Heliyon 9 (2023) e20367

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Effect of saline intrusion on rice production in the Mekong River Delta

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ARTICLE INFO

JEL classification:
Q12
Q34

Keywords:
Saline intrusion
Rice production
Difference in difference method
Mekong River Delta

ABSTRACT

Saline intrusion is increasingly threatening the rice farming system in The Mekong River Delta (MRD). Identifying the impact of this disaster on rice farming and providing promptly adaptable solutions is an urgent issue. This study evaluates the influence of saline intrusion on rice productivity of households in the MRD. We utilize the quasi-experimental method, the difference-in-difference (DID) method, with farm level panel data on rice farming extracted from the Vietnam Household Living Standards Survey (VHLSS) in 2014 and 2016. The empirical results indicate that households affected by saline intrusion have lower total production and lower productivity compared to the unaffected group. The affected group has lower total revenue of approximately 4969.8 thousand VND per ha and lower net revenue, on an average of 4679.3 thousand VND per ha, compared to the comparable unaffected group. Among the subsamples of different regions, the damage magnitude of households in severely affected regions by salinity intrusion is higher than in less severely affected areas. Some policy implications that can be proposed from this research are that the management agency should continue to update information on weather and climate change scenarios for forecasting and timely information for rice farmers. The agency comprehensively evaluates the effectiveness of transformed models of sustainable agricultural production adapted to salinity intrusion and replicates high-effective production models; restructure rice cultivation following the salinity intrusion level of each locality.

1. Introduction

The Mekong River Delta (MRD) region plays an essential role in the agricultural development of Vietnam, with the total agricultural area of about 4 million hectares, accounting for more than 50% of the country's rice production and 90% of total volume for agriculture export in Vietnam [1]. Recently, salinity intrusion has increasingly affected river deltas worldwide, and Vietnam's MRD is no exception [2]. It has become a serious threat to rice farming in the MRD and other regions in Vietnam. If the sea level rises from 0.2 to 0.6 m, 100–200 thousand hectares of Vietnam's delta will be submerged. A 1-m rise in water will inundate 0.3 to 0.5 million hectares

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https://doi.org/10.1016/j.heliyon.2023.e20367
Received 30 July 2023; Received in revised form 17 September 2023; Accepted 20 September 2023
Available online 21 September 2023

of the Red River Delta, and 90% of the MRD would be flooded [3]. Among developing countries, Vietnam is the country that the most severely affected by salinity intrusion [2]. According to the forecast of Ministry of Natural Resources and Environment in Vietnam, the MRD will be seriously affected by saline intrusion if the sea level rises by 1 m. Most of the areas would lose 25%–50% of their land to floods. If the rivers rise 0.5–1 m, the water will reach the height of the existing dike system. Due to the impact of rising sea levels globally, 15,000–20,000 square kilometers of the MRD's coastal areas will be inundated and nine of its 13 provinces will be submerged [4]. Therefore, rice production will be severely affected.

In the past, floods were the main cause of disruption in agricultural production in this area [5]. However, in recent years, salinity intrusion has become the biggest challenge for farm-households in agricultural production areas in Vietnam. Salinity intrusion in this delta is caused by a decrease in the upstream flow rate due to the construction of hydroelectric dams. Rising sea levels due to climate change also reduces the hydrological pressure in MRD, allowing saltwater to penetrate more inland [3,5,6].

In the MRD, the salinity intrusion occurs naturally because this is a region heavily influenced by water and has little protection infrastructure [7]. During the dry season, with low river discharge to the sea, tides from the South China Sea and the Gulf of Thailand often bring saltwater deep inland and often affects approximately 1.8 million hectares of land in the delta, of which 1.3 million hectares are affected by salinity above 5 gl − 1 [8]. In 2015–2016, the dry season year was heavily influenced by the El Nino's effect; saltwater intruded more than 90 km inland, causing heavy crop losses in 11 out of 13 provinces in the delta. Hence, rice production was severely affected in the coastal provinces of the Mekong Delta [9,9]. An estimated two million people lost income from agricultural production, while two million faced water shortages due to drought and salinity intrusion [10]. Saline intrusion also hurts households' livelihoods and adaptability, especially the agricultural livelihood vulnerability of coastal inhabitants to the shocks caused by salinity intrusion, so many households are concerned about this natural disaster and have adopted some solutions [11]. However, the effectiveness of the adaptation strategies is still minimal [12,13].

In Vietnam in general and the MRD in particular, the problem of saltwater intrusion, its impact on agricultural farming systems, and farmers' adaptation to saline intrusion have been extensively studied by scholars in different fields [11,12,14,15]. However, studies on the causality of salinity intrusion on outcomes of rice production have yet to be conducted extensively. In addition, certain limitations in each study need to be filled. For example [16], used stochastic frontier analysis and data from direct interviews with households in Thua Thien Hue province - the Central region in Vietnam - to estimate rice cultivation's technical efficiency and productivity. They then analyzed the impact of saline intrusion on these indicators. However, this study was performed on a relatively small scale, so the results cannot readily be generalized to wider areas. The characteristics of each geographical area and the level of saline intrusion are different in each region. Hence, the results of this study are not highly representative for other areas, specifically the Vietnamese Mekong Delta.

[17] estimated the decrease in productivity and the increase in input costs of rice-growing households in Soc Trang province - located in the Mekong Delta under the impact of severe intrusion in the 2015/2016 crop year. The results show that households

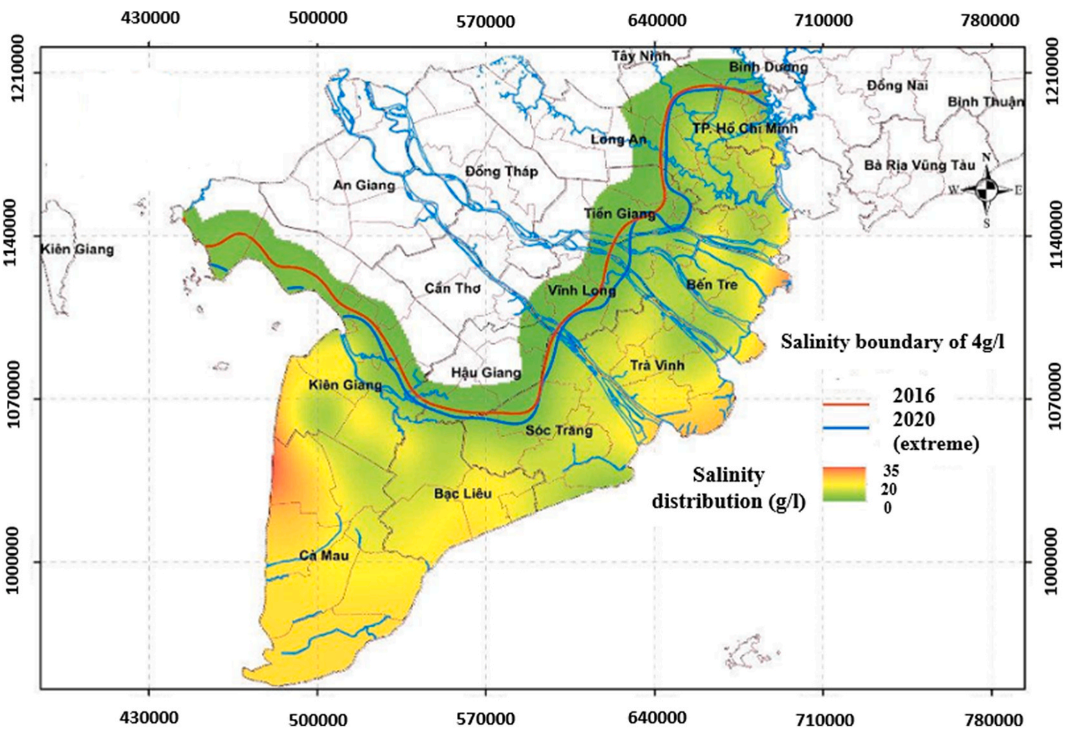

Fig. 1. The map of saline intrusion in the MRD of the period of 2016–2020.
Source: CCNDPC, 2020

affected by saline intrusion significantly decreased productivity compared to their counterpart in the unaffected area with the same natural environmental conditions and socio-economic characteristics. However, the changes in productivity and other indicators compared to years not affected by saline intrusion were not estimated in this study. In addition, this study was implemented in a relatively small area, so the results may not be representative of the whole MRD.

The earlier limitations indicate that the impact of saltwater intrusion on rice production performance, especially on the indicators to measure rice farming performance over the years under the severe influence of saline intrusion in the MRD, has not been comprehensively studied. Specifically, information on the effect of saline intrusion on changes in total production, productivity, total revenue, etc. is still limited. The previous study by Ref. [17] was carried out in some areas severely affected by the saline intrusion, so the damage caused by saline intrusion is considerable. However, the scenario may differ in the whole MRD region because the impact of saltwater intrusion in each province could be different. As a result, natural disaster adaptation policies for the entire MRD region could differ depending on severity of salinity intrusion in the various provinces.

Using data from the Household Living Standards Survey (VHLSS), this study estimates the magnitude of changes in total production, productivity, main input cost, and total revenue from rice-production in the MRD under saline intrusion. Particularly, this study uses a quasi-experimental method to identify the impact of saline intrusion on rice production for the entire MRD region. Based on the empirical results, we provide policy implications for the sustainable development of rice farming towards adaptation to climate change, specifically the saline intrusion in the MRD.

2. Saline intrusion in the Mekong river Delta in the period of 2016–2020

The impact of El Nino 2015/2016 caused the Mekong Delta to suffer the most severe saline intrusion in more than 60 years. Drought and related reductions in groundwater levels have resulted in the most widespread saltwater intrusion in 90 years [10]. Early 2016 witnessed a decrease in rainfall by 20–50% below the 10-year annual average, with no rain from January to March 2016 in the MRD. In coastal areas, saline water penetrates 20–30 km further inland than average - up to 90 km inland in some areas [18]. While an annual event, this level of saline intrusion, due to poor rainfall, reduced runoff in the Mekong River, and groundwater depletion, is the largest ever recorded. Saline intrusion causes river water to become too salty for human or animal use or irrigate crops [10]. About 244,805 ha of rice farming in the MRD were damaged or lost - 8.6% of the total rice area: Ca Mau and Ben Tre were severely damaged at about 40.6% and 30.6%, respectively [18].

Fig. 1 shows severe saline intrusion in 2016 and 2020; the salinity intrusion boundary line of these two years extends more than 90 km inland in some areas. The year 2016 witnessed the most extreme inland saline intrusion in history; most of the coastal provinces of the Mekong Delta had a salinity of 4 g/l or more, a level that would affect rice farming and other crops. Therefore, rice farming was most severely damaged by the saline intrusion, as reported by the Ministry of Agriculture and Rural Development [19].

The data exhibited in Fig. 2 shows that most of the coastal provinces in the Mekong Delta have suffered damages from saltwater intrusion, especially in Ben Tre, Tra Vinh, and Ca Mau, with losses ranging from 12 to 40.6% of the total grown area. Also, according to the 2016 MARD report, the damaged or lost productivity of households ranges from 30% to 70%, even many farmers lose entirely.

The 2019/2020 season saw another serious saltwater intrusion, causing damage to rice production at the MRD. The cause of this saltwater intrusion is that the rainy season in 2019 in the Mekong River basin appeared late, the rainy season duration was short, and the total flow volume of this year was only medium-low. The flow from the upstream in the dry season has decreased rapidly, falling to a deficient level compared with the average document of many years from 1980 to the present [20]. Two important upstream factors that dominate water sources and saline intrusion in the 2019/2020 dry season in the MRD are the storage in Tonle Sap and the flow to

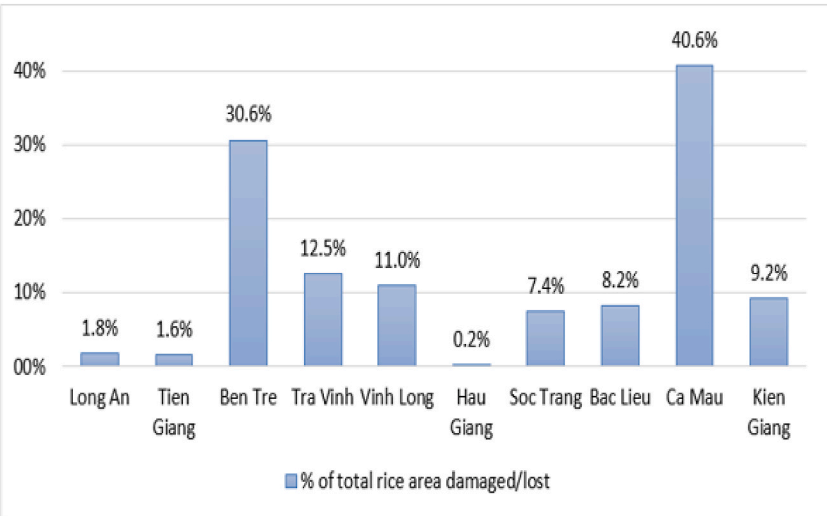

Fig. 2. Hectares of rice crops affected by the saline intrusion in 2016 - % of the total rice area grown. Source: CCNDPC, 2016.

Kratie (the beginning of the Mekong Delta). The water flow to the MRD is seriously deficient compared to the average of many years, even lower than the whole year 2015–2016 (the year of the most extreme saline intrusion ever recorded). It was the leading cause of early, deep, and prolonged saltwater intrusion in the dry season 2019/2020. This salinity intrusion has caused severe damage to the provinces of Ca Mau, Ben Tre, Tra Vinh, Soc Trang, Kien Giang, and Vinh Long, with yield losses of 30%–70% [21].

3. Methodology

To identify the impact of salinity intrusion on rice production, we use the difference-in-difference (DID) method. The DID method is the quasi-experimental method with individual panel data that uses certain groups exposed to the variable of interest and others not exposed to the variable of interest. This approach, transparent and often at least superficially reasonable, is well-suited to estimating the effects of dramatic changes in the economic environment or changes in government policy or a standard tool in program evaluation literature [22–25]. The value of treatment effect is the difference between two potential outcomes, with the potential outcome being a function of treatment status [26]. Since the units are never observed in both the treated and untreated states [27,28], identification requires comparing treated units with those in the comparable untreated group.

This study applied the DID estimation method, which has been commonly used by the previous studies in assessing the effectiveness of policies, the effects of natural disasters, etc. [29–31]. This method compares measured outcomes of interest before and after treatment between treated and control groups while controlling for observed covariates. The significant advantage of this approach is that observed and unobserved time-invariant confounding variables, which can be correlated with the treatment and outcome of interest, are reduced in the regression [30].

Denote h as a binary variable indicating affected by the saline intrusion, h equals 1 if a household is affected by the saline intrusion, and h equals 0 if otherwise. Further, let Y denote the observed value of rice production outcomes. This variable can have two potential values depending on the value of h. $Y = Y_1$ for $h = 1$, and $Y = Y_0$ for $h = 0$. Each household reports their rice production outcomes before and after being affected by the saltwater intrusion where Y_{1t} represents rice production outcomes of the affected households and Y_{0t} represents rice production outcomes for the unaffected farmers. Variable t is a dummy that takes the value of 1 if the year is affected by the saline intrusion, takes the value of 0 if the saline intrusion does not affect rice farming in that year. For unaffected households, expected rice production outcomes is determined by specific household characteristics, ηh, and time effects experienced by all households, γ. Therefore, the rice production outcomes equation for each

$$Y_{0t} = \eta h + \gamma * t + \varepsilon_{0t} \tag{1}$$

unaffected household is:

$$Y_{ht} = \eta h + \gamma * t + \beta D_{h*t} + \varepsilon_{ht} \tag{2}$$

We add a dummy, D_h, to represent for the saline intrusion's effect to rice production outputs equation.

Where β is the effect of the saline intrusion on rice production outcomes. This is followed by the difference of the expected rice production outcomes by unaffected households before and after being affected by the saline intrusion.

$$E(Y_{ht}|h = 0, t = 0) - E(Y_{ht}|h = 0, t = 1) = \gamma_0 - \gamma_1 \tag{3}$$

$$E(Y_{ht}|h = 1, t = 0) - E(Y_{ht}|h = 1, t = 1) = \gamma_0 - \gamma_1 + \beta \tag{4}$$

and the difference of the expected rice production outcomes by affected households before and after being affected by the saline intrusion.

From here, we can estimate changes in rice production outcomes under the saline intrusion's effect by estimating the average treatment effect on the treated

$$E(Y_{ht}|h = 0, t = 0) - E(Y_{ht}|h = 0, t = 1)$$

$$-E(Y_{ht}|h = 1, t = 0) - E(Y_{ht}|h = 1, t = 1) = \beta \tag{5}$$

Let i and t indicate the household i and year t, respectively. The DID with the regression specification can be written as:

$$Y_{it} = \beta_0 + \beta_1 Group_i + \beta_1 Time_t + \beta_{DID}(Group_i * Time_t) + \beta X_{it} + \delta(Region) + a_i + \mu_{it} \tag{6}$$

where Y_{it} represents the outcome variables of interest: total production, productivity, total revenue, and total main input cost. These are considered essential and common indicators used to measure the efficiency of rice cultivation in previous studies [13,16,17,30]. These outcomes are also known that they are frequently affected by natural disasters that have been shown by previous studies [16,17]. $Group_i$ is a dummy that takes the value of 1 if the household affected by saline intrusion (treatment group), takes the value of 0 if the household is not affected by saline intrusion (control group). $Time_t$ is a dummy that takes the value of 1 if the year is affected by the saline intrusion, takes the value of 0 if the saline intrusion does not affect rice farming in that year. X_{it} is a vector of control variables for sociodemographic characteristics; these variables include household size, gender, age, ethnic group, education, qualifications, and living place of the household's head, credit access, irrigation service access, total farming area. The term *region* is a region dummy to capture the region fixed effect, which addresses unobserved factors that changed across the regions. The term a_i represents unobserved time-invariant individual household heterogeneity that may be correlated with the treatment and other unobserved characteristics

(μ_{it}). Household-level error is captured by μ_{it}. Finally, β_{DID} is the interaction coefficient between $Group_i$ and $Time_t$, which is the estimate of interest captures the impact of saline intrusion on the measured outcomes.

4. Data

This study utilizes data from the Household Living Standards Survey (VHLSS) that is surveyed every two years in Vietnam. According to the Ministry of Agriculture and Rural Development [32], saltwater intrusion seriously affected rice farming in the coastal provinces of the Mekong Delta in the 2015/2016 and 2019/2020 crop years. Therefore, this study takes advantage of the VHLSS dataset in 2014 and 2016 to extract 567 and 518 households in the two years, respectively, in 13 provinces of the Mekong Delta to analyze the impact of saltwater intrusion on the performance of rice farming. In 2014, rice cultivation was not affected (or very slightly affected) by the saline intrusion, while the year 2016, specific areas were seriously affected by the saline intrusion in the MRD.

This study divided households in the 2-year panel data into two groups presented in Table 1 – G0 (control group) and G1(treatment group) to analyze the impact of saltwater intrusion on rice production performance. G0 is the group which was not affected by saline intrusion during the two years; G1 is the group that was affected by saline intrusion in 2016 but was not affected by saline intrusion in 2014.

The selection of households representing the control and treatment groups was based on the salinity level and salinity boundaries in the MRD regions in 2015/2016 because the loss of rice productivity depends on the salinity level. Rice is considered to be a relatively salt-tolerant crop. The threshold for NaCl tolerance of rice is EC = 4 dS/m (2.56 g/l) [33]. According to Ref. [34], the salt tolerance threshold of rice is EC = 3 dS/m (1.92 g/l). Rice yield reduces by 10–15% if EC > 4 dS/m (>2.56 g/l), and the magnitude of damage is even by 20–50% if EC > 6 dS/m (>3 g/l) [35]. Therefore, the selected households representing the treatment group are located in the areas with salinity level ranging from 2.5 to 3 g/l or more; this is the salinity level affecting rice growing and reducing rice yield significantly. According to Fig. 3, the areas with a salinity level of 2.5 g/l or more are mostly in the coastal provinces, including Ca Mau, Ben Tre, Tra Vinh, Bac Lieu, Soc Trang, and some areas of Long An, Tien Giang, and Kien Giang provinces. Therefore, the treated units were selected in these areas. The untreated households (control group) were chosen in areas with salinity levels below 2 g/l, where there was no or minimal effect on rice farming.

The mean difference test of the potential covariates of the two groups is shown in Table 2. It aims to examine the balance between treated and control groups in 2014. The results show that most variables are well balanced except for two variables: irrigation service access and farming area. In areas which is not subject to saline intrusion, generally there is a better irrigation system, namely a system of canals that carry more water for irrigation and drainage. Therefore, households' ability to access irrigation services in these areas is higher than households located in areas which is affected by the saline intrusion. We also controlled for this variable in the DID analysis by including them as covariates. In addition, the rice fields are extensive in the provinces located deep inland, so the arable land ownership of households in these areas is also substantial. Meanwhile, rice fields are often smaller in some provinces or regions affected by saline intrusions, such as Tra Vinh, Ben Tre, and Ca Mau. However, there was no significant difference in the mean values of the measured outcomes between the treatment group and the control in 2014. Compared with 2016, the difference in these outcomes between the two groups was much lower.

The simple difference-in-difference relies on sample means calculated step by step based on equations (1)–(5). Table 3 illustrates the difference-in-difference in the outcomes of rice production. Our treatment group decreased their total production and productivity by 20% and 13%, respectively after being affected by the saline intrusion. However, these two outcomes stay relatively unchanged in the control group between these two periods. The treatment group's total revenue and net revenue decreased in the year affected by the saline intrusion. The reductions of these indicators are 14.46% and 23.7%, respectively; however, there is only a relatively small change in total main input cost. In contrast, these indicators are relatively stable in the control group.

5. Empirical results

5.1. The impact of saline intrusion on total production and productivity of rice farming

The empirical results of the impact of the saline intrusion on the interest outcomes are estimated based on equation (6). The empirical results of the impact of the saline intrusion on the total production and productivity are presented in Table 4. The findings show that all the coefficient of interest show significant negative signs, indicating that households that were affected by saline intrusion have significantly lower total rice production and productivity (at the 0.01 level of significance) than non-affected

Table 1
The number of households in both treated and control groups.

Household	VHLSS (2014[n])	VHLSS (2016[a])	Panel data (2014, 2016)
G_0	337	328	131
G_1	230	190	73
Total	567	518	204

Note: [n] the year not affected by the saline intrusion.
[a] The year affected by the saline intrusion.
Source: the VHLSS from 2014 to 2016.

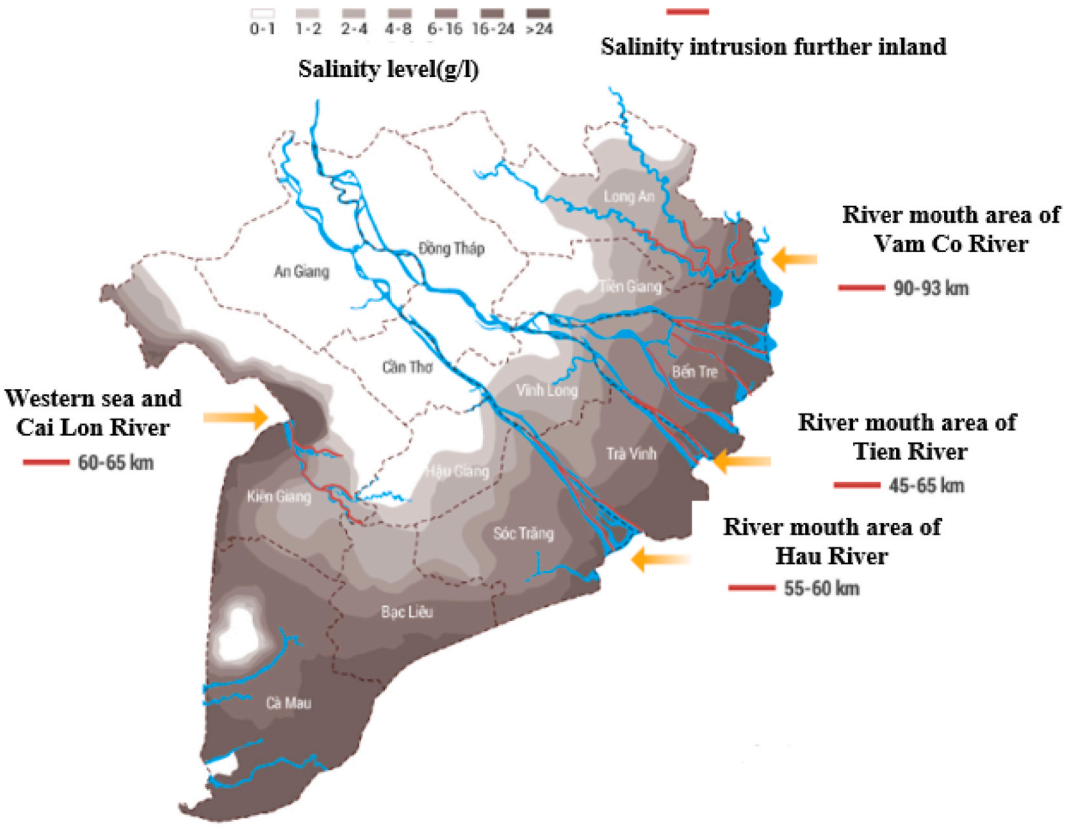

Fig. 3. Salinity distribution in the MRD under the saline intrusion in 2015/2016.
Source: Vietnam academy for water resource, 2015.

Table 2
The mean difference in characteristics of households and the measured outcomes between the treatment group and control group in 2014.

Variables	G_1 (affected) Treatment group			G_0 (unaffected) Control group			Difference		
	Obs	Mean	S.D	Obs	Mean	S.D	Obs	Mean	S.E
Household size (person)	73	4.16	1.37	131	4.25	1.27	204	0.09	0.19
Head's gender (1 = male)	73	0.82	0.39	131	0.82	0.39	204	0.01	0.06
Head's age (year)	73	49.79	10.96	131	51.21	12.71	204	1.41	1.77
Head's ethnic group(1 = Kinh group)	73	0.88	0.33	131	0.94	0.24	204	0.06	0.04
Head's education(from grade 1–12)	73	5.38	3.74	131	5.35	3.75	204	0.03	0.55
Head's qualification (from primary – doctoral degree)	73	0.99	1.34	131	1.05	1.64	204	0.07	0.23
Living place (1 = urban, 0 = rural)	73	0.05	0.23	131	0.12	0.33	204	.08	0.04
Credit access (1 = access, 0 = not access)	73	0.14	0.35	131	0.18	0.38	204	0.04	0.05
Irrigation service access (1 = access, 0 = not access)	73	0.05	0.23	131	0.33	0.47	204	0.27***	0.06
Farming area (hectare)	73	2.51	2.18	131	3.21	3.17	204	0.70*	0.42
Total production (kg/household)	73	16446.96	15167.48	131	20098.92	20618.59	204	3651.95	2754.20
Productivity (kg/ha)	73	6167.72	1302.51	131	6210.60	817.63	204	42.87	148.59
Total revenue (1000 VND/ha)	73	33023.61	7384.15	131	31353.57	4029.67	204	1670.04	798.45
Total main input cost (1000 VND/ha)	73	15319.62	5207.91	131	15041.78	3440.50	204	277.85	607.23
Net revenue (1000 VND/ha)	73	17703.98	6836.37	131	16311.79	4142.75	204	1392.19	768.75

Notes: ***, * represent statistical significance at 1%, 10%, respectively.
Source: The author's calculation from VHLSS from 2014 to 2016.

households.

The result shows evidence of the negative impact of saline intrusion on rice production performance. The total production of affected households is, on average 2914.59 kg per household lower than that for comparable non-affected households. The damage caused by saline intrusion in 2016 has also resulted in a severe decrease in productivity - leading to a lower total production of households affected by the saline intrusion. For large-scale producers, the decreased amount could not have a significant impact on

Table 3
The difference in difference in outcomes (by the sample means).

Outcomes	Groups	Before (2014)	After (2016)	Difference in difference
Total production (kg/household)	Treatment	16446.96 (15167.48)	13158.06 (12420.50)	3288.9
	Control	20098.92 (20618.59)	20951.12 (27570.66)	
Productivity (kg/ha)	Treatment	6167.72 (1302.52)	5360.31 (1413.57)	807.41
	Control	6210.59 (817.63)	6147.72 (1017.42)	
Total revenue (1000 VND/ha)	Treatment	33023.61 (7384.15)	28247.99 (8014.60)	4775.62
	Control	31353.57 (4029.67)	31402.59 (5865.38)	
Total main input cost (1000 VND/ha)	Treatment	15319.62 (5207.91)	14746.66 (5180.67)	572.96
	Control	15041.78 (3440.50)	14538.40 (3550.39)	
Net revenue (1000 VND/ha)	Treatment	17703.98 (6836.37)	13501.34 (6771.13)	4202.64
	Control	16311.79 (4142.75)	16864.18 (4810.75)	

Source: The author's calculation from VHLSS from 2014 to 2016.

Table 4
Estimated results comparing the measured outcomes between the treated and control groups.

Variables	Total production				Productivity			
	Model Without Fixed Effect		Model With Fixed Effect		Model Without Fixed Effect		Model With Fixed Effect	
	Coef	S.E	Coef	S.E	Coef	S.E	Coef	S.E
Time dummy	889.34*	492.24	904.13**	515.34	−39.61	104.92	−78.33	110.50
Treat G_1 vs. G_0	1613.07**	666.22	–	–	162.16	158.71	–	–
Treat G_1 vs. G_0 * Time	−2901.97***	813.05	−2914.59***	814.95	−718.29***	172.79	−761.47***	174.75
Household size (person)	−123.24	177.55	−270.67	412.62	45.21	43.21	−24.00	88.48
Head's gender (1 = male)	485.79	647.92	4220.95	2838.01	349.23**	161.70	−382.33	608.55
Head's age (year)	10.54	21.39	73.05	91.22	0.05	5.32	7.72	19.56
Head's ethnic group(1 = Kinh group)	−612.02	860.76	−5631.52*	3250.27	258.87	214.43	73.72	696.95
Head's education(from grade 1–12)	65.46	97.95	94.28	150.00	12.62	22.73	16.07	32.16
Head's qualification (from primary – doctoral degree)	−80.49	235.96	−711.88*	442.43	−2.61	56.18	−29.13	94.87
Living place (1 = urban, 0 = rural)	−498.38	816.91	–	–	−45.18	206.58	–	–
Credit access (1 = access, 0 = not access)	384.68	676.20	1456.86	1103.87	236.51	158.55	96.42	236.70
Irrigation service access (1 = access, 0 = not access)	2010.50***	597.81	3145.57**	1410.60	549.15***	145.56	222.78	302.47
Farming area (hectare)	6825.98***	78.43	6902.22***	144.88	44.33**	18.64	−10.66	31.07
Constant	−2558.40	1708.25	−3198.65	6230.98	5064.33***	422.42	6058.92***	1336.09
Household Fixed Effect	–		Yes		–		Yes	
Region Fixed Effect	–		Yes		–		Yes	
R-squared	0.96		0.95		0.20		0.04	
Observation	408		408		408		408	

Notes: ***, **, * represent statistical significance at 1%, 5%, and 10% respectively.

their livelihoods, but for small producers, this level of damage has a severe effect on their livelihoods. Therefore, it could be challenging for small-scale farmers with a production area of less than 1 ha to maintain their livelihood by cultivating rice.

The results also show that the rice productivity of affected households is, on average, 761.47 kg per hectare lower than that for comparable non-affected households. The results of this study are consistent with several studies by Refs. [16,17,36] whose findings that salinity intrusion greatly influences rice yield of the MRD provinces. However, compared with previous studies, the magnitude of saline intrusion's effect is lower given that this study was conducted at a bigger scale in the MRD with varying levels of yield losses caused by the saline intrusion. Meanwhile, some previous studies only surveyed a few localities heavily affected by saltwater intrusion, so that the damage would be more significant. Rice cultivation productivity decreased by about 10–15% in some areas. However, the rice yield decreased by 50%, even up to 70% in areas with high salinity intrusion (Ministry of Agriculture and Rural Development, 2016). Given the impact of saline intrusion, the areas severely damaged by saline intrusion in 2016 and 2020 have gradually converted from rice farming to other farming models such as shrimp and salt-tolerant crops. In some regions with lower salinity intrusion, farmers often intercrop in agriculture, such as rice-shrimp or rice with other crops.

5.2. The impact of saline intrusion on total revenue, total main input costs and net revenue of rice farming

Table 5 shows the results of the analysis on the effects of saline intrusion on revenue, total main input costs, and net revenue. The findings indicate that the coefficient of interest shows negative sign, and they are statistically significant except for the outcome of main input cost. It means that affected households have lower total revenue, and net revenue of rice farming than comparable non-affected households. The total revenue of affected households is, on average, 4969.84 thousand VND per hectare lower than that of the comparable non-affected group. The group's net revenue affected by saline intrusion is also 4933.48 thousand VND lower than that

Table 5
Estimated results comparing the measured outcomes between the treated and control groups.

Variables	Total revenue				Total main input cost				Net revenue			
	Model Without Fixed Effect		Model With Fixed Effect		Model Without Fixed Effect		Model With Fixed Effect		Model Without Fixed Effect		Model With Fixed Effect	
	Coef.	S.E	Coef.	S.E	Coef.	S.E	Coef.	S.E	Coef.	S.E	Coef.	S.E
Time dummy	225.79	601.81	−69.21	631.46	−462.52	371.93	−494.96	390.21	698.71	577.41	425.75	68.65
Treat G_1 vs. G_0	2580.67***	902.34	–	–	1229.50**	599.64	–	–	1358.19*	822.98	–	–
Treat G_1 vs. G_0 * Time	−4705.57***	991.32	−4969.84***	998.57	−27.15	611.47	−36.37	617.08	−4679.34***	952.42	−4933.48***	962.51
Household size (person)	386.77	245.45	−113.53	505.59	41.13	163.59	−17.46	312.43	351.18	222.20	−96.07	487.33
Head's gender (1 = male)	1188.83	916.65	−2165.25	3477.47	962.45	622.10	941.30	2148.95	263.35	820.09	−3106.54	3351.89
Head's age (year)	−2.05	30.16	59.83	111.77	46.66**	20.43	68.87	69.07	−47.90*	27.02	−9.04	107.74
Head's ethnic group(1 = Kinh group)	1486.10	1215.75	−3052.84	3982.63	−147.08	823.89	2441.54	2461.12	1792.43*	1088.63	−5494.38	3838.81
Head's education(from grade 1–12)	106.90	129.60	51.16	183.80	78.08	83.79	74.11	113.58	30.26	119.89	−22.95	177.16
Head's qualification (from primary – doctoral degree)	70.22	319.68	−19.77	542.12	−46.82	210.06	−63.55	335.01	127.52	292.29	43.78	522.54
Living place (1 = urban, 0 = rural)	−279.46	1169.72	–	–	482.17	801.71	–	–	−732.97	1040.02	–	–
Credit access (1 = access, 0 = not access)	1933.80**	903.34	205.99	1352.59	1528.34***	587.66	1595.18*	835.85	553.78	831.77	−1389.19	1303.75
Irrigation service access (1 = access, 0 = not access)	2358.29***	826.84	863.94	1728.43	2717.34***	551.32	1685.66	1068.11	−357.71	748.32	−821.73	1666.01
Farming area (hectare)	130.53	106.09	−191.48	177.52	96.34	69.63	−114.32	109.70	15.62	97.08	−77.16	171.11
Constant	25303.35***	2396.18	34047.36***	7634.96	9932.76***	1617.78	8073.72*	4718.13	15136.90***	2152.42	25973.64***	7359.24
Household Fixed Effect	–		Yes		–		Yes		–		Yes	
Region Fixed Effect	–		Yes		–		Yes		–		Yes	
R-squared	0.15		0.17		0.15		0.05		0.10		0.001	
Observation	408		408		408		408		408		408	

Notes: ***, **, * represent statistical significance at 1%, 5%, and 10% respectively.

of comparable unaffected households. Meanwhile, the production cost of the total main inputs of both groups was not statistically different. Most of the main input costs of households in different areas for rice cultivation are relatively similar, so the difference in the costs between these two groups is meager if considered on a large scale. On the other hand, the period of rice affected by saltwater intrusion is usually 1–2 weeks after the flowering stage. At the same time, most of the main input costs are allocated backward from this stage; the costs from this stage onwards are relatively low. Thus, if the rice is affected by saltwater intrusion and leads to damage, farmers would not continuously invest from the stage. However, farmers may use more fertilizers and pesticides to stimulate the growth of rice plants at the early stages. Therefore, there is no significant difference between main input costs between two groups.

5.3. The impact of saline intrusion on rice production in different regions

To identify the heterogenous effects of saline intrusion on rice production, we further examine whether saline intrusion has different effects on rice production across the different regions. Based on the severity of the saline intrusion, we separate farm households into two groups – severely affected regions and less severely affected regions. Table 6 represents the DID results across different regions.

Regarding the total production per household, the total production of affected households is, on average 2377.91 kg per household lower than that for comparable non-affected groups in the severely affected regions or the regions with high salinity levels. Meanwhile, this figure is 2996.49 kg per hectare in the less severely affected sites or the regions with lower salinity levels. The damage caused by saline intrusion in the total production per household is higher in regions with lower salinity levels. The reason is that households in lower salinity level regions would have higher rice cultivation areas than households in high salinity level areas, so the total loss per household would be higher. However, it does not mean that the magnitude of the saline intrusion's effect in regions with high salinity levels is lower since, in terms of productivity loss per hectare, the damage would be more significant in areas with higher salinity levels. The rice productivity of affected households is, on average 890 kg per hectare lower than that for non-affected households in regions with higher salinity. Meanwhile, this figure is nearly 596 kg per hectare in lower salinity regions.

Table 7 shows that the total revenue loss in regions with higher salinity level is higher than in areas with lower salinity level. The total revenue of affected households is, on average, 6227.46 thousand VND per hectare, more deficient than that for the comparable non-affected group in the higher salinity regions. Whereas, in areas with lower salinity, the total revenue of affected households is almost 3872 thousand VND, more inferior than the comparable control group. However, there is virtually no significant difference in the net revenue loss amongst regions with different levels of salinity intrusion. Compared with households not affected by the saline intrusion, the loss in net revenue of affected households is roughly the same in various regions.

6. Conclusions and policy implications

The MRD provinces face increasingly severe saline intrusion in Vietnam. This natural disaster has negatively impacted rice production and agricultural farming systems in this area over the years. This study analyzes the impacts of saline intrusion on rice production performance by employing the difference-in-difference (DID) method with the VHLSS household level panel data. Our

Table 6
Estimated results comparing the measured outcomes between the two groups in different regions.

Variables	Total production				Productivity			
	Severe affected regions		Less severe affected regions		Severe affected regions		Less severe affected regions	
	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.
Time dummy	897.13	548.97	693.24	528.20	−62.26	111.97	−85.85	106.18
Treat G_1 vs. G_0	–	–	–	–	–	–	–	–
Treat G_1 vs. G_0 * Time	−2377.91**	1170.57	−2996.49***	1089.02	−890.09***	238.76	−596.35***	218.92
Household size (person)	−208.98	537.58	−446.86	443.67	118.53	109.66	−22.53	89.19
Head's gender (1 = male)	6501.32	3443.70	−613.96	4002.94	−496.76	702.41	−148.40	804.70
Head's age (year)	98.47	98.63	118.66	118.08	14.95	20.12	7.74	23.74
Head's ethnic group(1 = Kinh group)	−13224.15	5933.73	−2163.70	4167.75	−990.43	1210.30	937.66	837.83
Head's education(from grade 1–12)	163.68	201.36	243.18	177.55	16.93	41.07	39.61	35.69
Head's qualification (from primary – doctoral degree)	−1082.10	600.53	−1039.28	576.85	−20.92	122.49	−64.06	115.96
Credit access (1 = access, 0 = not access)	1665.02	1404.22	1018.72	1241.82	129.94	286.42	90.61	249.64
Irrigation service access (1 = access, 0 = not access)	2678.90	1660.35	2621.67	1613.01	73.17	338.66	115.31	324.26
Farming area (hectare)	6908.32***	167.53***	7002.89***	158.42	2.88	34.17	−1.15	31.85
Constant	102.20	7990.37	−4647.54	8520.21	6033.38***	1629.79	5068.66	1712.80
Household Fixed Effect	Yes		Yes		Yes		Yes	
Region Fixed Effect	Yes		Yes		Yes		Yes	
R-squared	0.925		0.956		0.027		0.040	
Observation	330		340		330		340	

Notes: ***, **represent statistical significance at 1%, 5%, respectively.

Table 7
Estimated results comparing the measured outcomes between the two groups G_1 and G_0 in different regions.

Variables	Total revenue				Net revenue			
	Severe affected regions		Less severe affected regions		Severe affected regions		Less severe affected regions	
	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.	Coef.	S.E.
Time dummy	64.71	630.13	37.01	595.31	444.10	637.65	494.41	581.25
Treat G_1 vs. G_0	–	–	–	–	–	–	–	–
Treat G_1 vs. G_0 * Time	−6227.46***	1343.61	−3872.00	1227.41	−4835.35***	1359.65	−4952.64***	1198.41
Household size (person)	968.90	617.06	−7.02	500.06	304.37	624.42	117.54	488.24
Head's gender (1 = male)	−3500.99	3952.84	−2052.82	4511.64	−3618.54	4000.04	−2084.24	−4405.05
Head's age (year)	96.80	113.22	−42.93	133.09	40.70	114.57	−58.63	129.95
Head's ethnic group(1 = Kinh group)	−5474.56	6811.01	481.50	4697.39	−7400.74	6892.34	−4497.34	4586.41
Head's education(from grade 1–12)	−16.08	231.13	156.60	200.11	−40.07	233.89	104.71	195.38
Head's qualification (from primary – doctoral degree)	300.56	689.32	−183.86	650.15	142.77	697.55	−173.91	634.80
Living place (1 = urban, 0 = rural)	–	–	–	–	–	–	–	–
Credit access (1 = access, 0 = not access)	44.07	1611.83	199.32	1399.64	−1230.29	1631.08	−1225.45	1366.57
Irrigation service access (1 = access, 0 = not access)	196.95	1905.83	−281.87	1817.99	−2682.05	1928.58	−961.53	1775.04
Farming area (hectare)	−31.47	192.29	−170.60	178.55	0.36	194.59	−151.07	174.33
Constant	29965.72***	9171.73	35542.56	9602.98	23843.63**	9281.25	25721.45	9376.10
Household Fixed Effect	Yes		Yes		Yes		Yes	
Region Fixed Effect	Yes		Yes		Yes		Yes	
R-squared	0.019		0.0003		0.163		0.007	
Observation	330		340		330		340	

Notes: ***, **represent statistical significance at 1%, 5%, respectively.

findings suggest that saline intrusion negatively affects rice farming's total production, productivity, revenue, and net revenue in the MRD provinces. More specifically, the farm households affected by saline intrusion have lower total production of approximately 2914.59 kg per year and lower productivity on average of 761.47 per hectare, compared to the comparable unaffected group. The affected group has lower total revenue of approximately 4969.84 thousand VND per hectare and lower net revenue on an average of 4679.34 thousand VND per hectare compared to the unaffected group. Furthermore, the results also show the heterogeneous effect of saline intrusion across regions. Specifically, the productivity and total revenue loss in the severely affected regions is more extensive than in the non-severely affected regions. In contrast, the loss in total production is more considerable in the non-severe areas due to the larger scale of production compared to the production scale of the severely affected regions.

To better adapt to the increasingly severe saline intrusion and to minimize the damage caused by this disaster, it is essential to address appropriate solutions from the relevant management agencies. Given correct effect measures of salinity intrusion on farm production, management agencies should promptly forecast and provide information on the saline intrusion so farmers can develop a suitable schedule for rice farming. In 2016, high salinity intrusion was at the late stage of rice growth. Therefore, early cut-off dates for harvesting rice or changing the planting schedule one month earlier could help farmers avoid stretching the crop into periods of high salinity by late March and April. Although forecasting and providing information on intrusion scenarios have been carried out since the severe saltwater intrusion event in 2016, it is still crucial to continue implementing this solution by updating information on weather and climate changes, specifically saline intrusion. Evaluate the effectiveness of transformed models of sustainable agricultural production towards adaptation to salinity intrusion and replicating the effective production models in other areas similarly affected by this natural disaster. It is possible to replace rice farming with better salt-tolerant crops or cultivate in combination models such as rice-shrimp, rice-other crops, etc., to reduce the risk of farming. In fact, in some locality, farmers have converted from rice farming to these production models, and these conversion models were evaluated with relatively high efficiency [37,38]. These recommendations have also been considered in Resolution 120/NQ-CP dated November 17, 2017 of the Government of Vietnam on sustainable development of the Mekong River Delta in response to climate change and restructuring of the agricultural sector.

However, this study still has certain limitations. Although the study is conducted in a large-scale region, the number of observations in the panel data is relatively low because it is only based on available VHLSS data. Therefore, this may affect the representativeness of the study results. On the other hand, because only based on available data, some control variables that can affect the outcomes of rice production, such as rice variety, arable land quality, etc., are not included in the research model, which may lead to certain biases in the estimates. Although there have been many studies on the effects of salinity intrusion and various adaptation measures for different areas affected by salinity intrusion, information on the effectiveness of each adaptation in different regions is still minimal. In this study, the authors only mentioned the specific impact of saline intrusion on rice production and recommended some solutions for rice farmers. Therefore, future studies need to focus on assessing the effectiveness of adaptations, thereby selecting sustainable adaptation solutions for each region.

Funding

This work was supported by Korea Ministry of Environment as "The SS(Surface Soil conservation and management) projects [grant number 2019002820004].

Data: The data that support the findings of this study are available from Vietnam General Statistics Office. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of Vietnam General Statistics Office.

Author contribution statement

Keo Sa Rate Thach: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Ji Yong Lee: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper. My Trang Ha; Cao Minh Tuan: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Rodolfo Nayga; Jae-E Yang: Analyzed and interpreted the data; Wrote the paper

Data availability statement

The authors do not have permission to share data.

Declaration of competing interest

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

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