaller pores by roller compaction. Other measurements, such as the profiles of penetration resistance and the movements of position markers inserted in the soil, showed that two intensively compacted layers were created: one up to about 2 cm directly above the plow sole, and another several centimeters below the soil surface.



Tractor size: 47.8 kW
Roller weight: 960 kg
Width: 200 cm

Tractor size: 47.8 kW
Roller weight: 1,200 kg
Roller load with hydraulic cylinder: 1,700 kg
Width: 200 cm

Tractor size: 25 kW
Roller weight: 350 kg
Width: 150 cm

Photo 1. Prototype rollers: a) Drum roller, b) Steel tube roller, c) Vibratory roller

Table 1. Measurement results of basic intake rate (I_b) (modified from Fukami et al. 2014a)

Number of roller passes		I_b^* mm h ⁻¹	SD	Reference values I_b of dry-seeded rice field in Northern Kyushu area
Test 1	0	74	25	A field in Munakata, Fukuoka 5.7 Fields in Amagi, Fukuoka**
	1	24	20	
	3	16	6	
	5	4	4	
Test 2	0	83	29	5.8
	5	6	5	
	10	4	1	

* Average of three plots

** Average of two fields

3. Effect of the vibratory roller

Fukami et al. (2014b) created two more types of rollers to make leakage prevention treatment more efficient. The first type shown in Photo 1 b) uses steel pipes instead of oil drums and adopts a hydraulic cylinder applied diagonally backward to increase the roller load from 1,200 kg to 1,700 kg. The second type shown in Photo 1 c) is a vibratory roller in which the curved shanks of the vibrating subsoiler were replaced with steel tubes 40 cm in diameter and 150 cm in width. The compaction tests in the field using these rollers showed effective leakage reduction in gray lowland soil with moisture content close to the plastic limit, regardless of compaction load, number of compactions, or running speed. The vibratory roller was lighter than the two other types of rollers as the high impact on the soil was largely due to vibration, so this roller could be used with a tractor with 25 kW of output, a type commonly used in Kyushu.

Fukami et al. (2017) conducted further compaction tests using a vibratory roller to study ways to reduce the

number of roller compactions at different soil moisture levels and roller speeds. Given that both factors affect the degree of water leakage control, water leakage was found to be sufficiently prevented at roller compaction with soil moisture content at the plastic limit (Table 2). They also observed compacted soil using X-ray CT scans that showed that a flatter pore shape and a smaller volume of macropores when water leakage was sufficiently prevented. The tests showed that use of the vibratory roller and attention given to moisture conditions can cause deformation of the soil structure needed to prevent leakage, when compacting the soil twice.

4. Water leakage prevention process that can be implemented in farmer's fields

Based on the above findings, a leakage prevention process that could be implemented in farmer's fields was demonstrated (Consortium for a Low-cost Paddy Rotation System in Northern Kyushu 2016). This process typically takes 30 - 40 minutes per 10 a.

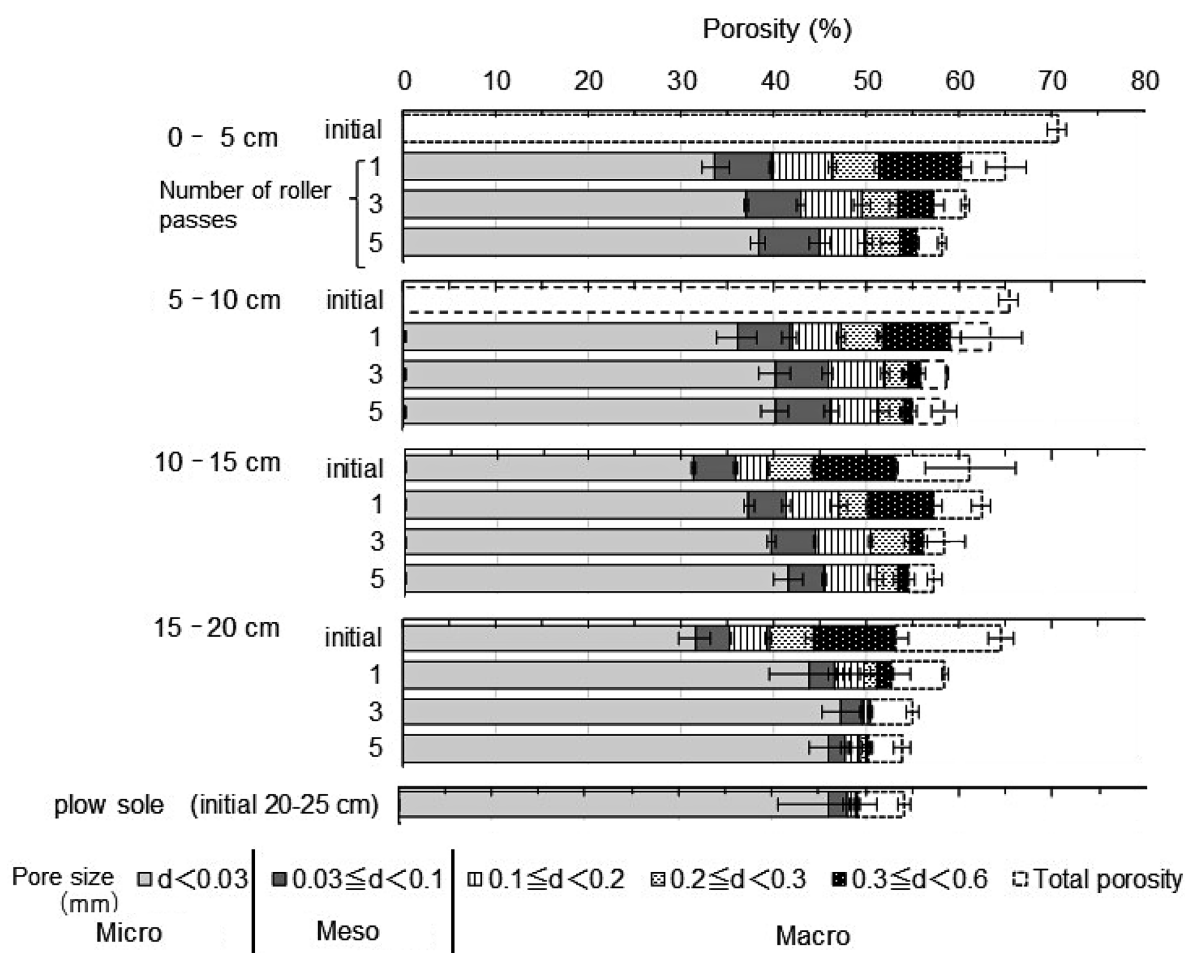


Fig. 4. Pore size distribution before and after roller compaction (modified from Nakano and Fukami 2017)

The pore size was conveniently divided based on the soil moisture characteristic curve.

d: equivalent pore diameter (mm) calculated from soil water potential

(1) Using a vibratory roller

The use of a vibratory roller was proposed. Although we used a customized product in our tests, we adopted a ready-made roller (SV2-T; Kawabe Agricultural Industry Co., Ltd.) to facilitate introduction of this method. The SV-T roller (weighting 280 kg) can be attached to a three-point link and moved by a 22 kW (30 PS) class tractor. To prevent machine failure, the roller should be operated at

Table 2. Water leakage from the roller-compacted field (after 2nd pass) and ANOVA results of the effects of soil moisture and operating speed (modified from Fukami et al. 2017)

Soil moisture (%)	Speed (km h ⁻¹)	Water leakage (cm day ⁻¹)	
		1	2
32		15.4	48.3
		12.3	41.0
39		1.8	2.3
		1.4	1.7
Fixed source of variation		$P > F^c$	
Soil moisture ^a		< 0.001	
Speed ^b		0.001	
Soil moisture x Speed		0.002	

a. soil moisture: soil moisture before compaction

b. speed: roller operation speed

c. $P > F$: P value

Plastic limit of the test field topsoil: 38%

the PTO rotational speed specified by the manufacturer (750 rpm-1,400 rpm), with the PTO turned off when lifting the rollers. As the roller's effectiveness is much lower at low PTO rotational speeds, operation has been suggested at 1,000 rpm-1,100 rpm. After the compaction operation, the tractor's tire tracks were found more concave than the areas compacted by the roller, making it less likely for water to penetrate. Thus, the effective width of leakage prevention is the width of the roller plus the width of the tractor tires on each side (i.e., approximately 150 cm).

(2) The soil should be moderately moist during compaction.

When the soil is compacted, the total porosity due to water passages decreases, but subdividing the macropores it is also important. The procedure for checking the appropriate moisture condition for roller compaction on-site is as follows: Take a handful of soil from the top 5-cm layer and tightly squeeze it into a ball just before applying the roller. If you can make it into a ball, the soil is suitably moist. Otherwise, the soil has the wrong moisture level (Fig. 5). For example, Photo 2 shows a moisture check in a farmer's fields (numbered) in 2018. Fields other than Nos. 1 and 6 (which are too dry) were judged as having the appropriate moisture. Performing roller compaction at an inappropriate moisture level runs the risk of the macropores being insufficiently collapsed. Even if compacting is repeated, the effect will be insufficient.

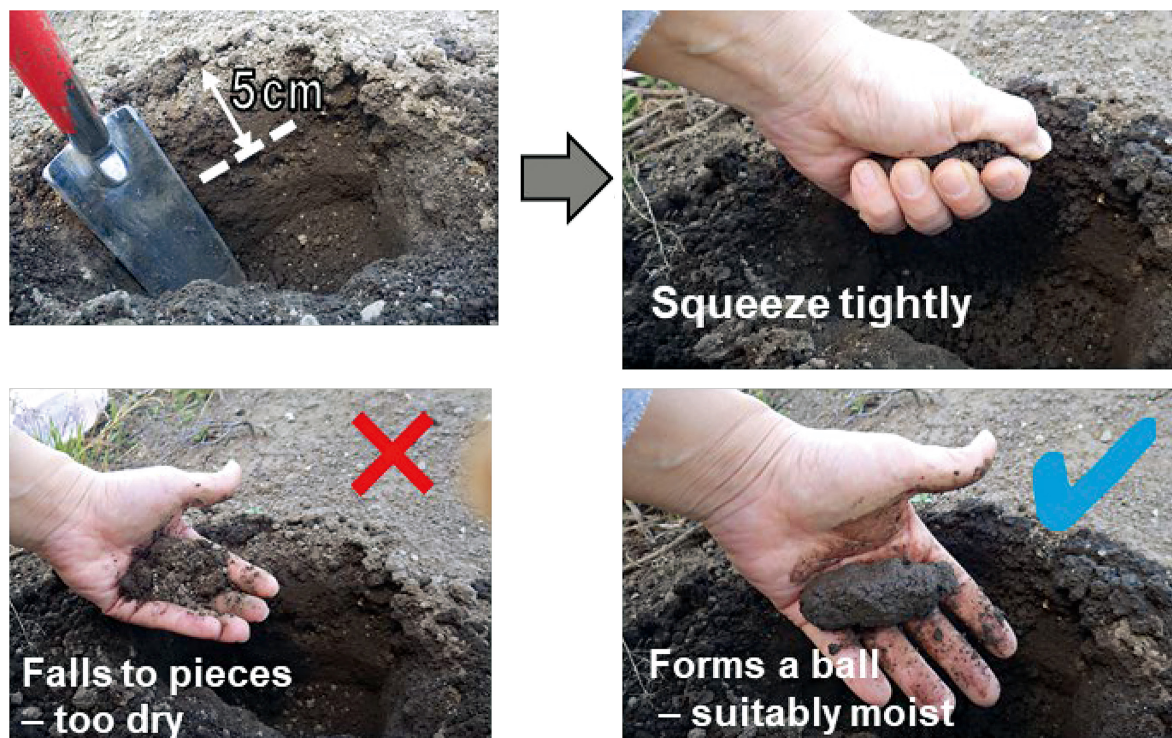


Fig. 5. On-site judgment of whether soil moisture is suitable for the roller compaction process

As the soil immediately after tillage is often in an appropriately moist state for roller compaction, it is preferable to use a sowing machine that can perform tillage (with straw plowing) and sowing in one pass. The combination of a one-operation seeding method and the vibratory roller has been demonstrated for use of a shallow layer seeding machine (MD40SH-SR1500; Sato Farm Machines Company) as specified in the manual (Consortium for a Low-cost Paddy Rotation System in Northern Kyushu 2016). The use of the partially shallow tilling and sowing method (Kawamura et al. 2013) has been fine, too.

(3) The entire field should be compacted, without leaving any gaps.

In field demonstration tests, a single pass of the vibratory roller at a speed of 1.8 km/h over soil with an appropriate water content resulted in the reduction rate of the ponding water depth being within an appropriate value of 20 mm/day or less. The test fields also included severely leaking fields where the permeability of the plow sole immediately before rice cultivation exceeded 1,000 mm/day. Based on our experience in working under different conditions and in different fields, a single compaction at an upper speed limit of 3 km/h appeared to be sufficient. However, water leakage may occur in areas over which the roller does not pass. It is thus important to perform compacting operation over the entire field without any gaps, so as to form a continuous permeation-suppressive layer. As it is difficult to completely compact the edges of a field using the roller, a safe alternative would be two laps of compression under the outermost

tractor tire.

The current status and future development of our proposed method

1. Method of dry direct-seeding rice cultivation made possible after winter cropping

Figure 2 shows an outline of the work process for the direct sowing of rice in dry fields for double-cropping cultivation with winter wheat or barley, incorporating the above-mentioned water leakage prevention process. After the wheat or barley is harvested, the field is tilled, with surface straw being plowed in and the rice seeds sown. The soil is then compacted with a vibratory roller to prevent water leakage. When the rice has grown 2 - 4 leaves, the field is flooded and then managed in the same way as with transplant cultivation.

The first technical manual (Consortium for a Low-cost Paddy Rotation System in Northern Kyushu, 2016) showed the use of a shallow layer seeding machine and a vibratory roller in the dry-direct seeding of rice. However, farmers who introduce a rice-wheat double cropping system in northern Kyushu already have seeding machines for soybean or wheat. These sowing machines were confirmed as being capable of sowing paddy rice. This means that a rice and wheat farmer can easily take on direct seeing cultivation in dry fields, by simply obtaining a vibratory roller. Even in fields where a plow sole survey during barley and wheat cultivation had detected extremely high permeability, no leakage problems were seen during dry-seeded rice cultivation



Photo 2. On-site diagnosis (with each number denoting a different field)

when the roller compaction process had been performed. The yield was comparable to that obtained with transplant cultivation. There is growing interest in the new method in the Chikugo area of northern Kyushu. The focus of outreach activities is the Study Group of Labor-saving and Low-cost Cultivation, established by the Minamichikugo Agricultural Extension Center. As a result of collecting various demonstration examples, the technical points have been narrowed down to four, and a simplified manual was issued (NARO Kyushu Okinawa Agricultural Research Center 2019). The four key points are (1) information on seeding machines, (2) on-site evaluation of soil moisture conditions suitable for the roller compaction process, (3) information on the vibratory roller used in the water leakage prevention process, and (4) weed control.

Basically, weed control is performed three times: an herbicide is applied to the soil after seeding, a foliar herbicide is applied before flooding the field, and an herbicide is applied in the flooded condition. In each case, only herbicides specifically registered for the direct sowing of rice can be used. It is also important to apply the necessary chemicals at the appropriate times in the field, as pest control in transplanted seedling boxes is not available for direct sowing.

2. Future developments

The use of vibratory rollers to prevent water leakage in dry fields has been adopted mainly in gray lowland soil areas, but this technique has also been tested in andosols, which are more prone to seepage. Farmers are likely to consider using this method if the water depth requirement is the same as that in the surrounding transplanted fields. It has also been tried where there is no winter crop, though in this case, other factors may need to be considered due to the different state of the field after wheat cultivation. Even so, such direct sowing of dry fields can be implemented with only a small investment, and this method may be potentially adopted by small and medium-sized farmers regardless of their cropping system. The current method is designed for farmers with tractors delivering 22 kW-29 kW (30 PS-40 PS). However, to achieve the work efficiency required by a farmer with large tractors or large fields, improvements are being made to the vibratory roller.

In Japan's agricultural scene, technology for saving labor using robotic tractors is gaining ground. Use of a vibratory roller is likely to be suitable for robotization. It is necessary to halt the vibration when the roller is lifted at the headland of the field, and the entire field must be evenly compressed. These are demands that require skill and alertness on the part of a tractor driver, but are simple

tasks that are amenable to robotic control. And in order to enable compacting under the appropriate moisture conditions, two operators should ideally perform the seeding and compacting processes, thereby leaving a minimal time gap between both processes. Conversely, when a robot performs one task, only one operator is needed to complete the job. Based on the above, the compacting process using a vibratory roller is likely to be a type of work suitable for robot tractors. Studies are now being conducted to realize robotic compaction.

Acknowledgements

Financial support was provided as grants from the NARO Bio-oriented Technology Research Advancement Institute, as part of their special project on revitalizing the management entities of Japan's agriculture, forestry and fisheries (2017-2019), and the special scheme to create dynamism in agriculture, forestry and fisheries by deploying highly advanced technology (2014-2015).

Our series of studies was conducted with the assistance of Masamitsu Yamai, Takayuki Aramaki, Toshihisa Kaneko, Mitsuaki Nakamura, and other farmers belonging to the Study Group on Labor-saving and Low-cost Cultivation; Ryohei Okuno, Yoshio Tanamachi, Hiroaki Kojima, and other staff members of the Minamichikugo Agricultural Extension Center; and Akitoshi Honbu, Hiroto Ito, Hiroyuki Itoh, Yasutaka Kawaguchi, Yukinari Kawahara, Keiji Miike, Teruyuki Miike, Makoto Nakajima, Sadako Nakao, Makiko Setoguchi, and Yuka Sugimoto. We are extremely grateful for their help.

References

- Aichi Agricultural Research Center (2007) *Guidebook for the V-furrow No-Till Direct Seeding of Rice, 4th edition*. <https://www.pref.aichi.jp/nososi/seika/singijutu/singijiyutu74-4-7.pdf> [In Japanese].
- Consortium for a Low-cost Paddy Rotation System in Northern Kyushu (2016) *Technical manual on rice, wheat and soybean rotation with general use of up-cut rotary tillage based on direct seeding of rice*. https://www.naro.affrc.go.jp/publicity_report/publication/files/c66cbc61d4cbeccdfae83e09b0c8d46e.pdf [In Japanese].
- FAO (2017) *Food and agriculture data, Trade/Crops and livestock products/Export quantity*. <http://www.fao.org/faostat/en/#data>.
- Fukami, K. et al. (2014a) Use of a leakage prevention technique on a direct-seeded dry paddy field in a warm region. *J. Jpn. Soc. Agric. Mach. Food Eng.*, **76**, 341-347 [In Japanese with English summary].
- Fukami, K. et al. (2014b) *Water leakage prevention technique on a direct-seeded dry paddy field in a warm region by roller compaction*. <http://www.naro.affrc.go.jp/laboratory/>

- karc/prefectural_results/files/H26_1_suiden.pdf [In Japanese].
- Fukami, K. et al. (2017) Water leakage control by using vibratory roller on a dry-seeded rice field in southwestern Japan. *Soil and Tillage Research*, **166**, 138-146.
- Inoue, H. (1993) Lateral water-flow clayey agricultural field with cracks. *Geoderma*, **59**, 311-325.
- Kanmuri, H. et al. (2015) Permeability reduction caused by surface compaction in large dry paddy fields under direct-seeding rice cultivation. *Japanese Journal of Farm Work Research*, **50**, 103-113 [In Japanese with English Summary].
- Kawamura, Y. et al. (2013) Effect of partially shallow tillage and sowing method on the quality and yield of wheat (*Triticum aestivum* L.) and labor-saving cultivation. *Japanese Journal of Farm Work Research*, **48**, 111-120 [In Japanese with English Summary].
- Kawasaki, T. (1990) Study on the suitable soil moisture of rotary tillage in paddy fields. *Transactions of the Japanese Society of Irrigation, Drainage and Reclamation Engineering*, **147**, 69-77 [In Japanese with English Summary].
- Kyushu Okinawa Agricultural Research Center, NARO (2019) *Seeding and compacting! Method for dry direct-seeding of rice after wheat or barley cultivation*. https://www.naro.affrc.go.jp/publicity_report/publication/files/216799cde830b429e2e8425bdbc5285c.pdf [In Japanese].
- Ministry of Agriculture, Forestry and Fisheries of Japan (2016) *2015 Census of Agriculture and Forestry*. <https://www.maff.go.jp/j/tokei/census/afc2015/280624.html>.
- Ministry of Agriculture, Forestry and Fisheries of Japan (2017) *Latest direct sowing situation*. https://www.maff.go.jp/j/seisan/ryutu/zikamaki/z_genzyo/attach/pdf/index-7.pdf.
- Nakano, K. et al. (2010) Characterization of hydraulic property of plow sole under double-cropped paddy fields in southern Japan. *Proceedings 19th World Congress of Soil Science*, CD-ROM.
- Nakano, K. & Fukami, K. (2017) Soil pore-structure in a surface layer compacted with a roller for the dry-seeded rice cultivation. *J. Jpn. Soc. Soil Phys.*, **136**, 27-35 [In Japanese with English Summary].
- Tanaka, K. (1991) The Malayan-Type Rice Culture and Its Distribution. *Tonan Ajia Kenkyu*, **29**, 306-382 [In Japanese with English Summary].
- Tohoku Agricultural Research Center, NARO (2016) *Dry direct-seeding rice cultivation technical manual - Using a plough and grain drill ver. 3.1*. https://www.naro.affrc.go.jp/publicity_report/publication/files/dry-seeding_rice_v3.1.pdf [In Japanese].
- USDA (2020) *World agricultural production*. <https://apps.fas.usda.gov/psdonline/circulars/production.pdf>.
- Yamazaki, F. et al. (1966) The role of cracks in subsoil on underdrainage in clayey reclaimed paddy fields. *Transactions of JSIDRE*, **16**, 1-8 [In Japanese with English summary].