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Impacts of alternate wetting and drying on rice farmers' profits and life cycle greenhouse gas emissions in An Giang Province in Vietnam

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ABSTRACT

Few studies have simultaneously evaluated the impact of alternate wetting and drying (AWD) on profit and life cycle greenhouse gas (LC-GHG) emissions based on a farm survey for all rice (*Oryza sativa* L.)-cropping seasons in a year. This study explores whether AWD allows farmers to increase profits and reduce LC-GHG emissions compared with conventional water management. To achieve this objective, survey data were collected by a structured interview from two groups of farmers in An Giang Province in Vietnam: one group was defined as AWD farmers who attended a training course and answered that they conducted AWD, and the other was defined as non-AWD farmers who did not attend the course and answered that they did not conduct AWD. The survey data were analysed by a regression approach and cradle-to-farm gate life cycle assessment. The results showed that the impact of AWD on profit varied depending on the season. The impact of AWD on profit was significant and positive for the early wet season ($p < 0.05$) and throughout the year ($p < 0.1$), but the impact was not significant for the dry and late wet seasons. In contrast, LC-GHG emissions by AWD farmers were significantly lower for all seasons when compared to non-AWD farmers. Although few studies have analysed the impacts of AWD on profits in the early wet season, AWD farmers may obtain higher profits than non-AWD farmers due to water from precipitation, which may reduce severe water stress and alleviate some of the adoption constraints. Based on these results, this study recommends implementing AWD throughout the year in An Giang Province if irrigation and drainage systems are available. The results on seasonal variations in impacts and the overall annual impact of AWD on profits and LC-GHG emissions will help farmers make decisions and help to achieve mitigation targets in the nationally determined contribution under the Paris Agreement.

1. Introduction

The global agricultural sector has to increase production in response to an increase in food demand while overcoming the negative impact of climate change on production (FAO, 2016). Additionally, the sector must contribute to mitigating greenhouse gas (GHG) emissions to keep the temperature increase less than 1.5 °C above preindustrial levels before 2050 (IPCC, 2018). Nationally determined contributions (NDCs) under the Paris Agreement have increased the number of countries that have implemented agricultural technologies to achieve some of their targets. Adaptation measures to climate change by changing planting time, crop cultivars and species are essential to respond to the increase in food demand (IPCC, 2014). Multiple cropping of rice (*Oryza sativa* L.) in a year could be another way to respond to the increase in food demand within limited agricultural land and to maintain or improve farmers' incomes (Tran et al., 2021). However, the intensive rice-cropping system increases environmental loads, partly because of the shorter nonflooded period between cropping seasons. This leads to an increase in nonsoil CH_4 and N_2O emissions due to the limited time before the next cropping season starts, which increases the number of farmers who burn rice straw (Ngo et al., 2012). Additionally, the shorter nonflooded period has increased soil CH_4 emissions (IPCC, 2019). As a result, for example, yield-scaled soil GHG emissions are approximately three times higher under a double-cropping system where rice is harvested twice on the same land than under single-cropping systems (Feng et al., 2013). Yield-scaled life cycle greenhouse gas (LC-GHG) emissions are also higher in double/triple rice-cropping systems than in single-cropping systems (Arunrat et al., 2016). Moreover, the global water demand has increased partly by intensive rice-cropping systems, and the impact of climate change is exacerbating water scarcity (Fahad et al., 2021a).

To mitigate the increased LC-GHG emissions from intensive rice-

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cropping systems while adapting to drought and unpredictable weather (ASEAN, 2015), alternate wetting and drying (AWD) can become an important agricultural technology. The advantage of AWD is not only in mitigating climate change by reducing soil CH_4 emissions but also in improving water productivity because under AWD, water is applied to paddy fields when the water table reaches approximately 15 cm below the soil surface except for 1–2 weeks after transplanting and for heading and flowering stages (called safe AWD, Bouman et al., 2007), as described briefly in Fig. 1. The aerobic conditions caused by AWD inhibit CH_4 production by suppressing the anaerobic decomposition of organic matter. Despite the advantages, AWD is not always adopted by farmers. The adoption of AWD is constrained by field conditions (Lampayan et al., 2015), reliable water supply (Adhya et al., 2014), and infrastructure (e.g., Adhya et al., 2014; Sander et al., 2015), including reliable electricity supply at the time of irrigation (Kürschner et al., 2010), additional effort (Sander et al., 2015), pumping costs (Adhya et al., 2014), and/or financial benefits through an increase in yield or saving fuel costs (Yokoyama et al., 2016). The impacts of AWD on yield, profit and LC-GHG emissions vary depending on the conditions. No impact or positive impact on yield was reported under mild AWD where the water table was less than 15 cm below the soil surface (Carrijo et al., 2017), whereas yield reduction was reported under severe AWD where the water table was more than 15 cm below the soil surface (Carrijo et al., 2017). Increased profits by AWD compared with continuous flooding were reported for several countries, including the Philippines, Vietnam and Bangradesh (Lampayan et al., 2015; Truong et al., 2013) in the dry season. On the other hand, Moya et al. (2004) in Hubei Province in China in the summer season and Rejesus et al. (2011) in the Philippines in the dry season reported that the profits of AWD farmers were not significantly higher than those of non-AWD farmers. Based on a model simulation, Fertitta-Roberts et al. (2019) observed a reduction in LC-GHG emissions when AWD was introduced to California rice production for April–June. However, the authors warned about a severe yield reduction that would erase the benefits of the reduction in yield-scaled LC-GHG mitigation by AWD. Based on field experiments in Thailand, Sriphirom et al. (2019) reported that yield-scaled LC-GHG emissions for the wet season were higher under AWD than under continuous flooding but not during the dry season. The authors attributed the higher yield-scaled LC-GHG emissions for the wet season to rainfall, which lowered grain yield and increased LC-GHG emissions due to incomplete AWD. Based on a farm survey, Leon et al. (2021) reported that AWD allows farmers to reduce LC-GHG emissions without sacrificing yield in An Giang Province in Vietnam for the early wet season.

Climate change will increase the incidence of abiotic stress, including drought, extreme temperature, salinity, etc. (Fahad et al., 2021b). Plants can adapt to short-term abiotic stress by generating antioxidant enzymes to scavenge overproduced reactive oxygen species (Fahad et al., 2019). Plants also respond to stress by closing stomata, reducing the photosynthesis rate, decreasing the water content, and damaging chloroplasts with phytohormones such as abscisic acid (Fahad et al., 2021c). Exogenous application of chemicals like abscisic acid will reduce the negative impacts of stress on plant growth and yield (Fahad et al., 2021d). Nevertheless, under prolonged abiotic stress, overproduced reactive oxygen species may overwhelm antioxidant control, which in turn will damage cells extensively and kill them (Fahad et al., 2021d). Climate change is threatening crop production (Fahad et al., 2021c).

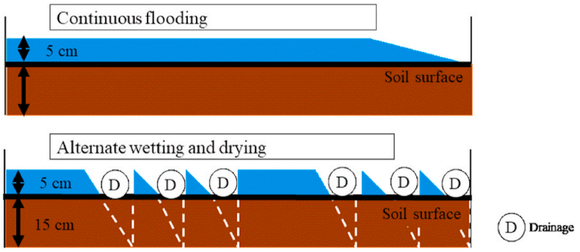

Fig. 1. Water management for continuous flooding and alternate wetting and drying.

To further increase the adoption of AWD to fulfil NDCs, it is essential to evaluate the impacts of AWD on profit and LC-GHG emissions throughout the year. To date, many studies have evaluated the impacts of AWD on profit for the dry season (Lampayan et al., 2015; Rejesus et al., 2011; Truong et al., 2013), which is a season when AWD is especially effective at mitigating water shortages (Setyanto et al., 2018) and reducing soil CH_4 emissions (Yagi et al., 2020). However, few studies have evaluated the impacts of AWD on profits together with LC-GHG emissions based on a farm survey for seasons other than the dry season and throughout the year. Furthermore, such information is increasingly important to be able to disseminate agricultural technology further and to achieve mitigation targets in NDCs under increasing intensive cropping systems. As some of the benefits of AWD have been reported, it was hypothesized that farmers may reduce LC-GHG emissions while increasing profits by AWD for all cropping seasons in a year. In this study, AWD farmers were defined as those who attended a training course and answered that they were conducting AWD, and non-AWD farmers were defined as those who did not attend the course and answered that they did not conduct AWD. It was considered that non-AWD farmers implement continuous flooding. Similar to this study, the adoption of AWD was determined depending on attendance to a training course in Vietnam (Truong et al., 2013) and depending on the regional training course and farmers' involvement in the Philippines (Sander et al., 2015). The main objective of this study was to evaluate whether AWD allows farmers to increase profit and reduce LC-GHG emissions in the early wet, late wet and dry seasons and throughout the year based on a farm survey.

2. Materials and methods

2.1. Study area

An Giang Province is one of the provinces in the Vietnam Mekong Delta (Fig. 2), and rice is grown two to three times a year. The main sowing/transplanting and harvesting months for the dry season (winter-spring) are November–December and March–April, respectively. The respective months for the early wet season (summer-autumn) are April–May and July–August. The late wet season (autumn-winter) starts in July–September and ends in October–December, and for the rainy season, their respective months are July–September and November–January (Phan et al., 2018). AWD was introduced into An Giang Province as a technological package known as 'one must do 5 reductions

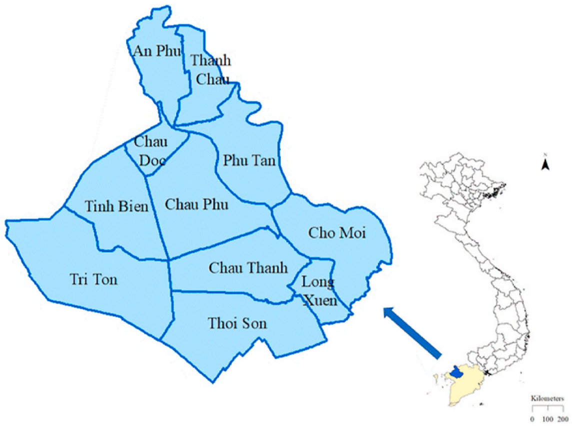

Fig. 2. An Giang Province in the Mekong Delta in Vietnam. Mekong Delta: yellow, An Giang province: blue.

(1M5R)' in which certified seeds must be used and the consumption of seeds, fertilizer, chemical pesticides, water and postharvest losses are reduced (Lampayan et al., 2015). Water is irrigated or drained by private pumps and/or communal pumping stations (Tran and Weger, 2018). In the late wet season, some fields are fallowed due to heavy rain or local government requirements. That is, the government requires farmers to grow rice in 8 seasons in three years and inundate the paddy field with flood water in the 9th season, i.e., 3-3-2 cycles, to remove toxic chemicals and to improve soil fertility with sediment deposition (Tran and Weger, 2018).

2.2. Data collection

In selecting sample rice farms, a stratified random sampling technique was adopted. An Giang Province has 11 districts. From each district, a total of approximately 20 farmers, 10 AWD farmers and 10 non-AWD farmers, were selected randomly by local staff of the Department of Agriculture and Rural Development using a list of farmers. The survey was conducted for 100 AWD farmers and 100 non-AWD farmers after each cropping season, totalling 600 farmers. In case a farmer had several fields, the survey was conducted for all fields (1105 fields). The same farmers were surveyed for the 3 cropping seasons, but those missing in subsequent surveys were replaced with new farmers to maintain the sample size (i.e., 100 for AWD and 100 for non-AWD in each season). A structured interview was conducted after each cropping season: the early wet season in 2019 and the late wet and dry seasons in 2020. The farm-level survey was conducted by staff at Can Tho University. The survey collected the following information to calculate production costs and profits: purchase fees of machinery (in case farmers use their own machinery), rental fees of machinery (VND ha^{-1}), application rates and prices of agricultural inputs, wages of hired and family workers, irrigation costs, frequencies of checking water level in a week, sale price of rice (VND t^{-1}) and sale price of rice straw (VND ha^{-1}). The survey also collected information to estimate LC-GHG emissions in addition to some of the information described above: dates of sowing and harvesting, operating hours and specification of machinery (weight and power), frequencies of irrigation, rice yield, and rice straw management. Additionally, the survey collected observable variables of farmers, such as the highest education and ages of farmers, sizes of each field and total rice fields cultivated, and off-farm income.

In addition to the farm survey, an interview survey was conducted either at agricultural cooperative or community pumping stations ($N = 27$). From the survey, information on the number of drainage events, operating hours of pumps, area that receives drainage services, fuel type and fuel consumption were collected in each rice-cropping season.

Available data to analyse profit and LC-GHG emissions were different, as missing values were different. The details of the samples are described in Table 1.

2.3. Estimating LC-GHG emissions

2.3.1. Goal and scope definition

Life cycle assessment (LCA) was conducted following ISO 14040 (ISO, 2006a) and 14044 (ISO, 2006b). A goal of this study was to estimate LC-GHG emissions from AWD and non-AWD farmers for each rice crop season. A cradle-to-farm gate LCA was conducted where the production of materials and management were included, but drying and milling of rough rice was excluded since farmers sold rice immediately after harvest. Functional units were defined as either the production of 1 kg of paddy rice or 1 ha of paddy rice per crop.

2.3.2. Estimating soil CH_4 and N_2O emissions

Soil CH_4 and N_2O emissions were calculated following the IPCC (2019) Tier 1 method. The emission factors and scaling factors are summarized in Appendix 1.

$$CH_4 = EF_{CH4} \times SF_{wrc} \times SF_{wrf} \times SF_{oaa} \times Days \tag{1}$$

$$SF_{oaa} = \left(1 + \sum_i ROA_i + CFOA_i\right)^{0.59} \tag{2}$$

where CH_4 is a soil CH_4 emission during the rice cultivation period, EF_{CH4} is the emission factor of the daily CH_4 emission factor for Southeast Asia, SF_{wrc} is a scaling factor for the water regime during the cultivation period, SF_{wrf} is a scaling factor for the water regime before the cultivation period, SF_{oaa} is a scaling factor for organic matter application, Days is a cultivation period obtained from the present survey, ROA_i is the application rate of straw, and $CFOA_i$ is the conversion factor of organic amendments. It was assumed that all straw and stubble were returned to the soil in the case of incorporation; 5% (weight) of rice straw, including stubble, was incorporated in the case of removal and composting; 20% of rice straw, including stubble, was incorporated and the remaining 80% was burned in the case of burning (IPCC, 2019).

A scaling factor of 2.41 was chosen for the water regime before cultivation (SF_{wrf}, Eq. (1)) for both double- and triple-cropping fields based on the following reasons: the farmers in this study answered that the fallow period between cropping seasons was approximately one month; and it was reported that rice fields were inundated by flood water on average 102 days for double-cropping systems and 26 days for triple-cropping systems in the late wet season (Chapman et al., 2016). Based on these reasons, it was considered that the following two cases were unsuitable for this study: SF_{wrf} is 1 for a case of nonflooded preseason <180 days, which is used for multiple rice cropping with a ≥ 1 month fallow period between two rice-cropping seasons; SF_{wrf} is 0.89 for a case of nonflooded preseason >180 days, which is used for a single rice-cropping system (IPCC, 2019).

$$\mathrm{N_2O_{Ni/De}} = \left(\mathrm{N_f} + \mathrm{N_{cr}}\right) \times \mathrm{EF_D} \times \mathrm{a} \tag{3}$$

$$\mathrm{N_2O_L} = \left(\mathrm{N_f} + \mathrm{N_{cr}} + \mathrm{N_{com}}\right) \times \mathrm{Frac_L} \times \mathrm{EF_L} \times \mathrm{a} \tag{4}$$

$$\mathrm{N_2O_v} = \left\{\left(\mathrm{N_{fu}} \times Frac_{vu}\right) + \left(\mathrm{N_{fo}} \times Frac_{vo}\right) + \left(\mathrm{N_{com}} \times Frac_{vcom}\right)\right\} \times EF_v \times a \tag{5}$$

where $N_2O_{Ni/De}$ is the soil N_2O emissions from the nitrification/denitrification process; N_f is the N amount applied as fertilizer (kg N ha^{-1}); N_{cr} is the N amount applied from crop residue; EF_D is the emission factor of N_2O emission; a is 44/28; N_2O_L is the N_2O emissions by leaching and runoff; N_{com} is the N amount applied from compost; $Frac_L$ is the fraction of N lost by leaching and runoff; EF_L is the emission factor of N_2O emission by leaching and runoff; N_2O_v is the N_2O emissions via

Table 1

Number of farmers/fields surveyed and analysed in this study.

		Early-wet season		Late-wet season		Dry season	
		Non-AWD	AWD	Non-AWD	AWD	Non-AWD	AWD
Surveyed		100 (187)	100 (199)	100 (178)	100 (186)	100 (173)	100 (182)
Analysed	Profit	91 (173)	88 (175)	95 (164)	95 (178)	96 (164)	100 (182)
	LC-GHG	83 (154)	83 (161)	95 (167)	92 (172)	88 (149)	100 (182)

Numbers outside and inside parentheses are the number of farmers and fields, respectively.

redeposition of NH_3 and NO_x and their products; N_{fu} is the N amount applied from urea; N_{fo} is the N amount applied from other synthetic fertilizers; $Frac_{vu,}$ $Frac_{vo}$ and $Frac_{vcom}$ are fractions of N volatilized for urea, for other synthetic fertilizers and for compost; and EF_v is the emission factor of N_2O emission by volatilized N. The amounts of above- and belowground crop residues were estimated using the yield obtained in this study, the ratio of 1.4 for aboveground residue to paddy grain (IPCC, 2019), the ratio of 0.16 for belowground biomass to aboveground biomass (IPCC, 2019) and the dry matter content of 0.89 for paddy grain (IPCC, 2019). The nitrogen application from crop residue was estimated by multiplying the amounts of above- and belowground residues (dry matter kg) by their nitrogen contents: 0.7% for the aboveground residue (IPCC, 2019) and 0.64% for belowground residue (Ogawa et al., 1988).

Both soil N_2O emissions from crop residues and soil CH_4 emissions were estimated taking into account the previous crop season rice straw management and yield (Costa et al., 2020). In contrast, nonsoil CH_4 and N_2O emissions from burning crop residue and GHG emissions from the production of agricultural materials and machinery use were calculated based on the current crop season management. If no data for the previous crop season were available, it was assumed that the crop residue management and/or yield was the same as the current management. Emissions from burning were estimated by multiplying emission factors of 2.7 g kg^{-1} for CH_4 emissions and 0.07 g kg^{-1} for N_2O emissions by the amount of straw residue.

2.3.3. Estimating GHG emissions

As farmers did not remember the application of agrochemicals well, this study asked about the types of agrochemicals. The application rates of active ingredients were derived from some products sold in Vietnam (Leon et al., 2021): 0.27 kg ha^{-1} for molluscicides based on averages of 7 products; 0.41 kg ha^{-1} for herbicides based on averages of 5 products; 0.17 kg ha^{-1} for insecticides based on averages of 4 products; 0.15 kg ha^{-1} for fungicides based on averages of 6 products; and 0.001 kg ha^{-1} for rodenticides based on 1 product. Additionally, few farmers remembered the machinery specification; this study used the same specification as Leon et al. (2021), which is presented in Appendix 2.

2.3.4. Impact assessment

The global warming potential with a time horizon of 100 years (IPCC, 2013: CO_2:1, CH_4: 28, and N_2O:265) was calculated using MiLCA Ver. 2.3 software with the IDEA (version 2.3) database (JEMAI, Tokyo, Japan) for fossil fuels and electricity in Vietnam and Simapro 9.0 with ecoinvent (Version 3.0) for the other inputs in Fig. 3. The agronomic inputs in Table 5 were converted to CO_2-eq using the method IPCC 2013 GWP 100a.

2.4. Calculating costs and profits

In An Giang Province, most farmers were renting machinery for land preparation, sowing, fertilizer/agrochemical application and harvesting. The rent includes not only the use of machinery but also the fuel and operator costs. In addition to the outside operators provided by the rental, family workers and/or workers hired by the farmers sometimes helped in the farming operation.

Costs for sowing (VND ha^{-1}) were obtained by summing the costs of seeds, costs of the renting machinery, and wages of workers hired by farmers and/or family labourers. Similarly, the costs of fertilizers and agrochemicals were obtained by summing the costs of either fertilizer or agrochemicals, the costs of the renting machinery, and the wages of workers hired by farmers and/or family workers. Costs of water management were calculated by summing the costs of irrigation and/or drainage and wages for checking the water level during a cropping season. When machinery was owned by farmers, the cost of machinery was obtained by summing the depreciated costs of machinery, wages of hired and/or family workers and costs of fuels. In this case, the depreciated cost of machinery was obtained by multiplying the purchase price of machinery by the ratio of operating hours relative to the lifetime of the machinery. Fuel or electricity costs were obtained by multiplying fuel or electricity consumption by the price of fuel (VND per litre) or electricity (VND per kWh). Labour costs were obtained by multiplying wages by working hours. When wage rates were not answered, average daily wages for farm workers in 2012 (General Statistics Office of Vietnam, 2012) were used instead. All prices and monetary data were deflated/inflated based on the consumer price index in Vietnam with 2020 as the base year. The deflated/inflated wages are as follows: 26, 907 VND $hour^{-1}$ for land preparation, 25,460 VND $hour^{-1}$ for sowing, 25,278 VND $hour^{-1}$ for agrochemical application, and 30,818 VND $hour^{-1}$ for harvesting. Total costs were obtained by summing the costs of land preparation, sowing, fertilizer/agrochemical application, harvesting and water management. Revenue was obtained by multiplying the yield (t ha^{-1}) by the sale price of rice (VND t^{-1}) and adding the revenue of straw. Profits were derived by subtracting total costs from the revenue. Costs and profits were presented in US dollars using the 2020 average exchange rate (1$ = 23,208 VND).

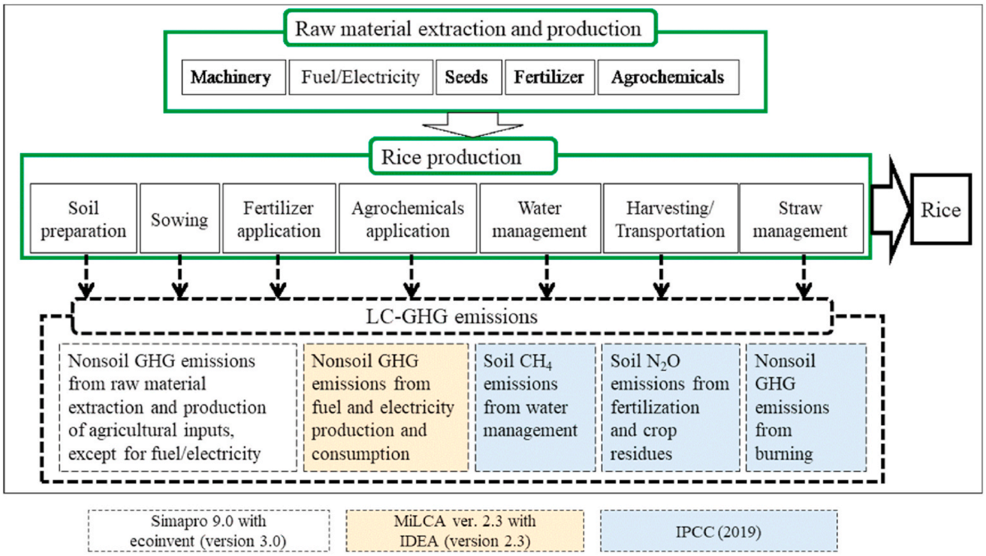

Fig. 3. A system boundary of rice cultivation.

Table 2

Descriptive statistics of farmers[§].

	Early-wet season		Late-wet season		Dry season	
	Non-AWD	AWD[‡‡]	Non-AWD	AWD[‡‡]	Non-AWD	AWD[‡‡]
Age[†]	48.9	49.8	50.4	50.7	49.0	50.5
Area (ha)	1.2	1.6[a]	1.5	1.5	1.5	1.6
Total Area (ha)[‡]	3.0	4.2[a]	3.1	3.8[b]	3.0	3.8[a]
Off-farm income*	0.6	0.6	0.5	0.5	0.5	0.5
Education 1[⁑]	0.3	0.3	0.4	0.4	0.4	0.4
Education 2**	0.5	0.5	0.4	0.4	0.4	0.4
Education 3[⁂]	0.2	0.2	0.2	0.2	0.2	0.2

[§]The sample sizes for AWD and non-AWD are shown in Table 1 for profit. [†] = Age of farmer; [‡] = total area of rice fields cultivated; * = 1 if yes, = 0 otherwise; [⁑] = 1 if the highest education of farmer is primary school, = 0 otherwise; ** = 1 if the highest education of farmer is secondary school, = 0 otherwise; [⁂] = 1 if the highest education of farmer is high school, = 0 otherwise; and [‡‡] letters "a" and "b" show that differences between non-AWD and AWD are significant at $p < 0.05$ and at $p < 0.1$, respectively.

2.5. Statistical analysis

Descriptive statistics were calculated for several variables, such as operation hours of machinery, inventory data and costs and profits of rice cultivation. T tests were conducted to test differences in the mean values between AWD and non-AWD farmers.

A regression approach was used to compare AWD farmers and non-AWD farmers and to evaluate the impacts of AWD (Wooldridge, 2002, pp. 608–614) by controlling for potential observable selection bias, which allows us to compare the impact of AWD for similar farmers. This method allows for isolation of the impact of AWD from other factors. Although the propensity score matching method can be used for the same purpose (Wooldridge, 2002), it was not used in this study because it does not use unmatched observations, and the sample size in this study was not large, especially when separately analysing each cropping season.

Using the regression approach, variables that might influence the outcome were controlled. Because AWD was introduced as a technological package in An Giang Province and this package included recommendations on the use of certified seeds, seeds/fertilizer/agrochemical application rates, and water and postharvest losses, to isolate the impact of AWD on the outcome, we controlled for the following variables in the regression: seeds/nitrogen application rates, frequencies of agrochemical application (times) and type of water management in addition to some sociodemographic characteristics. The regression approach consists of estimating the following equation by ordinary least squares (OLS):

$$Y_i = \gamma + \alpha AWD_i + \beta x_i + \delta (x_i - \bar{x}) AWD_i + \varepsilon_i \tag{6}$$

where Y_i is the outcome variable, such as costs of water management, total cost, sales price, yield, profit and LC-GHG emissions; x_i is a vector of observable variables; $\bar{x}$ is the mean of the observable variables; and α, β, γ and δ are parameters to be estimated. The parameter α is the average treatment effect (ATE), which is the expected difference in outcomes between AWD and non-AWD farmers. The p values of the estimated α were used to test the significance of the impacts of AWD on the outcomes. The p values were obtained using heteroskedasticity robust standard errors.

2.6. Sensitivity analysis

It was assumed that farmers were able to practice AWD throughout the year based on previous studies (Lovell, 2019; Truong et al., 2013; Yamaguchi et al., 2016), and farmers classified as AWD in this study answered that they conducted AWD. Even so, they may not have been able to conduct AWD properly during the late wet season because of precipitation. Therefore, this study estimated soil CH_4 emissions during the late wet season when the farmers were not able to conduct AWD at all, such as in the case of continuous flooding, or implemented single drainage. Scaling Factor 1 was used for the water regime during the cultivation period (SF_{wrc} in Eq. (1)) for the case when AWD was not conducted at all and called AWD_CF. Alternatively, a scaling factor of 0.71 was used for the case of a single drainage and called AWD_SD.

3. Results

3.1. Descriptive statistics

3.1.1. Respondents

Table 2 shows a summary of the respondents. Unlike the water management, the farmers had similar characteristics except for the average size of individual paddy fields and the average total area of cultivated paddy fields. According to the descriptive statistics, individual cultivated paddy fields of AWD farmers were significantly larger than those of non-AWD farmers in the early wet season. Moreover, the average total cultivated area of AWD farmers was significantly larger than that of non-AWD farmers in all seasons.

3.1.2. Operating hours of machinery

According to an interview survey of agricultural cooperative and private pumping service providers that provide irrigation and/or drainage services, drainage services were provided mainly in the late wet seasons. The average operation hours of pumps for drainage and electricity consumption were 1.6 h ha^{-1} and 239 kWh ha^{-1},

Table 3

Operating hours of machinery[§].

Machinery	Early-wet season**		Late-wet season		Dry season	
	Non-AWD	AWD[†]	Non-AWD	AWD[†]	Non-AWD	AWD[†]
Tractor (four-wheel)	3.8	3.6	3.3	3.8[a]	2.9	3.1
Rotary	3.8	3.6	3.3	3.8[a]	2.9	3.1
Tractor (two-wheel)	3.2	3.1	1.7	2.0[a]	1.5	1.7[b]
Sowing	3.1	2.9	2.4	2.4	2.2	2.5[a]
Fertilizer application	6.4	5.6	6.5	5.8	5.3	6.0
Agrochemical application	17.2	14.2[a]	15.5	14.4	16.8	16.1
Pumping operation	30.5	25.3[a]	28.7	28.5	36.7	29.7[a]
Water level check (time per week)	4.6	4.1[a]	4.8	4.9	5.2	5.3
Combine harvester	2.0	1.9	1.9	2.2[a]	1.8	2.0[a]
Transportation (rice)	2.0	1.7[a]	1.9	1.9	1.7	1.8

[§]The sample sizes for AWD and non-AWD are shown in Table 1 for LC-GHG; **Leon et al. (2021); and [†] letters "a" and "b" show that differences between non-AWD and AWD are significant at $p < 0.05$ and at $p < 0.1$, respectively.

Table 4
Rice straw residue management before the cropping season (%)§.

	Early wet season		Late wet season		Dry season	
	Non-AWD	AWD	Non-AWD	AWD	Non-AWD	AWD
Burning	81.2	74.5	84.4	76.2	77.2	72.0
Compost	0.6	4.3	0.0	1.7	0.0	0.0
Removal	11.0	16.8	13.8	18.0	19.5	18.1
Incorporation	7.1	4.3	1.8	4.1	3.4	9.9

§The sample sizes for AWD and non-AWD are shown in Table 1 for LC-GHG.

respectively. Table 3 shows the operating hours of machinery. The pumping operation hours of AWD farmers were significantly lower than those of non-AWD farmers, except in the late wet season. The insignificant operation hours in the late wet season could be explained by the increase in drainage operations. Water level checks were on average between 4.1 and 5.3 times a week. AWD farmers checked the water level significantly less than non-AWD farmers in the early wet season ($p < 0.05$), but the frequencies did not differ significantly in the other seasons.

3.1.3. *Straw management*

Table 4 shows rice straw management, which was used to estimate soil CH_4 and N_2O emissions based on straw management conducted before the cropping season. Across all categories of water management and cropping seasons, burning straw was the most common straw management, conducted by at least 72.0% of farmers. The second most common straw management was removal. However, there were variations in straw management across seasons and water management. For example, the proportion of AWD farmers who incorporated rice straw was larger (9.9%) before the dry season started compared to other seasons (4.3% before the early wet season and 4.1% before the late wet season started). The proportion of non-AWD farmers who removed rice straw was slightly higher before the dry season (19.5%) than during the other seasons (between 11.0% and 13.8%). The incorporation of rice straw by non-AWD farmers was the lowest (1.8%) before the late wet season started.

3.1.4. *Agricultural input and output data*

Table 5 shows inventory data for the early wet (Leon et al., 2021), late wet and dry seasons. Irrespective of the water management, the application rates of nitrogen fertilizer were the highest in the dry season, followed by the late wet season and early wet season. The yield was the highest in the dry season for both AWD and non-AWD farmers. The area-scaled LC-GHG emissions of AWD farmers in the dry season were higher than those in the other seasons, whereas the yield-scaled LC-GHG emissions were the lowest. On the other hand, the area-scaled LC-GHG emissions of non-AWD farmers in the early-wet season were higher than those in the other seasons, whereas the yield-scaled LC-GHG emissions were the lowest in the dry season. Details of Table 5 are shown in Appendix 3.

3.1.5. *Average production costs for rice cultivation*

Table 6 shows the average production costs and profits of rice cultivation. Irrespective of the water management and cropping season, the contribution of costs of agrochemicals to the total cost was the highest, followed by fertilizer and water management (details are shown in Appendix 4). The average costs of water management were lower for AWD farmers than for non-AWD farmers, except in the late wet seasons.

3.2. *The impacts of AWD on costs, profits of production and LC-GHG emissions*

Table 7 shows the impacts of AWD on the costs of water management, total costs, yield, sale price of rice, profits and LC-GHG emissions, controlling for factors that will influence the outcomes and using the

Table 5
Inventory data for rice cultivation§.

			Emission factors		Early wet season*		Late-wet season		Dry season		Unit (ha)
			kg CO_2-eq	Unit	Non-AWD	AWD†	Non-AWD	AWD†	Non-AWD	AWD†	
Input	Machinery	Tractor (four-wheel)‡	8.23	kg^{-1}	0.7	0.7	0.6	0.7^{a}	0.5	0.6	kg
		Rotary‡	6.64		1.3	1.2	1.1	1.3^{a}	1.0	1.0	
		Tractor (two-wheel)‡	8.23		0.2	0.1	0.1	0.1^{a}	0.1	0.1^{b}	
		Sowing‡	5.79		0.03	0.02	0.02	0.02	0.02	0.02^{b}	
		Fertilizer application‡	5.79		0.05	0.04	0.05	0.05	0.04	0.05	
		Agrochemical application‡	5.79		0.1	0.1^{a}	0.1	0.1	0.1	0.1	
		Pumping operation‡	5.79		0.8	0.6^{a}	0.7	0.7	0.9	0.7^{a}	
		Combine harvester‡	6.77		7.7	7.4	7.4	8.3^{a}	6.9	7.6^{a}	
		Transportation (rice)‡	6.77		7.7	6.6^{a}	7.2	7.3	6.5	6.8	
	Seed	Rice seed	1.67		171.7	162.9^{a}	185.8	167.0^{a}	176.3	167.9^{b}	
	Fuels/ Electricity	Gasoline	2.85	litre^{-1}	16.6	13.6^{a}	24.1	22.3	19.2	19.5	litre
		Diesel	2.99		71.5	63.8^{a}	66.8	69.3	69.2	67.7	
		Electricity	0.592	kWh^{-1}	42.3	31.3^{b}	148.8	168.2	51.8	39.5^{b}	kWh
	Fertilizer	Total N	-	kg^{-1}	129.1	115.1^{a}	133.0	116.2^{a}	135.9	122.8^{a}	kg
		Urea	Urea 3.32		90.3	84.0^{a}	98.8	82.3^{a}	101.8	88.1^{a}	
		DAP	DAP 2.81		18.0	18.9	20.0	17.0^{a}	19.0	19.5	
		NPK	NPK 4.00		20.8	12.3^{a}	14.2	16.9	15.1	15.3	
		Total P_2O_5	-		66.9	60.6^{a}	65.4	60.4^{a}	64.3	64.8	
		DAP	DAP 1.43		46.1	48.7	51.2	43.5^{a}	49.2	49.8	
		NPK	NPK 1.46		20.8	11.9^{a}	14.2	16.9	15.1	15.1	
		Total K_2O	-		44.8	52.8^{a}	47.0	47.1	50.0	49.2	
		KCl	KCl 0.80		30.5	44.9^{a}	38.5	36.6	40.8	39.8	
		NPK	NPK 0.51		14.2	7.9^{a}	8.5	10.6	9.2	9.4	
	Agrochemicals	Active substance	10.6		1.8	1.8	2.1	1.6	1.7	1.8	
Output	Harvest	Paddy rice	-	-	6.2	6.2	6.2	6.2	6.9	7.1^{b}	t
	Emission to air	Soil GHG emissions: CH_4	Described in Section 2.3.2.	-	14376	7541^{a}	13670	7633^{a}	13898	8258^{a}	kg CO_2-eq
		Soil GHG emissions: N_2O			471	547^{a}	478	547^{a}	489	581^{a}	
		Nonsoil GHG emissions: Burning			491	428^{a}	458	391^{a}	567	506^{b}	
		Nonsoil GHG emissions: Management*			1285	1179^{a}	1383	1323^{a}	1293	1236^{a}	
		Life cycle GHG **			16622 (2.7)	9696^{a} (1.6)	15989 (2.6)	9893^{a} (1.6)	16246 (2.4)	10582^{a} (1.5)	

§The sample sizes for AWD and non-AWD are shown in Table 1 for LC-GHG.; *Leon et al. (2021); † letters "a" and "b" show that differences between non-AWD and AWD are significant at $p < 0.05$ and at $p < 0.1$, respectively.; and ‡ input used for machinery was derived by multiplying the weight of machinery (Appendix 2) by the ratio of operating hours (Table 3) of the machine relative to the lifetime of the machine. The lifetime was obtained from the Ecoinvent database (version 3). ***Management is the sum of GHG emissions, except for soil CH_4, soil N_2O and burning. **: Numbers outside and inside the parentheses are the number of area-scaled (kg CO_2-eq ha^{-1}) and yield-scaled (kg CO_2 kg^{-1}) GHG emissions, respectively.

Table 6
Average production costs and profits of rice cultivation[§].

	Early wet season		Late-wet season		Dry season	
	Non-AWD	AWD[†]	Non-AWD	AWD[†]	Non-AWD	AWD[†]
Land preparation ($\$\ \mathrm{ha}^{-1}$)	75.8	70.8[b]	67.7	69.4	64.0	67.8[a]
Sowing ($\$\ \mathrm{ha}^{-1}$)	96.7	102.9[b]	100.7	99.1	97.3	97.2
Fertilizer ($\$\ \mathrm{ha}^{-1}$)	219.3	202.7[a]	219.4	203.1[a]	206.4	207.9
Agrochemicals ($\$\ \mathrm{ha}^{-1}$)	239.8	270.5[a]	293.1	279.8	298.7	300.0
Harvest ($\$\ \mathrm{ha}^{-1}$)	86.9	86.2	85.2	87.0	85.4	81.1[a]
Water Management ($\$\ \mathrm{ha}^{-1}$)	123.5	111.6[a]	151.6	157.9	134.3	130.4
Total cost ($\$\ \mathrm{ha}^{-1}$)*	840.2	844.5	913.5	891.9	883.3	883.3
Selling price ($\$\ \mathrm{t}^{-1}$)	214.5	222.1[a]	246.6	248.2	237.8	235.5
Profit ($\$\ \mathrm{ha}^{-1}$)	499.8	542.9	624.8	629.1	754.0	792.8

[§]The sample sizes for AWD and non-AWD are shown in Table 1 for Profit. [†]The letters "a" and "b" show that differences between non-AWD and AWD are significant at $p < 0.05$ and at $p < 0.1$, respectively. *The straw component has been deducted from the cost.

Table 7
Average treatment effects[†] of AWD on production costs, sale price and profits[§].

	Early wet season		Late-wet season		Dry season		Throughout the year	
	ATE	P value	ATE	P value	ATE	P value	ATE	P value
Water Management	−8.9	0.019	−1.1	0.843	−4.6	0.272	−3.1	0.272
Total cost	23.3	0.079	8.8	0.561	26.8	0.045	22.5	0.006
Sale price	9.9	0.004	4.6	0.181	−2.4	0.318	4.7	0.017
Yield	0.2	0.114	0.02	0.847	0.2	0.082	0.2	0.023
Profit	70.4	0.021	18.9	0.591	8.2	0.807	39.4	0.056
LC-GHG emissions	−6606	0.000	−5838	0.000	−5730	0.000	−6105	0.000

[†]ATE is described in Section 2.5; and [§]the sample sizes for AWD and non-AWD are shown in Table 1 for Profit.

regression approach (details are shown in Appendix 5). The table shows that AWD significantly increased sale price, yield and profits in several seasons but not in all seasons. The impact of AWD on the cost of water management was negative and significant in the early wet season but not significantly different from zero in the other seasons. The impact of AWD on the total cost was significant and positive in the early wet season ($p < 0.1$), in the dry season and throughout the seasons ($p < 0.05$). The impact of AWD on sale price was positive and significant in the early wet season ($p < 0.05$) and throughout the year ($p < 0.05$). The impact of AWD on yield was positive and significant in the dry season ($p < 0.1$) and throughout the year ($p < 0.05$). For profits, the impact of AWD was positive and significant in the early wet season ($p < 0.05$) and throughout the year ($p < 0.1$), but the impact was not significant in the dry and late wet seasons. The impact of AWD on LC-GHG emissions was significantly reduced by AWD for every crop season and throughout the year.

3.3. Sensitivity analysis

This study assumed that AWD would be conducted even in the late wet seasons based on previous studies (Lovell, 2019; Truong et al., 2013; Yamaguchi et al., 2016) and information collected in this study from irrigation/drainage service providers (Section 3.1.2). However, if AWD was not practised properly due to precipitation, the effects of AWD may be weakened. According to this study, soil CH_4 emissions may be reduced by 28% in the case of single drainage (Fig. 4) and −1.5% in the case where AWD was not practised properly due to precipitation compared with non-AWD. Soil N_2O emissions under the AWD_CF were reduced by 10% compared with non-AWD due partly to lower nitrogen fertilizer application rates by AWD farmers compared with non-AWD farmers.

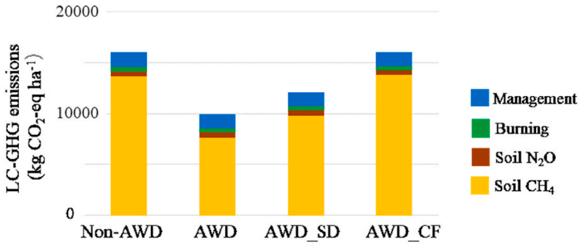

Fig. 4. Changes in LC-GHG emissions depending on the water regime in the late wet season.
Non-AWD: Non-AWD farmers; AWD: AWD farmers; AWD_SD: AWD farmers who were not able to conduct AWD but conducted a single drainage during the late wet season; AWD_CF: AWD farmers who were not able to conduct AWD at all, similar to continuous flooding due to heavy precipitation; and Management is the sum of the GHG emissions in Table 5, except for soil CH_4, soil N_2O and burning.

4. Discussion

Intensive rice cropping can be one of the measures to respond to increasing food demand. In the Mekong Delta, a single rice system was practised in the rainy season (Lua Mua, Tanaka, 1995). However, controlling water by irrigation and drainage and introducing shorter growing season varieties allowed farmers to grow rice twice a year (Young et al., 2002), and full-dike systems for floodwater prevention have allowed triple rice cropping in a year (Tran et al., 2018). With the increasing number of cropping seasons, however, the nonflooded period between cropping seasons has been shortened, increasing soil CH_4 emissions (IPCC, 2019; Sander et al., 2017) by changing some conditions, such as soil temperature, rice varieties, crop residue inputs and annual flooding duration, for rice cropping (Feng et al., 2013). AWD is one of the essential technologies to mitigate and adapt to climate change (ASEAN, 2015). However, uncertainties in the impacts of AWD on yield and profit are one of the factors constraining the adoption of AWD.

4.1. Impact of AWD on profit and LC-GHG emissions

In this paper, we found positive and significant impacts of AWD on profits, although there were seasonal variations partly due to variations in agricultural management. Although the dry season is the most effective season to mitigate and adapt to climate change, the insignificant impact of AWD on profits was observed, which agreed with Rejesus et al. (2011). The positive and significant impact of AWD on total costs and insignificant sale prices (Table 7) may explain the insignificant impact of AWD on profits. The insignificant impact of AWD on the sale price, which is inconsistent with Truong et al. (2013), may imply a lower quality of rice. Water stress under AWD may have reduced evapotranspirational cooling, which in turn may have increased chalkiness in kernels without harming yield (Graham-Acquaah et al., 2019). In contrast to the dry season, although few studies have analysed the impacts of AWD on profits in the early wet season, based on this study, AWD may be recommended since AWD farmers receive significantly higher profits than non-AWD farmers, probably due to water from precipitation, which may reduce severe water stress (Carrijo et al., 2017). The positive impact of AWD on the selling price of rice (Table 7) may be partly attributed to the higher quality of rice (Truong et al., 2013). Precipitation might alleviate some of the adoption constraints, such as water supply (Adhya et al., 2014) and abiotic stress. The insignificant impact of AWD on profit in the late wet season (Table 7) can be partly explained by the additional costs of drainage (Table 6). It was reported that AWD in the wet season is less efficient due to drainage costs (Truong et al., 2013). The insignificant impact of AWD on the sale price of rice and yield in the late wet season can be other reasons why the impact of AWD on profit was not significant.

Despite concerns about higher yield-scaled LC-GHG emissions due to a decrease in yield (Fertitta-Roberts et al., 2019; Sriphirom et al., 2019), both area- and yield-scaled LC-GHG emissions were significantly reduced ($p < 0.05$) by AWD for every cropping season. The seasonal variations in agricultural management and yield influenced LC-GHG emissions. For example, nitrogen fertilizer application was the highest in the dry season (Table 5). Stuart et al. (2018) also reported that many farmers in Can Tho city applied higher or similar amounts of nitrogen in the dry season than in other cropping seasons, whereas the opposite results were reported by Nguyen et al. (2014). The higher electricity consumption in the late wet season can be attributed to drainage operations (Table 5). However, in addition to the contribution of agricultural inputs, CH_4 emissions contribute most to LC-GHG emissions from rice cultivation (Leon et al., 2021), which depends on water management, organic matter application rates, cultivation periods, and nonflooded periods after the previous crop season (as suggested by IPCC, 2019, and reflected in the formulation of Eq. (1) above). Unlike water management, farmers burned rice straw on-site throughout the year in An Giang Province (Table 4). The limited fallow period due to intensive rice cropping seems to be an important determinant of straw management rather than water management. However, factors other than the fallow period between cropping seasons may also influence rice straw management. For example, Nguyen et al. (2014) reported that the proportion of burning straw (by dry weight) decreased as rainfall increased in Can Tho city in Vietnam. The highest area-based LC-GHG emissions in the early-wet season for non-AWD farmers and in the dry season for AWD farmers can be partly explained by the highest incorporation rate (Table 4). In addition to straw management, CH_4 emissions are also influenced by water management in the fallow period (Cai et al., 2000; Sander et al., 2014). The highest CH_4 emissions in the cropping season after the fallow period were observed when paddy fields in the fallow period were flooded; and the second highest CH_4 emissions occurred when the fallow period was characterized by dry and wet conditions caused by rainfall (Sander et al., 2014). According to the IPCC Tier 1 method (IPCC, 2019), the scaling factor for the water regime before cultivation varied between 0.89 and 2.41 (Section 2.3.2). That is, the intensive cropping system increased CH_4 emissions by between 1.1 times and 2.7 times, assuming that factors other than the scaling factor were kept constant. Based on a meta-analysis, Feng et al. (2013) also reported that yield-scaled GHG emissions from a double-cropping system were three times higher than those from a single-cropping system. Moreover, LC-GHG emissions, especially yield-scaled LC-GHG emissions, were influenced by yield. The yield was the highest in the dry season (Table 5). This was also reported by Arai et al. (2021), Taminato and Matsubara (2016) and Truong et al. (2013). The second highest season for yield varied between studies: either the late wet season (Truong et al., 2013) or the early wet season (spring-summer, Taminato and Matsubara, 2016). According to the General Statistics Office of Vietnam (2021), the yield was the highest in the dry season, followed by the early wet season and late wet season in 2020. Accordingly, yield-scaled LC-GHG emissions were the lowest in the dry season for both AWD and non-AWD farmers (Table 5).

According to the present study, area-scaled LC-GHG emissions can be reduced by approximately between 35% (dry season) and 42% (early wet season) or between 37 and 41% based on yield-scaled LC-GHG emissions by AWD farmers compared with non-AWD farmers (Table 5). That is, AWD farmers can contribute to reducing either area-scaled LC-GHG emissions by approximately 35–42% or yield-scaled LC-GHG emissions by 37–41%, which were increased by the intensive rice-cropping system with non-AWD farmers.

4.2. Uncertainty analysis

It was assumed that AWD was conducted during the late wet season in the same way as the other seasons, as it was reported that AWD was conducted by over 66 and 67% of farmers in An Giang Province even in the early wet (summer-autumn) and late wet (autumn-winter) seasons, respectively (Lovell, 2019). It was also reported that AWD was climatically suitable at over 90% in the dry season and 34% in the wet season in the Philippines (Sander et al., 2017) and suitable for both the dry and wet seasons on the central plain of Thailand (Prangbang et al., 2020). Implementing AWD in the late wet season by utilizing a drainage system was also reported by Yamaguchi et al. (2016). This study agreed with the present study, which reported additional costs for drainage (Section 3.1.5). The reduction in soil CH_4 emissions by AWD during the wet seasons has been reported by many studies. Based on a meta-analysis in Southeast Asia, Yagi et al. (2020) reported that CH_4 emissions were reduced by water management (single and multiple drainage), although water management was not efficient in the wet season. Based on measurements at farmer fields in An Giang Province, Uno et al. (2021) reported that CH_4 emissions were reduced by multiple drainage events compared with continuous flooding even in the late wet season, except for a site where water was not drained well. Additionally, based on field experiments in central Vietnam, Tran et al. (2018) reported that CH_4 emissions were reduced by AWD in which paddy fields were irrigated whenever the water table was below the soil surface and by site-specific

AWD in which paddy fields were irrigated depending on the growth stage of rice in the wet season. The sensitivity analysis in this study showed that even if AWD were not practised properly, LC-GHG emissions would still be reduced by 24% with single drainage. However, LC-GHG emissions would be increased by 0.2% with AWD farmers if water was not controlled effectively at all, similar to continuous flooding (AWD_CF in Fig. 4). This is partly due to additional CH_4 emissions caused by a higher proportion of AWD farmers with straw incorporation than non-AWD farmers before the late wet season (Table 4), despite the reduction in N_2O emissions (Section 3.3).

The present study calculated the benefits of AWD on LC-GHGs considering the trade-offs, including between soil CH_4 and N_2O emissions. Furthermore, the benefits of AWD on farmers' profits were calculated based on the regression approach, finding that the effect of AWD was most pronounced in the early-wet seasons. However, it is uncertain whether the present results can be applied directly to other regions of Vietnam and other countries. Additional data for other regions and seasons will help the estimation of LC-GHG emissions and costs or profits adapted to the agricultural management, social, economic and environmental conditions of that region or crop season. Another source of uncertainty is the impact of nitrogen fertilizer on CH_4 emissions and soil organic carbon and the impact of AWD on soil organic carbon. The increase in soil CH_4 emissions is explained by increases in carbon sources and emission pathways by enhanced plant growth with nitrogen fertilizer (Neue and Roger, 2000). However, there have been no agreements in studies on the influences of nitrogen fertilizer on soil CH_4 emissions (Wassmann et al., 1993) and soil carbon content (Li and Zhang, 2007). The reduction in soil carbon is attributed to the enhanced mineralization of soil organic carbon under the aerobic conditions caused by AWD. Livsey et al. (2019) reported that soil organic carbon was reduced under AWD based on a meta-analysis of 12 studies. In contrast, no significant change was reported by Tirol-Padre et al. (2018) after 3 years of experimentation in the Philippines, Vietnam, Thailand and Indonesia. It is, therefore, essential to examine whether LCA of AWD should incorporate the changes in CH_4 emissions and soil organic carbon. Another source of uncertainty relates to the adoption of AWD by farmers. Even though the expected benefits of AWD are positive, a proportion of farmers might not adopt the new technology, thereby limiting the environmental benefits of AWD. Therefore, it is advisable to propose, in addition to AWD, several choices of agricultural technologies for the mitigation and/or adaptation to climate change. For example, LC-GHG emissions and costs can be reduced by reducing the current application rates of nitrogen fertilizer, phosphate, potassium and seeds, which are still higher than the upper range of the recommended application rates. The recommendation varies depending on the soil type and districts (Sub-Department of Plant Protection: SDPPA, 2014) and is lower than the actual application rates shown in Table 5 in Section 3. Specifically, the recommended application rates are between 60.3 and 100 kg N ha^{-1} for nitrogen fertilizer, 30.4 and 60.0 kg P_2O_5 ha^{-1} for phosphate fertilizer, 25 and 42 kg K_2O ha^{-1} for potassium fertilizer and 80 and 100 kg ha^{-1} for seeds. To decide the alternative choices of agricultural technologies for mitigation and/or adaptation, further LCA and cost analysis will be needed. Another source of uncertainty is that the present study did not evaluate the combination of AWD and adaptation measures to climate change. According to the IPCC, the two adaptation measures with the highest benefits on yield were cultivar adjustments and combining cultivar adjustments with changing planting dates (IPCC, 2014). These adaptation measures may help to alleviate some of the barriers to adopting AWD and to increase the benefits of AWD. Another source of uncertainty is that the present study did not calculate the externalities of GHG emissions, as this goes beyond the scope of this study but could be the subject of future research. It is said that the cost of pollution should be paid by the polluters (United Nations, 1992). Pollution can be reduced by using subsidy programs. The calculation of the externality will help farmers make socially optimal decisions on the consumption of agricultural material, rice straw management, annual cropping times, and further adoption of AWD. This in turn will help to increase production in response to an increase in food demand while reducing the negative impact of production on climate change.

5. Conclusions

AWD will play an important role in mitigating CH_4 emissions and improving water productivity. Many field studies and meta-analyses have reported a reduction in CH_4 emissions by AWD in the wet season as well as in the dry season. However, few studies have been conducted to evaluate the impact of AWD on profits in the wet seasons. As intensive rice cropping is becoming more common, evaluation of the impact of AWD on profits throughout the year is needed. This study examined the impact of AWD on profit and LC-GHG emissions for the whole rice-cropping season in a year. The results revealed that the impact of AWD on profit was positive and significant for the early wet season ($p < 0.05$) and throughout the year ($p < 0.1$), but the profit of AWD farmers was not significantly higher for the dry and late wet seasons. In contrast, the impact of AWD on LC-GHG emissions was significant and negative for all seasons. As AWD in the early wet season and throughout the year is beneficial for farmers and mitigates climate change, this study recommends implementing AWD throughout the year if irrigation and drainage systems are available. However, additional mitigation technology will help to reduce LC-GHG emissions to the level that existed before the introduction of the intensive rice-cropping system. As one of the potential methods, the duration of inundation in the late wet season could be adjusted in a way in which soil fertility is increased, while LC-GHG emissions are reduced.

These results were based on 3 consecutive surveys that occurred in 2019–2020. To use AWD to fulfil the NDCs, a continuous survey is required to examine annual variations in the impact of AWD on profit and LC-GHG emissions.

CRediT authorship contribution statement

Ai Leon: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Taro Izumi:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Emission factors and Scaling factors used to estimate CH_4 and N_2O emissions

EF_{CH4}	1.22	$Frac_L$	0.24
SF_{wrc}	1 for non-AWD farmers	EF_L	0.011
	0.55 for AWD farmers		
SF_{wrf}	2.41	$Frac_{vu}$	0.15 for urea
$CFOA_i$	1 for incorporation of straw <30 days before cultivation 0.17 for compost	$Frac_{vo}$	0.11 for other synthetic fertilizers
		$Frac_{vcom}$	0.21 for compost
EF_D	0.003 for non-AWD farmers	EF_v	0.014
	0.005 for AWD farmers		

Appendix 2. Machinery used for rice cultivation (Leon et al., 2021)

Operation	Fuel	Fuel consumption[⁑] (litre $hour^{-1}$)	Machinery specification
Tillage	Diesel	5	Tractor: 25–30 PS (four-wheel) [‡], 1273 kg
			Rotary: 272 kg
Puddling	Diesel	3	Tractor: 8–12 PS (two-wheel), 325 kg
			Wooden plank: 1.8 m, 16 kg
Sowing	Gasoline	1.2	Power sprayer: 7.9 kg, 10–25 L
		0	Drum seeder: 10 kg*
Fertilizer	Gasoline	1.2	Power sprayer: 7.9 kg, 10–25 L
Agrochemicals	Gasoline	1.2	Power sprayer: 7.9 kg, 10–25 L
		0	Backpack sprayer: 4.0 kg, 10–18 L
Combine harvester	Diesel	10	Combine harvester: >60 PS[‡], 5000 kg
Transportation (rice)	Diesel	10	Carrier: >60 PS[##], 5000 kg
Water pumping[§]	Diesel	1	Water pump: 25 kg
	Gasoline	1	Water pump: 25 kg
	Electricity	3 (kWh)	Water pump: 25 kg
Bailing	Diesel	2.61[†] (litre $tonne^{-1}$)	Tractor: 25-30 PS, 1273 kg
			Bailer: 1515 kg

[⁑] :Fuel consumption was obtained from Japanese machines, as many of the machines in Vietnam are imported from Japan (Sakata, 2014).

[‡] Takeshima et al. (2018).

*Singh et al.

[##] Sakata (2014).

[§] Fuel consumption for water pumping is based on farmers' answers in this study.

† Nguyen et al. (2016).

Appendix 3. Inventory data for rice cultivation

		Early wet season								Late wet Season							
		Non-AWD				AWD				Non-AWD				AWD			
		Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max
Tractor (four-wheel)	kg ha^{-1}	0.7	0.5	0.1	3.6	0.7	0.5	0.0	2.8	0.6	0.3	0.2	2.2	0.7	0.5	0.1	3.6
Rotary‡		1.3	1.0	0.2	6.8	1.2	0.8	0.0	5.2	1.1	0.6	0.3	4.1	1.3	0.9	0.2	6.8
Tractor (two-wheel)		0.2	0.1	0.0	0.5	0.1	0.1	0.0	0.7	0.1	0.0	0.0	0.2	0.1	0.1	0.0	0.7
Sowing		0.03	0.02	0.00	0.1	0.02	0.02	0.00	0.1	0.02	0.01	0.00	0.1	0.02	0.01	0.00	0.1
Fertilizer application		0.1	0.04	0.00	0.1	0.04	0.03	0.00	0.2	0.05	0.05	0.00	0.2	0.05	0.04	0.00	0.2
Agrochemical application		0.1	0.1	0.0	0.5	0.1	0.1	0.0	0.4	0.1	0.1	0.0	0.3	0.1	0.1	0.0	0.4
Pumping operation		0.8	0.4	0.0	2.8	0.6	0.3	0.1	2.5	0.7	0.3	0.0	2.0	0.7	0.3	0.0	2.1
Combine harvester		7.7	3.1	2.4	19.2	7.4	3.3	2.6	19.7	7.4	3.2	1.9	25.6	8.3	4.1	3.8	26.9
Transportation		7.7	4.6	1.9	28.8	6.6	3.8	1.7	25.6	7.2	3.2	1.6	18.9	7.3	3.9	1.0	26.9
Rice seed		171.7	36.1	60.0	246.2	162.9	41.3	60.0	250.0	185.8	39.3	70.0	300.0	167.0	37.2	80.0	250.0
Gasoline	litre ha^{-1}	16.6	15.3	0.0	103.8	13.6	10.7	0.0	71.7	24.1	18.2	0.8	108.7	22.3	15.3	3.2	69.6
Diesel		71.5	29.3	26.8	211.4	63.8	27.1	25.9	222.0	66.8	24.3	25.4	179.7	69.3	26.5	19.6	152.7
Electricity	kWh ha^{-1}	42.3	52.4	0.0	150.0	31.3	50.7	0.0	200.0	148.8	118.8	0.0	372.3	168.2	118.1	0.0	479.0
Total N	kg ha^{-1}	129.1	35.9	72.0	240.2	115.1	23.5	38.0	181.9	133.0	38.3	69.1	268.8	116.2	26.0	63.2	245.6
Total P_2O_5		66.9	29.9	9.3	181.2	60.6	22.1	14.0	108.4	65.4	25.1	18.5	158.7	60.4	17.7	27.6	118.2
Total K_2O		44.8	27.6	0.0	120.0	52.8	20.3	14.4	148.5	47.0	25.5	4.0	126.0	47.1	20.1	12.3	93.0
Active substance		1.8	0.4	1.0	2.9	1.8	0.5	0.7	3.4	2.1	4.7	0.0	61.7	1.6	0.5	0.4	3.0
Paddy rice		6.2	1.2	3.8	9.6	6.2	0.8	3.8	8.0	6.2	0.8	3.8	7.7	6.2	0.7	3.8	7.8
Soil CH_4	kg CO_2-eq ha^{-1}	14376	4005	7503	36487	7541	2015	4857	16777	13670	2225	9135	23805	7633	2022	4347	16707
Soil N_2O		471	118	272	833	547	109	203	808	478	123	265	901	547	112	348	1046
Burning		491	256	0	902	428	259	0	747	458	246	0	724	391	283	0	732
Management		1285	239	888	2208	1179	201	733	1772	1383	235	950	2144	1323	221	874	1881
Life cycle GHG		16622	3995	9147	37895	9696	2091	6631	18679	15989	2360	10747	25903	9893	2089	6332	18723

		Dry season								Throughout the year							
		Non-AWD				AWD				Non-AWD				AWD			
		Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max	Mean	Std.Dev.	Min	Max
Tractor (four-wheel)	kg ha^{-1}	0.5	0.3	0.1	1.8	0.6	0.3	0.1	2.2	0.6	0.4	0.1	3.6	0.6	0.4	0.0	3.6
Rotary‡		1.0	0.6	0.2	3.4	1.0	0.5	0.2	4.1	1.1	0.8	0.2	6.8	1.2	0.8	0.0	6.8
Tractor (two-wheel)		0.1	0.0	0.0	0.3	0.1	0.0	0.0	0.3	0.1	0.1	0.0	0.5	0.1	0.1	0.0	0.7
Sowing		0.02	0.01	0.00	0.1	0.02	0.01	0.00	0.0	0.02	0.02	0.00	0.1	0.02	0.02	0.00	0.1
Fertilizer application		0.04	0.03	0.00	0.2	0.05	0.04	0.00	0.1	0.0	0.04	0.00	0.2	0.0	0.04	0.00	0.2
Agrochemical application		0.1	0.1	0.0	0.4	0.1	0.1	0.0	0.5	0.1	0.1	0.0	0.5	0.1	0.1	0.0	0.5
Pumping operation		0.9	0.3	0.0	2.2	0.7	0.3	0.0	1.9	0.8	0.3	0.0	2.8	0.7	0.3	0.0	2.5
Combine harvester		6.9	2.4	2.9	13.5	7.6	2.8	3.2	17.8	7.3	3.0	1.9	25.6	7.8	3.5	2.6	26.9
Transportation		6.5	2.9	1.9	15.4	6.8	3.1	1.3	19.2	7.1	3.7	1.6	28.8	6.9	3.6	1.0	26.9
Rice seed		176.3	39.7	100.0	269.2	167.9	38.8	100.0	300.0	178.2	38.8	60.0	300.0	166.0	39.1	60.0	300.0
Gasoline	litre ha^{-1}	19.2	13.6	0.5	67.8	19.5	15.1	0.0	128.4	20.1	16.2	0.0	108.7	18.6	14.4	0.0	128.4
Diesel		69.2	33.7	19.4	195.6	67.7	33.1	8.9	366.3	69.1	29.2	19.4	211.4	67.0	29.2	8.9	366.3
Electricity	kWh ha^{-1}	51.8	63.0	0.0	230.4	39.5	50.7	0.0	166.0	83.1	97.7	0.0	372.3	79.9	101.4	0.0	479.0
Total N	kg ha^{-1}	135.9	38.9	73.8	367.4	122.8	35.5	60.5	243.5	132.7	37.7	69.1	367.4	118.2	29.2	38.0	245.6
Total P_2O_5		64.3	29.1	0.0	151.8	64.8	23.2	0.0	141.8	65.6	27.9	0.0	181.2	62.0	21.2	0.0	141.8
Total K_2O		50.0	27.1	0.0	138.0	49.2	25.6	3.1	138.5	47.2	26.7	0.0	138.0	49.6	22.3	3.1	148.5
Active substance		1.7	0.5	0.5	2.8	1.8	0.5	0.7	2.9	1.9	2.8	0.0	61.7	1.7	0.5	0.4	3.4
Paddy rice		6.9	1.1	4.0	9.6	7.1	1.2	3.8	11.0	6.4	1.1	3.8	9.6	6.5	1.1	3.8	11.0
Soil CH_4	kg CO_2-eq ha^{-1}	13898	3543	8644	31202	8258	2793	5127	21831	13974	3322	7503	36487	7825	2340	4347	21831
Soil N_2O		489	124	279	1206	581	140	345	1071	479	121	265	1206	559	123	203	1071
Burning		567	238	0	902	506	318	0	1032	503	251	0	902	443	292	0	1032
Management		1293	228	752	2376	1236	250	768	2215	1322	238	752	2376	1247	233	733	2215
Life cycle GHG		16246	3535	11037	32973	10582	2789	6743	23241	16278	3345	9147	37895	10075	2387	6332	23241

Appendix 4 Production costs and profits of rice cultivation

		Early wet season							
		NonAWD				AWD			
		Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Land preparation	$ ha^{-1}	75.8	21.0	23.9	136.1	70.8	27.0	5.4	195.7
Sowing	$ ha^{-1}	96.7	27.8	60.3	342.7	102.9	34.2	55.6	382.5
Fertilizer	$ ha^{-1}	219.3	57.2	118.4	397.2	202.7	43.7	119.4	443.8
Agrochemicals	$ ha^{-1}	239.8	97.4	83.1	517.1	270.5	124.4	43.8	723.9
Harvesting	$ ha^{-1}	86.9	15.8	59.3	151.7	86.2	15.9	57.8	141.2
Water management	$ ha^{-1}	123.5	34.4	39.2	213.8	111.6	35.2	47.7	224.2
Total cost	$ ha^{-1}	840.2	139.8	547.2	1176.3	844.5	173.2	482.6	1577.0
Selling price	$ t^{-1}	214.5	25.0	173.5	311.3	222.1	41.9	169.0	491.2
Profit	$ ha^{-1}	499.8	321.8	−289.0	1365.9	542.9	309.2	−293.3	1801.1
		Late wet season							
		Non-AWD				AWD			
		Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Land preparation	$ ha^{-1}	67.7	14.5	32.5	129.9	69.4	14.7	34.3	124.5
Sowing	$ ha^{-1}	100.7	21.0	48.0	227.7	99.1	31.0	48.7	386.0
Fertilizer	$ ha^{-1}	219.4	52.1	97.7	408.0	203.1	47.4	40.5	386.7
Agrochemicals	$ ha^{-1}	293.1	102.0	64.5	611.8	279.8	143.1	21.8	762.7
Harvesting	$ ha^{-1}	85.2	15.0	57.2	120.2	87.0	16.7	58.2	164.6
Water management	$ ha^{-1}	151.6	49.0	40.1	295.3	157.9	52.5	40.2	262.2
Total cost	$ ha^{-1}	913.5	124.9	573.1	1266.8	891.9	175.0	333.6	1348.7
Selling price	$ t^{-1}	246.6	36.9	173.5	320.2	248.2	28.7	195.7	400.3
Profit	$ ha^{-1}	624.8	341.9	−205.2	1400.4	629.1	281.6	−155.1	1792.5
		Dry seaon							
		Non-AWD				AWD			
		Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Land preparation	$ ha^{-1}	64.0	14.0	13.4	109.9	67.8	15.0	13.7	145.6
Sowing	$ ha^{-1}	97.3	18.0	55.5	146.2	97.2	22.8	39.3	206.8
Fertilizer	$ ha^{-1}	206.4	56.8	92.7	508.4	207.9	55.9	102.2	384.0
Agrochemicals	$ ha^{-1}	298.7	105.5	81.0	577.4	300.0	125.0	55.8	745.4
Harvesting	$ ha^{-1}	85.4	15.9	54.6	132.6	81.1	14.0	36.6	125.0
Water management	$ ha^{-1}	134.3	36.4	41.5	260.8	130.4	40.5	37.6	294.9
Total cost	$ ha^{-1}	883.3	139.0	611.8	1232.3	883.3	152.1	568.8	1430.5
Selling price	$ t^{-1}	237.8	21.4	185.3	314.5	235.5	23.1	196.0	318.9
Profit	$ ha^{-1}	754.0	281.0	112.3	1581.3	792.8	325.9	113.6	1529.6
		Throughout the year							
		Non-AWD				AWD			
		Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Land preparation	$ ha^{-1}	69.3	17.6	13.4	136.1	69.3	19.7	5.4	195.7
Sowing	$ ha^{-1}	98.2	22.8	48.0	342.7	99.7	29.7	39.3	386.0
Fertilizer	$ ha^{-1}	215.1	55.7	92.7	508.4	204.6	49.3	40.5	443.8
Agrochemicals	$ ha^{-1}	276.5	104.9	64.5	611.8	283.7	131.5	21.8	762.7
Harvesting	$ ha^{-1}	85.9	15.6	54.6	151.7	84.7	15.7	36.6	164.6
Water management	$ ha^{-1}	136.2	41.9	39.2	295.3	133.4	47.3	37.6	294.9
Total cost	$ ha^{-1}	879.0	138.0	547.2	1266.8	874.7	168.1	333.6	1577.0
Selling price	$ t^{-1}	232.7	31.5	173.5	320.2	235.3	33.7	169.0	491.2
Profit	$ ha^{-1}	624.8	332.1	−289.0	1581.3	659.2	322.9	−293.3	1801.1

Appendix 5. Parameter estimates from the regression approach

	Early wet season Dependent variables											
	Water management		Total cost		Sales price		Yield		Profit		LC-GHG emissions	
	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value
AWD	−8.87	0.019	23.27	0.079	9.94	0.004	0.163	0.114	70.40	0.021	−6605.52	0.000
Age	0.37	0.242	−1.26	0.183	0.17	0.371	0.012	0.163	4.40	0.077	19.03	0.622
Area	0.00	0.248	0.00	0.183	0.00	0.711	0.000	0.241	0.00	0.980	0.05	0.156
Total Area	0.00	0.024	0.00	0.282	0.00	0.313	0.000	0.114	0.00	0.688	−0.03	0.193
Off-arm	−7.34	0.204	−6.38	0.733	5.89	0.066	−0.208	0.241	−6.28	0.894	−941.27	0.216
Seed	0.10	0.245	0.93	0.003	−0.09	0.207	0.003	0.260	−0.49	0.515	18.31	0.101
N	0.19	0.019	1.40	0.000	0.32	0.000	0.011	0.001	2.98	0.000	2.67	0.815
Pest	−0.29	0.785	15.76	0.000	−0.18	0.830	0.003	0.939	−17.30	0.071	−61.59	0.712
Edu_1	23.31	0.007	−127.92	0.000	5.95	0.381	0.725	0.042	338.19	0.000	251.41	0.741
Edu_2	15.00	0.059	−139.12	0.000	10.45	0.051	1.180	0.001	465.35	0.000	1933.97	0.026
Edu_3	13.73	0.066	−135.55	0.000	8.19	0.142	1.505	0.000	521.36	0.000	1205.81	0.185
δ_Age	0.19	0.631	4.13	0.006	0.18	0.633	−0.012	0.276	−4.86	0.152	−22.91	0.580
δ_Area	0.00	0.056	0.00	0.079	0.00	0.779	0.000	0.004	0.00	0.148	−0.01	0.685
δ_Total Area	0.00	0.157	0.00	0.919	0.00	0.676	0.000	0.022	0.00	0.094	0.01	0.558
δ_Off-farm	3.01	0.719	31.50	0.289	0.47	0.946	0.317	0.157	44.19	0.501	487.41	0.562
δ_Seed	−0.19	0.078	−1.37	0.010	−0.34	0.057	−0.002	0.653	−1.45	0.210	−20.32	0.089
δ_N	−0.16	0.239	−0.16	0.764	0.24	0.098	−0.005	0.254	0.65	0.601	18.88	0.129
δ_Pest	2.57	0.061	19.66	0.001	1.15	0.570	−0.034	0.454	−18.30	0.184	−49.71	0.775
δ_Edu_1	−5.57	0.667	106.83	0.021	4.85	0.637	−1.177	0.029	−346.12	0.032	−74.88	0.935
δ_Edu_2	1.51	0.895	111.56	0.014	−1.51	0.870	−1.586	0.003	−465.35	0.002	−1939.93	0.043
δ_Edu_3	1.46	0.897	103.93	0.028	−1.77	0.865	−1.643	0.002	−478.28	0.003	−166.31	0.881
cons	58.45	0.016	551.53	0.000	170.00	0.000	2.749	0.001	−263.69	0.244	12341.35	0.000

	Late wet season Dependent variables											
	Water management		Total cost		Sales price		Yield		Profit		LC-GHG emissions	
	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value
AWD	−1.14	0.843	8.76	0.561	4.64	0.181	0.019	0.847	18.90	0.591	−5838.27	0.000
Age	0.63	0.150	−1.18	0.403	−0.57	0.084	0.008	0.240	−0.38	0.900	−22.81	0.290
Area	0.00	0.512	0.00	0.692	0.00	0.155	0.000	0.484	0.00	0.276	−0.03	0.077
Total Area	0.00	0.166	0.00	0.413	0.00	0.181	0.000	0.055	0.00	0.843	−0.01	0.080
Off-arm	−8.41	0.347	−6.47	0.769	1.51	0.803	−0.025	0.868	9.43	0.873	202.45	0.644
Seed	−0.33	0.001	−0.42	0.080	−0.07	0.404	0.001	0.476	0.19	0.793	3.16	0.524
N	0.02	0.830	0.55	0.026	0.33	0.000	0.004	0.038	2.59	0.001	10.04	0.032
Pest	0.50	0.686	13.50	0.000	0.20	0.883	−0.046	0.168	−19.55	0.192	49.51	0.420
Edu1	−8.88	0.591	−37.17	0.407	11.80	0.435	−0.501	0.287	12.04	0.907	3270.25	0.001
Edu_2	1.95	0.890	5.53	0.896	19.29	0.157	−0.322	0.460	66.61	0.463	2977.08	0.000
Edu_3	−13.00	0.405	13.79	0.742	28.00	0.037	−0.664	0.131	17.72	0.840	2888.16	0.001
δ_Age	−0.46	0.426	5.05	0.007	0.54	0.177	−0.002	0.865	−1.76	0.657	55.46	0.038
δ_Area	0.00	0.975	0.00	0.649	0.00	0.028	0.000	0.584	0.00	0.494	0.10	0.001
δ_Total Area	0.00	0.282	0.00	0.010	0.00	0.154	0.000	0.042	0.00	0.591	0.01	0.513
δ_Off-farm	26.34	0.030	25.44	0.423	0.41	0.957	0.044	0.819	−13.21	0.855	−180.00	0.741
δ_Seed	0.17	0.269	1.27	0.004	0.01	0.958	0.000	0.957	−1.36	0.172	3.00	0.697
δ_N	−0.06	0.772	0.66	0.245	−0.02	0.901	−0.002	0.584	−1.15	0.409	−3.99	0.627
δ_Pest	1.17	0.509	7.67	0.153	−2.32	0.120	0.065	0.094	−10.28	0.527	−114.88	0.147
δ_Edu_1	34.74	0.293	31.19	0.552	−7.28	0.676	−0.234	0.718	−156.47	0.328	−3107.57	0.017
δ_Edu_2	31.87	0.315	28.19	0.590	−19.00	0.235	−0.372	0.556	−268.56	0.078	−2843.57	0.014
δ_Edu_3	0.10	0.997	11.76	0.836	−18.05	0.288	0.023	0.971	−126.53	0.425	−2935.79	0.012
cons	177.20	0.000	887.61	0.000	223.96	0.000	6.249	0.000	461.04	0.016	12651.26	0.000

	Dry season Dependent variables											
	Water management		Total cost		Sales price		Yield		Profit		LC-GHG emissions	
	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value
AWD	−4.57	0.272	26.8	0.045	−2.44	0.318	0.22	0.082	8.18	0.807	−5729.89	0.000
Age	0.43	0.188	1.9	0.066	0.28	0.166	0.00	0.803	−0.50	0.833	12.36	0.699
Area	0.00	0.059	0.0	0.807	0.00	0.117	0.00	0.435	0.00	0.802	0.07	0.321
Total Area	0.00	0.585	0.0	0.276	0.00	0.080	0.00	0.227	0.00	0.718	−0.04	0.017
Off-arm	−9.24	0.135	−39.2	0.064	2.65	0.471	−0.06	0.774	41.61	0.417	−434.49	0.501
Seed	−0.09	0.252	0.5	0.079	−0.04	0.492	0.00	0.069	0.27	0.672	5.67	0.487
N	0.08	0.189	1.3	0.000	0.13	0.001	−0.01	0.000	−2.22	0.000	−5.12	0.375
Pest	−1.00	0.297	7.2	0.038	−0.12	0.818	0.03	0.348	−2.06	0.783	−16.41	0.852
Edu1	−37.77	0.041	−293.1	0.000	−20.02	0.008	−0.36	0.283	70.68	0.407	842.31	0.404
Edu_2	−37.10	0.032	−261.6	0.000	−19.17	0.001	0.01	0.968	125.19	0.078	1332.09	0.140
Edu_3	−52.83	0.002	−277.7	0.000	−19.12	0.002	−0.14	0.685	113.21	0.184	541.16	0.492
δ_Age	0.59	0.209	0.1	0.961	−0.37	0.126	−0.02	0.244	−6.21	0.082	−9.36	0.787
δ_Area	0.00	0.013	0.0	0.843	0.00	0.383	0.00	0.385	0.00	0.170	−0.05	0.503
δ_Total Area	0.00	0.459	0.0	0.564	0.00	0.494	0.00	0.172	0.00	0.253	0.09	0.000
δ_Off-farm	−3.85	0.673	−17.4	0.566	−4.88	0.320	−0.01	0.969	−19.93	0.780	549.44	0.456
δ_Seed	0.16	0.231	0.2	0.664	0.03	0.698	0.00	0.169	−1.11	0.218	−12.89	0.174

(*continued on next page*)

(*continued*)

δ_N	−0.10	0.358	−0.8	0.048	−0.10	0.132	0.01	0.063	1.83	0.046	−5.44	0.510
δ_Pest	2.36	0.118	15.1	0.002	−0.45	0.579	0.00	0.926	−18.62	0.077	176.99	0.101
δ_Edu_1	76.21	0.006	314.3	0.000	−3.99	0.862	0.96	0.078	−118.77	0.565	−5679.98	0.004
δ_Edu_2	68.49	0.011	271.4	0.001	−4.92	0.828	0.69	0.140	−140.69	0.481	−5328.25	0.005
δ_Edu_3	83.65	0.002	270.9	0.001	−5.57	0.805	0.60	0.256	−166.91	0.421	−4005.17	0.030
cons	164.27	0.000	758.3	0.000	230.94	0.000	7.24	0.000	926.39	0.000	15115.78	0.000
	Throughout the year											
	Dependent variables											
	Water management		Total cost		Sales price		Yield		Profit		LC-GHG emissions	
	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value	Coefficient	p value
AWD	−3.10	0.272	22.55	0.006	4.70	0.017	0.16	0.023	39.41	0.056	−6105.07	0.000
Age	0.61	0.004	0.37	0.591	0.11	0.472	0.00	0.641	0.62	0.714	−0.73	0.968
Area	0.00	0.078	0.00	0.224	0.00	0.484	0.00	0.270	0.00	0.629	0.01	0.474
Total Area	0.00	0.269	0.00	0.003	0.00	0.377	0.00	0.008	0.00	0.640	−0.02	0.004
Off-arm	−7.57	0.054	−12.55	0.282	2.27	0.394	−0.15	0.159	−8.10	0.790	−408.89	0.224
Seed	−0.05	0.356	0.38	0.018	0.01	0.892	0.00	0.040	0.27	0.529	4.20	0.318
N	0.12	0.011	1.20	0.000	0.29	0.000	0.00	0.285	0.94	0.033	1.66	0.687
Pest	−0.29	0.647	11.45	0.000	−0.18	0.792	0.01	0.759	−9.87	0.157	45.67	0.394
Edu1	−24.25	0.032	−180.21	0.000	−16.46	0.024	−0.57	0.052	−43.13	0.579	1469.54	0.015
Edu_2	−26.45	0.012	−158.84	0.000	−12.66	0.060	−0.33	0.229	13.20	0.854	2207.68	0.000
Edu_3	−34.88	0.001	−156.16	0.000	−9.34	0.178	−0.32	0.252	26.29	0.718	1476.13	0.006
δ_Age	0.05	0.879	2.45	0.010	0.00	0.984	0.00	0.547	−3.12	0.165	20.56	0.298
δ_Area	0.00	0.012	0.00	0.312	0.00	0.967	0.00	0.292	0.00	0.797	0.02	0.426
δ_Total Area	0.00	0.030	0.00	0.009	0.00	0.876	0.00	0.005	0.00	0.314	0.03	0.003
δ_Off-farm	4.87	0.403	7.05	0.688	−0.68	0.869	0.09	0.524	9.22	0.824	347.79	0.379
δ_Seed	0.04	0.596	0.07	0.832	−0.16	0.069	0.00	0.237	−1.62	0.008	−4.75	0.357
δ_N	−0.12	0.161	−0.31	0.281	−0.03	0.701	0.00	0.316	0.81	0.261	2.88	0.602
δ_Pest	0.95	0.319	12.35	0.000	−1.21	0.200	0.00	0.908	−21.59	0.011	−77.87	0.200
δ_Edu_1	45.56	0.017	190.48	0.000	16.61	0.147	0.46	0.248	3.29	0.978	−2634.65	0.008
δ_Edu_2	46.05	0.013	176.09	0.000	10.23	0.361	0.18	0.632	−85.62	0.453	−3195.83	0.001
δ_Edu_3	39.83	0.034	162.44	0.000	7.95	0.492	0.20	0.609	−72.19	0.540	−1855.27	0.056
cons	130.23	0.000	710.95	0.000	198.55	0.000	6.20	0.000	521.36	0.000	13928.58	0.000

δ shows the interaction terms in Eq. (6) (i.e. $(x_i - \overline{x})AWD_i$)

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