Agr. Nat. Resour. 55 (2021) 119–130

AGRICULTURE AND NATURAL RESOURCES

Journal homepage: http://anres.kasetsart.org

Research article

Improving water use efficiency and productivity in rice crops by applying alternate wetting and drying with pregerminated broadcasting in farmers' fields

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Article Info

Article history:
Received 4 July 2020
Revised 12 January 2021
Accepted 15 January 2021
Available online 26 February 2021

Keywords:
Alternate wetting and drying,
Gas emission,
Water saving,
Farmer's field

Abstract

The supply of irrigation in Thailand is currently insufficient to satisfy rice production demands, despite the country being the world's leading rice producer and exporter. Thus, traditional rice production based on flooding systems should be changed to water-saving management using the so-called alternate wetting and drying method (AWD). This research introduced a suitable AWD 5/-15 broadcasting method into farmer's fields in eight provinces of Thailand in the dry and wet seasons of 2016. The results showed that the AWD practice increased grain yields by 8–22% in the dry season compared with the yields from farmer's practices. The AWD practice reduced total water use by 5–30% and increased water productivity 10–35% compared with farmer's traditional practices. In addition, the total CH_4 emissions from the AWD practice in the dry season were lower than those from farmer's practices by 7–83%, but the AWD practice in the wet season resulted in decreased CH_4 emissions at only three out of the eight sites. The total N_2O emissions were slightly different between the AWD and farmer's practices. However, in both AWD and farmer's practices, N_2O emissions were much lower than CH_4 emissions. Finally, the incomes and net profits in both seasons were significantly higher using AWD from 4.4–13.5 USD/ha and 45.8–60.8 USD/ha, respectively, while the total costs for both practices were not significantly different. Thus, AWD practices may help farmers decrease their water supply risk, especially in the dry season, and increase profits from rice production.

Introduction

Thailand is the 6th largest rice producer and one of the world's leading rice-exporting countries (Silalertruksa et al., 2017). However, rice production requires a larger amount of water than other crops and other sectors (Guerra et al., 1998)). The largest rice-producing areas in Thailand are in the central region, which covers approximately 906,000 ha or 44% of the total watershed area (Office of Agriculture and Economics, 2016). In addition, based on the results of water scarcity studies, dry season rice cultivation in the central region should be the focus of policymakers when identifying measures to improve the efficiency of irrigation water use (Silalertruksa et al.,

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https://doi.org/10.34044/j.anres.2021.55.1.16

2017). In Thailand, the amount of irrigation water available over the past 5 yr has not been sufficient to fulfill the demand created by agricultural rice production in the dry season from December to April (Ngammuangtueng et al., 2019). The current water supplies in Thailand are again critically low due to adverse weather conditions in 2019, which caused problems for agricultural production; in particular, for rice production in the dry season, with approximately 0.2 million ha of agricultural land being affected by drought, and most of the affected area containing rice crops (United States Department of Agriculture, 2020). Thus, the Thai government has restricted irrigation supplies for rice production to ensure sufficient water for household consumption and ecological management until the wet season arrives (Ngammuangtueng et al., 2019). Therefore, the dry season rice area in 2019 declined by 45% from the same period in 2018, due to strict government controls on the release of irrigation water for rice production due to the critically low reservoirs in the major rice-growing areas (United States Department of Agriculture, 2020). Consequently, the development of water management practices to increase water use efficiency and productivity as well as to promote appropriate land and resource management is necessary for the sustainability of rice production (Xinchun et al., 2017).

In general, Thailand has two rice cultivation seasons. The first crop is grown in the wet season (May–October), while the second crop is grown in the dry season (November–April), and this second crop is grown in irrigated areas (Silalertruksa et al., 2017). Irrigation water accounts for approximately 70–75% of the total water used for rice cultivation in the dry season. In addition, pregerminated seed broadcasting is a technique that is commonly used in irrigated areas (Silalertruksa et al., 2017).

Rice cultivation in Thailand mainly uses the wet system. Thus, continuous water management for rice production is the conventional method in the lowlands; this method requires a total water supply of 700–1,500 mm per cropping season (Bhuiyan, 1992). However, continuous water management leads to high amounts of surface runoff, seepage and percolation, which together can account for 50–80% of the total water input (Sharma, 1989). In addition, continuous water management can enhance methane (CH_4) production, which accounts for 72% of total emissions by the agricultural sector (Bharati et al., 2001; Singh et al., 2003). Furthermore, an increase in CH_4 emissions in irrigated rice paddy fields is caused by the broadcasting of rice seeds, which increases the plant density and biomass (Chareonsilp et al., 2000).

The alternate wetting and drying (AWD) technique, a water-saving method for rice cultivation, has been promoted among farmers because of the increasing drought situation, as AWD can decrease irrigation water use in rice paddy fields without decreasing grain yields (Price et al., 2013; Chidthaisong et al. 2018). The AWD technique can reduce water use by 14.8–47.5% compared with conventional methods (Lampayan et al., 2015; Sibayan et al., 2018; Tran et al., 2018). In addition, many researchers have reported that CH_4 emissions could be reduced by AWD application in rice paddy fields (LaHue et al., 2016; Sibayan et al., 2018; Chidthaisong et al., 2018). However, the International Rice Research Institute's AWD technique is recommended for use with transplanting methods (Bouman and Tuoung, 2001), while most farmers in Thailand use the broadcasting method to grow rice.

Ruensuk et al. (2016) reported that the AWD 5/-15 method was suitable for use with the pregerminated broadcasting method on a small scale compared with the AWD 5/-10 and 5/-20 methods at seven rice research stations of the Rice Department, Ministry of Agriculture and Cooperatives, Thailand. The AWD 5/-15 method reduces the amount of irrigation water used by approximately 20% without decreasing grain yields. Moreover, CH_4 emissions were reduced under AWD with the broadcasting method. Thus, experiments related to and validation of the AWD technique in farmers' fields are needed to increase adoption by farmers and to address uncertainties regarding the effects of using AWD with the broadcasting method to reduce the amount of water used, reduce gas emission and explain variations among sites. Therefore, the current research introduced a suitable AWD 5/-15 system for use with the pregerminated broadcasting method (Ruensuk et al., 2016) in large farm fields in eight provinces located in central and northeastern Thailand. The objectives were to compare the amount of water used, gas emissions, grain yields, production costs, income and net profits of rice cultivation between the AWD system with the pregerminated broadcasting method and traditional farmers' practices in both the dry and wet seasons.

Materials and Methods

Experimental sites and field preparation

The experiments were conducted in the dry season (January–April) and wet season (June–September) in 2016 in farmers' paddy fields in eight provinces that represented broadcasting paddy fields in irrigation areas. The experimental sites were in seven provinces in the central region and one province in the northeastern region of Thailand: Pathum Thani (PTT), Bangkok (BKK), Chachoengsao (CCS), Nakhon Nayok (NKN), Ang Thong (AT), Chai Nat (CT), Phichit (PC) and Sakon Nakhon (SKN), as shown in Fig. 1. A data logger (WatchDog 2000 Series Micro Stations; Spectrum Technology Inc.; USA) was used to record daily air temperatures (minimum and maximum) and the amount of rain throughout the experimental period. In addition, soil sampling for soil analysis was performed according to methods described by the Rice Department (Rice Department, 2020a). Six samples from each site were collected before sowing. All the soil samples were collected at a depth of 40 cm. Stones and plant residues were removed from the samples, which were then dried in a hot-air oven. The plastic bags were used to store the soil samples prior to chemical analysis. The soil properties (organic matter, available phosphorus, available potassium, cation exchange capacity (CEC), soil pH and soil type) were analyzed by the soil laboratory at the Pathum Thani Rice Research Station, Rice Department, Ministry of Agriculture and Cooperatives.

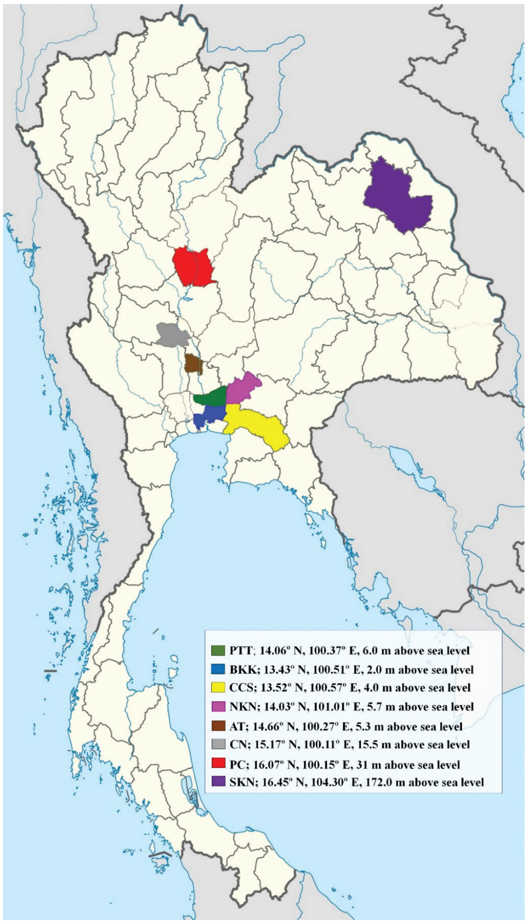

Fig. 1 Eight sites where alternative wetting and drying experiments were performed in dry and wet seasons in central Thailand—Pathum Thani (PTT), Bangkok (BKK), Chachoengsao (CCS), Nakhon Nayok (NKN), Ang Thong (AT), Chai Nat (CT), Phichit (PC)—and northeastern Thailand—Sakon Nakhon (SKN)

First, after harvesting the previous crop, the paddy fields were plowed, and plant residues were removed from the field. The experimental fields were plowed again 2 wk before growing rice using the pregerminated broadcasting method to establish new field layouts. Next, one field at each farm was divided into two practices (AWD and farmers' practices), with 1 ha/practice. The distance between the fields representing each practice was greater than 10 m.

Rice growth conditions

The pregerminated broadcasting method was applied in this experiment. Rice seeds of various rice cultivars (depending on the site and season) were sown at a rate of 125 kg/ha. The AWD practice was started 20 d after broadcasting (DAB). Water was applied to a level 5 cm above the soil surface and allowed to infiltrate the soil surface to -15 cm (5/-15 cm). The water was reirrigated again to a level 5 cm above the soil surface. This protocol was repeated until the booting stage (R2). After that, the water depth was maintained at 5 cm, and the field was dried 2 wk before harvest (R6). On the other hand, the farmers' practice involved continuous flooding by maintaining a water depth of 10 cm above the soil surface, and the water levels were not allowed to be more than 5 cm above the soil from 15 DAB to R6.

Chemical fertilizer was applied twice for both the AWD and the farmers' practices. A chemical fertilizer was applied at 20 DAB at a rate of 37.5 kg N/ha (diammonium phosphate), 37.5 kg of P_2O_5/ha, and 37.5 kg of K_2O/ha. At the tillering stage (45 DAB), the fertilizer was applied again at a rate of 37.5 kg N/ha (urea). A herbicide mixture of fenoxaprop-p-ethyl + ethoxysulfuron was applied to both the AWD and the farmers' practices at an 8.9% (weight per volume) effective concentration rate of 500 g/ha active ingredient at 12 DAB. Pesticides were applied when diseases infected the rice plants at a rate that met the economic threshold. The rice cultivation practices in the AWD field followed the recommendations from the Rice Department, Ministry of Agriculture and Cooperatives, while the cultivation in the farmers' fields depended on the practices of each farm.

Water use measurement

Ten water tubes were installed in the AWD fields after broadcasting of the pregerminated rice seeds to observe the water level below the soil surface. In the wet season, the water management in the AWD practice in this study could not be controlled due to rainfall interference; however, this practice was successfully used to control the water level in the dry season. Thus, successful AWD was defined here as an AWD cycle with a water depth of 5 cm above the soil surface and decreasing to 15 cm below the soil surface continuously from 20 DAB until R2. On the other hand, an AWD system was considered unsuccessful when the water level exceeded the 5 cm limit above the soil surface due to rainfall. In addition, in an unsuccessful AWD resulted if the water levels did not decrease to -15 cm below the soil surface during the same period as successful AWD. The water levels were measured once per day between 0800 hours and 0900 hours using a watermark in a water tube (Lampayan et al., 2015). The amount of irrigation water on the AWD sites was calculated in two steps. First, the water depth in the soil was calculated based on Equation 1:

$$d = [(Ps - Pw) \times Bd \times D]/100 \quad (1)$$

where d is the water depth in the soil (measured in millimeters), Ps is the percentage soil moisture content under flooded conditions, Pw is the percentage soil moisture content in dry soil before reflooding, Bd is the soil specific gravity and D is the soil depth (millimeters). Next, the irrigation amount was calculated based on Equation 2:

$$Q = (Ht - d) \times A/100 \quad (2)$$

where Q is the amount of irrigation water when applied at -15 to 5 cm (measured in cubic meters), Ht is the water level from -15 to 5 cm (2,000 mm), d is the water depth in the soil (millimeters) and A is the area of the paddy field (square meters).

The amount of irrigation water at each site in the farmers' fields was calculated under flooded conditions based on Equation 3:

$$Q = (H \times A)/1000 \quad (3)$$

where Q is the amount of irrigation water when applied at 5 to 10 cm (measured in cubic meters), H is the water level from 5 to 10 cm (500 mm) and A is the area of the paddy field (square meters).

The total amount of rainfall was recorded from the start of broadcasting to 1 wk before harvest time. The seasonal water use per practice was calculated as the sum of all the irrigation water and rainfall amounts.

Measurements of methane and nitrous oxide

Square, closed chambers were made from acrylic resin; each chamber was 60 cm long, 60 cm wide, and 60 cm high, and a small fan installed at the top of each chamber was turned on to circulate the air in the chamber when the gas samples were collected (Minamikawa et al., (2015). The gas sampling method followed the protocol described by Chidthaisong et al. (2018). Six chambers were installed in each field 1 d before the first gas sampling at a soil depth of 10 cm. In addition, a wooden bridge was constructed in each field to avoid disturbing the soil and causing artificial CH_4 ebullition during gas sampling. Gas sampling was started at 7 DAB from 0900 hours to 1100 hours, and collections were continued every 7 d at the same time until harvest. A plastic syringe was used to evacuate gas samples at intervals of 0 min, 5 min, 10 min, 15 min and 20 min from the top of the chamber.

The gas analysis equipment consisted of an Agilent 7890B (Agilent Technologies Inc.; USA) gas chromatograph equipped with an FID and operating at 300°C for CH_4 and an ECD operating at 300°C for N_2O as well as a HaySep Q packed column, which was operated at the Prachin Buri Rice Research Station. N_2 and He were used as carrier gases for the FID and ECD, respectively, at a flow rate of 20 mL/min. The gas fluxes per hour from the paddy field were calculated based on linear regression, as described by Minamikawa et al. (2015).

Grain yield measurements

The harvested paddy rice grain from six samples (2 m × 5 m) distributed over 1 ha from each field was threshed, cleaned, dried and weighed. A digital moisture meter was used to measure grain moisture content, and a moisture content of 14% was used to calculate the grain yield that was converted to units of kilograms per hectare. The six samples of paddy rice grain from each practice were evaluated for the percentage of head rice derived from milled rice with lengths longer than or equal to three-quarters of the average length of the entire milled rice. In addition, the weight of the grain yield divided by the total water volume used during the growth period was calculated to observe the water productivity.

Production cost, income and net profit analysis

The rice production cost in this study was divided into two categories: variable costs (labor wages, amendment materials and opportunity costs associated with loans) and fixed costs (land rent, equipment deterioration and opportunity costs associated with equipment). Income was determined as the sale of 14% paddy rice grain, and the grain price depended on the rice cultivar. The differences among incomes and production costs were presented as the net profits.

Statistical analysis

The R program (version 3.6.1, 2017; R Core Team, 2014) was used for statistical analysis. Independent t tests (degrees of freedom, df =10) were performed at an alpha level of 0.05 to compare grain yield, head rice, gas emissions, total water use and water efficiency among the AWD and farmers' practices at each location. On the other hand, paired sample t tests (df=7) were performed at alpha level of 0.05 to compare economic data among the AWD and farmers' practices in each season. The data from all experiments for each parameter were used to obtain the mean and SD. The SEs of the means were also calculated and were presented in the graphs as error bars.

Results

Weather and soil properties

The microclimatic data for the eight sites in the dry season (January–April) and wet season (June–September) in 2016 are shown in Fig. 2. The duration of the growing period in each season was approximately 120 d. The range of maximum temperatures in the dry season (33.1–36.0°C) from the eight sites was higher than that in the wet season (32.4–34.9°C), while the range of minimum temperatures in the dry season (20.9–24.6°C) was lower than that in the wet season (25.0–25.9°C). Thus, the temperature differences between the maximum and minimum temperatures in the dry season were greater than those in the wet season. In addition, the maximum temperatures were recorded during March–May, while the minimum temperatures were recorded in January at every site. These periods were in the dry season.

The total rainfall amounts at the eight sites during the dry season was in the range 13.7–97.9 mm. The lowest and highest values of the total rainfall amount were recorded in PC and PTT provinces, respectively. The rainfall amounts in the wet season were in the range 468.5–1094.0 mm. The lowest and highest total rainfall amounts were recorded in AT and SKN provinces, respectively (Fig. 2).

The soil at the eight sites had two textures: clay (PTT, BKK, CCS, NKN, AT, CN and PC) and sandy loam (SKN), while the soil chemicals differed among the eight sites. The organic matter was in range 0.4–6.6%, available P in the range 0.3–20.1 mg/kg, available K in the range 21–307 mg/kg, cation exchange capacity in the range 6.9–43.4 meq/100 g soil and soil pH in the range 4.5–6.6. In addition, the soils in NKN province were

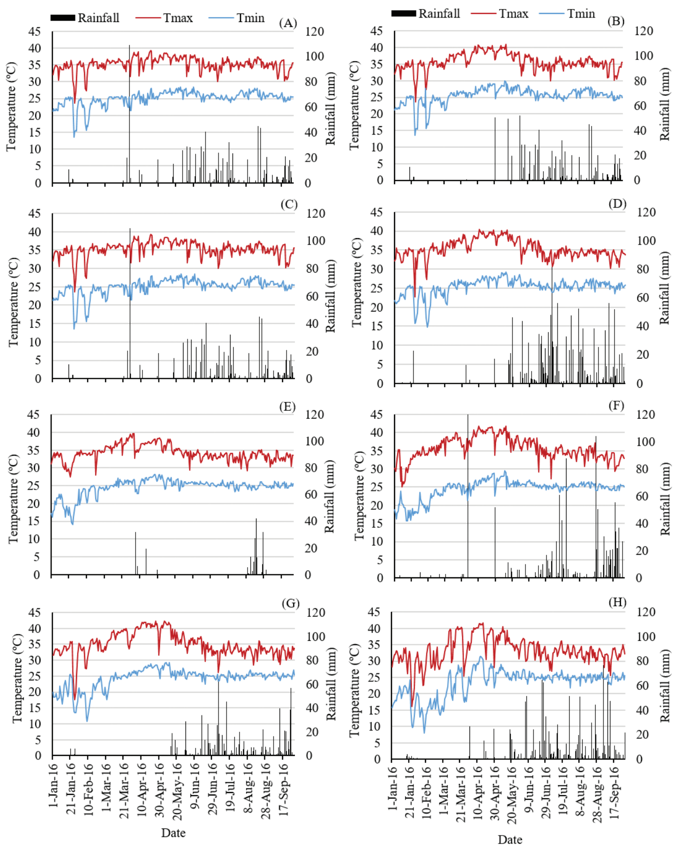

Fig. 2 Maximum temperature, minimum temperature and rainfall from January to September 2016 at eight study sites: (A) Pathum Thani (PTT); (B) Bangkok (BKK); (C) Chachoengsao (CCS); (D) Nakhon Nayok (NKN); (E) Ang Thong (AT); (F) Chai Nat (CT); (G) Phichit (PC); (H) Sakon Nakhon (SKN)

identified as very strongly acidic to moderately acidic, while the soils at the other sites were identified as neutral to slightly acidic. The soil nutrients in SKN province were the lowest when compared with those in the other locations and were lower than those recommended by the Rice Department (Rice Department, 2020b). Therefore, the soil nutrients in most locations (except SKN) were adequate for rice cultivation (Table 1).

Grain yield and milling quality

The paddy grain yields varied among the eight sites and two seasons because the rice cultivars that each farmer used for each site and each season differed according to the recommendations from the Rice Department, Ministry of Agriculture and Cooperatives. In addition, the soil properties and weather conditions among the eight sites were different and may have affected the grain yield. In the dry season, the RD41 cultivar was grown in PTT, NKN and PC provinces, PTT1 was grown in BKK, CCS and AT provinces and RD61 and the Sakon Nakhon cultivars were grown in CN and SKN provinces. In the wet season, PTT1 was grown in PTT and CCS provinces, RD41 was grown in CN and PC provinces and the PSL2, RD57, RD31 and Phuphan1 cultivars were grown in BKK, NKN, AT and SKN provinces, respectively.

The comparison of grain yield across locations and seasons was not statistically analyzed because different rice cultivars were grown at each location. However, the trend of mean grain yield from the eight locations was lower in the dry season than in the wet season (Fig. 3A). The trend of grain yields in both the AWD system and farmers' fields in the dry season in PTT and CN provinces, which grew the RD41 and RD61 cultivars, respectively, produced high yields compared to those at other locations, and the grain yield from the 0 AWD system in SKN province was the lowest. In addition, in the wet season, PTT province, which grew PTT1, had the highest grain yield, while CCS (growing PTT1) and AT (growing RD31) provinces had the lowest grain yields (Fig. 3A).

In the dry season, the paddy grain yields from the AWD practices were higher than those from farmers' practices at every site except for SKN province. Comparing the AWD system and farmers' practices, the highest percentage of yield increase (22% difference) was in CCS province, while the lowest percentage of yield difference was in AT and BKK provinces (7% and 8% differences, respectively), as shown in Fig. 3A. Considering the paddy grain yields in SKN province, the grain yield from the AWD practice was lower than that of the farmers' practices, with a 70% difference, because the soil type (sandy loam) was not suitable for applying an AWD practice. In addition, brown planthoppers were observed throughout the AWD field but were not detected in the farmers' field.

In the wet season, the trend of grain yield was similar to that for the dry season. The highest percentage of yield difference between the AWD fields and farmers' fields was in BKK province (39% difference), while the grain yields in NKN, AT, CN and PC provinces had slightly different yields (2–3% differences), as shown in Fig. 3A. In addition, in BKK province, the grain yield in the farmers' fields was much lower than that in the AWD fields (Fig. 3A), because the rice plants in farmers' fields were infected by blast disease, which was not found in the AWD fields. However, the use of the AWD practice in the wet season was identified as unsuccessful because the water levels in the AWD experiment did not decrease at any site to -15 cm, which was due to the high frequency and amount of rainfall in the wet season.

The milling quality of the collected rice was significantly different between the AWD field and farmers' field at each site in both the dry and wet seasons. However, the milling quality varied among all eight sites and between seasons. Thus, the water savings caused by the AWD practice increased the grain yields but did not affect the quality of head rice after the milling process. However, most of the percentages of head rice in the AWD practice were higher than those in the farmers' practices, especially in the dry season (Fig. 3B).

Total volume of water use and water productivity

The total water used (irrigation + rainfall) compared between the AWD fields and farmers' fields could be evaluated in the dry season only because, in the wet season, rain continued to fall, adding water to the paddy fields. Therefore, the soil was saturated with water, and the soil surface could not sufficiently dry to allow the water to descend to -15 cm for a meaningful comparison. In addition, the rainfall amounts in the wet season at the eight sites were in a wide range (4,690–12,520 m^3/ha), as shown in Fig. 4, while the total water amount (irrigation and rainfall) in the dry season at the eight sites was in the smaller range 5,011–7,901 m^3/ha), as shown in Fig. 5A. Thus, the rainfall amounts in the wet season were sufficient to meet the rice requirements and thus, the AWD practice was not practical in the wet season.

However, considering the dry season, the seasonal total water use varied among the eight sites and the amount of water used was significantly less for the AWD practice compared to the farmers' practice in PTT, BKK, CN and PC provinces. The exception was in CCS province, where the amount of water used in the farmers' practice was higher than that used in the AWD practice. However, there was no significant difference between the amounts of water used by AWD and the farmer's practices in NKN and AT provinces. Compared with farmers' practices, the AWD practice had reduced total water use (irrigation and rainfall) by 5–30%. The highest percentage of water reduction was in SKN province (30% reduction), while NKN and AT provinces had the smallest reduction in water (5% reduction), as shown in Fig. 5A. The water use efficiency data are provided in Fig. 5B. The water use efficiency increased significantly for the AWD practice, varying in the range 10–35% compared with that for the farmers' practices at every site except in SKN province.

CH_4 and N_2O emissions

The CH_4 fluxes varied among the eight sites and between practices (Fig. 3C). Generally, in the dry season, the total CH_4 emissions from the AWD fields were lower than those from farmers' fields, while the percentages of CH_4 reduction in the AWD fields and farmers' fields were different among the eight sites. Comparing the AWD and farmers' practices, the highest percentage of CH_4 reduction was in PTT Province, followed by CCS, SKN, PC, NKN, AT and CN provinces. However, in BKK province, CH_4 emissions from the AWD field were higher than those from the farmers' field. In contrast, CH_4 emissions in the wet season were puzzling because CH_4 emissions from the farmers' fields in five provinces (PTT, BKK, CCS, AT and

Table 1 Paddy soil properties derived from eight study sites where alternative wetting and drying (AWD) practices and farmers' practices for rice production were tested in 2016

Treatment	Province					
	pH (1:1)	OM (%)	Available P (mg/kg)	Available K (mg/kg)	CEC (meq/100 g soil)	Soil texture
			Pathum Thani			
AWD 5/-15	5.3 ± 0.72[a]	3.0 ± 0.23[a]	2.7 ± 0.23[a]	204 ± 3.5[a]	27.8 ± 2.1[a]	Clay
Farmer's practice	5.5 ± 0.62[a]	2.8 ± 0.18[a]	0.5 ± 0.12[b]	185 ± 2.9[b]	26.2 ± 1.8[a]	Clay
			Bangkok			
AWD 5/-15	5.7 ± 0.52[a]	5.8 ± 0.26[b]	6.6 ± 0.32[a]	280 ± 4.3[b]	27.6 ± 2.8[b]	Clay
Farmer's practice	5.8 ± 0.81[a]	7.2 ± 0.32[a]	4.7 ± 0.25[b]	307 ± 2.3[a]	30.8 ± 1.9[a]	Clay
			Chachoengsao			
AWD 5/-15	5.0 ± 0.47[a]	4.6 ± 0.18[a]	14.0 ± 0.31[b]	207 ± 5.1[b]	26.4 ± 2.6[b]	Clay
Farmer's practice	5.5 ± 0.55[a]	5.3 ± 0.26[a]	16.0 ± 0.22[a]	214 ± 4.8[a]	28.6 ± 3.0[a]	Clay
			Nakhon Nayok			
AWD 5/-15	4.5 ± 0.43[a]	5.8 ± 0.35[a]	4.9 ± 0.45[b]	222 ± 3.9[a]	35.4 ± 3.4[b]	Clay
Farmer's practice	4.5 ± 0.25[a]	5.5 ± 0.21[a]	8.3 ± 0.25[a]	183 ± 4.8[b]	43.4 ± 2.6[a]	Clay
			Ang Thong			
AWD 5/-15	6.4 ± 0.62[a]	4.2 ± 0.32[a]	20.1 ± 0.15[a]	123 ± 2.8[a]	16.7 ± 2.8[a]	Clay
Farmer's practice	6.3 ± 0.38[a]	3.1 ± 0.22[a]	18.3 ± 0.24[b]	114 ± 4.2[b]	17.4 ± 1.9[a]	Clay
			Chai Nat			
AWD 5/-15	5.4 ± 0.52[a]	5.2 ± 0.15[a]	2.2 ± 0.16[a]	62 ± 4.1[b]	27.0 ± 3.2[b]	Clay
Farmer's practice	5.7 ± 0.58[a]	5.1 ± 0.24[a]	1.3 ± 0.11[b]	75 ± 3.7[a]	33.3 ± 2.5[a]	Clay
			Pichit			
AWD 5/-15	5.5 ± 0.84[a]	3.6 ± 0.12[a]	11.2 ± 0.21[a]	68 ± 2.8[a]	26.7 ± 2.9[a]	Clay
Farmer's practice	5.9 ± 0.34[a]	3.0 ± 0.16[a]	11.3 ± 0.24[a]	65 ± 2.4[b]	26.1 ± 2.0[a]	Clay
			Sakon Nakhon			
AWD 5/-15	4.7 ± 0.31[a]	0.9 ± 0.11[a]	1.9 ± 0.21[a]	21 ± 3.0[b]	6.9 ± 1.4[b]	Sandy loam
Farmer's practice	5.1 ± 0.29[a]	0.4 ± 0.14[b]	0.5 ± 0.20[b]	34 ± 2.8[a]	20.3 ± 2.1[a]	Sandy loam
Suitable soil properties for rice cultivation (Rice Department, 2020)	5.5–6.5	1–2	5–10	60–80	10–15	-

OM = organic matter; CEC = cation exchange content
Values presented as mean ± SD.
Different lowercase superscripts in the same column in each location indicate a significant difference at the 0.05 level based on a t-test.

CN) were lower than those from the AWD fields, while the CH_4 emissions from the AWD fields in the other two provinces (NKN and SKN) were lower than those from the farmers' fields. In addition, the CH_4 emissions between the AWD and farmers' practices in PC province were not significantly different (Fig. 3C).

The relative N_2O fluxes varied in the same manner as the CH_4 fluxes. The seasonal total N_2O emissions were slightly different between the AWD and farmers' practices. In the dry season, the N_2O emissions in the AWD fields of five provinces (PTT, CCS, NKN, AT and CN) were lower than those in the farmers' fields, while the N_2O emissions in the AWD fields were higher than those in the farmers' fields in BKK, PC and SKN provinces. In addition, N_2O emissions between the AWD and farmers' practices in CCS, NKN and CN provinces were not significantly different. In the wet season, N_2O emissions were lower in the AWD fields than in the farmers' fields in CCS and CN provinces, while in PTT, BKK, NKN, AT, PC and SKN provinces, the AWD practice produced N_2O emissions that were not significantly different from those produced by the farmers' practices (Fig. 3D). However, the N_2O emissions in both the AWD system and the farmers' practices were much lower than the CH_4 emissions.

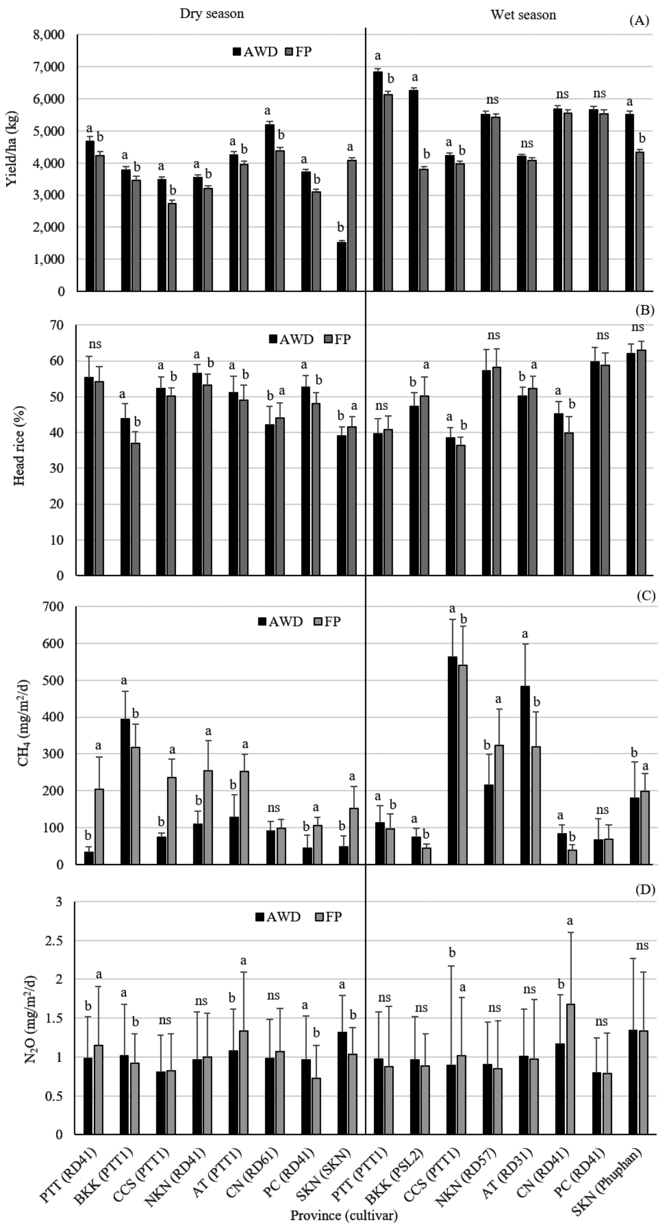

Fig. 3 Grain yield (A), head rice (B) CH_4 emissions (C) and N_2O emissions in wet and dry cultivation seasons for AWD practice and farmers' practices at eight study sites (see Fig. 1 caption for full names of province abbreviations), where different lowercase letters above columns indicate pairwise significant differences ($p < 0.05$) within each province, ns = not significant and error bars indicate ± SD

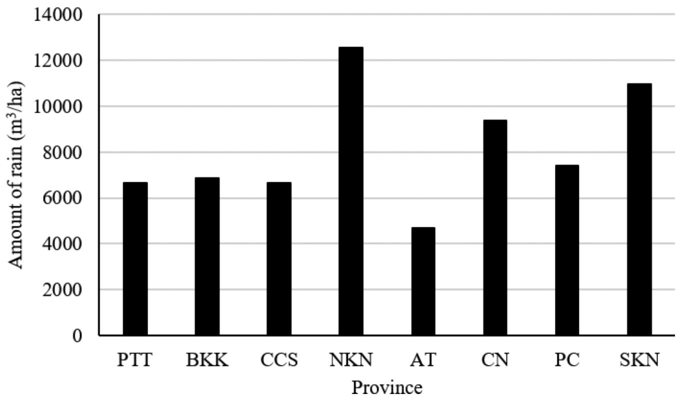

Fig. 4 Rainfall amounts in wet season at eight study sites (see Fig. 2 caption for full names of province abbreviations)

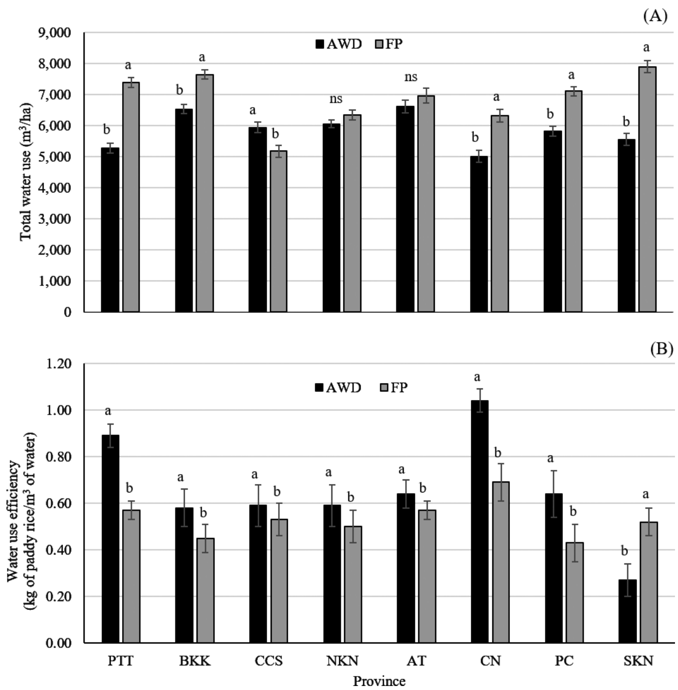

Fig. 5 Total water use (irrigation and rainfall) (A) and water use efficiency (B) for alternative wetting and drying (AWD) practice and farmers' practices (FP) in dry season for eight study sites (see Fig. 1 caption for full names of province abbreviations), where different lowercase letters above columns indicate pairwise significant differences within each province ($p < 0.05$), ns = not significant and error bars indicate ± SD

Production cost, income, and net profit

The production costs, incomes and net profits were converted to US dollars per hectare (USD 1 = THB 32.23). The total cost of rice cultivation varied among the eight sites; labor costs and land rent for each site were the main factors contributing to this variation. The comparisons of total costs, incomes and profits for each site were not statistically analyzed because these data came from a whole field (each 1 ha of AWD and farmers' practice) that had not been replicated (Figs. 6A and 6B). However, the statistical analysis to compare the total costs, incomes and profits between the AWD and farmers' practices in each season was analyzed based on the means from the eight sites (Fig. 7).

The results shown in Fig. 6A indicate the trend that when the AWD practice was used in the dry season in PTT, AT, CN and PC provinces, the total cost for rice cultivation decreased by 5–19% compared with that for farmers' practices, while the rice cultivation costs of the AWD practice in BKK, CCS, NKN and SKN provinces were higher than for the farmers' practices by 5–10%. In the wet season, the total costs of the AWD practice at four sites (PTT, BKK, CCS and SKN) were higher than those for farmers' practices by 3–18%, while the total costs of the AWD practice were lower by 1–27% than those of the farmers' practices for the four other sites (NKN, AT, CN, and PC), as shown in Fig. 6B. Considering the mean total costs for the eight sites in each season, the total cost compared between AWD and farmers' practices was not significant (Fig. 7).

The incomes from selling paddy grain depended on the cultivar and were derived from the grain yields and selling prices. Therefore, incomes depended on the grain yields at each site and were different among sites. However, when considering both the dry and wet seasons, the results showed that incomes from the AWD practice were higher than those from farmers' practices at every site. An exception was found in the SKN Province in the dry season, as the income derived from the AWD practice was lower than that derived from the farmers' practices. The incomes derived from the AWD practice at seven sites (excluding SKN province) in the dry season were in the range USD 863–1280/ha and were 9–22% higher than those of the farmers' practices, while the incomes from the AWD practice in the wet season were in the range USD 977–1,335/ha and were 2–49% higher than those of the farmers' practices (Figs. 6A and 6B). In addition, the mean incomes from the AWD practice on the eight sites in each season were significantly higher than from the farmers' practices by 4.4 USD/ha in dry season and by 13.5 USD/ha in dry season (Fig. 7).

Higher net profits were recorded in the dry season for the AWD practice at seven sites (excluding SKN province) and were in the range USD 19–664/ha. The net profits for the farmers' practices for five sites were in the range USD 22–596/ha, and the other three sites had net losses in the range USD -39/ha to USD -364/ha. The net profits of the AWD practice in the wet season (USD 16–665/ha) were higher than those of the farmers' practices (USD -16/ha to USD 467/ha) at seven sites (excluding PTT province). In addition, a net loss was recorded

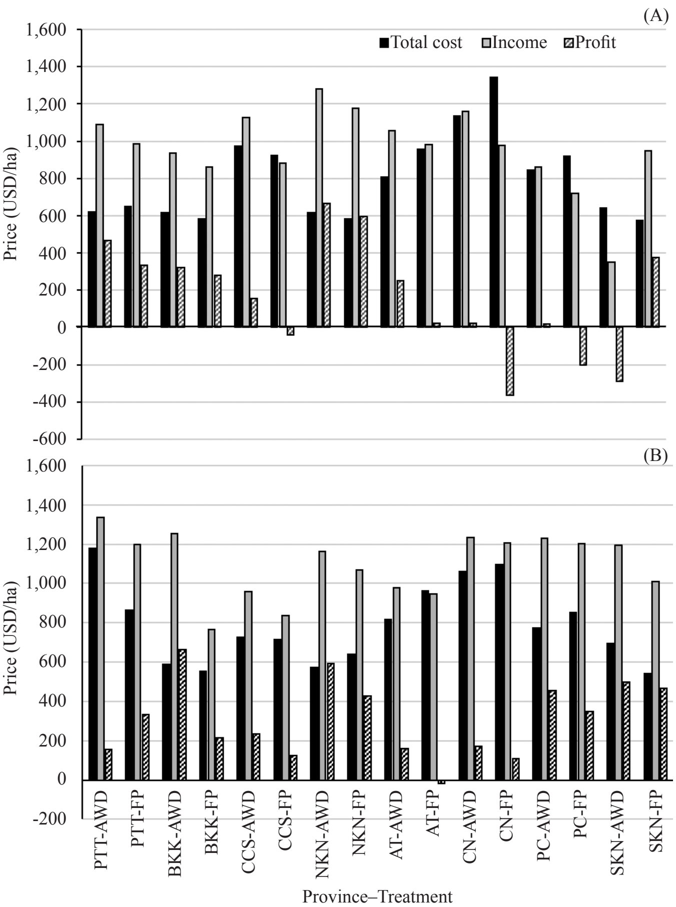

Fig. 6 Total costs, incomes and profits for alternative wetting and drying (AWD) practice and farmers' practices (FP) in the dry season (A) and wet season (B) at eight study sites (see Fig. 1 caption for full names of province abbreviations)

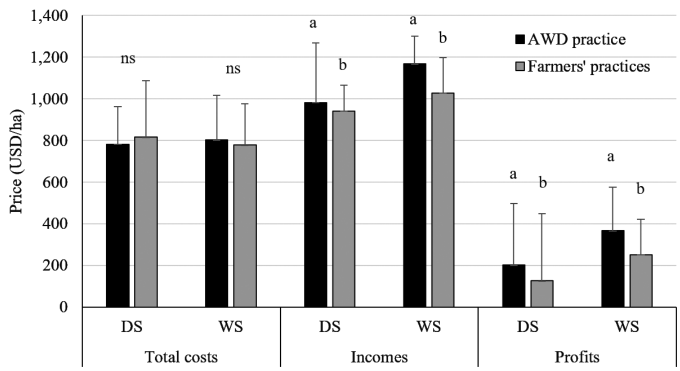

Fig. 7 mean of total costs, incomes and profits in dry (DS) and wet (WS) seasons for alternative wetting and drying (AWD) practice and farmers' practices (FP) at eight study sites (see Fig. 1 caption for full names of province abbreviations), where different lowercase letters above columns indicate pairwise significant differences within either dry or wet season ($p < 0.05$) across provinces, ns = not significant and error bars indicate ± SD

for only the farmers' practice in NKN province (Figs. 6A and 6B). Therefore, the mean net profits for the AWD practice from the eight sites in each season were significantly higher than for the farmers' practices by 60.8 USD/ha in dry season and by 45.8 USD/ha in wet season (Fig. 7).

Discussion

Many research publications have confirmed that the AWD technique is successful in maintaining or increasing grain yields in rice production (Sibayan et al., 2018; Tirol-Padre et al., 2018). Different AWD results depend on the specifications of the AWD technique and experimental conditions, such as climate, soil type, groundwater depth, crop management practices and the rice cultivars used (Carrijo et al., 2017; Ullah and Datta, 2018). However, most studies of the AWD technique experimented with the transplanting method based on small scale areas at research stations (Zhou et al., 2017; Sibayan et al., 2018). The main irrigation area for rice production in Thailand is in the central region, where the broadcasting method is used (Silalertruksa et al., 2017). Thus, the current experiment applied the AWD technique with the broadcasting method at small scales (Ruensuk et al., 2016) to actual paddy fields.

In the current study, the trend of the mean grain yield from the eight locations in the dry season was lower than that in the wet season. This may suggest that in the dry season, the water supply was limited and that the air temperature varied substantially between the vegetative (low temperature) and reproductive phases (high temperature). Shimono et al. (2002) reported that low temperatures in the vegetative stage can cause slow growth, reduce seedling vigor and reduce tillering, while high temperatures in the reproductive stage can lead to floret sterility and yield losses (Jagadish et al., 2010). On the other hand, in the wet season, the water supply was adequate and the air temperature during the growth period varied only slightly.

In the dry season, the grain yields for the AWD practice (5/-15 cm) at seven of the eight sites (excluding SKN province) were clearly higher than those for the farmers' practices. This result indicated that the timing and number of rewetting-drying cycles at -15 cm did not negatively affect grain yields. However, the grain yield for the AWD practice in SKN province was lower than that for the farmers' practices; the soil type (sandy loam) at this location was not suitable for the application of the AWD system, as water drains quickly from sandy loam, causing water savings to be limited (Howell et al., 2015). The grain yields in the wet season for the AWD practice at every site were higher than those for the farmers' practices; however, the yields were slightly different because in the wet season, the AWD system could not successfully control water levels. The grain yield from the farmers' field in BKK province was affected by blast disease, which was not found in the AWD practices. This suggested that disease reduction occurred as a result of the AWD system, which reduces humidity within the crop canopy and improves systemic resistance (Sander, 2019). However, the water conditions were slightly different for both the AWD system and the farmers' practices in the wet season.

Norton et al. (2017) reported that the grain yields from AWD practices were higher than those from farmers' practices by 12.0–15.4%, while the grain yield from the AWD practice in the current study, especially in the dry season, increased grain yields by 7–22%. Thus, AWD application during the vegetative stage of rice enhanced the root growth for maximum nutrient uptake and resulted in more productive tillers, which increased the grain yields at harvesting (Chidthaisong et al., 2018: Ruensuk et al., 2016). In addition, rhizosphere drying caused by AWD can also increase oxygenation and alter plant hormone signaling to enhance the grain filling rate, particularly in inferior spikelets (Zhang et al., 2012), thereby increasing plant water use efficiency. The current study confirmed that AWD had no negative impacts on rice yields when a broadcasting method was applied in farmers' fields in both the dry and wet seasons.

Silalertruksa et al. (2017) reported that water use by paddy rice in the main area of rice cultivation in Thailand is in the range 6,800–7,500 m^3/ha, but the results of the current study revealed that the total water used per unit area for rice cultivation in the fields with AWD in the dry season among the eight sites varied in the range 5,011–6,615 m^3/ha. The total water used by the farmers' practices was in the range 5,177–7,900 m^3/ha, which was close to the total water use reported by Silalertruksa et al. (2017). Maneepitak et al. (2019) reported that the total water input was reduced by 19% in the wet season and by 39% in the dry season under AWD compared with conventional practices, while the water used in the current study decreased by 5–30% in the dry season. In addition, the water used in AWD at some sites (CCS, NKN, AT) was not significantly decreased compared with farmer's practice. Thus, farmers should be encouraged to use the AWD technique for rice cultivation, especially in the dry season, to decrease irrigation water use in paddy fields due to the increasing drought situation, as this technique did not decrease yields. However, the AWD technique cannot be applied in every situation.

Increased water productivity and the maintenance of grain yields are of critical importance for sustainable rice production under changing climate scenarios, and these goals can be achieved with the broad adoption of AWD systems (Ullah and Datta 2018). Chidthaisong et al. (2018) reported that the AWD technique could significantly improve water productivity in rice production and produced results similar to those of Tirol-Padre et al. (2018). In addition, Maneepitak et al. (2019) mentioned that the water productivity when using AWD was 46% greater than that when using conventional practices in the dry season. Thus, in the current study, water productivity was significantly higher (10–35%) in the AWD practices than in the farmers' practices at every site except for SKN province.

The AWD technique is a suitable water management method for effectively reducing CH_4 emissions from paddy fields (LaHue et al., 2016; Liang et al., 2016). The CH_4 emissions in the current study had large variations among sites and seasons. However, high variations in CH_4 emissions have already been reported in many published studies (Chidthaisong et al., 2018; Tirol-Padre et al., 2018). The environmental factors that affect CH_4 emissions and cause large variations in CH_4 fluxes include air temperature, humidity, soil type, soil properties, microsite characteristics, microbial activity and cultural practices. (Plaza-Bonilla et al., 2014; Wang et al., 2017). In addition, the high spatial variability in CH_4 fluxes that were commonly found at the sites in the current study could be partly attributed to the fine texture and the high acidity of the sulfate soil (Chidthaisong et al., 2018). In the current study, the soil at every site was identified as clay (except for SKN) with a low pH. Compared with the CH_4 emissions under the farmers' practices, the AWD practice resulted in reduced CH_4 emissions at every site. However, the CH_4 emissions differed between the wet and dry seasons: in five of the eight sites, where the CH_4 emissions from the AWD practice were higher than those from the farmers' practices. Liang et al. (2016) suggested that the efficiency of water control in AWD practices (by allowing the soil to dry) could decrease the CH_4 emissions in paddy fields. However, in the wet season, the reductions in CH_4 emissions for the AWD practice were not because of efficient water control but rather because soil drying in the AWD practice was not sufficient to reduce CH_4 emissions. Thus, using AWD with the broadcasting method can reduce CH_4 emissions in paddy fields, especially in the dry season.

There were large variations in N_2O fluxes in the current study in both the dry and wet seasons, which was similar to the CH_4 fluxes. However, in both seasons, the total N_2O was slightly affected by the AWD technique. The N_2O emissions from the eight sites in the dry and wet seasons varied in the ranges 0.73–1.34 and 0.79–1.67 mg/m^2/day, respectively. These N_2O emission levels were similar to those observed in many other field studies (Sibayan et al., 2018; Chidthaisong et al., 2018). In addition, the trends in the N_2O emissions for the AWD practice were not greater than those for farmers' practices at any site. However, Sibayan et al. (2018) and Xu et al. (2015) reported that total N_2O emissions in different seasons were significantly affected by cropping season and water management methods and that AWD increased N_2O emissions, especially in the dry season. On the other hand, Tirol-Padre et al. (2018) reported that whether N_2O emissions increase in paddy fields was dependent on site-specific factors. In addition, N fertilizer application induced N_2O emissions in rice production fields. (Yang et al., 2007; Chidthaisong et al., 2018). These results suggested that in the current study, N fertilization in the AWD practice and farmers' practices was performed at the same rate and timing and that the fertilizer was applied under flooded conditions. Thus, the N_2O emissions between the AWD field and farmers' fields were not different.

In the current study, the total costs for the AWD practice were not significantly different to the farmers' practices in both seasons. However, the amounts in each cost item differed among sites such as labor and materials costs (variable costs) and the land rent (fixed cost). On the other hand, Yamaguchi et al. (2016) and Karim et al. (2014) reported that cultivation under AWD decreased production costs compared with those of conventional practices. However, the net profits in this study were significantly higher for the AWD practice than for the farmers' practices for both seasons due to the higher income from grain yields in the AWD practice than in the farmers' practices. The net profits of the AWD practice in SKN were in fact a net loss due to the brown planthopper infestation. furthermore, at some sites (CCS, CN, PC provinces in the dry season and AT province in the wet season), the farmers' practices resulted in net losses. These results suggested that there were higher net profits from applying AWD practices, as grain yields should be increased, thus decreasing production costs on a per yield basis. In general, rice production in Thailand is a high-risk situation with low profit because rice cultivation is often dependent on unpredictable weather conditions. However, when the weather is not a concern, low prices and high production costs (including labor, energy and chemical costs) are major factors contributing to lost profits (Ngammuangtueng et al., 2019). Thus, AWD practices may help farmers decrease their water supply risk, especially in the dry season, and the AWD method can increase profits from rice production.

The AWD 5/-15 practice was identified as a promising approach to increase water use efficiency and the net profits from rice production. The focus of AWD practices should be on dry season cultivation, which is a routine practice for rice production in the irrigation areas of Thailand. However, it is difficult to control water levels in the wet season using the AWD practice, as the water level depends on rainfall, especially in lowland areas. Therefore, the use of the AWD technique with the pregerminated seed broadcasting method could be an alternative approach for farmers in irrigation areas.

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