

REVIEW

Improved Mechanization Efficiency in Grain Maize Cultivation Employing a Crop Rotation System in Upland Fields Converted from Paddy Fields

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Abstract

The demand for labor-saving crops and domestically produced feed has increased, as has the cultivation of grain maize in upland fields that were previously used for rice cultivation. Compared to wheat and soybeans, grain maize can be managed more efficiently in large-scale operations and on large plots, making the application of highly efficient cultivation and harvesting systems advantageous during optimal periods. Plowing tillage maintains grain maize growth and yield, increases root lodging resistance, and reduces work time by 19%-36% compared to conventional rotary tilling. Also, using a maize header for harvesting reduces work time by 21% while maintaining accuracy comparable to a reel header. Standard operating procedures for highly efficient work systems, from cultivation to harvest, have been developed and implemented for social adoption and extension. This review assesses various aspects of these integrated, highly efficient work systems for grain maize production in upland fields converted from Japanese paddy fields.

Discipline: Crop Science

Additional key words: lodging, maize header, plowing tillage, root, yield

Introduction

1. Background of the reintroduction of grain maize in upland converted fields

Due to a decline in rice demand and prices resulting from a shrinking population and shifts in dietary habits, the total area of agricultural land dedicated to rice cultivation has continued to decrease in Japan (Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF) 2025a). Due to the decline in rice cultivation in Japan's paddy fields, which account for approximately 54% (as of 2023) of the country's arable land (MAFF 2023a), full utilization is necessary. Concurrently, the agricultural sector is experiencing a demographic shift with an aging and diminishing farming population (MAFF 2022), along

with an increasing concentration of agricultural operations and scale of farming activities. Consequently, the need for labor-saving crops that are adaptable to arable farming environments has increased. Japan imported 15.27 million tons of maize in 2022, primarily from the US and other countries (MAFF 2023b), which is more than twice the amount of rice produced in Japan that same year (6.70 million tons) (MAFF 2025a). Of the imported maize, 11.45 million tons (75%) were used as animal feed (MAFF 2023b). Thus, since the 2010s, there has been a significant shift toward cultivating grain maize for feed in converted paddy fields to enhance domestic production of concentrated feed and labor-efficient management.

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2. Status of technology development on grain maize in Japan

In Japan, maize for concentrated feed (grain maize) is used to produce grain (MAFF 2025b), as shown in Figure 1. The machinery used for cultivating grain maize can also be used to cultivate soybeans. Unlike soybeans, grain maize does not require intertilling or ridging, and relatively little management is required for pest control, making grain maize more labor-efficient. Since it is possible to rotate maize with wheat and soybeans, the introduction of grain maize is expected to stabilize wheat and soybean production in areas where crop failures due to continuous cropping are an issue (Tomizawa 2016). Up to 73,000 ha of grain maize was grown mainly in Hokkaido until the 1960s, according to the statistics of agriculture, forestry, and fisheries of the Ministry of Agriculture and Forestry and MAFF. However, low yields and competition with cheaper imported grain maize led to a decline in domestic maize cultivation, with cultivation at scale resuming only in the 2010s (MAFF 2025b, Ministry of Agriculture and Forestry 1968, Shinoto 2024). Given the marked decrease in cultivation during this period, technological developments related to grain maize cultivation and harvesting stagnated.

Hokkaido has once again taken the lead in the technological development of cultivating grain maize in Japan, including cultivation systems (Nakatsu et al. 2015a, 2015b, 2015c), fertilizer application rates (Tomizawa et al. 2017a, 2017b), harvesting, drying, preparation (Inano et al. 2017), and management evaluation (Araki 2019). However, the scale of the production base, field plots, and work machinery employed in Hokkaido differs from that of other prefectures. Consequently, it has become necessary to develop technologies tailored to the specific scale of each prefecture.

3. Background of demand for a highly efficient system with plowing tillage

Although most of the grain maize produced in the prefectures is grown in upland fields that have been converted from paddy fields, it is susceptible to damage



Fig. 1. Grain maize (a) just before harvest and maize kernels (b) just after harvesting by combine

The grain maize in (a) is shown with the husk peeled back.

from wet conditions (Kanno et al. 2010, 2014, 2023). One of the causes of moisture damage is the presence of a plow sole pan. Approximately 20 years ago, a method of dry direct seeding rice cultivation was developed that uses plowing and compaction to eliminate the need for a plow sole pan, incorporating the use of existing crop machinery. This innovation was developed to enhance crop stability in crop rotation systems within paddy fields (Otani et al. 2013). Starting in 2014, studies were initiated in the Tohoku region for introducing grain maize on crop rotation methods in paddies employing dry direct seeding rice with plowing and compaction as the primary method (Shinoto 2017). Plowing tillage (PT) is a faster operation than rotary tilling (RT), which is the conventional method employed. PT enables timely seedbed preparation and seeding, even under unstable weather conditions. Employing this labor-saving method is crucial given the decline in the number of agricultural workers and the increase in agricultural scale.

This study describes a highly efficient system for cultivating and harvesting grain maize in converted paddy fields in the Tohoku region. The plowing cultivation system discussed in this manuscript involves the application of chisel plowing for tillage and a power harrow for seedbed preparation.

Highly efficient system for grain maize cultivation and harvesting in converted paddy fields

Figure 2 shows the proposed, highly efficient system for cultivating and harvesting grain maize in converted paddy fields. The results of on-site farm experiments demonstrated that replacing conventional RT with PT, a more efficient cultivation system, reduced overall work time by 36% (Miyaji et al. 2020). In particular, the time spent on seedbed preparation and seeding was reduced by 74% and 56%, respectively. During the harvesting phase, the use of a maize-specific header, as opposed to a standard reel header, reduced harvesting time by 21% (Shinoto et al. 2023a). Adopting this system not only increases the daily work area, enhancing productivity with limited manpower, but also capitalizes on the labor-saving advantages inherent in grain maize cultivation.

Labor-saving and stable cultivation of grain maize by PT in upland converted fields

1. Effects of plowing tillage on the growth and yield of grain maize

To assess the suitability of PT for introducing grain maize into converted paddy fields, we compared its

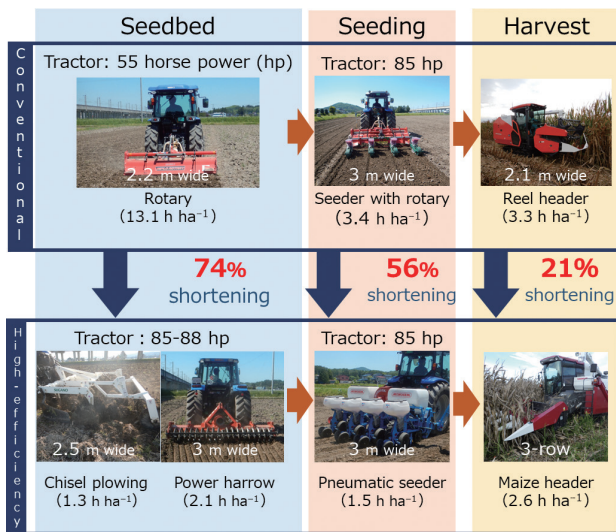


Fig. 2. Highly efficient system for grain maize cultivation and harvesting in upland fields converted from paddy fields

Data cited from Miyaji et al. (2020) and Shinoto et al. (2023a).

effects on growth and yield with those of RT. We examined two maize varieties with relative maturities (RM) of 108 days (Pioneer, 34N84) and 115 days (Pioneer, 34B39) that were sown in late May in converted paddy fields in Iwate Prefecture. Throughout the growing period, no significant differences were observed between the tillage methods in plant height and leaf color up to silking, aboveground dry matter weight, nitrogen uptake, yield, or yield components (ear length, kernel number, and 100-grain weight) (Shinoto et al. 2017, 2018a, 2018b). This shows that the growth and yield of grain maize under PT are comparable to those under RT. Further comparisons were made using six maize varieties (RM108–118) over the 2016–2017 seasons, and no significant differences in growth or yield were observed. This result was attributed to the tillage method and interaction between the varieties and the tillage method (Shinoto et al. 2020). Revisions and obsolescence of cultivars occur more quickly in grain maize than they do in rice, wheat, or soybeans. Our results showed that new maize cultivars can be grown successfully with PT, achieving growth and yield levels similar to those obtained using RT.

2. Effects of plowing tillage on physical and chemical soil properties

Soil penetration resistance at a depth of 0 cm–5 cm showed no significant difference between PT and RT fields (Shinoto et al. 2017, 2018b, 2019b, 2020, 2021). However, at a depth of 5 cm–20 cm, penetration resistance

was greater with PT than with RT (Shinoto et al. 2017, 2018b, 2019b, 2020, 2021). In terms of fertilizer distribution, more than 95% of the fertilizer under PT was distributed at a depth of 0 cm–10 cm, whereas in RT, fertilizer distribution was more uniform through a depth of 0 cm–20 cm (Shinoto et al. 2018b). Chemical properties of the soil, such as nitrate nitrogen, exchangeable potassium, and available phosphorus, were assessed at the six-leaf stage. These findings showed that the parameters were higher or tended to be higher in PT fields than in RT fields at a depth of 0 cm–10 cm (Shinoto et al. 2018b). This combination between fertilizer application and PT was observed for nitrate nitrogen, hot-water extractable nitrogen, and exchangeable potassium at a soil depth of 0 cm–5 cm. This combination of fertilizer application and PT resulted in superior soil chemical properties at the surface layer during the sixth-leaf growth stage, compared with RT, which exhibited almost uniform fertilizer distribution (Shinoto et al. 2018a, 2021, 2023a). Despite these early-stage significant differences, no differences in soil chemical properties were observed at the mature stage between PT and RT (Shinoto et al. 2018b, 2023c).

These results demonstrate that PT in converted paddy leads to differences in surface soil chemical properties from RT, primarily due to variations in soil penetration resistance and fertilizer distribution. Although grain maize growth and yield were lower under PT without fertilizer (primarily due to higher hot-water extractable nitrogen, an indicator of available nitrogen), the more favorable soil chemistry of the surface layer in fertilized PT fields produced growth and yield comparable to RT (Shinoto et al. 2023c). This indicates that strategic fertilizer distribution is crucial in maintaining comparable growth, especially in fields of varying soil fertility.

3. Effects of plowing tillage on root systems and root lodging in grain maize

Differences in soil physical properties resulting from tillage methods influence the bleeding rate, which reflects both root system function (physiological activity) and root distribution (Anderson 1987, Guan et al. 2014, Tsuji et al. 2002, Watanabe et al. 1994). Our findings showed no significant differences in bleeding rate between RT and PT, indicating similar root activity (Shinoto et al. 2018a). Although root length density was not significantly different overall, PT tended to increase root length density from the tassel formation stage to the milk stage, suggesting an effect of PT on root distribution (Shinoto et al. 2017). Therefore, we investigated root length density by soil depth at different growing seasons and calculated the root depth index (RDI), which



Fig. 3. Roots of grain maize in the maturity stage in rotary tilling and plowing tillage in Andosol

measures the average depth of the root system. Our findings showed that in PT, root length density at the soil surface increased and became shallower after the seventh leaf stage, compared to RT, mainly due to differences in soil hardness (Shinoto et al. 2021). At maturity, the root system under PT was approximately 1 cm shallower than that under RT (Shinoto et al. 2018a) (Fig. 3). The shallower root system under PT resulted from an increase in nodal root length density after the sixth-leaf growth stage, particularly during the sixth-leaf stage and tassel formation stage, which affected nodal root elongation and branching (Shinoto et al. 2023b). In conclusion, while PT in converted paddy fields had minimal impact on root physiology, it significantly altered the distribution of the root system in grain maize, leading to shallower root architecture.

The shallower root system under PT potentially reduces root lodging resistance. This is particularly important for grain maize, which is typically taller than other crops. In converted paddy fields with Andosol soil, the horizontal pulling resistance-value (HPR-value), an indicator of root lodging resistance, was lower in PT than in RT, indicating superior resistance in PT-treated fields (Shinoto et al. 2020). Interestingly, less lodging was observed after a typhoon in 2017, suggesting that PT enhances root lodging resistance at the field level (Shinoto et al. 2020). This study found that grain maize cultivated under PT in converted paddy fields develops more roots than RT in the surface layer, where soil hardness increases rapidly. This adaptation can enhance a crop's resistance to root lodging.

4. On-site farm experiments

Initial findings from studies conducted in converted Andosol paddy fields at the Tohoku Agricultural Research Center of the National Agriculture and Food Research Organization (NARO) were corroborated in farmers' fields, which are primarily comprised of Gleysol soil, a typical paddy soil type.

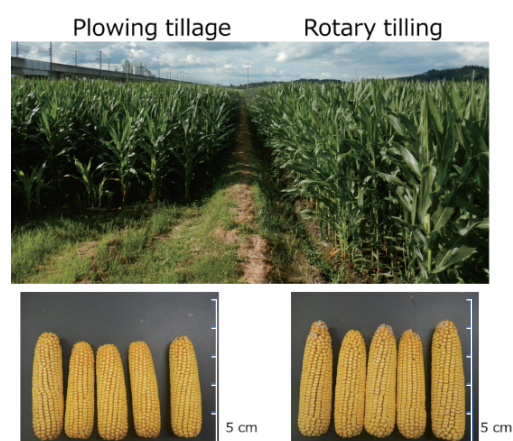


Fig. 4. Plots (top row) and ears (bottom row) comparing rotary tilling and plowing tillage in a farmer's fields



Fig. 5. Field conditions (a) before and (b) after lodging caused by an extratropical cyclone following Typhoon 18 in 2017

Images from Shinoto et al. (2019a).

a: Yellow ripening stage (97 days after seeding), b: Mature stage (133 days after seeding)

The number and percentage of seedlings established were not significantly different between PT with a pneumatic seeder and RT with a rotary seeder (Shinoto et al. 2019b), indicating that PT with a pneumatic seeder can reduce work expenditure while maintaining seeding accuracy comparable to RT with a rotary seeder. In practice, farmers introducing PT in the Tohoku region mainly choose pneumatic seeders (Koda & Miyaji 2020a). As observed in paddy fields with Andosol soils, the growth and yield of grain maize cultivated under PT in Gleysol were comparable to those grown under RT (Shinoto et al. 2019b) (Fig. 4). Soil penetration resistance was greater at depths of 0 cm-5 cm or more, resulting in shallower root systems. Although traits of root lodging (i.e., culm length, ear height, HPR, and HPR-value) did not differ markedly between the tillage treatments, root lodging status was generally lower under PT than under RT (Shinoto et al. 2019a), as shown in Figure 5. The crop yield per unit area was 11.2 t ha⁻¹ for RT and 11.7 t ha⁻¹ for PT, with similar yields. However, the total harvested

yield by combine harvesters was 6.1 t ha⁻¹ for RT and 7.0 t ha⁻¹ (15% moisture) for PT, which is 13% higher, indicating that PT improved root lodging resistance and reduced losses during combine harvesting. Furthermore, fumonisin concentrations of fungal toxins tended to be lower in PT than in RT under conditions of root lodging caused by typhoons (Shinoto et al. 2019b). This suggests that improved root lodging resistance may also contribute to reduced weather-related risks and improved quality. Since root lodging is significant in terms of increased harvesting time and damage to combines, improved root lodging resistance is a significant advantage for farmers.

In on-farm site experiments conducted in 2020 without root lodging due to a typhoon, the combined yields of RT and PT were 8.2 t ha⁻¹ and 8.7 t ha⁻¹ (15% moisture) and were similar or slightly higher for PT. When maize headers were used for harvesting, the total work time of PT was 19% lower than that of RT (Tables 1, 2). These results were similar to those obtained for the field demonstration test plots in previous years (Miyaji et al. 2020). The reduction in work time for PT compared with RT was mainly due to a 29% reduction for tillage and seedbed creation (RT: 4.9 h ha⁻¹→PT: 1.7 h ha⁻¹+1.8 h ha⁻¹) and a 68% reduction for seeding, respectively

Table 1. Operation schedule and labor allocation in plowing tillage in 0.6 ha across seasons

Date	Operation	Operation hours (h ha ⁻¹)	Total operation hours (h ha ⁻¹)	Laborers
2019 Fall	Drainage (subsoiler)	1.8	1.8	1
2 May	Sludge compost distribution	1.3	1.9	1.5
2 May	Tillage	1.7	1.7	1
26 May	Fertilization	0.5	0.8	1.5
26 May	Seed bed	1.8	1.8	1
26 May	Seeding	1.4	1.4	1
26 May	Drainage (open ditch)	1.1	1.1	1
28 May	Residual herbicide	0.8	1.6	2
23 June	Post-emergence herbicide	0.7	1.4	2
21 Oct	Harvesting (maize header)	2.7	5.4	2
2020 Fall	Residue treatment	1.1	1.1	1
	-	-	20	-

The time required to maintain the levees is not included. Operation hours for drainage (subsoiler), residual herbicide, and residue treatments are sourced from Miyaji et al. (2020).

Table 2. Operation schedule and labor allocation in rotary tilling in 0.6 ha across seasons

Date	Operation	Operation hours (h ha ⁻¹)	Total operation hours (h ha ⁻¹)	Laborers
2019 Fall	Drainage (subsoiler)	1.8	1.8	1
2 May	Sludge compost distribution	1.1	1.7	1.5
13 May	Tillage	4.9	4.9	1
26 May	Fertilization	0.6	0.9	1.5
26 May	Tillage and seeding	4.4	4.4	1
26 May	Drainage (open ditch)	1.7	1.7	1
28 May	Residual herbicide	0.8	1.6	2
23 June	Post-emergence herbicide	0.8	1.5	2
21 Oct	Harvesting (maize header)	2.5	5.0	2
2020 Fall	Residue treatment	1.1	1.1	1
	-	-	24.6	-

The time required to maintain the levees is not included. Operation hours for drainage (subsoiler), residual herbicide, and residue treatments are sourced from Miyaji et al. (2020).

(RT: 4.4 h ha⁻¹→PT: 1.4 h ha⁻¹) (Tables 1, 2). Therefore, the study showed that grain maize cultivated with PT in converted paddy fields not only accelerates the work process but also improves root lodging resistance and maintains growth and yield over RT. These findings demonstrate that PT is a labor-saving, robust cultivation method.

Efficient harvesting by domestic combines

Harvesting grain maize with a combine equipped with a maize header is a common practice globally (Shinoto et al. 2018c, 2018d). In Hokkaido, which had the largest area under grain maize cultivation in Japan in 2022, the adapting imported combines originally designed for harvesting wheat and soybeans to include maize headers has advanced considerably (Inano et al. 2017). These combines have been introduced to local farmers (Araki 2019). Even within the prefecture, some farmers use foreign-made combines fitted with either maize or reel headers for harvesting (Koda & Miyaji 2020a, 2020b). However, compared to Hokkaido, paddy fields in other prefectures are smaller and farm roads are narrower, making it difficult to use imported combines. Consequently, there is a need for harvesting technology that employs domestic combines better suited to the smaller fields and road conditions in prefectures.

Research on harvesting technology for grain maize using domestic combines began in 2014, initially employing a reel header (Shinoto et al. 2015). The configuration of this domestic combine features a bar-type threshing cylinder and several enhancements designed to improve efficiency and minimize crop loss. For example, the header has a finger plate to minimize ear drop, a left-side divider to facilitate crop uptake, and reinforcements that reduced the number from six tines to three to accommodate the greater load compared to rice and wheat (Fig. 6). The operation of the header is unique because it harvests immediately below the uppermost ear, thereby collecting the stems and leaves above the ear as well. While head loss ranged from 5%-20% in 2015, it decreased to 0%-15% in 2016, with threshing losses remaining under 0.5% due to improved prototype parts (Shinoto et al. 2023a). In addition, the cutting width of 2.1 m used in many prefectures typically allows for harvesting two rows at a time (Fig. 7a). Since 2018, a grain maize kit has been commercially available for domestic combines equipped with a bar-type threshing cylinder. Also, a domestic combine with a screw-type threshing cylinder has been developed (Shirahata et al. 2017), and kits for this model have also become commercially available.

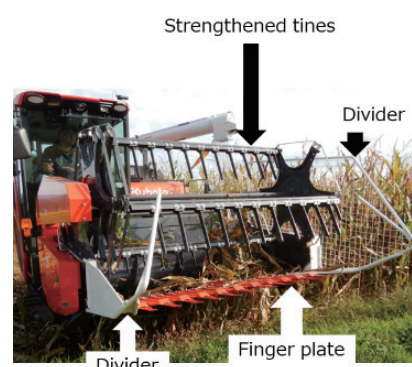


Fig. 6. Reel header combine for harvesting grain maize

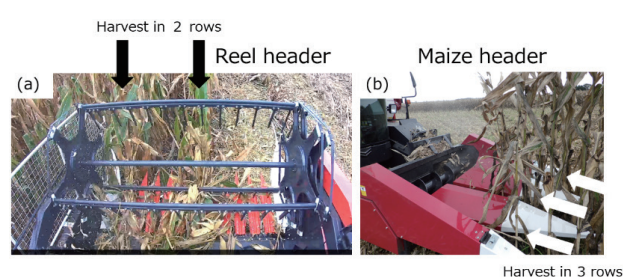


Fig. 7. Comparison of harvesting with (a) a reel header and (b) a maize header

Although the reel header can be used with various crops, it increases the load on the threshing unit by also pulling in the stem above the uppermost ear. In addition, since the moisture content of both the grain and the stem significantly affects harvest quality, it is essential to reduce this to optimize harvesting. Therefore, we developed a harvesting technology featuring a maize header designed explicitly for grain maize.

The maize header is essentially comprised of two rollers that feed the stalks downward, snapping only the ears onto the header and then feeding only the ears to the threshing and sorting section (Abe et al. 2022). Compared to a reel header, the harvesting accuracy of a three-row maize header installed on a domestic combine with a bar-type threshing cylinder was found to be comparable (Kanai et al. 2020). Specifically, the harvesting speed using the maize header was 1.4 m s⁻¹, and that of the reel header was 1.0 m s⁻¹ (Kanai et al. 2020). Therefore, compared to the reel header, the three-row maize header (Fig. 7b) was shown to be a high-efficiency harvesting method that maintains harvesting accuracy. In on-farm site experiments, harvesting time with a maize header was 21% lower than with a reel header (Shinoto et al. 2023a), further confirming that maize headers can enhance the efficiency of harvesting systems.

Implementation and extension of research results

A highly efficient system for grain maize cultivation using PT and maize headers converted from paddy fields has been formalized into a standard operating procedure (NARO 2026). Additionally, an educational video for producers is available online (NARO 2023), serving as a tool to facilitate the extension and adoption of grain maize cultivation. Furthermore, NARO is collaborating with various stakeholders, including producers, prefectural and municipal governments, manufacturers, and agricultural cooperative organizations, to expand the use and cultivation area of grain maize. As a result of these efforts, the area dedicated to grain maize in the Tohoku region has expanded from 124 ha in 2021 to 561 ha in 2023, representing an increase of more than 450% over the three years (Shinoto 2024).

The challenges facing the expansion of grain maize in Japan extend beyond technological barriers to include a wide range of institutional and social infrastructure issues. Indeed, all parties need to work together to create a new crop from scratch, a crop that has ceased to be produced in Japan. This involves not only technology providers but also compound feed companies, which require a large production scale (e.g., 500 t to 1,000 t). A key challenge will be to develop a system that reduces storage and distribution costs, while simultaneously increasing production volumes and maintaining quality. To achieve this, it is essential to communicate the significance and value of grain maize and to foster sustainable relationships among the parties involved.

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