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The application of best management practices increases the profitability and sustainability of rice farming in the central plains of Thailand

Alexander M. Stuart[a,*], Anny Ruth P. Pame[a], Duangporn Vithoonjit[b], Ladda Viriyangkura[b], Julmanee Pithuncharurnlap[b], Nisa Meesang[c], Prarthana Suksiri[c], Grant R. Singleton[a], Rubenito M. Lampayan[a,d]

[a] Crop and Environmental Sciences Division, International Rice Research Institute, DAPO Box 7777, Metro Manila, Philippines
[b] Thailand Rice Department, Bangkok, 10900, Thailand
[c] Land Development Department, Bangkok, 10900 Thailand
[d] College of Engineering and Agro-Industrial Technology, University of the Philippines Los Baños, College, Laguna, Philippines

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ABSTRACT

There is a need to increase the resource use efficiency and sustainability of rice production in the intensive lowland irrigated rice growing areas of Thailand where farmers face challenges such as the overuse of inputs that cause negative environmental effects, rising input and labor costs, declining rice farm gate prices, and water scarcity. Since 2012, a set of integrated best management practices based on Cost Reduction Operating Principles (CROP) has been promoted to rice farmers by the Thailand Rice Department. Through replicated farmer participatory field trials, we evaluated the performance over three seasons of three integrated best management packages that included CROP recommendations, CROP + alternate wetting and drying (AWD), and CROP + drum seeder (DS) technology and compared these with standard farmer's practice (FP). We also provide an economic and productivity assessment of the large-scale (160–800 ha) application of CROP practices across eight sites in the Chao Phraya river basin. In the field trials, farmers that applied CROP practices reduced fertilizer inputs by a mean of 50–64% per season with no yield penalty and were able to increase their net income versus FP by a mean of 26% across all three seasons. The CROP + DS treatments also reduced seed rates by 60–67% and consistently showed the largest benefits over FP, with increases in mean net income per season in the range of 29–46%. Due to water shortages in the dry season, all treatments followed forced-AWD. However, even with limited water supply, high yields were still attained across all plots, giving farmers the assurance that yields can be maintained with AWD practices. Results from the large-scale application of CROP practices showed farmer groups reduced costs by 6–36% ($\bar{x}$ = 17%) and increased net income by 21–131% ($\bar{x}$ = 79%) when compared with the same season in the previous year. The results of these studies indicate that through an increase in income and a decrease in inputs that cause negative environmental impacts, the adoption of improved agronomic practices can enhance the sustainability of intensive rice production.

1. Introduction

In Asia, the growing human population and decreasing agricultural land area have intensified the global pressure to increase food production in remaining agricultural land (GRiSP, 2013). However, agricultural intensification has led to an increased use of chemical and organic inputs, which are associated with a number of negative environmental effects such as climate change, a degrading natural environment, and biodiversity loss (Lobell et al., 2009; Mueller et al., 2012; Phalan et al., 2014). In addition, the high use of inputs to maximize yield is in most cases not the most economically profitable practice for farmers as it can increase the susceptibility of rice plants to pests and diseases, especially when inputs are applied excessively or unnecessarily (Altieri, 2002; Heong et al., 2013; Ma et al., 2014; West et al., 2014). For long-term agricultural sustain-

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[*] Corresponding author at: International Rice Research Institute, DAPO Box 7777, Metro Manila, Philippines.
E-mail address: a.stuart@irri.org (A.M. Stuart).

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ability, farm management practices that have a negative effect on both the environment and on farmers' profit margin should be avoided. Overall, farmers should use practices that are able to sustain current agricultural productivity but avert degradation of the environment that may lead to loss in productivity over the long term (Altieri, 2002).

Thailand is one of the world's largest producers and exporters of rice, with the major rice growing areas located in the northeast region and in the lower north and central plains of the Chao Phraya river basin. Roughly 70% of the rice area in Thailand is rainfed, but the irrigated area, located mainly in the Chao Phraya river basin, accounts for 49% of the total annual rice production (Kupkanchanakul, 2000; USDA-FAS, 2015b). A recent study by Stuart et al. (2016) in Nakhon Sawan province within the central plains of Thailand found that rice farmers were over-applying nitrogen (N) fertilizer and that their mean farm yield during the wet season (WS) of 2013 was 1.4 t ha^{-1} (or 23.3%) lower than the attainable farm yield (the mean yield of the top decile). Although this yield gap is relatively small compared to the yield gap in some regions in other Southeast Asian countries, there is clearly potential for rice farmers in this region to reduce their inputs and increase their yields.

The rice industry in Thailand is facing a number of challenges that threaten its sustainability. In 2014, rice farmers faced a 50% decline in farm gate prices for rice as a result of falling domestic rice prices and of the discontinuation of the Thai Government's rice pledging scheme (USDA-FAS, 2015a; Attavanich, 2016). The rice-growing area in the Chao Phraya river basin also is identified as a hot-spot of water scarcity due to increased competition with urban and industrial users (Bouman et al., 2007). This became apparent between early 2013 and mid-2016, when rice farmers in the Chao Phraya river basin faced irrigation restrictions and water shortages due to low reservoir levels and below-average rainfall (USDA-FAS, 2015b). This, coupled with rising rural wages and input costs, has magnified the focus on increasing the resource use efficiency and sustainability of rice production in a region where water shortages are becoming increasingly likely.

Since 2012, the Thailand Rice Department (TRD) has promoted a set of integrated best management practices based on the Cost Reduction Operating Principles (CROP). CROP practices aim to increase income by 20% by reducing costs whilst maintaining or increasing yields by following the "Three must do" and "Three must reduce" recommendations. This is similar to the "Three Reductions, Three Gains" crop management technology that was introduced to rice farmers in Vietnam which has since evolved into 'One Must Do Five Reductions' (Huan et al., 2005; Huelgas and Templeton, 2010). For CROP, the "Three must do" recommendations include 1) planting no more than two crops per year, 2) using high-quality seeds, and 3) recording farming production costs and income in a diary. On the other hand, the "Three must reduce" recommendations include reducing 1) seed rate applications, 2) incorrect fertilizer application practices, and 3) unnecessary chemical applications.

As part of an adaptive farmer participatory research platform, we established replicated production-scale field trials of three integrated best management packages that included CROP recommendations, alternate wetting and drying (AWD) and drum seeding (DS) technologies. In this paper, we evaluate the performance of these different sets of "best practices" against farmer's practice in relation to yield, resource use efficiency, and profitability. The main objectives of this study were to reduce the economic and environmental costs of rice production and promote water-saving technologies whilst at the same time increasing or maintaining productivity. In addition, we provide an economic and productivity assessment of the application of CROP on a large scale in several sites in the Chao Phraya river basin.

Table 1
Baseline soil properties at 0–15 cm soil depths in the field trial sites in Nakhon Sawan, Thailand.

Soil properties	Range	Mean ± S.D.
pH (1:1 soil:water)	5.42–7.21	6.08 ± 0.69
EC (dS m^{-1}) (1:1 soil:water)	0.02–0.15	0.06 ± 0.04
Soil Organic Matter (%)	1.64–4.13	2.99 ± 0.79
Available P (mg kg^{-1})	5.2–54.5	17.8 ± 16.8
Exchangeable K (mg kg^{-1})	170–326	232 ± 53

2. Methods

2.1. Experimental site

Farmer participatory field trials were established in Nong Jikree and Sapansong villages in Nakhon Sawan province in the central plains of the Chao Phraya river basin (15°12′N 100°21′E) where rice farming is the primary livelihood. Each village site had established Community Rice Centers that are rice farmer groups who are registered with the government extension office and who interact with local extension specialists (Soitong, 2010). Rice is grown twice a year: the first or wet season (WS) crop is from June to October and the second or dry season (DS) crop is from January to May. The mean farm size is 4.9 ha (±1.2 SE), with a mostly clay soil type (Stuart et al., 2016; Table 1). The main crop establishment method is wet direct-seeding using a mechanical knapsack sprayer. Due to labor scarcity, a majority of the farmers in these areas practice farm mechanization, from land preparation to harvesting. The overuse of production inputs such as fertilizers, seeds, and pesticides is one of the current inefficient practices in the region (Stuart et al., 2016; unpublished data).

2.2. Experimental design and treatment details

To account for spatial variability, a randomized complete block design was established, consisting of four treatments in each block replicated over three sites for the 2013 DS and eight sites for the 2014 WS (Table 2). The four treatments applied were (i) CROP, (ii) CROP + AWD, (iii) CROP + DS, and (iv) Farmer's Practice (FP). These treatments were selected to address the main needs identified by the farmers during focus group discussions in both villages. In each block, one to two farmers were selected, depending on their field size, to apply the CROP treatments and another farmer was selected to follow FP in a neighboring field. This was to minimize the transfer of CROP practices to the FP field. Farmers were selected based on the willingness to participate in the field trials. All farmers in each block planted the same rice variety. Two blocks (including the same farmers) were common throughout all three seasons. One block was common for the first two seasons and another block was common for the latter two seasons. After the end of each season, meetings were held with participating farmers to evaluate the technologies and practices and to facilitate farmer learning in an adaptive research approach (Flor et al., 2016). At the maturing stage of the second and third season rice crops, farmer field days were held to promote the CROP practices, AWD, and drum seeder technology to the wider community.

In the 2015 DS, low reservoir levels led to irrigation restrictions that prohibited the planting of a dry season crop. For the 2015 WS, low reservoir levels and below-average rainfall restricted rice planting only to areas reached by irrigation water. Hence, for the 2015 WS, field trials were established only in Nong Jik Ree village due to its close proximity to the main irrigation canal and only three treatments per block were applied: CROP, CROP + DS, and FP. These blocks were replicated over three sites.

For all the CROP treatment fields, land preparation, fertilizer application, and pest management followed CROP recommenda-

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Table 2
Field activities and crop management practices for the four field trial treatments in Nakhon Sawan, Thailand.

Activity/operation	CROP	CROP + AWD	CROP + DS	FP
Plot size (ha)	0.2–0.5	0.2–0.8	0.2–0.8	0.5–3.2
Crop establishment	Broadcasting	Broadcasting	Drum seeding	Broadcasting
Cultivar	RD 31, PTT 1	RD 31, PTT 1	RD 31, PTT 1	RD 31, PTT 1
Seeds	Certified seeds	Certified seeds	Certified seeds	Certified seeds
Seed rate (kg ha^{-1})				
2013 DS	125	125	50	125
2014 WS	125	125	50	155
2015 WS	94	–	50	125
Date sown				
2013 DS	27 Nov–3 Dec	27 Nov–3 Dec	27 Nov–3 Dec	27 Nov–3 Dec
2014 WS	9–10 Jul 3–5 Aug	9–10 Jul 3–5 Aug	9–10 Jul 3–5 Aug	9–10 Jul 3–5 Aug
2015 WS	8 Jun	–	8 Jun	8 Jun
No. of replicates 2013 DS	3	3	3	3
2014 WS	7	8	8	8
2015 WS	3	3	3	3
Fertilizer application (DAS)[a]				
1st	20–30	20–30	20–30	20–30
2nd	40–45	40–45	40–45	35–65
3rd	60–75	60–75	60–75	65–90
Date harvested				
2013 DS	4–5 Apr	16 Apr	4–5 Apr	
2014 WS	19–22 Oct 29–30 Nov	19–22 Oct 29–30 Nov	19–22 Oct 29–30 Nov	19–22 Oct 29–30 Nov
2015 WS	7–9 Oct	–	7–9 Oct	7–12 Oct

[a] DAS = Days After Sowing.

tions (Table 3) while farmers followed their own practices in the FP fields to serve as control to examine how each of the treatments compared with the current practice. Since majority of the farmers in the area applied seeds using a knapsack sprayer, the CROP, CROP + AWD, and FP treatments fields used the same practice. In the CROP + DS treatment fields, seeds were applied using a manually pulled drum seeder. Irrigation was applied based on CROP recommendations in the CROP and CROP + DS treatment fields and on AWD recommendations (described below) in the CROP + AWD treatment fields. In the FP fields, irrigation was applied following the farmer's usual practice. Before the start of the trials, selected farmers had preliminary on-site briefing and training sessions on the protocols. Farmers in all the fields were asked to record their farming practices, the inputs applied, and the associated economic costs for the whole cultivation period – from land preparation to harvesting – in a farmer diary. These were used to calculate inputs and production costs for each treatment plot.

Field water tubes were installed in all fields in both villages. In the CROP + AWD plots, the field water tubes were used to determine when to irrigate the plots. In the other treatments, the tubes were used only to monitor the water level dynamics in the field. AWD is a water-saving technique that is widely introduced in a number of countries in Asia, wherein the field is allowed to be alternately flooded and non-flooded. The non-flooded state can vary from 1 to more than 10 days depending on soil type, weather conditions, and growth stage of the crop. To facilitate the easy implementation of AWD, a "field water tube" is used to monitor the depth of ponded water. Irrigation is applied when ponded water has dropped to

Table 3
Recommended practices based on the Cost Reduction Operating Principles (CROP).

Practice	Recommendation
Seed quality	Use certified seed
Seed rate (kg ha^{-1})	Broadcasting: 94–125 Transplanting: 44 Parachute transplanting: 31
Soil preparation	No straw burning Soil plowing and turn over to promote straw decomposition Irrigate to accelerate straw degradation Soil surface leveling
Weed control	Pre-emergence herbicide application after sowing Appropriate herbicide for the type of weed Herbicide application if weed spread is more than 20% of total field area No rain/irrigation in the field during herbicide application
Pest management	Regular field inspection Follow instructions indicated on pesticide product label
Fertilizer application	Follow recommendation based on results from soil analysis (see Rice Department, 2010) Conduct soil analysis every three years
Water management	Drain water before sowing Water levels: 5 cm above soil surface during early tillering stage 10–15 cm above soil surface during mid-tillering to milky-ripe stages
Harvesting	Drain water from the field two weeks after flowering Harvest at physiological maturation stage
Recording	Regular recording of production costs

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15 cm below the surface of the soil, a threshold which is called “safe AWD” because it is not expected to have a yield penalty. With safe AWD, Lampayan et al. (2015a) reported a 25% water saving on average.

All drum seeding treatment plots were puddled and leveled thoroughly and excess water was drained before sowing without allowing the soil surface to become dry. Rice seeds were pre-germinated by soaking in water for 24 h and incubating for another 24 h. The sprouted seeds were then air-dried for 10–15 min before sowing to facilitate the separation of seeds. The drum seeder was calibrated by adjusting the holes to the desired seeding rate of 50 kg ha^{-1}. The seeds were then sown by a farmer pulling the drum seeder while walking at a steady pace. For this treatment, a business model was developed and the service provision cost for the drum seeder was calculated as 40% of the mean labor cost for sowing using farmer practice.

2.3. Soil sampling and analysis

Soil samples from the two villages were collected in each rice field plot during land preparation before the treatments were imposed. Soil fertility was assessed from organic matter, phosphorus (P), and potassium content and recommendations for fertilizer application were provided for each field based on these results (Rice Department, 2010). For the FP fields, the farmers followed their own practice of fertilizer application.

2.4. Measurements and data collection

Farmers recorded details of all their field activities including costs for labor and other inputs in farmer diaries which were checked by the researchers every two to three weeks. The grain yields reported were determined by measuring the total grain harvested per plot by combine-harvester. These were verified by manually harvesting two randomly placed 10 m^2 quadrats per plot. Grain yields were adjusted to 14% moisture content (MC).

2.4.1. Agrohydrology and water input measurements

The field water level in each plot was recorded using field water tubes to help describe the agrohydrological conditions across treatments and seasons. The tubes were also used to estimate the amount of irrigation input in the plots by recording the field water level before starting irrigation and after irrigation was completed. For each irrigation event when the field water level did not fall below the soil surface, the amount of irrigation applied (in mm) was calculated as the difference of the field water depths before and after irrigation, as shown below:

$$I = d_f - d_i$$

where, I = irrigation (mm); d_i = initial field water depth (mm); d_f = final water depth (mm).

Under AWD conditions, when field water level falls below the soil surface, the water level is termed as perched water table. Irrigation input in this case was computed as:

$$I = d_f + (\theta_s - \theta_i) \times D$$

where θ_s = soil water content at saturation (cc/cc); θ_i = soil water content when field water falls below the ground surface (cc/cc), in most cases, this soil moisture was assumed as the field capacity especially when the perched water table depth is 15 cm or more from the soil surface; D = depth of perched water table (mm).

Total water input was calculated as the sum of the amount of water applied from irrigation and rainfall. Daily rainfall data were taken from the Chainat weather station which was 19–24 km away from the study sites. The total amount of rainfall (mm) received by each plot was computed as the sum of the daily rainfalls from sowing up to 10 days before harvest.

2.4.2. Water productivity calculation

Water productivity denotes the amount of rice grains produced over a volume of water used (Bouman et al., 2007). In our study, water productivity was calculated as kg grain m^{-3} total water input (rainfall and sum of all irrigations, excluding land preparation).

2.5. Large Field Project

The Large Field Project was established in 2014 by the TRD in collaboration with the Department of Agricultural Extension, Land Development Department, Cooperative Promotion Department, and the private sector. In 2014, three irrigated rice production sites in the Chao Phraya river basin were selected, with each site being approximately 160 ha. In 2015, five irrigated rice production sites were selected, with an approximate area of 800 ha per site.

In each site, all farmers received high-quality seeds, training in CROP, crop establishment methods and AWD technology, and support for market linkages. Recommendations for fertilizer application were given following the soil analysis of each farmer’s field. In addition, a selection of farmers attended farmer field schools on Integrated Pest Management (IPM), following the “Smart Farmer” approach (Soitong, 2010) and community IPM centers were established for pest monitoring surveys. Farmers also received support and training on crop establishment and AWD technology. In 2014, all of the farmers in Kampaeng Phet and approximately 50% of the farmers in Nakhon Sawan applied seedlings with a mechanical transplanter for seed production while the other farmers practiced seedling broadcasting (parachute transplanting). In Phitsanulok, all the farmers applied seeds with a mechanically-pulled drum seeder. In each site during 2015 approximately 50% of the farmers applied seeds with a mechanically-pulled drum seeder while the other farmers practiced broadcast seeding. Farmers recorded in diaries details of all their field activities, including costs for labor and other inputs, and their harvested crop yield. This information was checked and validated by researchers at the end of each season.

Due to considerable variation in farm-gate price for rice between years, and because some farmer groups fetched a higher price by selling rice as seed, total income was calculated using a standardized farm gate price of 7 THB kg^{-1} (0.23 USD kg^{-1}) for freshly harvested rice grain (adjusted to 22% MC) for all seasons. This was the average farm gate rice price in the study area for 2014–2015.

2.6. Data analysis

Using SPSS version 18 (SPSS Inc., Chicago, IL, USA), linear mixed models with maximum likelihood estimation were used to analyze differences between treatments over the three cropping seasons. Fixed effects entered into the model included season (as a repeated variable with diagonal repeated covariance) and treatment. Site was included as a random effect with no intercept to account for the block design. Dependent variables that produced non-normally distributed residuals were analyzed using rank transformation. Pairwise comparisons of main effects were conducted using the Bonferroni test.

3. Results

3.1. Field trials of integrated best management packages

3.1.1. Inputs

In the CROP + DS treatment, the seed rate was significantly reduced by 60–67% over the first two seasons as compared to the other treatments that used broadcast seeding (Tables 4 and 5). In

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the third season, the seed rate of the CROP + DS treatment was still lowest at 50 kg ha^{-1}. However, farmers implementing CROP and one of the FP farmers reduced their seed rate from 125 kg ha^{-1} to 94 kg ha^{-1}, the lowest CROP recommended seed rate for broadcast seeding (see Table 3). Fertilizer application rates were also reduced in all CROP treatments compared to FP, with significant reductions in N application rates (mean reduction per season ranged from 50 to 64%) for all seasons and in P application rates (mean reduction

Table 4
Key inputs and outputs (mean values followed by standard error in parenthesis) of crop production across four field trial treatments over three seasons.

	CROP		CROP + AWD		CROP + DS		FP	
2014 DS:								
Seed rate (kg ha^{-1})	125.00	(0.00)	125.00	(0.00)	50.00	(0.00)	125.00	(0.00)
Fertilizer rate (kg ha^{-1})								
Nitrogen	38.08	(0.71)	38.08	(0.71)	38.08	(0.71)	95.92	(8.54)
Phosphorus	2.93	(2.93)	2.93	(2.93)	2.93	(2.93)	16.98	(3.56)
Potassium	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	6.36	(6.36)
PFP$_N$ (kg grain kg N^{-1})	122.81	(13.38)	134.23	(4.16)	120.99	(10.09)	55.81	(6.90)
No. of pesticide applications	2.33	(0.67)	2.33	(0.67)	2.33	(0.67)	4.67	(1.20)
Herbicide	1.00	(0.00)	1.00	(0.00)	1.00	(0.00)	2.00	(1.00)
Fungicide	1.00	(0.58)	1.00	(0.58)	1.00	(0.58)	0.67	(0.33)
Insecticide	0.33	(0.33)	0.33	(0.33)	0.33	(0.33)	2.00	(0.00)
No. of biocontrol applications	0.67	(0.67)	0.67	(0.67)	0.67	(0.67)	0.00	(0.00)
Grain yield[a] (t ha^{-1})	4.66	(0.44)	5.11	(0.14)	4.61	(0.38)	5.24	(0.22)
2014 WS:								
Seed rate (kg ha^{-1})	125.00	(0.00)	125.00	(0.00)	50.00	(0.00)	154.69	(6.11)
Fertilizer rate (kg ha^{-1})								
Nitrogen	44.34	(5.11)	43.47	(4.51)	43.47	(4.51)	121.53	(28.86)
Phosphorus	5.02	(1.77)	4.39	(1.66)	4.39	(1.66)	43.76	(9.80)
Potassium	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)	0.00	(0.00)
PFP$_N$ (kg grain kg N^{-1})	120.65	(11.68)	118.61	(10.17)	123.89	(9.07)	83.00	(37.45)
No. of pesticide applications	3.71	(0.61)	3.88	(0.55)	3.88	(0.55)	3.50	(0.46)
Herbicide	1.86	(0.14)	2.00	(0.19)	2.00	(0.19)	2.00	(0.19)
Fungicide	0.57	(0.30)	0.63	(0.26)	0.63	(0.26)	0.50	(0.19)
Insecticide	1.29	(0.29)	1.25	(0.25)	1.25	(0.25)	1.00	(0.19)
No. of biocontrol applications	0.29	(0.18)	0.25	(0.16)	0.25	(0.16)	0.25	(0.16)
Grain yield (t ha^{-1})	5.06	(0.27)	4.89	(0.22)	5.16	(0.22)	5.39	(0.10)
2015 WS:								
Seed rate (kg ha^{-1})	93.75	(0.00)			50.00	(0.00)	125.00	(18.04)
Fertilizer rate (kg ha^{-1})								
Nitrogen	45.00	(1.88)			45.00	(1.88)	91.67	(21.83)
Phosphorus	3.64	(3.64)			3.64	(3.64)	3.27	(1.67)
Potassium	0.00	(0.00)			0.00	(0.00)	6.23	(3.17)
PFP$_N$ (kg grain kg N^{-1})	93.67	(9.20)			101.75	(8.73)	52.26	(12.14)
No. of pesticide applications	1.33	(0.33)			1.33	(0.33)	1.67	(0.33)
Herbicide	1.00	(0.00)			1.00	(0.00)	1.33	(0.33)
Insecticide	0.33	(0.33)			0.33	(0.33)	0.33	(0.33)
No. of biocontrol applications	0.67	(0.67)			0.67	(0.67)	0.67	(0.67)
Grain yield (t ha^{-1})	4.19	(0.32)			4.56	(0.29)	4.27	(0.13)

[a] Adjusted to 14% MC.

Table 5
Linear mixed model results of the effects of field trial treatment and season on input, output and economic variables.

Dependent variable	Treatment				Season				Treatment*Season			
	Numerator d.f.	Denominator d.f.	F	P	Numerator d.f.	Denominator d.f.	F	P	Numerator d.f.	Denominator d.f.	F	P
Seed rate[a]	3	17.3	49.342	**<0.001**	2	14.1	8.317	**0.004**	5	14.3	4.754	**0.009**
Nitrogen	3	40.5	25.190	**<0.001**	2	31.4	1.063	0.357	5	36.4	0.446	0.813
Phosphorus[a]	3	20.3	14.832	**<0.001**	2	23.8	4.740	**0.019**	5	21.9	5.500	**0.002**
Potassium[a]	3	8.1	1.581	0.268	1	18.1	2.848	0.109	3	12.1	1.499	0.264
PFP$_N$	3	42.6	11.049	**<0.001**	2	41.7	4.796	**0.013**	5	34.1	0.845	0.527
No. of pesticide applications	3	16.7	5.256	**0.010**	2	23.1	34.668	**<0.001**	5	20.0	6.323	**0.001**
No. of biocontrol applications	1	557.3	3.027	0.082	1	471.9	49.666	**<0.001**	3	184.6	10.715	**<0.001**
Grain yield	3	20.0	1.356	0.285	2	32.4	15.603	**<0.001**	5	21.9	1.827	0.149
Seed cost	3	23.4	162.490	**<0.001**	2	16.2	35.589	**<0.001**	5	17.8	4.484	**0.008**
Fertilizer cost	3	46.5	46.399	**<0.001**	2	41.6	3.426	**0.042**	5	39.3	4.752	**0.002**
Pesticide cost	3	13.7	0.059	0.980	2	13.8	0.432	0.658	5	13.6	4.667	**0.011**
Labor cost	3	19.2	0.804	0.507	2	16.0	12.287	**0.001**	5	15.5	0.512	0.763
Total production cost	3	23.3	19.338	**<0.001**	2	17.7	2.821	0.086	5	19.3	0.454	0.805
Total income	3	16.3	0.493	0.692	2	27.6	12.091	**<0.001**	5	20.0	0.811	0.555
Net income	3	20.1	3.921	**0.024**	2	33.6	10.516	**<0.001**	5	18.7	0.585	0.711
Benefit: Cost ratio	3	26.8	10.502	**<0.001**	2	35.7	10.734	**<0.001**	5	26.1	0.509	0.766

The bold values indicate significance at 0.05 probability level.

[a] Analyzed using rank-transformed data.

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ranged from 83 to 90%) for the first two seasons. In the third season, FP farmers applied lower rates of P than in previous seasons. In all three seasons, there was a significant increase in N use efficiency, as determined by the partial factor productivity of applied N (N PFP_N) for the CROP treatments as compared to FP.

Herbicides were used by all farmers. Chemical insecticides, fungicides and biocontrol agents were used by both CROP and FP farmers to control yellow stemborers and brown spot in the 2014 DS and WS and rice thrips, rice leaf folders, sheath blight, and dirty panicle disease in the 2014 WS. However, in the 2014 DS, CROP farmers applied significantly less chemical pesticides than FP farmers, with two thirds of the CROP farmers using only biocontrol agents for insect control. In the 2015 WS, there was an overall decrease in the number of applications of chemical pesticides and no farmers applied chemical fungicides.

3.1.2. *Grain yield*

Mean yields were highest in the 2014 WS and lowest in the 2015 WS, ranging from 4.2 to 5.4 t ha^{-1}(Table 4). However, there was no significant difference in yield between seasons or treatments (Table 5).

3.1.3. *Agrohydrological conditions*

Fig. 1 shows the daily water level fluctuations in the study sites during the 2014 DS. Between treatments, no significant differences were observed in field water level fluctuations across the four treatments. During this season, all treatments were under AWD conditions by default as the water available in the supply canal was limited and farmers could not maintain flooded conditions in non-AWD treatments. On average, there were about 12 cycles of wetting and drying under the CROP and FP treatments and 11 cycles under the CROP + AWD and CROP + DS treatments. Also, rainfall during this season was very low (only 4.5 mm during the crop growth period) and irrigation by pumping was the main source of water. In each AWD cycle, a ponded water depth of 5–8 cm was added in all treatments after each irrigation period, which was then allowed to recede to 10–15 cm below the soil surface before the next irrigation was added. Irrigation interval was about 6–8 days.

In the 2014 WS, the AWD plots experienced ponded water most of the time due to high rainfall. However, few drying conditions were also observed when the water level dropped below the soil surface (Supplementary Fig. 1). In the non-AWD plots, field water depths were not monitored weekly but only during irrigation events. During this season, the sources of water for crop use were both from rainfall and irrigation. Similarly, in the 2015 WS, plots had mostly ponded water condition, with a few occasions of drying conditions (Supplementary Fig. 2). Water management following FP practice for all treatments was similar in this season. On average, only about 6 and 5 irrigations were added as supplemental irrigations in the 2014 WS and 2015 WS, respectively (data not shown), to avoid water stress when rainfall did not come on time.

3.1.4. *Water input and water productivity*

There were no significant differences in the total amount of rainfall, irrigation, and total water input (rainfall + irrigation) between treatments ($P > 0.05$). Water productivity was similar for all treatments.

In the 2014 DS, total water input ranged from about 925–994 mm which was mainly (99.5%) from irrigation and was lower than the total water inputs in the 2014 and 2015 WS (1020–1050 mm and 1119–1132 mm, respectively). Due to lower total water input, the highest mean water productivity occurred during the 2014 DS (0.47–-0.54 kg m^{-3}). Water productivity during the 2014 and 2015 WS ranged from 0.48 to 0.51 and 0.37 to 0.40 kg m^{-3}, respectively. Total rainfall was about 46% of the total water input in the 2014 WS and about 57% in the 2015 WS.

3.1.5. *Economic analysis*

Across all three seasons, there was a significant reduction (by a mean of 60–64%) in the amount that farmers spent on seeds for the CROP + DS versus FP treatments (Tables 5 and 6). However, the treatment x season interaction suggests that the difference was not significant for the 2015 WS when there were lower seed rates at one FP site. In the first two seasons, there also was a significant reduction (by 73%) in the amount that farmers spent on fertilizer inputs for all CROP treatments versus FP. In the third season, the difference was still substantial but lower at 53% due to a reduction in the amount spent on fertilizer inputs by the FP farmers. In the 2014 DS, the mean amount spent on chemical and biocontrol pesticides was higher for the CROP treatments than for FP, but in subsequent seasons it was lower for the CROP treatments.

For all three seasons, the total production cost per hectare was significantly lower (by 13–21%) for the CROP treatments than for FP. The net income and benefit:cost ratio were consistently higher for the CROP treatments than for FP, with a 8–46% (or 41–159 USD ha^{-1}) increase in profit. This equates to a net income increase of 202–884 USD per farmer based on mean farm size.

3.2. *Large Field Project*

Following the large-scale implementation of the Large Field Project, rice production costs were reduced across all sites by 5.5–20.7% in 2014 and 5.5–35.5% in 2015 when compared with the previous wet season (Table 7). In addition, the mean yield increased across all sites in 2014 and in all but one site in 2015. There were overall increases in profit ranging from 21 to 131%, resulting in a mean increase in income of USD 554 per farmer.

4. Discussion

Through improved crop management practices, rice crop yields in the central plains of Thailand can be maintained whilst reducing inputs and their associated economic and environmental costs. Similar results have been obtained in other intensive irrigated rice-producing regions in Asia (Huan et al., 2005; Tin et al., 2008; Alam et al., 2013; Chen et al., 2014), highlighting the potential of improved agronomic practice to enhance the sustainability of intensive rice production in developing countries (George, 2014).

In this study, farmers who followed CROP were able to increase their net income over standard farmer's practice by a mean of 26% across all three seasons, meeting the CROP objectives of an increased income by 20%. The majority of the cost savings obtained by CROP farmers was met through a 50–64% reduction in fertilizer inputs, which, based on the results of the first two seasons, contribute to 20–22% of the total production costs.

Even though there were significant reductions in fertilizer inputs following CROP practices, rice yields were maintained and even slightly increased in the 2015 WS. This supports the findings by Stuart et al. (2016) that suggest that the mean fertilizer use in the region is above optimal and likely to be in excess of the plants' uptake. Although, to optimize nutrient management over the long term and to avoid soil nutrient mining, repeated soil analyzes are required, as recommended for CROP practices. Several studies have shown that when fertilizers are used excessively in rice production, reductions in fertilizer inputs can lead to significant reductions in N and P losses through reduced N and P leaching, N runoff, NH_3 volatilization, and N_20 emissions (Pampolino et al., 2007; Chen et al., 2014; Xue et al., 2014; Stone and Hornberger, 2016). Thus, a 60–64% reduction in fertilizer inputs is expected to translate to a

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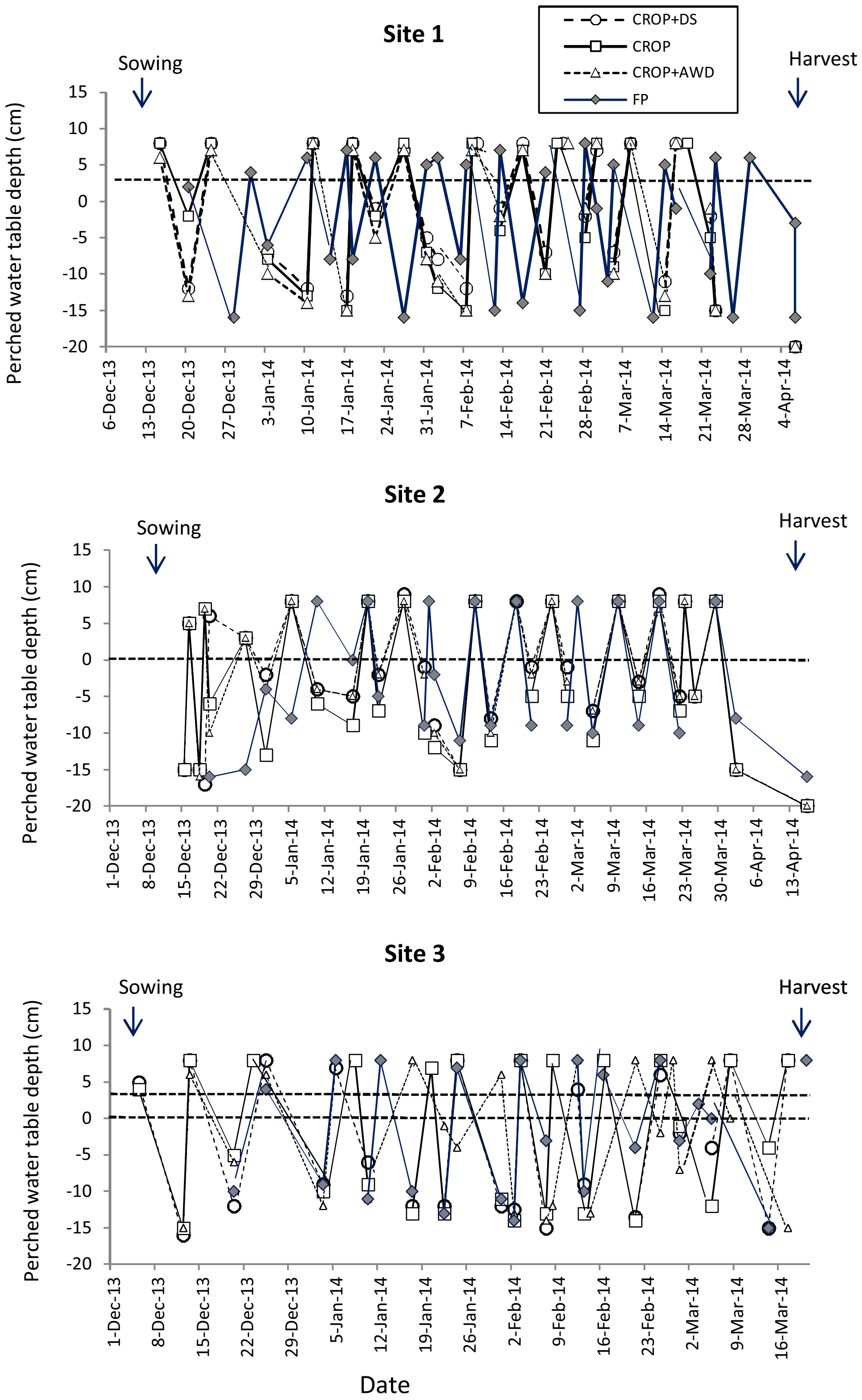

Fig. 1. Field water depths of each treatment plot in three field trial sites in Nakhon Sawan province during the 2014 DS.

substantial reduction in N and P losses to the environment and thus mitigate negative environmental effects such as eutrophication and pollution (Ma et al., 2014).

Rice farmers following CROP practices showed a significant reduction in chemical pesticide use in the 2014 DS and a slight reduction in the 2015 WS with no yield penalty. Similar results were reported in the Mekong Delta after the “Three Reductions, Three Gains” campaign to reduce pesticide use (Huan et al., 2005; Huelgas and Templeton, 2010). In a multi-site study across Thailand, Vietnam, and China, it was found that rice yields even increased following a reduction of insecticide sprays in combination with growing nectar-producing plants on rice borders to promote nat-

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Table 6
Economic analysis (mean values followed by standard error in parenthesis) of crop production across four field trial treatments over three seasons.

	CROP		CROP + AWD		CROP + DS		FP	
2014 DS:								
Seed cost (USD ha^{-1})	82.71	(3.37)	82.71	(3.37)	33.09	(1.35)	82.71	(3.37)
Fertilizer cost (USD ha^{-1})	50.26	(8.08)	50.26	(8.08)	50.26	(8.08)	185.91	(14.60)
Pesticide cost (USD ha^{-1})[a]	50.26	(15.65)	50.26	(15.65)	50.26	(15.65)	36.27	(18.05)
Labor cost (USD ha^{-1})	194.18	(15.62)	194.18	(15.62)	198.25	(12.82)	199.40	(7.40)
Total production cost (USD ha^{-1})	711.65	(6.52)	711.65	(7.71)	659.15	(13.11)	829.67	(7.31)
Total income (USD ha^{-1})[b]	1098.74	(159.49)	1195.58	(79.87)	1077.46	(139.80)	1154.54[c]	(54.53)
Net income (USD ha^{-1})	387.09	(165.47)	483.93	(75.03)	418.31	(135.16)	324.87	(55.55)
Profit increase over FP (%)	19.15		48.96		28.76			
Benefit: Cost ratio	1.55	(0.24)	1.68	(0.10)	1.64	(0.20)	1.39	(0.07)
2014 WS:								
Seed cost (USD ha^{-1})	76.35	(0.00)	76.35	(0.00)	30.54	(0.00)	84.75	(3.99)
Fertilizer cost (USD ha^{-1})	47.80	(4.09)	46.72	(3.70)	46.72	(3.70)	163.20	(39.34)
Pesticide cost (USD ha^{-1})[a]	50.15	(7.31)	50.68	(6.36)	50.68	(6.36)	59.62	(4.72)
Labor cost (USD ha^{-1})	181.79	(14.43)	180.07	(12.61)	192.56	(16.86)	173.24	(3.90)
Total production cost (USD ha^{-1})	701.11	(21.76)	693.45	(20.27)	661.09	(20.81)	821.81	(41.03)
Total income (USD ha^{-1})[b]	1245.60	(61.86)	1227.06	(50.43)	1298.50	(54.76)	1314.39	(26.12)
Net income (USD ha^{-1})	544.48	(65.39)	533.61	(53.22)	637.41	(59.44)	492.58	(48.87)
Profit increase over FP (%)	10.54		8.33		29.40			
Benefit: Cost ratio	1.79	(0.10)	1.78	(0.08)	1.99	(0.11)	1.63	(0.08)
2015 WS:								
Seed cost (USD ha^{-1})	45.81	(0.00)			24.43	(0.00)	61.08	(8.82)
Fertilizer cost (USD ha^{-1})	54.76	(7.03)			54.76	(7.03)	116.75	(17.01)
Pesticide cost (USD ha^{-1})[a]	33.21	(9.91)			33.21	(9.91)	44.22	(4.14)
Labor cost (USD ha^{-1})	145.57	(27.81)			164.08	(33.34)	154.99	(23.72)
Total production cost (USD ha^{-1})	654.87	(49.40)			652.64	(54.17)	753.82	(32.46)
Total income (USD ha^{-1})[b]	1030.03	(96.41)			1119.75	(95.67)	1074.24	(25.68)
Net income (USD ha^{-1})	375.16	(47.29)			467.11	(44.56)	320.42	(7.17)
Profit increase over FP (%)	17.08				45.78			
Benefit: Cost ratio	1.57	(0.03)			1.72	(0.03)	1.43	(0.03)

[a] Includes all chemical pesticide and biocontrol input costs.
[b] Actual income farmers received for fresh grain.
[c] FP farmers in two sites received a lower price for their rice due to lower grain quality.

Table 7
A comparison of the rice production costs, yields, and incomes between the wet season (WS) crops before and after the implementation of the Large Field Project in lowland irrigated sites in the Chao Phraya river basin.

Province	Total area (ha)	No. farmers	Crop etablishment method		Production cost (USD ha^{-1})		Yield[a] (t ha^{-1})		Total income[b] (USD ha^{-1})		Net income (USD ha^{-1})		Cost reduction	Profit increase
			Before	After	Before	After	Before	After	Before	After	Before	After	(%)	(%)
2014 WS:														
Kampaeng Phet	160	62	MT,BS	MT	1130	1068	4.08	5.15	1050	1325	−80	258	5.5	130.9
Nakhon Sawan	165	50	MT,BS	MT,PT	1241	1092	4.56	5.41	1173	1391	−68	299	12.0	122.9
Phitsanulok	160	106	BS	DS	1031	818	4.73	5.46	1216	1405	184	587	20.7	68.6
Mean					**1134**	**993**	**4.46**	**5.34**	**1146**	**1374**	**12**	**381**	**12.8**	**107.5**
2015 WS:														
Chachoengsao	800	250	BS	BS,DS	778	669	5.79	6.10	1491	1570	712	901	5.5	21.0
Chainat	800	300	BS	BS,DS	1323	1059	6.18	5.63	1591	1449	268	391	12.0	31.5
Suphan Buri	800	200	BS	BS,DS	1298	960	4.63	5.50	1190	1416	−107	456	20.7	123.5
Sing Buri	800	181	BS	BS,DS	929	803	4.94	5.63	1271	1448	342	644	27.9	46.9
Ayuthaya	480	79	BS	BS,DS	1073	757	4.88	5.62	1255	1446	183	689	35.5	73.4
Mean					**1080**	**850**	**5.29**	**5.70**	**1360**	**1466**	**280**	**616**	**20.3**	**59.3**

MT = Mechanical transplanter, BS = Broadcast seeding, PT = Parachute transplanting, DS = Drumseeding.
[a] Adjusted to 14% MC.
[b] Calculated at 0.23 USD kg^{-1} fresh grain (at 22% MC).

ural enemies of insect pests (Gurr et al., 2016). Furthermore, pesticide use by farmers in our study declined across all treatments in the third season. As well as savings in input costs, reductions in pesticide application rates equate to reductions in labor for spraying, human exposure to pesticide poisoning, environmental contamination and biodiversity loss. In addition, a reduction in both fertilizers and pesticides would lead to a reduction in greenhouse gases that are emitted through their production and transport (Pampolino et al., 2007; Chen et al., 2014).

The use of the drum seeder demonstrated significant savings in input costs compared to broadcast seeding. In the first two seasons, seed costs contributed to 10% of the total production costs of farmer's practice. As a result of significant reductions in seed rates as well as fertilizer rates, farmer's plots that followed CROP + DS consistently showed the largest benefits over standard farmer's practice, with increases in income in the range of 29–46%. The use of the drum seeder is also expected to have other benefits for rice production when compared with broadcast seeding, such as optimum plant density, rows that facilitate weeding, and better plant spacing that allows good plant aeration and light penetration which helps to improve plant health and reduce pest and disease incidence (Balasubramanian and Hill, 2002). Unfortunately, the manually-pulled drum seeder did not save on labor when compared with

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farmer's practice, largely because farmers in the region apply seeds using a mechanical knapsack sprayer, but also because the farmers were familiarizing themselves with this new technology. The need to save on labor is presently being addressed through the development of tractor-pulled drum seeders by local manufacturers, one of whom was among the farmers who participated in the trials.

Due to limited availability of water in the 2014 DS, water use did not differ greatly between the AWD and non-AWD field plots. There was a reduced water delivery in the main canal during this season and farmers were in fact advised not to plant rice. Water had to be pumped communally from the main canal to the secondary canals, and then farmers had to pump water from the secondary canals to their fields on a rotation basis with the rest of the community. In normal years, the water level in the main canal is high enough to feed into the secondary canal by gravity and farmers are able to irrigate their fields (by gravity or pumping) from the secondary canals without restriction. In the 2014 DS, farmers, thus, experienced severe water shortage and the fields were only irrigated at 7–10-day intervals. In effect, the non-AWD fields were basically following forced-AWD. However, even with limited water use, the water level across all plots rarely dropped deeper than 15 cm and high yields were still attained, which gave farmers the assurance that yields can be maintained following AWD practices. These findings are consistent with the results of several studies in the Philippines (Bueno et al., 2010; Rejesus et al., 2011; Lampayan et al., 2015b), Vietnam (Lampayan et al., 2015a; Yamaguchi et al., 2016), and China (Liang et al., 2016) that demonstrated improved water efficiency without yield penalty. However, if the period between irrigations were to be extended beyond 7–10 day intervals, this would likely have negative effects on yield.

The experience that yields can be maintained whilst reducing water inputs using the principles of AWD will help to educate and assure farmers that they can save on irrigation water and pumping costs, and associated greenhouse gas emissions (Sander et al., 2014; Liang et al., 2016). Reduced water use by farmers at the top end of an irrigation system has the added benefit of increasing the availability of water for farmers downstream as well as for other uses (Palis et al., 2004; Lampayan et al., 2015a). In the 2015 WS, AWD was not strictly imposed due to the expectation of regular rainfall as in the 2014 WS. This also signifies that AWD is less likely to be of benefit to farmers during the wet season. Even so, there were periods of limited rainfall (2–3 weeks) when supplemental irrigation was needed, but dry field conditions were observed, suggesting that farmers were confident enough to allow their fields to dry for short periods based on their experience in the previous seasons. Without AWD practice, we would expect more frequent supplementary irrigation to occur.

In the third season, the neighboring FP farmers also had begun to change their practices by reducing seed and fertilizer rates. This change in practice is encouraging as it indicates that farmers begin to adopt the technologies being demonstrated in neighboring fields either through observation and communication with the treatment farmers or through attendance at a farmer field day that was held at the end of the 2014 WS. We expect that the advent of further field demonstrations, training sessions, meetings, and field days would lead to an increased adoption of improved practices and AWD as has occurred in Bangladesh, the Philippines, and Vietnam (Lampayan et al., 2015a).

The results from the Large Field Project demonstrate the benefits of large-scale application of best practices along with regular training and support of farmer groups. By reducing seed rates, fertilizer use, and pesticide use on a community scale, substantial economic savings were made and the likely benefits for the health of the rice farming community and environment are promising. However, because there were no control sites, we were only able to conduct a temporal analysis of the impact of the Large Field Project. Climatic variation between years can significantly affect yields (Lobell et al., 2009; Mishra et al., 2014), thus, the comparison of yields between years and, therefore, net income should be judiciously interpreted.

The variability in net income in the Large Field Project sites also highlights the vulnerability of rice farmers in the central plains of Thailand to fluctuations in rice prices and input costs. When comparing the results of the Large Field Project with the field trial results, the production cost of several sites in the Large Field Project were substantially higher, with farmers in some sites facing negative net income on average. In these sites, farmers on average spent substantially more on pesticide and fertilizer inputs than those in the field trials, possibly due to different environmental conditions. Some farmer groups also used a mechanical transplanter for seed production, which equated to substantially higher planting costs. In order to compare sites and years, we used a standardized farm gate price of 0.23 USD kg^{-1} for rice grain. However, the seed producing groups in the Large Field Project were able to collect a higher price for rice seed. Another factor for consideration is that prior to 2014, the government rice pledging scheme guaranteed 0.40 USD kg^{-1} for rice grain with 22% MC. This is roughly twice the current farm gate rice price and thus provided a significant buffer against increases in the costs of rice production.

5. Conclusion

Key challenges faced by rice farmers such as labor shortage, increased input costs, reduced availability of water, and a degrading environment highlight the need to increase the resource use efficiency and sustainability of rice production. Our findings demonstrate that fertilizer, seed, and pesticide use can be reduced in intensive lowland irrigated rice growing areas of Thailand by following best management practices with no yield penalty. The improved practices were found to reduce costs and increase profit. The Large Field Project demonstrated that farmers are willing to implement the package of best practice technologies and the benefits are replicable over large areas. Through an increase in income and a reduction in inputs that cause negative environmental impacts, the adoption of these practices can lead to a more economically, environmentally and socially sustainable rice production situation. In addition, increasing farmer's knowledge of water-saving technologies and reducing their risks as a result of reduced input costs can enhance their resilience against future adverse climatic events and periods of water scarcity.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fcr.2017.02.005.

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