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Rice variety and sustainable farming: A case study in the Mekong Delta, Vietnam

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ABSTRACT

The Mekong Delta (MKD) produces more than half of the total rice production in Vietnam. In the context of climate change, the Vietnamese government has implemented a development strategy for rice production in the MKD region to improve quality and reduce greenhouse gas emissions. The proportion of aromatic and high-quality rice production is gradually increasing to satisfy the export market. However, there is still an over-reliance on agrochemicals and the impact of overall efficiency of major rice groups is not well understood. This study measures the overall efficiency (OE) and input slacks of rice production in the MKD and considered low-emission rice farming. Using primary survey data from 380 households, the super-slack based measure (super-SBM) in data envelopment analysis (DEA) was employed to calculate the efficiency scores and non-radial slacks of each farm. The results indicated that both aromatic rice (AR) and high-quality rice (HR) groups achieved higher OE in the autumn-winter (AW) season than in the summer-autumn (SA) season. In addition, OE also increased in paddy farms greater than two hectares and in households that have cooperative membership and practice climate smart agriculture (CSA). For the input reduction strategies based on slacks, it was found that each rice group should have the seed density reduced by amounts ranging from 29 to 45 kg/ha. N fertilizer should also be reduced by 33 kg/ha and 35 kg/ha in the SA and AW seasons, respectively. It was estimated that rice farming can correspondingly mitigate N_2O emissions by 62–74.2 kg/km^2 in the SA season and 64.7–73 kg/km^2 in the AW season. Overall, the super-SBM model was effective in simultaneously estimating the overall efficiency and input overuse among paddy fields. In addition, the ranking of "super-efficient" rice farms also supports the restructuring policy of the government in establishing AR and HR production areas for export. Among the adaptation strategies, households that practice CSA techniques have smaller slacks of N fertilizer and irrigation. Low-emission paddy sector development in the MKD favors AR and HR if the CSA techniques are continuously promoted and strictly monitored by the Vietnamese government.

1. Introduction

The contribution of greenhouse gasses (GHGs) from agriculture is estimated to be 11–15% of the entire emissions. In which, the release from agricultural soils and rice cultivation report 39% and 9% of the total release, respectively (International Fertilizer Association 2018). Nitrous oxide (N_2O), which accounts for a third of the agricultural sector GHG emissions, has a global warming potential (GWP) of 265 over a hundred year lifespan (IPCC 2014). The potential for N_2O emissions increases when the availability of N rises (Bouwman et al., 1993) because it is claimed that N_2O production in agricultural soil arises mostly through the microbial transformation of inorganic N (Robertson and Groffman, 2007). Until 2030, the Intergovernmental Panel on Climate Change - IPCC evaluates that GHG emissions will increase by 35% to 60% (IPCC 2007). The increasing GHG emissions from paddy cultivation have become a major concern in recent years. It is reported that, together with the intensive farming policy, the total GHG emissions from the agriculture sector in Vietnam increased significantly from 1994 to 2013. Specifically, the emissions were at 52.4, 65.1, 88.3, 89.4 million tons of CO_2 equivalent in 1994, 2000, 2010, and 2013, respectively (MONRE 2014). According to the data reported in the two national GHG emission inventories in 2010 and 2013, the amount of emitted CO_2 from irrigated rice cultivation increased from 41.31 million tons to 42.51 million tons, respectively. In addition, the direct N_2O emissions from agricultural soils increased from 12.91 million tons in 2010 to 13.17 million tons in 2013 (MONRE 2017). Therefore, the most important criterion in the socioeconomic development progress of Vietnam and the Mekong Delta (MKD) is to develop crops that simultaneously ensure food production and reduce GHG emissions (Decision No.1393/QD-TTg).

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Regarding N_2O flux from agricultural soils, a significant source of this effusion comes from the consumption of synthetic N fertilizers in crop cultivating steps. Chai et al. (2019) recognized the application of N as the major cause to direct N_2O emissions. In paddy cultivation, increasing N use increases 4.56–7.11 g N_2O/kg N of the seasonal N_2O flux; the GWP also shows a squared reaction to N rate, peaking at 122–130 kg N/ ha (Kim et al., 2019). Moreover, the experiments by Zhang et al. (2014) in China helped to calculate the cumulative N_2O emissions during the 2011 growing season under different levels of N application. The results were at 23.09, 40.10, and 71.08 mg N_2O/m^2 at low-150 kg/ha, moderate-210 kg/ha and high-300 kg/ha of N application, respectively. Thus, it is recommended that the cultivators should reduce the high N fertilizer application in order to lessen the GWP while the optimum paddy yield is still maintained (Kim et al., 2019; Zhang et al., 2014; Snyder et al., 2009). It is claimed that the intensive farming and expanded demand scenario create such an extreme pressure on the rice fields, thereby causing soil degradation and imbalanced paddy ecosystem resulting in increasing environmental GHG emissions (Ali et al., 2019). About 90% of the world's rice is produced by Asian countries (Food and Agricultural Organization of the United Nation - FAOSTAT 2018), and 90% of the CH_4 produced in the world's paddy fields comes from this region (Smith et al., 2014). For this reason, understanding the CH_4 and N_2O release mechanisms in rice fields is necessary for developing well-organized strategies and changing conventional crop management regimes. Therefore, reducing GHG emissions becomes potential (Gupta et al., 2021). Zou et al. (2007), with their on-field assessment, concluded that the seasonal total N_2O is equivalent to 0.02% of the nitrogen applied under continuous flooding (CF) of paddy fields. The emission factor (EF) of nitrogen for N_2O was proposed to be 0.42% from the result of the ordinary least squared regression model. Moreover, Yan et al. (2005) also indicated that CH_4 emissions are significantly affected by organic fertilizer modification and water regimes in the growing seasons. Regarding the climate smart strategies for paddy cultivation, controlled irrigation or the alternative wetting and drying (AWD)[1] technique is believed to be effective for mitigating the CO_2 equivalents of CH_4 and N_2O emissions from fields (Linquist et al., 2015; Yang et al., 2012). Multiple drainage (MD), a simplified form of AWD, has also been practiced in the MKD. Uno et al. (2021) evaluated the consequence of this technique on yield and GHG emissions in paddy fields in An Giang province, where full dike systems are constructed for fresh water paddy production. The authors concluded that multiple drainage system can at the same time improve the output and reduce CH_4 emissions in paddy fields if it is adequately implemented. Specifically, MD fields report a significant increase at 22% in yield compared to traditional flooding fields. Although there is no difference in N_2O emissions found, seasonal total CH_4 emissions were markedly declined by 35% in MD plots. A study of CH_4 measurement by Vo et al. (2008) was conducted in paddy farms from different agro-ecological zones of the MKD. Through the emissions collected by using the closed chamber method, the overall emission factor of the entire delta is approximately 1.92 kg CH_4/ha/day, which is about 48% higher compared to the globally default value set by the IPCC (Food and Agricultural Organization of the United Nation - FAOSTAT 2006). However, this study by Vo et al. (2008) did not record the difference in farming patterns. Interestingly, the rice-beef-biogas integrated system presented in the study by Ogino et al. (2021) is believed to mitigate GHG emissions and energy consumption compared to the specialized rice and beef production system in Vietnam. Hanh et al. (2018) evaluated the nitrogen use efficiency of six rice varieties, including Chiem Tay, Te Tep, Re Bac Ninh, IR24, P6DB, and Khang Dan 18 in North Vietnam. P6DB and CT varieties, which present the smallest and largest effectiveness of nitrogen use, were chosen for a genetic testing in the next step. The results on nitrogen use efficiency are considered useful for further genetic analyses of sustainable agriculture.

The MKD is the main rice producing region, contributing 54.46% of the national rice farming area in 2019 (General Statistics Office - GSO 2018). Simultaneously, the GHG emission contribution from paddy cultivation in the MKD is proportionally similar (Vo et al., 2018). Vietnam's agricultural restructuring policy includes a priority strategy to identify and develop climate-adapted rice varieties that consume less chemical fertilizers, help reduce input costs, and lead to a large scale, low-emission agricultural system in the MKD (Decision No. 1898/QD-BCT, 2017). With respect to the paddy sector, the main target is to increase the proportion of high-quality rice cultivation areas in the entire rice growing area from 70% to 75%, this target is supported by the current 90% use rate by farmers of certified, climate-adapted seeds (Decision No. 555/QD-BNN-TT, 2016). In addition, the policy advocates the development of organic rice production and the diversification of rice-based products. Furthermore, the efficiency of the entire agricultural sector, in particular paddy production, can be enhanced by improving the following components: resilience, adaptive capacity, and potential for mitigating the effects of climate change. Indeed, by enhancing the overall efficiency, emissions from agricultural production can be reduced and segregation capacity can be improved (FAO 2013).

For the above reasons, understanding how overall efficiency can contribute to mitigation strategies of climate change's effects on rice production is both meaningful and necessary. Several previous works on production efficiency of paddy sector in the MKD have been conducted using two main approaches: parametric and non-parametric. With respect to the parametric method, Ho and Shimada. (2019) used data from 352 rice farm households in Long An, Ben Tre, and Tra Vinh provinces in MKD to apply the stochastic frontier approach (SFA). The results indicated that the mean technical efficiency of rice households is 77%, and that most rice farms in the MKD are performing decreasing returns to scale status. In addition, adaptation response, agricultural extension services, farm area, and geographical location are key influencing factors on rice farm inefficiency. In 2011, Khai and Yabe (2011) also used SFA to explore technical efficiency using the Vietnam Household Living Standard Survey (VHLSS); the efficiency score was high at 81.6%. The determinants of efficiency in their study include intensive labor, irrigation, and education. With regard to nonparametric methods, Le et al. (2017) employed the two-stage data envelopment analysis (DEA) to determine the efficiency of 200 rice producers in Dong Thap province. Farmers in their study achieved overall technical efficiency at 80.1%. Education had a positive impact, while formal credit, training, and cultivated rice areas had a negative influence on technical efficiency. With a hybrid method that combined SFA and DEA into an efficiency measurement, their results showed that technical efficiency is 76%, and the average scale efficiency score is nearly 1 (one). Farmer experience and adoption of advanced farming practices are believed to have a positive impact on efficiency scores. In summary, although national policies for the rice sector have been moving towards cleaner production with aromatic and high-quality rice, the information on efficiency coupling with input overuse and low-emission farming capacity for the major rice groups in the MKD is not well understood.

Parametric models (SFA) to estimate efficiency are characterized by a priori production function, except for a restricted unknown parameters set estimated from data. Nonparametric models (DEA) are by less to mention a priori restrictions; they are thus considered the most flexible method regarding economic production characteristics that can be requested (Bogetoft and Otto, 2011). The radial approach of DEA used in previous studies, including the Charnes, Cooper, and Rhodes (CCR) and the Banker, Charnes, and Cooper (BCC) models, assumes the proportional change in all inputs and outputs can be simultaneously changed without altering the proportions in which they are utilized. Despite their

[1] AWD is a water-saving technology that help reducing water consumption in rice fields without affecting the yield. AWD allows the water level to be 15cm below field surface and rice fields just need to be flooded about 15–25% of the cropping season.

extensively meaningful practices, the drawback of BCC and CCR models is that they fail to provide non-radial input or output slacks information (Tone et al., 2020). The slack-based measure (SBM) model proposed by Tone (Tone, 2001), a non-radial DEA method, captures the drawbacks of radial DEA and represents excesses in inputs (or shortfalls in output) to identify the efficiency scores of decision-making units (DMUs) in the objective function (Tran et al., 2019). The novelty of the SBM-DEA model is that it accounts for all inefficiency components of households, which the traditional radial DEA could not do. A recent study (Tho and Umetsu, 2022) used SBM to estimate the overall efficiency and overuse of inputs in rice production in the Mekong region; it indicates that the overall efficiency is low at 0.59, and there are quite large input slacks in cultivation steps. The study concluded that resources have not been used efficiently by regional farmers and sustainable farming practices should be implemented positively in order to reduce the input overuse. Particularly, seed and pesticides expenses should be cut down by 28 and 61 USD/ha, respectively. Also, the amount of inorganic fertilizers should be reduced by 155 kg/ha for producers to reach an efficient production frontier. However, due to insufficient data sources, the authors failed to provide the slacks (overuse) of N fertilizers and irrigation that cause N_2O and CH_4 fluxes in paddy fields. Furthermore, there is thus no information on the difference in efficiency scores and slacks based on rice groups and climate smart agriculture (CSA) models. Therefore, this study aims to calculate the overall efficiency (OE) and input slacks, especially N fertilizer and irrigation slacks, of major rice variety groups, and to examine low-emission rice farming in the MKD region. This work differs from the research in existing literature because the SBM model application is extended with the ranking of efficient households by super-SBM model. Through the comparison of efficiency and input slack between rice variety groups and CSA adoption, a valuable practical reference for the sustainability of the rice sector in the MKD will be provided.

The remainder of this paper proceeds as follows. Section 2 describes the methodology and data used in this study. The results and discussion are indicated in Section 3 and the final section provides the conclusion with policy recommendations for a green and low-emission rice sector in the MKD.

2. Methodology and data

2.1. Methodology

Data envelopment analysis (DEA) originated from Farrell (1957) and developed more favorably with studies of Charnes et al. (1978) and Banker et al. (1984). It is a mathematical programming approach and efficiency is measured among a set of decision-making units (DMUs). A DEA model can be input-oriented or output-oriented. Input orientation happens when we expect to minimize input use while still keeping the outputs stable, while output orientation indicates the possible increase in outputs using the same level of inputs.

2.1.1. Super efficiency

The expression "super efficiency" was originally suggested by Andersen and Petersen (1993). Through the concept of the radial DEA model, a framework for ranking and comparing efficient units was developed. In the radial-super-efficiency procedure, each DMU does not use itself as a peer, so the efficiency scores to be achieved can be greater than one. The larger super-efficiency score that a DMU can obtain, the better it performs. Fig. 1 provides a graphical illustration of super-efficiency technique. There are five DMUs *(A, B,* C, *D,* and *E)* that use two inputs to produce one output. When we apply standard DEA model these data, the DMUs *B,* C, and *D* all obtain an efficiency score of one (1) because they are on the frontier. However, when we apply the super-efficiency DEA methods, there is a feasibility of a greater than one (1) score for some of these DMUs. First, the case of *C* was considered. When the super-efficiency model was applied, *C* no longer belongs to the frontier and hence, the new frontier involved only two DMUs (*B* and *D).* Then, the projected point of C would be *C*'. In this case, the super-efficiency score for *C* was measured by *OC'/OC*, which was around 1.2. This result implied that *C* could increase input usage by 20% and remain within the technology defined by the other DMUs in the sample. *A* and *E,* which did not form part of the original DEA frontier, did not change from their original efficiency scores when the super-efficiency method was applied. The wide application of the super-efficiency method included sensitivity testing, identification of outliers, and a method for overcoming the bounded range problem in the second stage of linear regression. Hence, instead of the Tobit regression, we can use standard ordinary least squares regression methods in the next stage.

In paddy production, the reduction strategy of inputs (e.g., labor, material, capital) will not always be presented in a proportional way like it does in traditional DEA. Hence, if scientists want to evaluate the performance of DMUs using the efficiency scores as the unique index, the radial DEA approaches may mislead their decision. The reason for this problem is because radial DEA ignores the important slacks in presenting the efficiency scores (Tone, 2001; Tone, 2015). Meanwhile, the non-radial slack-based measure considers both radial and non-radial slacks (Tone, 2001). It also considers the overall efficiency of rice farms, segregates the assumption of proportionate changes in inputs, and directly calculates the slacks of each farm. The SBM model, similar to radial DEA model, has three forms in orientation: input, output, and non-oriented. An input-oriented SBM approach sets a target to reduce excessive input usage while keeping the existing output levels stable.

The number of SBM and super SBM applications in agriculture, especially in paddy production, is limited (Dong et al., 2018; Kocisova et al., 2018; Kuhn et al., 2020). Since the Vietnamese rice sector has limited resources, we applied an input-oriented SBM model to focus on sustainable strategies through efficiency scores and input slacks. The assumption of variable returns to scale (VRS) will be employed instead of the constant returns to scale (CRS) because not the cultivators could operate their production at the optimal scales (Masuda, 2018). For the definition of non-radial SBM model, please refer to Appendix 1 and the works of Tone (Tone et al., 2020; Tone, 2001). The following section is a brief description of super-SBM model, cited from Tone (Tone, 2017).

2.1.2. Input-oriented super-SBM

While the SBM model fails to provide more details about the differentiation of efficient DMUs, the super-SBM can rank multiple efficient DMUs. Efficiency scores were obtained from the super-SBM by eliminating the data of DMU_h itself from the estimation of the solution set. This can result in values of DMU_h that are considered as a "super-efficient" position (Tone et al., 2020).

To measure the minimum ratio-scale distance from the efficient frontier to the DMU_h (x_h, y_h) excluding itself, an input-oriented super-SBM model under the constant returns to scale assumption is described as follows:

$$\left[\text{Super SBM} - \text{IC}\right] \delta^* = \min \ 1 + \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ih}}$$

subject to

$$x_h + s^- = \sum\nolimits_{j=1, j\neq h}^{n} X_j\lambda_j \tag{6}$$

$$y_h - s^+ = \sum\nolimits_{j=1, j\neq h}^{n} y_j\lambda_j$$

$$\lambda \geq 0, s^- \geq 0, s^+ \geq 0$$

This model is under the constant returns-to-scale assumption. The VRS model can be presented if we add the following condition:

$$\sum\nolimits_{j=1, j\neq h}^{n} \lambda_j = 1 \tag{7}$$

The super-efficiency scores are larger than one (1) when they score one (1) in the ordinary SBM model. The higher the value of the super SBM score that a farm obtains, the more efficient that farm is. Some units

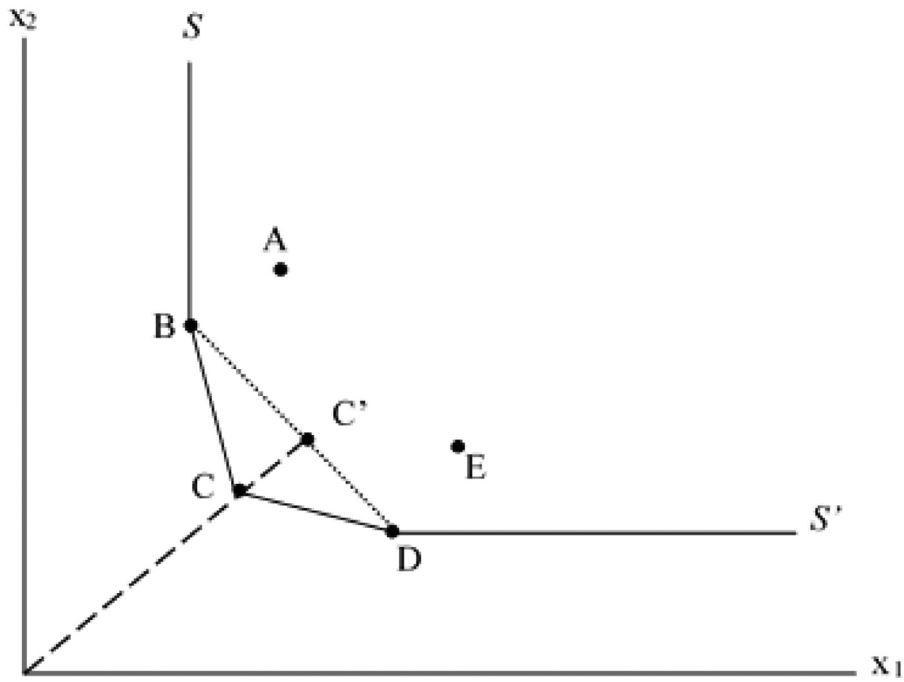

Fig. 1. Super efficiency (Coelli et al., 2005).

that present very large super-efficiency values (4 or higher) implies that those farms have a great influence on the production possibility set and should be treated as outliers (Zimkova, 2014). Therefore, the ranking of efficient paddy farms coupled with rice variety information will provide a useful reference for policy implications in the MKD region.

In the descriptive statistics section, one-way analysis of variance (ANOVA) (Fisher, 1919) was used to determine whether there were any statistically significant differences between the means of the three independent rice groups. For more details on homogeneity of variance and the significance of Levene's test, please refer to (Levene et al., 1960).

2.2. Study site and data collection

2.2.1. Study site

The MKD region can be classified into six agro-ecological zones, including the freshwater alluvial zone, the plain of reeds, the long Xuyen Quadrangle zone, the Trans-Bassac depression zone, the coastal zone, and the Ca Mau Peninsula zone (Xuan and Matsui, 1998; Duong et al., 2005). We conducted a survey[2] in the following provinces: An Giang province (Long Xuyen Quadrangle zone), Dong Thap province (plain of reeds), Can Tho city (freshwater alluvial zone), and Bac Lieu province (the coastal zone) (Fig. 2).[3] These four provinces were selected for the household survey because their locations cover over four ecological zones, they have good agricultural extension systems, and effective operations in their paddy cooperatives. In the crop year 2018, the paddy areas of An Giang, Dong Thap, Can Tho, and Bac Lieu provinces in the summer-autumn (SA) and autumn-winter (AW) were 388, 314.7, 154.8 and 102.9 thousand ha, respectively. Regarding total rice volume, An Giang ranked first with 2.19 million tons, followed by Dong Thap (1.89 million tons). Can Tho and Bac Lieu provinces produced 835.4 and 596.7 thousand tons of paddy rice, respectively (General Statistics Office - GSO 2018).

2.2.2. Data collection

Primary data were collected using structural questionnaires. We interviewed 100 paddy producers in each province on the following parameters: households' demographic information, paddy production activities, application of climate smart agriculture 1M5R,[4] 3R3G,[5] integrated pest management, and AWD practices. SA and AW[6] are the two main crop seasons in the production structure in these localities.

The DEA model has been conceptualized as an activity analysis model by many scientists (Koopmans, 1951). An activity analysis model is initiated by describing the different activities or processes in an organization. In a paddy farm model, products are made up of primary factors, such as labor, seeds, fertilizers, and other capital. In addition, there is the question of how densely to distribute seeds and fertilizers, and how to manage the labor between different production steps. In each situation, the constraints of these inputs reflect the available resources. Thus, DEA models are considered as activity analysis models, in which information about the activities is provided via actual observations (Bogetoft and Otto, 2011). The authors conducted a DEA super–SBM model with one output and ten inputs to calculate the efficiency scores, input slacks, and rank the most efficient farms among the sample units. The output was defined as the total plain rice yield (ton/ha) for the crop season. The ten inputs comprised four inputs with physical units, including seed sown density, N, P_2O_5, and K_2O in kilograms per hectare. The remaining six inputs, expressed in monetary units, were ex-

2 The household survey arose from the "Market Oriented Smallholder Value Chains" (MSVC) survey in 2018. This is a public–private partnership (PPP) between the Federal Ministry for Economic Cooperation and Development (BMZ) through Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and Olam International Limited.

3 For further details on agro-ecological zones of the MKD, please refer to Vo et al. (2018), Xuan and Matsui (1998), and Duong et al. (2005).

4 In "One Must Do Five Reductions" (1M5R) practice, Farmers are urged to use certified seeds—the "One Must" while the "Five Reductions" refer to reductions in sown seed density, nitrogen application, pesticide use, water use, and post-harvest losses (IRRI, 2012). For more details of this technique, please refer to Connor et al. (2020).

5 "Three reduction, three gains" (3R3G) means: reducing the amount of seed sown, fertilizer and pesticides; increasing productivity, product quality and economic efficiency (Huan et al., 2005).

6 In the MKD, the SA season is from March/April to July/August and the AW season is from August/September to November/December depending on the local recommendation of each province.

Fig. 2. Map of Vietnam, the Mekong Delta and the study site. *Source: Author's compilation, using GIS mapping.*

penditure on pesticides, herbicides, irrigation, hired labor, land preparation, and harvesting. The family labor for rice farming activities is measured by the number of working hours per hectare in each season. There was no significant correlation between these input variables used in the super-SBM model.[7] After dropping some households that lacked information on production steps and those that had extremely low output, we conducted an analysis on a sample of 380 paddy households from four provinces: An Giang, Dong Thap, Can Tho, and Bac Lieu. Each household was coded with a number based on the province (e.g., BL028, CT037, AG078, DT100).

3. Results and discussion

3.1. Descriptive statistics

In the study area, farmers produce three categories of rice varieties: aromatic rice (AR), high quality rice (HR), and medium quality rice (MR) (Table 1). The AR group is good quality rice, characterized by long slender grains, intermediate amylose, intermediate gelatinization temperature, high elongation ratio, and strong aroma (Cruz et al., 2000). In the SA season, 49.74% of farmers choose to plant this rice group, which includes the Dai Thom 8, Nang Hoa 9, Jasmine 85, and RVT varieties. This figure increases to 65% of the total producers in the AW season. The two AR varieties that were used predominantly in this study were Dai Thom 8 and Nang Hoa 9. The Dai Thom 8 variety has a low amylose content of 16.29%, and the cooked rice has a soft and fragrant taste. This variety is adaptable to many ecological zones, including saline areas and areas with aluminum content in the soils. The Nang Hoa 9 variety was bred from Jasmine 85 and AS996 varieties. It is disease resistant and tolerant to acidic sulfate soil. The rice product from Nang Hoa 9 is soft and has a sweet taste with a pineapple leaf aroma.

The next rice group is HR, which accounted for 48.42% and 30.78% of the sample in the SA and AW seasons, respectively. This is a group of rice varieties that are selected, bred, and released by the Mekong Delta Rice Research Institute (formerly O Mon Rice Institute; hence, these varieties are called OM). These OM rice varieties are commonly grown in the MKD, with high yields and good quality. They are also widely adapted to different agro-ecological zones and tolerate acidic and saline soils. OM varieties have long grain rice and a good appearance for export. In our study, OM5451 was the most widely cultivated HR among farmers. The final group of varieties is of medium quality, with sticky rice CK92 and chalky grain IR50404, accounting for only 1.84% and 4.21% of the producers in the two seasons, respectively. The IR50404 variety originated from the International Rice Research Institute (IRRI) and was imported into Vietnam in the early 1990s and released in 1992. This variety is popular among MKD farmers. Due to its high amylose content and chalkiness degree, IR50404 is not suitable to international tastes and thus has a very low commercial value. The main use of this variety is to prepare rice flour. Fig. 3 shows the proportion of these varieties cultivated in the four provinces within the study area. In the SA season, farmers in An Giang province mainly produce OM5451 and DT8, while Bac Lieu's farmers focus on aromatic DT8 and NH9 production. A similar proportion also occurs in households in the Dong Thap province. A total of 91% of farmers in Can Tho city cultivate OM5451 for domestic and export demands because of its high quality and resilience to pests and diseases. In the AW season, when weather is more advantageous, some households in the study area switch their production from HR to AR; in particular, farmers in An Giang and Can Tho changed from OM5451 to DT8. The production in Bac Lieu province does not change significantly since farmers mainly produce aromatics DT8 and NH9. The proportion of varieties in Dong Thap Province appears similar to the SA season. However, this information is only for reference, and the three

[7] There is significantly moderate correlation between N and P_2O_5 with the Pearson coefficient at 0.6281. The other variables have the weak correlation with coefficients smaller than 0.32.

Table 1
Rice varieties structure used by farmers in the study area.

Rice varieties	Origin	Year of release	SA season (%)	AW season (%)
Aromatic			49.74	65.00
Dai Thom 8	Vinaseed	2019	32.90	42.11
Nang Hoa 9	Hoa Tien Seed Ltd. Co.	2011	14.47	17.90
Jasmine 85	IRRI and CLRRI	1990	0.79	1.58
RVT	imported by Vinaseed	2011	1.58	3.42
High quality			48.42	30.78
OM5451	CLRRI	2011	44.47	27.37
OM4218		2010	2.37	2.11
OM4900		2009	1.32	0.79
OM7347		2011	0.26	0.26
OM2517		2004	0	0.26
Medium quality			1.84	4.21
IR50404	IRRI	1992	1.05	3.95
Sticky rice CK92	An Giang Rice Breeding Station	1992	0.79	0.26

Notes: Vinaseed - Vietnam National Seed Group Joint Stock Company; IRRI – International Rice Research Institute; CLRRI - Mekong Delta Rice Institute Source: Household Survey, 2018.

Table 2
Summary statistics on the output and inputs used in super-SBM model.

Variable	Unit	Summer-Autumn					Autumn-Winter				
		Whole sample	Aromatic	High quality	Medium quality	Prob>*F*	Whole sample	Aromatic	High quality	Medium quality	Prob>*F*
Output											
Rice yield	ton/ha	6.13	5.83	6.46	5.92	***	6.11	6.14	5.97	6.55	*
Inputs											
Seed density	kg/ha	164.17	144.52	182.56	211.43	***	162.93	154.36	177.07	191.90	***
N	kg/ha	110.64	103.46	117.75	117.78	***	107.85	105.34	114.15	100.55	
P_2O_5	kg/ha	73.49	69.44	77.53	76.38		72.83	73.17	73.41	63.26	
K_2O	kg/ha	55.95	45.95	66.10	58.92	***	54.82	51.40	61.72	57.14	**
Pesticides, herbicides	thousand VND/ha	4111.67	4384.37	3855.83	3473.82	**	3884.49	4067.56	3638.51	2856.96	***
Irrigation	thousand VND/ha	761.67	664.60	861.67	753.65	***	1152.68	1047.15	1274.05	1894.20	***
Hired labor	thousand VND/ha	1419.15	1466.49	1374.39	1317.58		1394.75	1440.90	1286.32	1475.04	
Land preparation	thousand VND/ha	1573.24	1431.23	1726.84	1370.16	***	1548.05	1512.46	1606.03	1673.39	
Harvest	thousand VND/ha	1938.06	1990.76	1887.90	1833.75		1958.60	2027.81	1798.93	2057.70	***
Family labor	hour/ha	6.07	6.50	5.77	2.48		5.96	6.84	4.66	1.81	

F-stat is used for comparison of mean value between rice groups
***, **, and * significant at 1, 5, and 10% probability level, respectively.
Source: Calculated from the Household Survey, 2018.

main groups AR, HR, and MR will be used for analysis in the generation of comparative efficiency scores.

The Vietnamese government has recently established a strategy for rice production in the period 2021−2030 by reducing the export volume and focusing on product quality. In this agricultural restructuring policy, by 2030, the proportion of AR, HR, and MR will account for approximately 25%, 40%, and 10% of the total farming area, respectively (942/QD-Ttg, 2017). The important HR varieties for export, such as OM5451, OM6976, OM7347, and OM4900, should account for 50–60% of the total cultivated area. In addition, there should be restrictive breeding of sticky rice and MR varieties such as IR50404 or OM576. However, bridging the economic benefits and environmental issues of these rice groups remains an open question.

The descriptive statistics of the output and input items used to estimate efficiency scores are presented in Table 2. Households in this study had an average land size of 2.77 ha, with the smallest size being just 0.26 ha and the largest one was 35.1 ha. In general, paddy farms obtained about 6.13 ton/ha and 6.11 ton/ha in SA and AW seasons, respectively. The HR group gave the highest yield at 6.46 ton/ha in the rainy season, while the AR only obtained 5.83 ton/ha. In the AW season, the AR group obtained a yield of 6.14 ton/ha, which was 170 kg more than that of the high-quality rice group, and less than the medium-quality rice output at 6.55 ton/ha. Regarding the inputs used, the seed sown density was relatively high in the two seasons, at more than 160 kg/ha. AR producers applied seeds at 145 kg/ha in SA and 154 kg/ha in the AW season, which was significantly lower than the density of high-quality and medium rice varieties. The amount of fertilizers used, such as nitrogen, phosphorus, and potassium was moderate and similar across the two seasons. In the SA season, farmers used slightly higher amounts of nitrogen fertilizer. The quantities of the other nutrients were approximately 73 kg/ha of phosphorus and 55 kg/ha of potassium. Importantly, when cultivating AR in the wet season, farmers consumed significantly less nitrogen (103.46 kg/ha) than HR (117.75 kg/ha) and MR (117.78 kg/ha). As mentioned above, GHG increases when more N fertilizer is consumed in paddy fields (Chai et al., 2019; Zou et al., 2007). Thus, this is a good signal to develop aromatic rice varieties that simultaneously achieve high yield, obtain good selling price, and mitigate GHG emissions owing to a lower consumption of N fertilizer. AR households also used significantly less potassium than the other two groups during the SA season. Among production cost items measured, the purchase of pesticides and herbicides was the costliest with an average of 4.1 and 3.8 million VND/ha in SA and AW seasons, respectively. Being aware of the high risks of pests and diseases, AR farmers have to pay more for pesticides than HR and MR. Paddy farms had much higher irrigation costs,

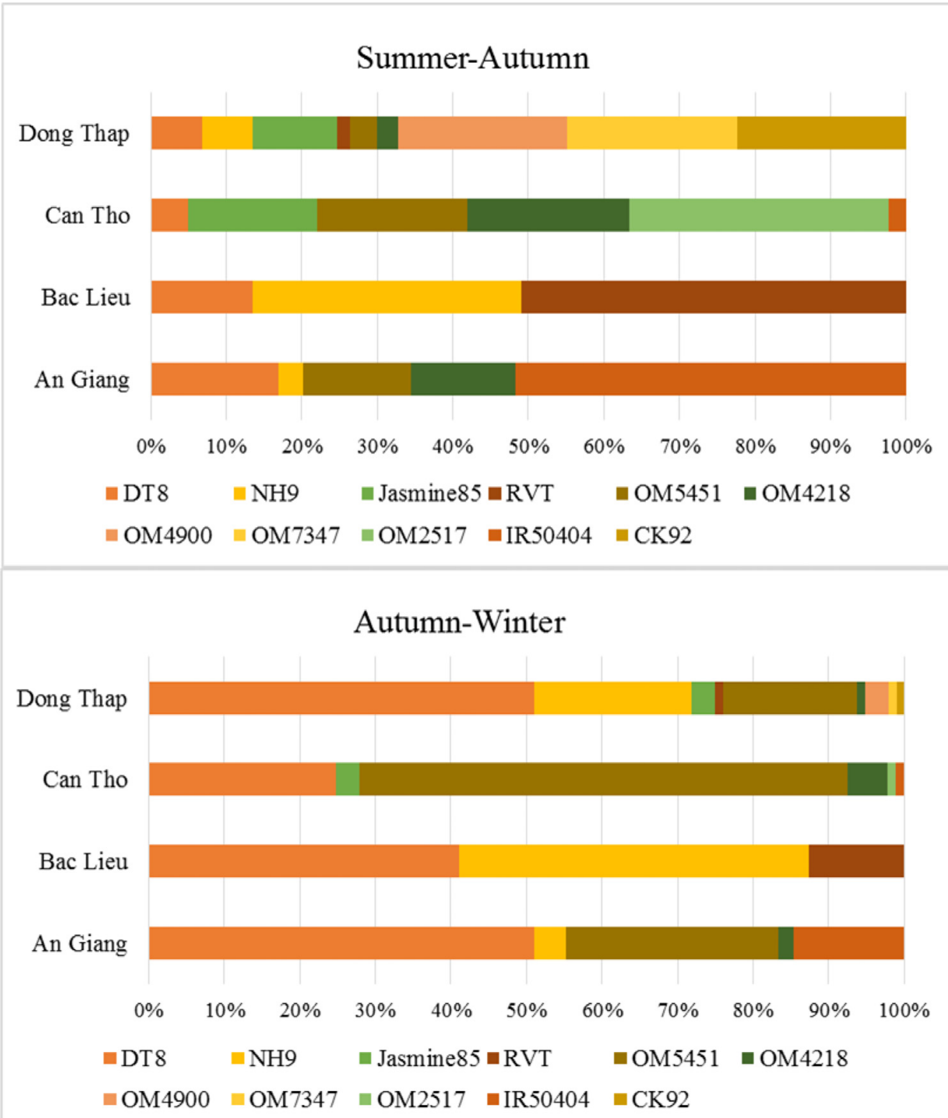

Fig. 3. The proportion of rice varieties in four provinces during two seasons in the MKD.

which included pumping and drainage activities in AW season at 1.1 million VND/ha when compared to SA wet season at 761,000 VND/ha. The opposite was true of land preparation costs. The harvesting cost calculated as a lump sum is lower in the SA season. Between the two seasons, there was not much difference in hired labor costs and family labor working hours.

Table 3
Super-SBM scores of rice production in MKD by rice groups.

Rice segment	SBM-IV	Std. Dev.	N	*Prob > F*
Summer-Autumn				
Aromatic	0.914	0.582	189	0.2813
High quality	0.830	0.544	184	
Medium	1.045	1.226	7	
Total	0.875	0.580	380	
Autumn-Winter				
Aromatic	0.917	0.682	247	0.9952
High quality	0.909	0.874	117	
Medium	0.911	0.525	16	
Total	0.915	0.740	380	

Source: Calculated from household survey in 2018.
The p-value for Levene's test centered at the median is 0.5347 and 0.976 for the SA and AW seasons, respectively.

3.2. Efficiency of rice production and sustainable farming in the MKD

3.2.1. Overall efficiency and input slacks

The results of the input-oriented super-SBM model under variable returns to scale are presented in Table 3. The overall efficiency of paddy farms in the MKD was high, and the AW season showed a more efficient estimate at 0.915 than the SA season at 0.875. The evidence showed that households that grow MR varieties in the SA season achieved the highest SBM score at 1.045 followed by AR and HR. However, the MR score decreased slightly to 0.911 in the AW season. In the AW season, some households switched from HR to AR rice production, and the efficiency scores of these two rice segments increased from 0.914 to 0.917 and from 0.830 to 0.909, respectively. This increase in overall efficiency occurred owing to the advantageous climate conditions with drier weather and less humidity. However, we failed to indicate a statistically significant difference in the overall efficiency scores between the three groups of rice.

In Table 4, super-SBM efficiency scores are presented in terms of farm characteristics, including farm size, cooperative membership, 1M5R, and AWD farming practices. In the SA season, paddy farms larger than 2 ha achieved significantly higher scores (98.1%) than those that were smaller than 2 ha (84.8%). Households with cooperative membership also had significantly higher efficiency (92.3%) than non-member households (76.9%). There are certain advantages for cooperative members, such as technical training support, access to an agricultural extension service, pilot and pioneering CSA programs, and project participation. In local areas, paddy cooperatives also have contracts with input suppliers and machinery services, such as tractors or combine harvesters. Therefore, cooperative members have the opportunity to operate their production efficiently and manage their input use more effectively. In addition, in this SA season, farmers who practiced CSA technology obtained significantly higher efficiency scores. The 1M5R adopters had a super SBM score of 97.8% compared to conventional farmers at 81.6%, while the score of AWD adopters was 1.085 and that of non-adopters was 0.835. Thus, it can be concluded that cooperatives and advanced farming packages lead to more efficient field management by members/participants in the disadvantageous weather conditions of the SA season. Although only 16% of households practiced AWD, this technique proved to be effective for paddy producers who reached a higher efficiency score of 1.144 in the AW season. This implies that the positive differences in the efficiency of the two farmer groups were mainly due to input reduction strategies. A similar circumstance amongst other groups was also evident; however, these figures were not statistically significant in the AW season. Difficulties for farmers in 1M5R and AWD application still exist, including weather conditions (Connor et al., 2020), the surface of rice field not adequately leveling, and inefficient operation of irrigation systems and water management by small households that are some distance from canals (Son et al., 2013).

In addition to SBM scores, it is important that the information on input slacks is fully understood because it demonstrates the excessive usage of inputs and how well the farmers respond in managing their resources during production in order to achieve the greatest efficiency. The slacks of the main input components by rice group are shown in Table 5. First, in the SA season, the largest and smallest slacks of seed density belonged to HR at 45.46 kg/ha and AR group at 29.70 kg/ha, respectively. In the AW season, farmers decided to reduce the amount and not waste seeds. The seed slack of the AR group appeared unchanged at approximately 29 kg/ha. The MR group generated equal slack of seeds at 30.21 kg/ha to AR; meanwhile, of the figure for the HR group was up to 38.24 kg/ha although it was reduced by 7 kg/ha compared to the SA season. The largest slacks of N, P_2O_5, and K_2O fertilizers were observed in the HR group in the SA season, followed by the MR and AR groups. Second, in the AW crop, farmers used N at 35 kg/ha with AR varieties. Due to the high risk of pests and disease in the SA season, farmers wanted to spray more pesticides and herbicides, which led to larger slacks in every rice variety group. Irrigation slacks between AR, HR, and MR in the AW season were much higher than those in the SA season. Producers have to pay for water pumped in and out of the field to maintain the continuous flooding (CF) status of rice plants. Between the rice groups categories, MR cultivation required an irrigation cost approximately 1.78 times higher than that of AR. In AW season, it is feasible to apply multiple drainage (Uno et al., 2021) or AWD techniques to reduce water use (Yan et al., 2005; Linquist et al., 2015; Carrijo et al., 2017; Chidthaisong et al., 2018), while simultaneously reducing the GWP of CH_4 emissions (Yan et al., 2005; Linquist et al., 2015; Chidthaisong et al., 2018).

Water-saving irrigation and field drying will reduce CH_4 emissions, while reducing the use of chemical fertilizers (N) which will reduce N_2O emissions from rice cultivation (MONRE 2017). The same conclusions were drawn from studies by Linquist et al. (2015), Snyder et al. (2009), Yang et al. (2012) and Zhang et al. (2014); i.e., reducing the flooding status in paddy fields by applying AWD and N fertilizer management will help households mitigate GHG emissions. Therefore, it is important to understand information on input slacks combined with CSA practices as presented in Table 6. Regarding N fertilizer use, the 1M5R adopters had significantly smaller slacks than non-adopters in the two seasons of 13.27 kg/ha and 12.84 kg/ha, respectively. In addition, CSA practice was also effective in reducing the wastage of water, as evidenced by smaller slacks in irrigation costs for 1M5R and AWD adopters. In the SA season, the difference in excessive irrigation cost between 1M5R and conventional farmers was approximately 177,000 VND/ha, while the difference between AWD adopters and non-adopters was 148,000 VND/ha. In the AW season, although the slacks were all larger than in the SA season, 1M5R and AWD were still efficient when the participants had significantly smaller slacks than non-participants. Managing nitrogen and irrigation slacks more efficiently by practicing 1M5R and AWD, farmers can better adapt to climate change, sequester more carbon in the soil, and reduce GHG emissions, such as N_2O emission intensity.

3.2.2. Potential reduction of N_2O emissions and ranking of super-efficient households

N_2O emissions increase exponentially with increasing N fertilizer at rates greater than the crops need (Millar et al., 2014; Woodbury and Wightman, 2017). Thus, paddy producers can significantly reduce N_2O emissions from their fields by more precisely estimating N fertilizer needs and reducing N slack in each production step (Millar et al., 2014). Based on the manual of GHG emissions estimation in agriculture (FAO 2015), we attempted to connect GHG mitigation with the reduction strategy of N. GHG emissions from synthetic N fertilizer consist of direct and indirect N_2O emissions (see Appendix 2). Direct N_2O emissions occur at the source (e.g. paddy fields) by microbial processes of nitrification and de-nitrification and indirect N_2O emissions are produced from atmospheric after re-deposition and leaching processes from managed soils. Since there has been no regional N_2O emission factor (EF) for paddy cultivation in the MKD, China's direct N_2O EF (0.003–0.012 kg N_2O–N/kg N input) (Smith and Braatz, 2001) for rice production, and the FAO (2015) N_2O EF (0.010 kg N_2O–N/kg N input) are available for reference. However, China's EF does not provide an indirect EF for rice production. Thus, we used the FAO (2015) N_2O EF for synthetic fertilizer use for both direct and indirect emissions. Table 7 presents the possible reduction of N_2O emissions by rice groups when the slacks of N fertilizer were reduced by 100% and 50%. In the SA season, it was estimated that if the slacks of N could possibly be reduced by 100%, AR, HR, and MR households can mitigate N_2O emissions by 62, 74.2 and 70.7 kg/km^2, respectively. If farmers can only reduce 50% of slacks, those figures will be 31, 37 and 35.35 kg/km^2 of N_2O, respectively, for the three rice groups. In the AW season, although the N application rate was similar to the SA season, the AR group had a larger slack of N. Thus, there was no need to apply approximately 100 kg of N per ha for AR production in the AW season. If it is possible to minimize 100% of N slacks, AR, HR and MR paddy producers should be able to decrease the amount of N_2O at 73, 64.7 and 66.3 kg/km^2, respectively. Regarding mitigation strategies, it is important to apply nitrogen fertilizer following these four principal management factors: right source at the right rate, right time, and right place (4R). These 4Rs should be used together in a comprehensive plan appropriate for the cropping system and also account for all sources of nitrogen input to crop fields. If the 4Rs are practiced and monitored well, they will increase crop yield and profitability, while also greatly reducing GHG emissions (Snyder et al., 2009).

Information on the 20 most super-efficient paddy farms is presented in Table 8. The AW season with advantageous weather conditions helped households reach much higher super-efficiency scores. Households with super-SBM scores > 4 (BL032, BL028, CT037, CT019, and BL036) were super-efficient DMUs and could be considered as outliers in the sample. There were households that appeared to be super-efficient in the two seasons with their unchanged AR and HR varieties, including BL032, BL034, and BL036 with Nang Hoa 9 variety; AG078 and DT032 with OM5451 variety; and BL028 and DT100 with Dai Thom 8 variety. BL032, BL034, and BL036 were cooperative members, which is why they were confident of the support from cooperatives when producing AR in the wet and rainy seasons. Although both AG078 and DT032 produced the same OM5451 variety, their products were sold at very dif-

Table 4
Super-SBM efficiency scores by farm characteristics.

Household characteristics	n	Super-SBM	Std. Dev.	diff	t-stat
Summer-Autumn					
Farm size					
>2 ha	153	0.979	0.505	0.173*	−2.8901
≤2 ha	227	0.805	0.665		
Cooperative membership					
Yes	264	0.923	0.608	0.154**	−2.3971
No	116	0.769	0.498		
1M5R practice					
Yes	140	0.978	0.475	0.163***	−2.6544
No	240	0.816	0.627		
WD practice					
Yes	61	1.085	0.486	0.250***	−3.1142
No	319	0.835	0.907		
Autumn-Winter					
Farm size					
>2 ha	153	0.949	0.537	0.058	−0.7561
≤2 ha	227	0.890	0.785		
Cooperative membership					
Yes	264	0.928	0.664	0.046	−0.5625
No	116	0.882	0.890		
1M5R practice					
Yes	140	0.993	0.474	0.125	−1.5989
No	240	0.868	0.854		
WD practice					
Yes	61	1.144	0.721	0.274***	−2.6724
No	319	0.870	0.793		

Note: ***,**, and * significant at 1, 5, and 10% probability level, respectively.
Source: Calculated from Household Survey, 2018.

Table 5
Input slacks of rice production in the MKD by rice variety group and by season.

Variables	Unit	Summer-Autumn				Autumn-Winter			
		Aromatic	High	Medium	*Prob > F*	Aromatic	High	Medium	*Prob > F*
N = 380		*n* = 189	*n* = 184	*n* = 7		*n* = 247	*n* = 117	*n* = 16	
Seeds	kg/ha	29.70	45.46	41.39	***	29.13	38.24	30.21	*
N		29.72	35.63	33.95		35.03	31.08	31.82	
P_2O_5		31.89	39.99	38.09	*	24.68	20.98	10.75	
K_2O		17.36	20.58	13.68		21.89	22.88	32.57	
Pesticides	thousand VND/ha	1520.23	1826.14	1558.04		1332.57	1451.24	933.04	
Irrigation		394.94	475.02	515.34		629.80	772.12	1121.34	**

Note: ***, ** and * indicate significance at the 1%, 5%, and 10% probability levels, respectively.
Source: Calculated from Household Survey, 2018.

Table 6
Input slacks of rice production in the MKD by season and by CSA practices.

CSA application	N	Slack seeds (kg/ha)		Slack N (kg/ha)		Slack irrigation (thousand VND/ha)	
		Mean	diff.	Mean	diff.	Mean	diff.
Summer-Autumn							
1M5R practice							
Yes	140	19.24	−9.55**	24.28	−13.27***	324.24	−176.85***
No	240	28.79		37.55		501.09	
AWD practice							
Yes	61	23.79	−1.76	30.94	−2.05	311.75	−147.93**
No	319	25.55		32.99		459.68	
Autumn-Winter							
1M5R practice							
Yes	140	22.87	−14.41***	25.56	−12.84***	412.33	−446.47***
No	240	37.28		38.40		858.80	
AWD practice							
Yes	61	27.90	−4.85	33.25	−0.50	526.45	− 199.96*
No	319	32.75		33.75		726.41	

Note: ***, **, and * significant at 1, 5, and 10% probability levels, respectively.
Source: Author's calculation based on Household Survey, 2018.

Table 7
Potential reduction of N_2O emissions when reducing synthetic N fertilizer slacks.

Items	Summer-Autumn			Autumn-Winter		
	Aromatic	High	Medium	Aromatic	High	Medium
N use (kg/ha)	103.46	117.75	117.78	105.34	114.15	100.55
Slack of N (kg/ha)	29.72	35.63	33.95	35.03	31.08	31.82
Direct N_2O (1) (kg/km^2)	46.70	56.00	53.36	55.04	48.83	50.01
Indirect N_2O (2) (kg/km^2)	15.18	18.20	17.34	17.89	15.87	16.25
N_2O emission = (1) + (2) (100% slack reduction) (kg/km^2)	61.88	74.20	70.70	72.96	64.70	66.26
N_2O emission = (1) + (2) (50% slack reduction) (kg/km^2)	30.94	37.10	35.35	36.46	32.35	33.13

Source: Calculated from Household Survey, 2018, based on FAO (2015).

Table 8
Super-SBM scores and ranking of the most 20 efficient paddy farms by season.

Summer-Autumn						Autumn-Winter					
Rank	Score	DMUs	Province	Variety	Category	Rank	Score	DMUs	Province	Variety	Category
1	5.339	BL032	Bac Lieu	Nang Hoa 9	aromatic	1	8.660	CT037	Can Tho	OM5451	high quality
2	5.181	BL028	Bac Lieu	Dai Thom 8	aromatic	2	6.487	CT019	Can Tho	Dai Thom 8	aromatic
3	3.777	CT019	Can Tho	Glutinous CK92	medium quality	3	4.528	BL032	Bac Lieu	Nang Hoa 9	aromatic
4	3.661	AG062	An Giang	OM5451	high quality	4	4.060	BL036	Bac Lieu	Nang Hoa 9	aromatic
5	3.010	DT032	Dong Thap	OM5451	high quality	5	3.879	AG078	An Giang	OM5451	high quality
6	2.961	CT084	Can Tho	OM5451	high quality	6	3.454	DT100	Dong Thap	Dai Thom 8	aromatic
7	2.603	AG078	An Giang	OM5451	high quality	7	3.222	CT027	Can Tho	Dai Thom 8	aromatic
8	2.500	DT017	Dong Thap	OM5451	high quality	8	2.842	AG062	An Giang	Dai Thom 8	aromatic
9	2.467	CT024	Can Tho	OM5451	high quality	9	2.443	BL028	Bac Lieu	Dai Thom 8	aromatic
10	2.460	AG040	An Giang	Dai Thom 8	aromatic	10	2.385	DT044	Dong Thap	Dai Thom 8	aromatic
11	2.412	CT067	Can Tho	OM5451	high quality	11	2.371	BL081	Bac Lieu	Dai Thom 8	aromatic
12	2.399	AG086	An Giang	OM5451	high quality	12	2.272	CT043	Can Tho	Dai Thom 8	aromatic
13	2.333	CT027	Can Tho	OM5451	high quality	13	2.240	AG080	An Giang	Dai Thom 8	aromatic
14	2.063	BL034	Bac Lieu	Nang Hoa 9	aromatic	14	2.097	CT026	Can Tho	OM4218	high quality
15	1.992	BL077	Bac Lieu	Dai Thom 8	aromatic	15	2.052	BL034	Bac Lieu	Nang Hoa 9	aromatic
16	1.920	DT100	Dong Thap	Dai Thom 8	aromatic	16	2.052	DT032	Dong Thap	OM5451	high quality
17	1.900	CT031	Can Tho	OM5451	high quality	17	2.004	AG008	An Giang	IR50404	medium quality
18	1.832	BL081	Bac Lieu	Nang Hoa 9	aromatic	18	1.988	BL041	Bac Lieu	Dai Thom 8	aromatic
19	1.756	BL036	Bac Lieu	Nang Hoa 9	aromatic	19	1.959	BL047	Bac Lieu	Nang Hoa 9	aromatic
20	1.744	BL047	Bac Lieu	Dai Thom 8	aromatic	20	1.950	BL099	Bac Lieu	RVT	aromatic

ferent prices during the two seasons. AG078 sold their paddy to traders at a price of 4950 VND/kg and 5200 VND/kg in the SA and AW seasons, respectively. DT032, with a pre-arranged farming contract, could obtain much higher prices at 6100 and 6200 VND/kg in the two seasons. Moreover, AG078, DT032, BL028, and DT100 all belonged to local paddy cooperatives.

In addition, some households preferred to change their rice varieties when the AW season began. They were: AG062 and CT027 changed from OM5451 to Dai Thom 8; BL081 changed from Nang Hoa 9 to Dai Thom 8; BL047 changed from Dai Thom 8 to Nang Hoa 9; and CT019 changed from sticky rice CK92 to Dai Thom 8. Among those households that practiced variety switching and were still super-efficient, household CT019 produced sticky rice CK92 in the SA season and was even more successful when changing to AR Dai Thom 8 in the AW season, with super-SBM scores of 3.77 and 6.48, respectively. This was good evidence of efficient farming owing to their cooperative membership and 1M5R package application in the field. Household BL047 changed from Dai Thom 8 in the SA season to Nang Hoa 9 in the AW season because of the contract between the enterprise and farmer. Thus, the selling price of paddy rice was also very high at 6300 VND/kg and 7200 VND/kg in the SA and AW seasons, respectively. Households AG062 and CT027 changed from OM5451 to Dai Thom 8 because they wanted to obtain higher output prices from individual traders at harvest.

The appearance of Dai Thom 8 and OM5451 varieties in the list of super-efficient households confirmed their super-efficiency when grown in different ecological zones in the MKD. In particular, aromatic Dai Thom 8 and Nang Hoa 9 varieties cultivated by households in Bac Lieu province appeared to be strongly adaptive to the environment and continued to be efficient overall. Thus, producing AR and HR using CSA techniques can not only bring economic benefits to farmers but can also protect the environment and mitigate GWP by reducing GHG emissions. The farming area and quantity of MR should strictly follow the government's recommendations.

4. Conclusion

After almost twenty years of focusing on intensive rice farming, the Vietnamese government now has a plan to develop and scale up ecosystem-based and community-based climate change adaptation models for the period 2021–2030. At present, rice production not only ensures food security in terms of quantity, but it also has to adapt to severe climate change and the producers must also ensure the environment is protected. The MKD region, which has many advantages in terms of ecological systems and climate, contributes 90% of the total national export volume. Our super-SBM study provides meaningful statistics of overall efficiency and input slacks based on the export of three main rice variety groups, especially AR and HR. Having a high efficiency score and smaller slacks of seeds and irrigation, AR has the most potential for future scale-up programs because these varieties bring economic benefits to producers and, at the same time, lead to a low-emission environment. However, AR cultivators still need to reduce the seed density by an average of 29 kg/ha in each season. N fertilizer should also be reduced by 33 kg/ha and 35 kg/ha in the SA and AW seasons, respectively. The recommended reduction of the HR group is 45.5 kg/ha of seeds and 38.2 kg/ha of N in the SA season. Those figures in AW seasons should be 38.2 and 31.8 kg/ha, respectively. The irrigation cost for all three groups of rice needs to be reduced in the AW season by applying the AWD technique in the field.

The super-SBM model has proven to be effective in estimating the overall efficiency and excessive usage of inputs among smallholders. Through the overuse of nitrogen, we estimated the possible mitigation of N_2O emissions by 62–74.2 kg/km^2 in the SA season and 64 kg /km^2 in the AW season. The ranking of paddy farms also supports the restructuring policy of the government in forming AR and HR production areas for export in freshwater alluvial and coastal areas. The positive operation of paddy cooperatives will also provide rice producers with technical support and the opportunity for contract farming with enterprises. CSA techniques such as 1M5R or AWD are expected to be continuously promoted among all groups of farming households. If these techniques are practiced well, lower GHG emissions in rice production can be expected through the reduction of excess fertilizers in the MKD. Further research topics include evaluating rice yields and nitrogen use efficiency with different fertilizer applications and water management practices, or estimating the nitrogen use efficiency of major rice varieties under different water regimes in the coastal areas of the MKD. Importantly, the adoption of CSA practices requires that they are economically attractive and can be adapted to field scales. Thus, it is important to simultaneously explore the economic benefits and GHG mitigation capacity that CSAs bring to different targeted rice variety groups in Vietnam. In addition, further field experiments are necessary to measure the GHG emissions and propose the emission factor under different N application rates and water regimes for AR and HR areas in the MKD.

The main shortcoming of this socioeconomic study is the absence of area specific information on the physical data of N_2O and CH_4 fluxes in paddy fields, which are mainly collected using the closed chamber method. Also, there are some unobservable variables that could explain farm efficiency that the super-SBM model cannot control, such as regional agro-ecological patterns, farmer motivation, and farmer skills. Hence, considering to apply the smooth bootstrap DEA proposed by Simar and Wilson (2000) could be useful because it estimates the bias and confidence interval for technical efficiency. This technique should be considered in future studies to improve the robustness of the SBM model.

Declaration of Competing Interests

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2022.100532.

APPENDIX 1

Cited from Tone (2001)

The SBM model

Let the set of DMUs be $J = \{1, 2,\dots, n\}$, and each DMU has m inputs and s outputs. We denote the vectors of inputs and outputs for DMU$_j$ by $x_j = (x_{1j}, x_{2j},\dots, x_{mj})^T$ and $y_j = (y_{1j}, y_{2j}, \dots, y_{sj})^T$, respectively. We define the input and output matrices X and Y as follows:

$$X = \left(x_1, x_2, \dots, x_n\right) \in R^{m\times n} \text{ and } Y = (y_1, y_2, \dots, y_n) \in R^{s\times n} \tag{1}$$

We assume that all data are positive, that is, $X > 0$ and $Y > 0$. The production possibility set is defined using a non-negative combination of DMUs in set J as:

$$P = \{(x, y)| x \geq \sum\nolimits_{j=1}^{n} \lambda_j x_j, 0 \leq y \leq \sum\nolimits_{j=1}^{n} \lambda_j y_j, \lambda \geq 0 \tag{2}$$

where $\lambda = (\lambda_1, \lambda_2, ..., \lambda_n)^T$ is called the intensity vector.

The inequalities in Eq. (2) can be transformed into equalities by introducing slack, as follows:

$$\begin{aligned} x &= \textstyle\sum_{j=1}^{n} \lambda_j x_j + S^- \\ y &= \textstyle\sum_{j=1}^{n} \lambda_j y_j - S^+ \\ & S^- \geq 0, S^+ \geq 0 \end{aligned} \tag{3}$$

where $s^- = (s_1^-, s_2^-, ..., s_m^-)^T \in R^m$ and $s^+ = (s_1^+, s_2^+, ..., s_s^+)^T \in R^s$ are called the input and output slacks, respectively.

Input-oriented SBM

The following linear program is solved to obtain the corresponding efficiency of DMU$_h$ = (x_h, y_h). This process is repeated n times for $h = 1,\dots, n$:

[SBM-I-C] (input-oriented SBM under constant returns-to-scale assumption)

$$\rho_I^* = \min_{\lambda, S^-, S^+} 1 - \frac{1}{m} \sum\nolimits_{i=1}^{m} \frac{S_i^-}{x_{ih}}$$

subject to

$$x_{ih} = \sum\nolimits_{j=1}^{n} x_{ij}\lambda_j + S_i^- (i = 1, ..., m) \tag{4}$$

$$y_{rh} = \sum\nolimits_{j=1}^{n} y_{rj}\lambda_j - S_r^+ (r = 1, ..., s)$$

$$\lambda_j \geq 0(\forall_j), S_i^- \geq 0(\forall_i), S_r^+ \geq 0(\forall_r)$$

ρ_1^* is called the SBM-input efficiency. A DMU$_h$ = (x_h, y_h) is called SBM-input-efficient if ρ_1^*= 1. This means that s^{-*}= 0; that is, all input slacks are zero. However, the output slack may be non-zero. Using an optimal solution (λ^*, s^{-*}, s^{+*}), we define a projection of DMU$_h$ = (x_h, y_h) by:

$$(\bar{x_h}, \bar{y_h}) = (x_h - S^{-*}, y_h + S^{+*}) \tag{5}$$

The projected DMU is the SBM-input efficient. Also, the input-oriented SBM score is not larger than the CCR efficiency score (Tone, 2001).

APPENDIX 2

Cited from FAO (2015)

Direct Emission (N_2O)

Direct Emission (N_2O) $= N\times\frac{44}{28} \times EF_1$

Where *Direct emission* (N_2O): direct emission N_2O from synthetic nitrogen additions to the managed soils, kg N_2O yr^{-1}

N = Consumption in nutrients of nitrogen fertilizers, kg N input yr^{-1}

EF_1 = 0.01; Emission factor for N_2O emissions from N inputs, kg N_2O–N/kg N input (Table 26A) (FAO, 2015; page 150).

Indirect Emission (N_2O)

Indirect Emission (N_2O) = N x$[(FRAC_{GASF} \times EF_4) + (FRAC_{LEACH} \times EF_5)] \times \frac{44}{28}$

Where *Indirect emissions* (N_2O) = Indirect N_2O emissions produced from atmospheric deposition of N, volatilized from managed soils, kg N_2O yr^{-1}.

N = Consumption in nutrients of nitrogen fertilizers, kg N input yr^{-1}

$FRAC_{GASF}$ = 0.1; Fraction of applied synthetic N fertilizer materials that volatilizes as NH_3 and NOx, kg N volatilized/kg of N applied (Table 28A) (FAO, 2015; page 150).

EF_4 = 0.01; Emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, kg N–N_2O/kg NH_3_N + NOx-N volatilized (Table 24A) (FAO, 2015; page 149).

$FRAC_{LEACH}$ = 0.3; Fraction of applied synthetic N fertilizer materials that leaches as NH_3 and NO_X, kg N leached/kg of N additions (Table 27A) (FAO, 2015; page 150).

EF_5 = 0.0075; Emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N/kg N (Table 25A) (FAO, 2015; page 149).

Emission (N_2O)

Emission (N_2O) = *Direct emission* (N_2O) + *Indirect Emission* (N_2O)

Where

Emissions (N_2O) = Total N_2O emissions from synthetic nitrogen additions to managed soils, kg N_2O.

Direct emissions (N_2O) = Direct N_2O emissions from synthetic nitrogen additions to managed soils, kg N_2O.

Indirect emissions (N_2O) = Indirect N_2O emissions from synthetic nitrogen additions to managed soils, kg N_2O.

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