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## Farmer-participatory evaluation of mechanized dry direct-seeding technology for rice in northeastern Thailand

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### ABSTRACT

Rice technologies that are designed to reduce risks due to climate variations, improve productivity, or overcome labor scarcity are important in tropical Asia. The objective of this study was to evaluate mechanized options for dry direct-seeding of rice in terms of the productivity and production costs in rainfed lowlands. In a series of on-farm research trials over 3 years in Ubon Ratchathani province, Thailand, we compared seeding by seed drills mounted on two-wheel tractors with manual broadcast seeding. Demonstration trials of seed drills and site-specific nutrient management in 2017 with 11 of 26 participating farmers produced 2.50 t ha<sup>-1</sup> of grain yield, but unexpected heavy storms forced the other 15 farmers to switch from dry to wet direct-seeding or manual transplanting. The seed drills produced 32% higher grain yield than manual broadcast seeding (3.3 vs. 2.5 t ha<sup>-1</sup>) in 2014, and 14–24% higher yield (3.3–3.6 vs. 2.9 t ha<sup>-1</sup>) in 2015. Mechanized seeding enabled seeding rate reduction by 50% in 2014 and by 52–61% in 2015, resulting in lower production costs than with manual seeding. Our results suggest that mechanized dry direct-seeding of rice with improved nutrient management can enhance farmer livelihoods in rainfed environments in northeastern Thailand. This approach can significantly reduce production costs compared with manual transplanting, while maintaining or increasing productivity compared with conventional manual broadcast seeding.

**Abbreviations:** THB: Thai Baht

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### KEYWORDS

Direct-seeded rice; farm mechanization; on-farm research; rainfed lowland; site-specific nutrient management

### Introduction

Northeastern Thailand is well known as a major producer of premium aromatic rice (Sarkarung et al., 2000; Vanavichit et al., 2018). Approximately 60% of the agricultural land (ca.  $9 \times 10^6$  ha) in the region is managed as a rainfed lowland rice ecosystem (OAE, 2013). Most of the rice-growing areas are rainfed. The region's soils are commonly highly weathered and sandy, low in nutrients, low in organic matter, and low in water-holding capacity (Wade et al., 1999). Erratic rainfall patterns create droughts and flash flooding, leading to low yields (2–3 t ha<sup>-1</sup>) and high yield fluctuations from year to year. Farmers are resource-poor, typically holding less than 4 ha per household (Jairin et al., 2017a). In addition, labor shortages have become increasingly serious because younger residents in rural areas are migrating to urban areas in search of a better livelihood. This trend has driven most rice farmers to shift from transplanting seedlings to dry direct-seeding. However, the poor crop establishment and inefficient weed control in this approach often constrain yields

(Kumar & Ladha, 2011; Yamane et al., 2018). Furthermore, severe pest outbreaks have become more frequent in direct-seeded rice fields, owing in part to ongoing climate change (Ali et al., 2014; Jairin et al., 2017b).

One alternative to mitigate the low productivity and low profitability may be mechanized rice establishment using seed drills. In particular, seed drills suitable for use with two-wheel hand tractors can be easily adopted by smallholder farmers who cannot afford big four-wheel tractors. This could reduce the need to use extremely high seeding rates (>250 kg ha<sup>-1</sup>) to compensate for poorer germination and higher pest damage with manual broadcast seeding (Ohno et al., 2018). A few types of seed drills fabricated by local Thai manufacturers and suitable for mounting on two-wheel tractors were recently introduced to farmers (Jairin et al., 2017a). Researchers predict that dibbling or line seeding using these seed drills will enable farmers to both reduce the seeding rate and control weeds more easily (Hayashi, Kamoshita et al., 2009).

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 Supplemental data for this article can be accessed [here](#).

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Another option to reduce the production cost with no yield penalty would be to improve fertilizer-use efficiency. Overuse of inorganic fertilizers in rice farming often causes low resource-use efficiency and environmental pollution due to N leaching and eutrophication (Fischer and Conner, 2018). Recent studies in tropical Asia suggested that improved fertilization based on site-specific nutrient management can significantly enhance rice productivity and profitability in rainfed lowlands (Banayo et al., 2018a, 2018b) and, at least in theory, reduce pollution. A single fertilizer application regime (40-12-10 kg of N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O ha<sup>-1</sup>) has long been recommended for the whole rainfed lowland area in northeastern Thailand (Soil Science Division, 2000). However, the response of rice yield to a given amount of fertilizer depends on the soil type and soil fertility (Dobermann & White, 1999), suggesting the need for different nutrient regimes at different sites. The topographic position of paddy fields in the undulating lands of this region will also greatly affect rice productivity in rainfed lowland rice because of differences in soil characteristics and in the severity of drought among positions (Haefele et al., 2016; Homma et al., 2003). Thus, relying on a single fertilizer regime is likely to result in low fertilizer-use efficiency of rice (Banayo et al., 2018a). To enhance fertilizer-use efficiency in rainfed lowland rice, the principle of site-specific nutrient management was proposed for northeastern Thailand after a series of on-farm trials in the 2000s demonstrated the viability of this approach (Haefele & Konboon, 2009). Subsequently, a user-friendly decision-support tool was developed to help farmers determine the amount of fertilizer they required from soil fertility and the topographic position of the rice field, and was successfully evaluated in fields in all provinces in the region (Wongboon et al., 2018).

In the present study, we designed an on-farm research project to validate the improved rice

management practices and disseminate knowledge of the new techniques. Our goal was to reduce the risks due to climate fluctuations, improve productivity, and help overcome the current labor scarcity in rainfed cultivation in tropical Asia. The specific objective of this study was to evaluate the on-farm performance of the mechanized dry direct-seeding technology for rice, combined with site-specific nutrient management, in the rainfed lowlands of Thailand.

## Materials and methods

### Set-up of on-farm research trials

The mean daily temperature during the trials (June to November), recorded at the meteorological station at the Ubon Ratchathani Rice Research Center (15°20'N, 104°41'E), 5–10 km from each farm site, was 28.0°C in 2014, 28.4°C in 2015, and 27.6°C in 2017, but the rainfall pattern varied greatly among years (Figure 1).

To provide a proof of the concept, we tested the combination of mechanized dry direct-seeding and improved nutrient management with participating farmers during the wet season of 2014. Two on-farm trials were set up at Don Chee village, Mueang district (15°19'N, 104°42'E), and Na Pho village, Khueang Nai district (15°24'N, 104°26'E), both in Ubon Ratchathani province. We selected two farmer leaders in the villages who were eager to transfer the innovative technologies to their neighbors. We compared three rice cultivation methods: manual transplanting of seedlings, manual broadcasting of dry seeds, and mechanized dry direct-seeding by seed drills. All treatments followed an improved nutrient management regime based on site-specific nutrient management for rainfed lowlands in northeastern Thailand (see Haefele & Konboon, 2009, for details). This approach is based on adapting the fertilizer regime to account for differences in the soil fertility and topographic position of the rice fields.

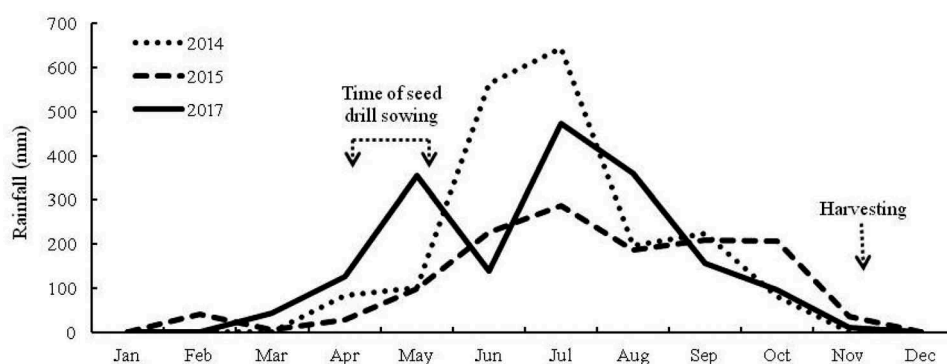


Figure 1. Monthly rainfall at Ubon Ratchathani province in 2014, 2015 and 2017.

### *In lower fields or valley bottoms*

- If fields without fertilizer application yielded  $\geq 3.0$  t ha<sup>-1</sup> in the previous crop, fertilizer application is not necessary. Because these fields are fertile, fertilizer application would increase the risk of lodging and pest damage.
- If fields without fertilizer application yielded 2.5–3.0 t ha<sup>-1</sup> in the previous crop, apply 20.6–12.5–6.3 kg N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O ha<sup>-1</sup>.
- If fields without fertilizer application yielded <2.5 t ha<sup>-1</sup> in the previous crop, apply 40.6–25.0–12.5 kg N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O ha<sup>-1</sup>.

### *In upper and middle terraces*

- Because of insufficient soil water, few crops at these locations can yield >2.0 t ha<sup>-1</sup>.
- If fields without fertilizer application yielded 1.5–2.0 t ha<sup>-1</sup> in the previous crop, apply 20.6–12.5–6.3 kg N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O ha<sup>-1</sup>.
- If fields without fertilizer application yielded <1.5 t ha<sup>-1</sup> in the previous crop, apply 40.6–25.0–12.5 kg N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O ha<sup>-1</sup>.

P and K fertilizers and one-third of the N were applied 20–30 days after sowing, and the remaining N was applied in two equal amounts at the early tillering stage (60 days after sowing) and at panicle initiation.

Farmers grew rice cultivar KDML105 under rainfed lowland conditions in the middle terrace fields. The size of each plot was 896–4824 m<sup>2</sup>. Dry seeds were broadcast by hand or drill-seeded from 10 to 12 June 2014; 30-day-old seedlings were transplanted on 15 July. For weed control, a pre-emergence herbicide (oxadiazon) was applied 0–3 days after sowing at 0.4 kg a.i. ha<sup>-1</sup>, and a post-emergence herbicide (2,4-D) was applied 20 days after emergence at 0.8 kg a.i. ha<sup>-1</sup>.

In the wet season of 2015, an on-farm trial was conducted with a participating farmer in Na Pho village comparing three types of seed drills with manual broadcasting. The treatments were arranged in a randomized complete block design with three replicates. After preparation of the dry land (two passes with disc harrows to a depth of 10–15 cm), dry rice seeds (cv. KDML105) were sown on dry soils on 12 June 2015 using one of three types of seed drill mounted on a hand tractor (Supplemental Fig. S1): Type I (Pong Karnchang Co., Ltd., Ubon Ratchathani, Thailand), Type II (Bothai Machinery Co., Ltd., Phetchabun, Thailand), and Type III (Changthong Co., Ltd., Khon Kaen, Thailand). Seeds were also broadcast by hand. The main difference in the three seed drills was in the opener mechanism, which creates openings in the dry soil's surface. The Type I planter dabbles seeds into five

V-shaped shallow ditches created by the planter with 25 cm between the rows and 20 cm between the hills. The Type II planter plants seeds in the ditches created by the double discs to create four rows with 25 cm between the rows. The Type III planter is similar to the Type II planter but has trailing coulters instead of discs. The improved nutrient management regime was applied to all mechanized direct-seeding plots (Table 1), while farmer nutrient management was followed in manual seeding. The plot size ranged from 1161 to 2466 m<sup>2</sup>.

During the wet season of 2017, on-farm demonstration trials were conducted with 26 participating farmers in Na Pho and Non Pho villages (15°24'N, 104°27'E), Khueang Nai district, Ubon Ratchathani province, in an effort to encourage implementation of the improved dry direct-seeding technology for rainfed lowland rice on a wider scale. The same three types of seed drills were used with the same improved nutrient management regime. Participating farmers operated seed drills by themselves in their own fields. Each field was divided into two plots (each 765–1555 m<sup>2</sup>) to allow a comparison of the improved nutrient management regime and a regime based on the farmer's own practices.

### **Measurements**

Before the on-farm trials in each year, we randomly collected soil samples to a depth of 15 cm, and analyzed the pH (H<sub>2</sub>O), organic matter content, available phosphorus, exchangeable potassium, and soil texture.

At physiological maturity, we counted the number of panicles within a 1-m<sup>2</sup> quadrat avoiding border rows and measured the height of 10 plants in each plot. The rice was harvested from all plants within a 10-m<sup>2</sup> quadrat avoiding border rows in each plot on 19 and 20 November 2014, 17 November 2015, and 10 November 2017. All harvested panicles were threshed and winnowed to determine grain yield, expressed at a 14% grain moisture level. The production cost was calculated in Thai Baht (THB) by summing up all the variable

**Table 1.** Fertilizer regimes in the on-farm research trial in Na Pho village, Ubon Ratchathani province in 2015.

Treatment	Basal application of N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O (kg ha <sup>-1</sup> )		Topdressing of N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O (kg ha <sup>-1</sup> )
	1st	2nd	
Site-specific nutrient management	13.8-25.0-12.5	13.8-0-0	13.8-0-0
Farmer nutrient management	28.8-28.8-14.4	–	13.1-13.1-13.1

costs (i.e. fuel, labor, herbicides, fertilizer, land preparation, and seeds). We calculated the net return from the production as the gross revenue (grain yield  $\times$  farm gate rice price) – the variable costs. We used this value as an indicator of the economic efficiency of the mechanized direct-seeding and the improved nutrient management.

We performed analysis of variance in IRRI's open-access software for statistical analysis (IRRI, 2014), which is implemented in the R statistical package (R Core Team, 2013).

## Results

Table 2 summarizes the soil properties in each year. Soils were sandy (fine sand, sandy loam, or loamy fine sand), were low in organic matter (0.3–0.6 wt% in 2014, 0.3 wt% in 2016, and 0.8 wt% in 2017), and had low pH (4.1–4.8).

### Validation of mechanized dry direct-seeding in 2014 and 2015

Table 3 summarizes the results in 2014. Plant height did not differ significantly among the planting methods. Although the number of panicles per  $m^2$  was significantly higher with manual broadcasting of seed, the yields with manual transplanting (3300  $kg\ ha^{-1}$ ) and mechanized seeding (3250  $kg\ ha^{-1}$ ) were significantly higher than with manual broadcasting (2480  $kg\ ha^{-1}$ ). The total cost of rice production was higher in the manual transplanting method than the mechanized seeding and manual broadcasting (Figure 2). However, mechanized seeding reduced the seed cost by 50% compared with manual broadcasting, while it slightly increased the cost for planting (i.e. the operation of seed drills). Given the return on the cost of rice production (Table 4), mechanized seeding gave the highest net return (23986 THB  $ha^{-1}$ ), representing an increase of 10908 THB  $ha^{-1}$  over conventional manual broadcasting and of 3781 THB  $ha^{-1}$  over manual transplanting.

**Table 3.** Grain yield, panicle number and plant height of rice in the three crop establishment methods in on-farm trials in Ubon Ratchathani in 2014.

Treatment	Plant height (cm)	Panicles ( $m^{-2}$ )	Grain yield ( $kg\ ha^{-1}$ )
Mechanized seeding of dry seeds	131 <sup>a</sup>	252 <sup>b</sup>	3,250 <sup>a</sup>
Manual broadcasting of dry seeds	125 <sup>a</sup>	414 <sup>a</sup>	2,480 <sup>b</sup>
Manual transplanting of seedlings	129 <sup>a</sup>	230 <sup>b</sup>	3,300 <sup>a</sup>

Values within a column followed by the same letters are not significantly different at 0.05 probability level of significance.

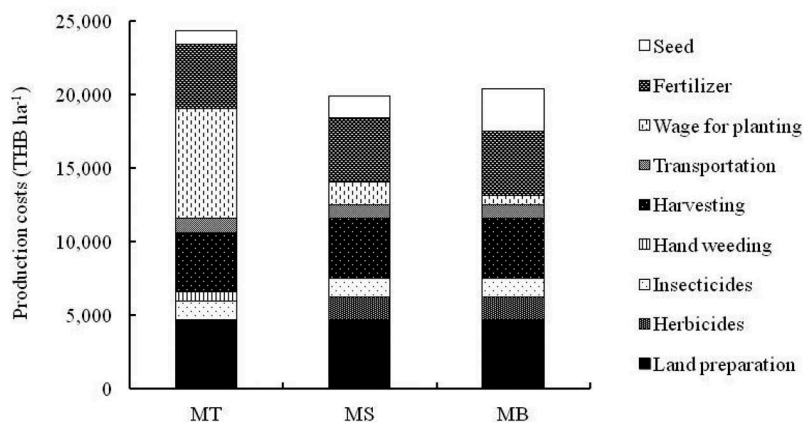
We combined the three types of seed drills with the improved site-specific nutrient management to allow a comparison with manual seeding plus farmer nutrient management in 2015. Plant height did not differ significantly among the treatments (Table 5), but the seeding rate with manual seeding (144  $kg\ ha^{-1}$ ) was more than double that used with the seed drills. Panicle number was similar between seeding methods. However, grain yield was higher in the treatments that combined the Types I and II seed drills with improved nutrient management than with manual seeding, by 404–723  $kg\ ha^{-1}$ . The total cost of rice production, which ranged from 21851 to 23846 THB  $ha^{-1}$ , did not differ significantly among the treatments. The increased labor cost with the improved practices by 1563 THB  $ha^{-1}$  was offset by the reduced costs of seed (by 1825–2200 THB  $ha^{-1}$ ) and fertilizer (by 1357 THB  $ha^{-1}$ ) relative to those of manual seeding and traditional fertilizer management. Consequently, the drill-seeding with site-specific nutrient management provided a much higher net return than manual seeding, by 6642–10087 THB  $ha^{-1}$  (Figure 3).

### On-farm demonstration trials of mechanized dry direct-seeding in 2017

A total of 26 farmers participated in the trials in 2017, but only 11 of them could test the seed drills in their fields. The other 15 farmers were unable to use the seed drills because of unexpected heavy storms at the start of the wet season (Figure 1), and instead changed to wet manual broadcast-seeding or manual transplanting. Farmers were able to use the seed drills from mid April

**Table 2.** Soil chemical properties in the on-farm research trials in Ubon Ratchathani province, Northeast Thailand, before the wet seasons of 2014, 2015 and 2017.

Year	Location	Soil pH (H <sub>2</sub> O)	Soil organic matter (%)	Available P (ppm)	Extractable K (ppm)	Soil texture
2014	Don Chee village, Mueang district	4.3	0.6	4.9	10.2	–
	Na Pho village, Khueang Nai district	4.7	0.3	22.2	16.4	Fine sand
2015	Na Pho village, Khueang Nai district	4.1	0.3	15.5	65.3	–
	Na Pho village, Khueang Nai district	4.8	0.8	12.1	26.5	Sandy loam, Fine sand, and Loamy Fine sand



**Figure 2.** Production costs of different cultivation methods, i.e. manual transplanting of seedlings (MT), mechanized seeding of dry seeds (MS), and Manual broadcasting of dry seeds (MB) in on-farm trials in Ubon Ratchathani in 2014 (1 THB = 0.0304 USD in 2014).

**Table 4.** Production costs, income, and net return of different cultivation methods in on-farm research trials in Ubon Ratchathani province (Don Chee village and Na Pho village) in 2014.

Treatment	Gross revenue <sup>a</sup> (THB ha <sup>-1</sup> )	Production cost (THB ha <sup>-1</sup> )	Net return <sup>b</sup> (THB ha <sup>-1</sup> )
Mechanized seeding of dry seeds	43,875 <sup>a</sup>	19,890	23,986 <sup>a</sup>
Manual broadcasting of dry seeds	33,380 <sup>b</sup>	20,402	13,078 <sup>b</sup>
Manual transplanting of seedlings	44,550 <sup>a</sup>	24,345	20,205 <sup>a</sup>

<sup>a</sup>Gross revenue = grain yield (kg ha<sup>-1</sup>) × farm gate rice price (US\$ kg<sup>-1</sup>), where the rice grains were sold to the millers (13.5 THB kg<sup>-1</sup>).

<sup>b</sup>Net return = gross revenue – production cost.

Values within a column followed by the same letters are not significantly different at 0.05 probability level of significance.

One THB = 0.0304 USD in 2014.

**Table 5.** Seeding rate, plant height at maturity, panicle number and grain yield in the on-farm research trial in Na Pho village, Ubon Ratchathani province in 2015.

Treatment	Seeding rate (kg ha <sup>-1</sup> )	Plant height (cm)	Panicles (m <sup>-2</sup> )	Grain yield (kg ha <sup>-1</sup> )
Improved practice using seed drill (Type I)	62.5	143 <sup>a</sup>	215 <sup>a</sup>	3575 <sup>a</sup>
Improved practice using seed drill (Type II)	68.8	137 <sup>a</sup>	249 <sup>a</sup>	3526 <sup>ab</sup>
Improved practice using seed drill (Type III)	56.3	134 <sup>a</sup>	304 <sup>a</sup>	3256 <sup>bc</sup>
Farmer practice	143.8	139 <sup>a</sup>	336 <sup>a</sup>	2852 <sup>c</sup>

Dry seeds were broadcast in farmer practice. The plots where the four-row seed drills were used received fertilizers based on site-specific nutrient management. Values within a column followed by the same letters are not significantly different at 0.05 probability level of significance.

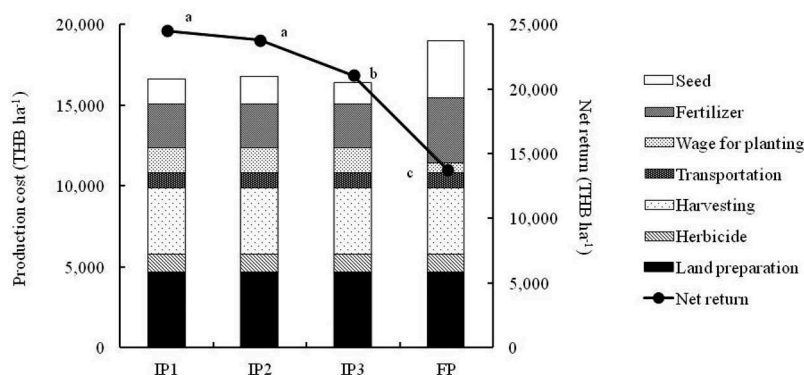
to mid May in Na Pho village but from early July in Non Pho village. The average seeding rate was 49 kg ha<sup>-1</sup>. All participating farmers applied more fertilizer (57–29–19 kg ha<sup>-1</sup> of N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O) than was recommended under the improved nutrient management regime (41–25–13 kg ha<sup>-1</sup>). The higher fertilizer rate produced a

higher number of panicles and greater plant height than under the improved nutrient management, but the panicle size was smaller (data not shown). Consequently, grain yield did not differ significantly between treatments (Table 6). The fertilizer cost was higher under farmer nutrient management than under improved nutrient management, but the net return above the fertilizer cost was not significantly enhanced with improved nutrient management. We interviewed all farmers about the acceptability of the seed drills and the improved nutrient management. Although they reported the risk of heavy storms, all claimed to be eager to adopt the mechanized seeding method and the improved nutrient management to lower their production costs, particularly if the higher yield and higher net return could be achieved.

## Discussion

Approximately 70% of the rice production areas in northeastern Thailand are dominated by old Thai aromatic rice cultivars (KDML105 and RD15), which are highly susceptible to pests and diseases as well as to drought and flooding (Jairin et al., 2009; Vanavichit et al., 2018). Breeding efforts have been under way for several decades, and new rice cultivars and near-isogenic lines that are more tolerant of these stresses have been developed within the KDML105 genetic background (Jairin et al., 2017b). To take full advantage of this genetic improvement of rice, improved management options such as those described here should be developed, demonstrated to farmers, and introduced, to help farmers reduce the risks while enhancing their productivity and profitability.

Transplanting of rice seedlings is widely practiced in tropical Asia (Kumar & Ladha, 2011), but recent labor



**Figure 3.** Production cost and net return of the improved practices (mechanized seeding and improved nutrient management) using seed drill Type I (IP1), Type II (IP2) and Type III (IP3), and farmer practice (FP) in on-farm trials on dry direct seeding of rice in 2015 (1 THB = 0.0279 USD).

**Table 6.** Grain yields, gross revenue, costs of fertilizer applications and the net return of site-specific nutrient management and farmer practice in on-farm demonstration trials of mechanized dry direct-seeding of rice in Khueang Nai district, Ubon Ratchathani province in 2017.

Nutrient management	Grain yield (kg ha <sup>-1</sup> )	Gross revenue <sup>a</sup> (THB ha <sup>-1</sup> )	Fertilizer cost (THB ha <sup>-1</sup> )	Gross return above fertilizer cost <sup>b</sup> (THB ha <sup>-1</sup> )
Site-specific nutrient management	2,500 <sup>a</sup>	37,500 <sup>a</sup>	1,827	35,673 <sup>a</sup>
Farmer nutrient management	2,580 <sup>a</sup>	38,719 <sup>a</sup>	3,526	35,193 <sup>a</sup>

<sup>a</sup> Gross revenue = grain yield (kg ha<sup>-1</sup>) × farm gate rice price (US\$ kg<sup>-1</sup>)

<sup>b</sup> Gross return above fertilizer cost (GRF) = gross revenue – fertilizer cost (Banayo et al., 2018a).

One THB = 0.0306 USD in 2017. Values within a column followed by the same letters are not significantly different at 0.05 probability level of significance.

shortages in rural areas such as those of the Mekong region have forced smallholder farmers to shift from manual transplanting to manual broadcast-seeding (Laing et al., 2018). Unfortunately, high seed costs and the poor weed control sometimes drive farmers to switch back to the original transplanting method (W. Wongboon, unpublished data). Our on-farm research trials in 2014 and 2015 showed that the grain yields and net return were improved by mechanized dry direct-seeding of rice with seed drills mounted on hand tractors (Tables 3 and 5), relative to the traditional manual broadcasting. The large panicles (i.e. grain weight per panicle) appears to be the main growth attribute responsible for the yield improvement with mechanized seeding, whereas manual broadcasting produced a much higher number of small panicles. The number of rainfed lowland rice areas where farmers use seed drills is rapidly increasing throughout north-eastern Thailand with support from the Thai government. However, the narrow range of soil moisture conditions suitable for the operation of seed drills

may limit dissemination of the technology, particularly where rainfall at the start of wet seasons is variable from year to year (e.g. the Mekong region; Adamson & Bird, 2010): these machines cannot be operated when the soil is too moist or is saturated after heavy storms, as we observed in 2017. One potential solution would be to advance to an earlier sowing date. Although current hand tractors cannot be used for preparation of hard surface soils before the start of the wet season, it could be worthwhile to investigate the use of four-wheel tractors for plowing, particularly where cultivars that have good seedling establishment in dry soils are available (Ohno et al., 2018). Where individual farmers cannot afford these tractors, it may be possible to form village-level cooperatives that purchase and share the equipment or utilize contract services.

Another problem is the low fertilizer-use efficiency in the conventional nutrient management regime in rice farming (Haefele & Konboon, 2009). A recent large-scale on-farm demonstration (291 sites in 20 provinces over 9 years) in our study area showed that the yield of transplanted rice increased by 10% under site-specific nutrient management (from 2.60 to 2.86 t ha<sup>-1</sup>) relative to farmer nutrient management, leading to an increased net return by around 100 USD ha<sup>-1</sup> (Jairin et al., 2017a; Wongboon et al., 2018). The yield advantage with improved nutrient management was correlated with crop yields under farmer nutrient management; that is, the lower the typical yield, the higher the yield gain from improved management (Wongboon et al., 2018). Although the yield gain was not observed in our on-farm demonstration trials in 2017, the improved nutrient management could reduce the production cost without sacrificing productivity (Table 6). The combination of increased labor and reduced seed and fertilizer cost with seed drills gave greater benefit for farmers in 2015 (Figure 3), in agreement with the recent on-farm

research in Laos (Laing et al., 2018). As suggested in the previous studies (Alam et al., 2013; Stuart et al., 2018), future research is needed to develop the guideline for the best management practices coupled with mechanized seeding of rice in the target region.

In conclusion, our on-farm research trials showed high potential benefits from the adoption of mechanized dry direct-seeding technology combined with site-specific nutrient management in rainfed lowland rice in north-eastern Thailand. These innovative technologies can decrease rice production costs, increase yields, or both, thereby improving net returns compared with manual seeding or transplanting. Compared with manual broadcasting a slight increase in the cost for sowing by using seed drills can be fully compensated by the reduced seed cost. Participating farmers, and particularly the seed producers, expressed their desire to adopt the mechanized planting and improved nutrient management. These results highlight opportunities to improve the livelihoods of smallholder farmers in rainfed environments and, with appropriate changes to account for local conditions, will be relevant to other areas in Southeast Asia.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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