Environmental efficiency of rice production in Vietnam: An application of SBM-DEA with undesirable output

TRUC-LINH LE[1,♥], THI-THUY-HAI LUU[1], NGA HUYNH[1], REBECCA H. CHUNG[2,♥♥]

[1]Department of Agriculture and Aquaculture, Tra Vinh University. No. 126, Nguyen Thien Thanh Street, Ward 5, Tra Vinh City, Viet Nam
Tel.: +84-94-3855692, ♥email: letruclinh@tvu.edu.vn
[2]Department of Tropical Agriculture and International Cooperation, National Pingtung University of Science and Technology. Pingtung 91201, Taiwan.
♥♥email: rebecca@mail.npust.edu.tw

Abstract. *Le TL, Luu TTH, Huynh N, Chung RH. 2020. Environmental efficiency of rice production in Vietnam: An application of SBM-DEA with undesirable output. Biodiversitas 21: 2710-2715.* In Vietnam, the agricultural sector is one of major sources of the country's greenhouse gas (GHG) emissions and over half of that comes from rice cultivation. This study evaluates the environmental efficiency of 400 rice farms in the Mekong Delta using slack-based measure (SBM) data envelopment analysis (DEA) with considering the total amount of CO_2-equivalent (CO_2-eq) emissions in the rice field as undesirable output. The findings revealed that the average environmental efficiency score of the farmers was very low, just only 0.461. Only 2.25% of the sample farms were environmentally efficient while majority of them (58%) obtained the efficiency values less than the mean indicating that their environmental efficiency needs to be further improved. The small rice farms were higher in environmental efficiency scores compared with large farms. The sample rice farmers who are members of agricultural cooperatives obtained a significantly higher environmental efficiency than the non-cooperative members. The estimated results of input and bad output excesses showed that about 1.35 tons of CO_2-eq ha^{-1} could be reduced and an average of 54.18 kg N ha^{-1} could be saved in order to improve the environmental performance of rice production in the study area.

Keywords: Environmental efficiency, greenhouse gas, rice production, slack-based measure data envelopment analysis

INTRODUCTION

Vietnam is an agricultural country with about 35% of its area is used for agricultural production. In 2015, agriculture contributes about 16% to GDP of the country (GSO 2016). This sector, however, also causes serious impacts on the environment. According to MONRE (2014), the agriculture sector accounted for the biggest share of 65% in 1994 and 43% in 2000 of total GHG emission of the country (130.8 and 150.9 million ton CO_2 equivalent (CO_2-eq), respectively). In 2010 it was ranked second with a share of nearly 36%, just after the energy sector at 57% of total 246.8 million ton CO2-eq. In addition, this figure is projected to continue increasing in 2020 and 2030. Therefore, the development of sustainable agriculture reducing the negative impacts on the environment is a matter of nationally great concern at present.

Rice is a staple food and a cash crop in Vietnam. Rice production dominates in the agriculture sector and makes the country being one of the world's largest rice exporter. On the one hand, it shows important values on food security and economic development of the country. On the other hand, rice production is one of the biggest sources of GHG emissions in agriculture where methane gas is commonly recorded in rice fields. In 2010 rice cultivation contributed 2.12 million tons CH_4 (or 44.6 million tons CO2-eq), accounting for over 50% of the agriculture GHG emissions (MONRE 2014).

The Mekong Delta is a very important area for rice cultivation but this is also one of the most severely influenced regions by climate change which is mainly caused by GHG. Numerous studies focusing on rice production and efficiency evaluations have been popularly conducted. In terms of efficiency measures, technical efficiency is the most popular research, followed by cost efficiency, and profit efficiency. Together with cultivating technique studies, assessment of environmental performance holds certain roles in showing how good their current efficiency and directions for them to seek suitable ways for environmental efficiency improvement. However, empirical studies related to the environmental efficiency measures on this important crop are quite limited while rice production particularly in the Delta causes land degradation, losses of biodiversity, water pollution, and an increase in GHG emissions. It is found that there was only one study of Tu et al. (2015) who applied stochastic frontier analysis (SFA) with the use of environmentally detrimental inputs to estimate environmental efficiency between ecological rice farmers and normal rice farmers in the Mekong Delta.

In empirical studies concerned on environmental evaluations, the environmental indicators can be adopted in the models as bad outputs or environmental detrimental inputs (Chung et al. 1997; Tyteca 1997) and environmental efficiency can be estimated by applying both SFA and DEA approaches. The environmentally detrimental inputs such as fertilizer, chemical, and energy application which

could cause environmental pollution were commonly applied in many previous studies related to evaluate the environmental efficiency of agricultural farms (Reinhard et al. 1999; Reinhard et al. 2000; Reinhard et al. 2002; Zhang and Xue 2005; Kiatpathomchai 2008; Abedullah et al. 2010; Bakhsh et al. 2014; Ullah and Perret 2014).

Although Reinhard et al. (2000) stated that DEA could be applied to analyze environmental efficiency, Song et al. (2013) stated that traditional DEA model could not perform well for this measurement when considering undesirable outputs. This is because all outputs in traditional DEA tend to be maximized from a given set of inputs. To cope with undesirable outputs in DEA, Tone (2004) proposed a slack-based measure (SBM) model which was improved from Tone (2001). The analysis could figure out the excesses of inputs, bad output, and the shortage of good output which could be considered as directions for efficiency improvements. This methodology was applied in many studies including Song et al. (2013); Chang (2013); Kuo et al. (2014); Song et al. (2015); Zhang et al. (2017). As mentioned by Song et al. (2015) that among approaches applied to environmental efficiency measures, the SBM model is the most popular one.

This study applied the SBM model with the consideration of one undesirable output and one environmental detrimental input to estimate environmental efficiency of the rice farmers in the Mekong Delta of Vietnam. The study findings would help to figure out the current status of rice production environmental efficiency and identify how much environmental detrimental input and undesirable output producers can be reduced in order to improve the environmental performances.

MATERIALS AND METHODS

Study area

The study was conducted in the provinces of Tra Vinh and Dong Thap in the Mekong Delta region, Vietnam (Figure 1). The delta is in the tropical climate zone where the climate is cool with the annual average temperature around 27°C and average humidity of 83-85%. This is one of the most fertile deltas in the world and suitable for rice cultivation and is the largest rice granary of Vietnam.

These two sample provinces are located in the upper and lower part of the Mekong River, respectively. Dong Thap is characterized by a large river channel that frequently silt-aggraded soil, and permanently fresh and non-saline water sources. Tra Vinh is enclosed by the Tien and the Hau rivers, two branches of Mekong River. These features have significant contributions to agricultural development of these two provinces.

Procedures

In this study, cross-section data at the farm level were used, which were collected from rice producers. A multi-stage procedure was applied for sampling. In the first stage, both Tra Vinh and Dong Thap provinces were purposively chosen as the study areas. Then, six districts, namely Cau Ke, Cang Long, Chau Thanh from Tra Vinh province, and Tam Nong, Thap Muoi, and Lap Vo from Dong Thap province, were chosen. At the district level, about 70 rice farms were randomly sampled in the third stage. Finally, a sample comprising of 400 rice producers was surveyed for this analysis.
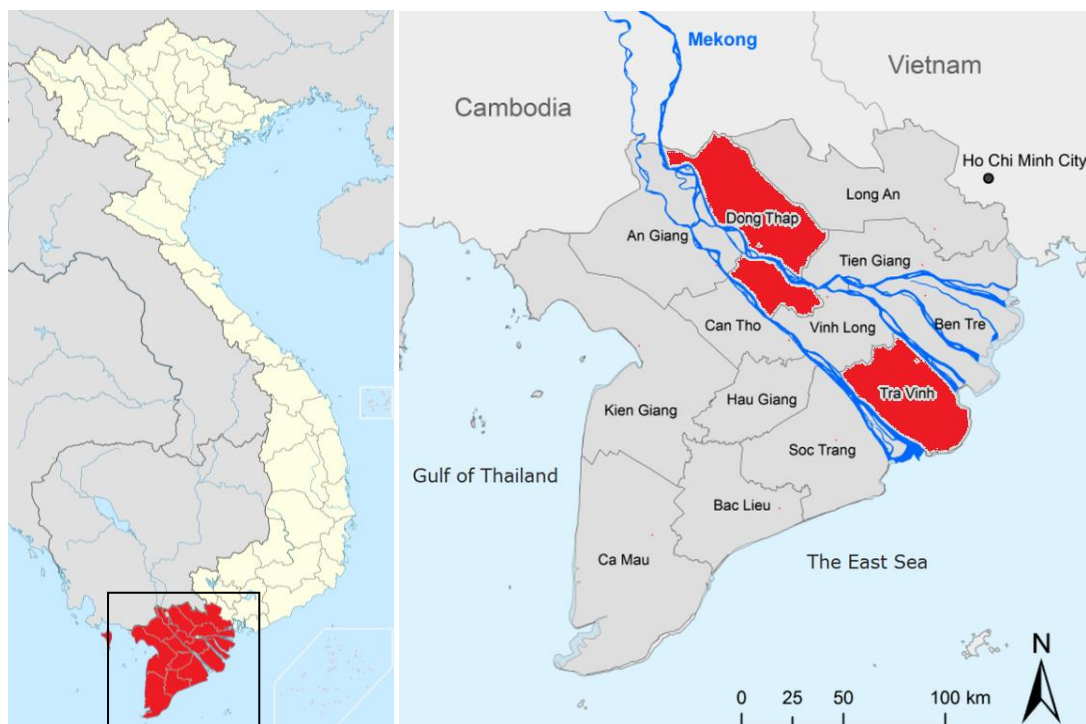

Figure 1. Map of Vietnam and Mekong Delta region, showing the study areas in Tra Vinh and Dong Thap

Table 1. Descriptive statistics of the input and output data of rice farms in 2014

Variable	Mean	Max.	Min.	SD.
Inputs				
Variable costs (1000 VND ha⁻¹)	17,156.40	23,453.67	13,728.00	1,565.98
Labor (man-days ha⁻¹)	30.11	43.00	21.00	3.66
Nitrogen application (kg N ha⁻¹)	105.15	247.00	54.00	26.02
Outputs				
Profit (Desirable output, 1000 VND ha⁻¹)	20,033.45	35,845.00	8,705.00	6,489.65
CO_2-eq emission (Undesirable output, ton ha⁻¹)	4.43	6.22	3.05	0.60

Note: *1 US$ = 21,270 VND (as of June 31, 2014)

The structured questionnaires were used for the face-to-face survey to collect related information on rice production in the winter-spring season in Tra Vinh and Dong Thap provinces. The survey was conducted during July- September 2014. Detailed information on key variables was selected for analyzing as follows.

Input variables. In this study, three normal inputs were observed in rice production. Labor and variable input cost are the two traditional inputs which were commonly applied in many studies. Labor variable is expressed in man-days per ha including hired and family labor. Variable costs, expressed in Vietnamese currency (1000 VND), include expenditures for seed, fertilizer, chemicals, land preparation, irrigation, harvest, and other miscellaneous costs. The other input is nitrogen application (kg N ha⁻¹) because it is one important factor related to greenhouse gas emission in rice production. The overuse of chemical fertilizer not only leads to high production cost, lower yield due to insect and disease damage, low quality, and consequently low competitiveness. Excessive nitrogen fertilization also pollutes air and water resources. In the Mekong Delta, the overuse of nitrogen fertilizer is quite popular because it significantly contributes to rice production improvement, and because this nutrient shows obvious effects rapidly. Low nitrogen use efficiency, however, makes a large share of this nutrient directly released to the environment. According to Ghosh and Bhat (1998), the recovery of nitrogen applied in wetland rice fields is just about 30-40% and this is also a major source of N losses. Zhang et al. (2014) stated that the overuse of fertilizer had a significant contribution to global warming. In practice, Phong and Loi (2015) found that nitrogen application is responsible for almost 27% of CH_4 emissions in rice cultivation in the Mekong Delta, just after rice soil (69%).

Output variables. This study selected profit of rice production as desirable output because this is often the final goal of most farmers. In order to produce the desired output of rice, the production process also generates some bads which are detrimental to the environment. The CH_4 emission released by rice cultivation is one of the most harmful factors resulting in the global warming impact. Normally, the GHG emission is commonly converted to the unit of CO_2-eq. Thus this study selected the total CO_2-eq emission as the undesirable output. Phong and Loi (2015) found that in case of rice production in the Mekong Delta the emission of CO_2 was about 609.6 g CO_2-eq kg⁻¹ of paddy rice. Hence, total CO_2 emission was calculated by multiplying this figure to the yield of rice per ha. Descriptive statistics of inputs, desirable output, and undesirable output are presented in Table 1.

As can be seen in Table 1 that the average nitrogen application of the farmers is not too high (105 kg N ha⁻¹) compared with 80-100 kg N ha⁻¹ recommendation in the winter-spring season in the Mekong Delta (Hach and Tan 2007). However, the data illustrates a very large range of this input from a quite low level of only 54 kg N ha⁻¹ to very high amount of 247 kg N/ha/crop. The total CO_2 emission per ha of rice ranges from 3.05 to 6.22 tons CO_2-eq ha⁻¹ due to the difference in average rice yield per ha of the farmers.

Data analysis

In this study, the undesirable outputs Slack Based Measure- Data Envelopment Analysis model was applied to estimate environmental efficiency for the rice farms. The procedure of the model is specified as follow:

Suppose that there are n decision-making units (DUMs) using x inputs ($x \in R^m$) to produce y good or desirable output ($y^g \in R^{s2}$) together with y bad or undesirable output $y^b \in R^{s2}$). The matrices of three factors expressed as follows:

$$X = [x_1, \ldots, x_n] \in R^{m \times n},$$
$$Y^g = [y_1^g, \ldots, y_n^g] \in R^{s_1 \times n},$$
$$Y^b = [y_1^b, \ldots, y_n^b] \in R^{s_2 \times n},$$

And all factors X, Y^g, and Y^b are assumed to be greater than 0.

The constant return to scale of the production possibility set (P) is described by:

$$P = \{(x, y^g, y^b) | x \geq X\lambda, y^g \leq Y^g\lambda, y^b \geq Y^b\lambda, \lambda \geq 0\}, \quad (1)$$

The SBM model proposed by Tone (2001, 2004) with undesirable outputs is expressed as follows:

$$\rho^* = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2}\frac{s_r^b}{y_{r0}^b}\right)} \quad (2)$$

Subject to $x_0 = X\lambda + s^-$; $y_0^g = Y^g\lambda - s^g$; $y_0^b = Y^b\lambda + s^b$; $s^- \geq 0, s^g \geq 0, s^b \geq 0, \lambda \geq 0.$

Where; s^-, s^g and s^b are slacks of inputs, good output, and bad output, respectively, and χ represents weight vector. The vectors $s^- \in R^m$ and $s^b \in R^{s2}$ represent the excesses of inputs used and undesirable output, while $s^g \in R^{s2}$ indicates the shortage of desirable outputs. When the efficiency of a DMU equals one ($\rho^* = 1$) meaning that the DMU is efficient even the presence of undesirable outputs, i.e., $s^- = 0$, $s^g = 0$, and $s^b = 0$. In contrast, if $\rho^* < 1$, which shows that the DMU is inefficient, the DMU needs to optimize the inputs, good outputs, and reduce bad output in order to improve its environmental efficiency score.

RESULTS AND DISCUSSION

The environmental efficiency of rice production was computed using the SBM - DEA model with undesirable output consideration and the assumption of the constant return to scale. The DEA-Solver Pro 5.0 software was adopted for analyzing and the estimated results were displayed in Table 2.

The rice producers in the sample study were found to acquire quite low at environmental performances with an average efficiency score of only 0.461. Further, there was a wide range of environmental efficiency values with a minimum of only 0.150 and a maximum of 1.000 showing that there is substantial variation in environmental efficiency among rice producers. These relatively low results show that the environmental performances of these farms need to be further upgraded. As regards the distribution of environmental efficiency values among the rice farms, it is observed that only 9 farms (2.25%) of 400 surveyed farms were environmentally efficient while over half of the sample farmers (58%) obtained the efficiency value less than the average score showing that the majority of rice farms were operating at a very low level of environmental efficiency.

To observe the differences in environmental performance of rice farms within the sample, these farms were classified into three categories including farm size, province, and agricultural cooperative membership. The results of the efficiency comparison were presented in Table 3. First regards the difference in environmental efficiency by farm size. It is to be noted that the average rice farm size in the study is 1.59 ha per farm. A farm with a size less than the mean is regarded as small while the large farm is equal or larger than the mean. It can be found that small farms tended to obtain slightly higher environmental efficiency scores than that in larger farms (0.47 and 0.44, respectively) at 10% level of significance, thus potential nitrogen reduction of large farms was significantly higher than that of small farms. However, the difference in potential reduction of CO_2 emission was insignificant between the two farm size scales. This may be because in the production process of the large farms require more investment which often leads to overuse or unbalances of input application such as chemicals or artificial fertilizer and the environment is obviously affected as a result. However, according to Demont and

Rutsaert (2017), small-sized farms was one of the most important weaknesses of the Mekong Delta rice farmers. Hence, the low environmental efficiency of large-sized farms in this study could be considered an inefficient sign of the rice growers in managerial skills and production technologies that need to be taken into consideration for further improvement of rice production.

For the cases of province category, the results obtained show that rice producers in Tra Vinh province had an average environmental efficiency score considerably higher than that of Dong Thap farmers (0.51 and 0.41, respectively). This means that the farmers in Dong Thap province need more improvement in CO_2 reduction and their nitrogen application than farmers in Tra Vinh province. In particular, the rice producers in Dong Thap could reduce CO_2 emissions by about 1.52 ton CO_2-eq ha^{-1} and nitrogen use of 64.19 kg N ha^{-1}. The higher environmental efficiency level of rice producers in Tra Vinh province may be due to their farm size is a little bit smaller than that in Dong Thap (1.19 and 1.99 ha per farm, respectively). The result is consistent with farm size and environmental efficiency relationships as mentioned before.

Comparing environmental efficiency scores of cooperative members and non-cooperative members, it can be observed that the average score of cooperative members was significantly higher than that of non-cooperative members (0.522 and 0.400, respectively) confirming the outstanding role of cooperative membership in the study. Therefore, non-member rice farmers have more potential reductions in CO_2 reduction (1.58 ton CO_2-eq ha^{-1}) and nitrogen application (57.97 kg N ha^{-1}) compared to 1.11 ton CO_2-eq ha^{-1} and 50.39 kg N ha^{-1} of cooperative members. The improvement in environmental efficiency of cooperative members maybe because they benefit from agricultural cooperatives which are considered self-help organizations. More importantly, agricultural cooperatives are also supported by the government's development policies such as technical or professional training, rural credit, etc.

Table 2. Environmental efficiency results in rice farms

Efficiency scores	Number of farms	Percentage (%)
1.00	9	2.25
0.09-1.00	3	0.75
0.80-0.90	13	3.25
0.70-0.80	26	6.50
0.60-0.70	40	10.00
0.50-0.60	49	12.25
0.40-0.50	83	20.75
0.30-0.40	93	23.25
0.20-0.30	67	16.75
<=0.20	17	4.25
Above average	168	42.00
Below average	232	58.00
Total	400	100
Mean	0.461	
Standard Deviation	0.191	
Maximum	1.000	
Minimum	0.150	

Table 3. Environmental efficiency scores and potential reduction in CO_2 emission and nitrogen application of rice farms by farm size, province, and cooperative membership

Variables	N	Mean EE	Potential reduction	
			CO_2-eq (ton/ha)	Nitrogen (kg/ha)
Environmental efficiency by farm size				
Large (>=1.59ha)	133	0.44	1.37	58.58
Small (<1.59ha)	267	0.47	1.33	51.99
t-value (large vs. small)		-1.63*	0.54	2.10**
Environmental efficiency by province				
Tra Vinh (TV)	200	0.51	1.17	44.17
Dong Thap (DT)	200	0.41	1.52	64.19
t-value (TV vs. DT)		5.07***	-6.46***	-6.78***
Environmental efficiency by cooperative membership				
Member	200	0.52	1.11	50.39
Non-member	200	0.40	1.58	57.97
t-value (member vs. non-member)		6.70***	-8.41***	-2.80***
Average potential reduction			1.35	54.18

Note: *, ** and *** indicate significant at 10, 5 and 1 % levels, respectively

Generally, the mitigation potential of CO_2 emissions in rice production in the study was estimated to be 1.35 ton CO_2-eq/ha and the potential nitrogen saving for them was 54.18 kg N ha^{-1}. There would be two possible explanations for the low environmental efficiency of rice production in the study. Technical inefficiency could be the first source of environmental inefficiency. Hach and Tan (2007) stated that "a skillful farmer can save fertilizer application and vice-versa". In addition, due to the low efficient use of nitrogen by rice crops in the region (only 40%), improving nitrogen use efficiency can be seen as an essential solution. The other may be the lack of environmental knowledge of the farmers. As reported by ADB (2013) that the running off of pesticide and fertilizer application could be due to the Vietnamese rice farmers lacking in motivations to apply sustainable management in natural resources. These indicate that management skills and farming techniques of the farmers hold very important positions in the production process. For instance, Tin et al. (2012) found that the combination of alternative irrigation (wetting and drying conditions) and nitrogen fertilization using leaf color chart showed good results in reducing of CO_2-eq emission by 31.6 %/ha/crop compared with the control model.

Mitigation of the GHG emission in the fields, however, is very complicated. Take the CH_4 emission as an example, de Miranda et al. (2015) summarized that there were many factors influencing on this gas emission including rice varieties, soil type, form and amount of fertilizer application, water management, etc. Furthermore, the cross-effect is another problem such as a high level of nitrogen fertilizer was used to reduce the CH_4 emission, but it also leads to another emission (NO_2). Thus, this study suggests that building advanced technologies on environmentally friendly rice cultivation methods will be still very necessary to increase the sustainability of the rice sector. In addition to technical training, the farmers should be educated on environmental issues relating to their farming and possible solutions to mitigate environmental impacts, such as effects of chemical fertilizer, pesticide

use, energy use on GHG emissions, and obviously serious results as well. This will enable the rice farmers to a better understanding of environmental protection and possibly efficient actions to cope with this global phenomenon.

In Vietnam, improvements in agricultural environmental efficiency will be meaningful and have certain contributions in sharing burdens of the country in GHG emission management in accordance with the longtime national goals on sustainable development. In which the Vietnamese government has just issued the resolution relating sustainable development strategies for the Mekong Delta. Specifically, in 2050 about 80% of agriculture of the region will be ecological and high-quality applied agriculture in order to boost the value as well as the competitive ability of agricultural products (Government of Vietnam 2017).

In conclusion, the environmental efficiency of 400 rice farms in the Mekong Delta was estimated using SBM-DEA with considering undesirable output. The results revealed that the average environmental efficiency score of the farmers was very low, just 0.461, and only 2.25% of the sample farms were environmentally efficient while the majority of them (58%) obtained the efficiency values less than the mean indicating that their environmental efficiencies need to be further improved. The findings also showed that a large amount of CO_2 emissions and nitrogen fertilizer could be reduced in order to improve the environmental performance of rice production in the study area.

Rice is still vital for food security of the increasing world population. Thus, the most important task is to improve rice production in combination with reducing environmental harms. In case of rice production in the Mekong Delta, this study suggests that training programs on the efficiency of input use and nutrient use are always essential to the rice farmers. Better production practices could result in better environmental performance. These would help the farmers apply fewer inputs and cause less negative effects on the environment. In addition to this, it is

indeed necessary to conduct more studies focusing on environmental efficiency measures showing the relationship between farming activities and environmental efficiency as well as identify determinants of environmental efficiency. This could be useful information for policymakers to adjust and supplement their strategies for sustainable agricultural development.

REFERENCES

Abedullah, Kouser S, Mushtaq K. 2010. Environmental efficiency analysis of basmati rice production in Punjab, Pakistan: Implications for sustainable agricultural development. Pak Dev Rev 49 (1): 57-72.

ADB. 2013. Viet Nam: Environment and climate change assessment. Asian Development Bank, Philippines.

Bakhsh K, Hassan S, Asif Kamran M, Saeed R. 2014. Determinants of environmental efficiency in bitter gourd production in Pakistani Punjab. Pak J Soc Sci 34: 167-176.

Chang YT. 2013. Environmental efficiency of ports: a data envelopment analysis approach. Marit Policy Manag 40: 467-478.

Chung YH, Färe R, Grosskopf S. 1997. Productivity and undesirable outputs: a directional distance function approach. J Environ Manag 51: 229-240.

de Miranda MS, Fonseca ML, Lima A, de Moraes TF, Rodrigues FA. 2015. Environmental impacts of rice cultivation. Am J Plant Sci 6: 2009-2018.

Demont M, Rutsaert P. 2017. Restructuring the Vietnamese rice sector: Towards increasing sustainability. Sustainability 9: 1-15.

Ghosh B, Bhat R. 1998. Environmental hazards of nitrogen loading in wetland rice fields. Environ Pollut 102: 123-126.

Government of Vietnam. 2017. Resolution No. 120/2017/NQ-CP on sustainable development in the Mekong Delta response to climate change. Government of Vietnam, Hanoi.

GSO. 2016. Statistical Yearbook of Vietnam 2015. Statistical Publishing House, Hanoi, Vietnam.

Hach CV, Tan PS. 2007. Study on site-specific nutrient management (SSNM) for high-yielding rice in the Mekong Delta. Omon Rice 15: 144-152.

Kiatpathomchai S. 2008. Assessing Economic and Environmental Efficiency of Rice Production Systems in Southern Thailand: An Application of Data Envelopment Analysis. [Dissertation]. Faculty of Agricultural Sciences, Nutritional Sciences and Environmental Management, Justus-Liebig University, Giessen.

Kuo HF, Chen HL, Tsou KW. 2014. Analysis of farming environmental efficiency using a DEA model with undesirable outputs. Apcbee Procedia 10: 154-158.

MONRE. 2014. Vietnam's the first bi-annual update for the United Nations Framework Convention on Climate Change. Vietnam Publishing House of Natural Resources - Environment and Cartography, Ha Noi.

Phong LT, Loi PT. 2015. Environmental impact assessment of rice production in the Mekong Delta. Sci J Can Tho Univ 24a: 106-116. [Vietnamese]

Reinhard S, Lovell CK, Thijssen G. 1999. Econometric estimation of technical and environmental efficiency: an application to Dutch dairy farms. Am J Agric Econ 81: 44-60.

Reinhard S, Lovell CK, Thijssen G. 2002. Analysis of environmental efficiency variation. Am J Agric Econ 84: 1054-1065.

Reinhard S, Lovell CK, Thijssen G. 2000. Environmental efficiency with multiple environmentally detrimental variables; estimated with SFA and DEA. Eur J Oper Res 121: 287-303.

Song M, Wang S, Liu Q. 2013. Environmental efficiency evaluation considering the maximization of desirable outputs and its application. Math Comput Model 58: 1110-1116.

Song X, Hao Y, Zhu X. 2015. Analysis of the environmental efficiency of the Chinese transportation sector using an undesirable output slacks-based measure data envelopment analysis model. Sustainability 7: 9187-9206.

Tin HQ, Cuc NH, Sanh NV, Anh NV, Hughes J, Hoa TT, Ha TT. 2012. Low CH4 emission rice production in AnGiang province - Dry season 2010-2011. Sci J Can Tho Univ 23a: 31-41. [Vietnamese]

Tone K. 2001. A slacks-based measure of efficiency in data envelopment analysis. Eur J Oper Res 130: 498-509.

Tone K. 2004. Dealing with undesirable outputs in DEA: A slacks-based measure (SBM) approach. National Graduate Institute for Policy Studies, Tokyo, Japan.

Tu VH, Yabe M, Trang NT, Khai HV. 2015. Environmental efficiency of ecologically engineered rice production in the Mekong Delta of Vietnam. J Fac Agric Kyushu Univ 60: 493-500.

Tyteca D. 1997. Linear programming models for the measurement of environmental performance of firms—concepts and empirical results. J Prod Anal 8: 183-197.

Ullah A, Perret SR. 2014. Technical-and environmental-efficiency analysis of irrigated cotton-cropping systems in Punjab, Pakistan using data envelopment analysis. Environ Manag 54: 288-300.

Zhang J, Fang H, Wang H, Jia M, Wu J, Fang S. 2017. Energy efficiency of airlines and its influencing factors: A comparison between China and the United States. Resour Conserv Recy 125: 1-8.

Zhang T, Xue B. 2005. Environmental efficiency analysis of China's vegetable production. Biomed Environ Sci 18: 21-30.

Zhang X, Yin S, Li Y, Zhuang H, Li C, Liu C. 2014. Comparison of greenhouse gas emissions from rice paddy fields under different nitrogen fertilization loads in Chongming Island, Eastern China. Sci Total Environ 472: 381-388.