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ARTICLE

Impact of Climate Change on Rice Production: New Empirical Evidence at Province Level in Vietnam

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ABSTRACT

Climate change is a pressing issue that poses severe threats to the development of the agricultural sector worldwide. Vietnam's agricultural system, especially rice cultivation, is no exception. This study employs an Error-Correction Model (ECM) to analyze the long-term and short-term effects of climate change factors, namely temperature and rainfall, on rice production across all 63 Vietnamese provinces between 2010 and 2023. The empirical findings show that there is a long-term relationship between climate factors, rural population, and rice production. Specifically, temperature factor negatively affects rice yields in both summer-autumn and winter-spring seasons, while the negative effect of rainfall factor is observed for annual average rice and summer-autumn rice crops among provinces in Vietnam. The empirical findings also show that of the human capital factor strongly enhances the provincial rice output in Vietnam. Moreover, the effects of climate change factors on rice production significantly vary across six regions in Vietnam. Building on these empirical findings, the paper provides several policy implications aimed at reducing the potential risks of climate change and contributing to the sustainable development of not only Vietnam's agriculture sector but also the nation's economy.

Keywords: Climate Change; Rice Production; Error Correction Model; Vietnam

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1. Introduction

Agriculture has long been regarded as one of the most important sectors contributing to Vietnam's socio-economic development [1, 2]. According to Vietnam Chamber of Commerce and Industry [3] the agriculture sector accounted for approximately one-fourth of the country's GDP, demonstrating its role in shaping Vietnam's economic structure. Aside from its economic contributions, agriculture sector is critical to maintaining Vietnam's social stability since it serves as a key source of employment. In 2022, the agriculture industry supported the livelihoods of 33.06 % of the total population, equivalent to nearly 17.6 million people in rural areas [4].

Undoubtedly, climate change has emerged as a serious threat to agricultural system since its productivity is heavily dependent on favorable climatic and natural conditions [5]. Among agroecosystems, rice cultivation seems to be more vulnerable to climate change [6–8]. The increase in average temperature, precipitation and other extreme weather events could lead to various adverse phenomena, including drought, flood, and salinity intrusion, resulting in soil degradation, water scarcity, and even biodiversity loss, ultimately damaging cultivation habitats and disrupting rice production stages [2, 9–12]. Rice is the primary staple food for Vietnamese people, making up around 94% of arable land and being cultivated across all regions [2]. Specifically, the Mekong Delta is the leading contributor to national rice production, accounting for 56% of the total output, followed by the Red River Delta, the Central Coast Region, and other regions including the Northeast, Northwest, Central Highlands, and Southeast, with 16%, 14% and 14% [13]. In 2020, the rice output of Vietnam reached approximately 42.7 million tons of rice, positioning itself as the world's fifth-largest rice producer and second-largest rice exporter [14]. This emphasizes the importance of Vietnamese rice production in maintaining national food security and global food supplies [15]. However, Vietnam's agriculture systems are extremely vulnerable to climate change and natural threats due to its complex topography with a long coastline of approximately 3,260 kilometers [1, 16–18]. Climate change scenarios outlined by the Ministry of Natural Resources and Environment in 2009 anticipated that rice yield decreases ranging from 4.2% to 12.5% by the year 2030 [19]. Similarly, a study by Dat and Thu [20] estimated that spring rice yields in the Red River Delta could decline by 3.7% in 2020 and by 16.5% by 2070, while summer rice productivity is expected to fall by 1% in 2020 and by 5% by 2070. Additionally, the authors also highlighted the detrimental impact of sea-level rise, projecting that a one-meter increase could result in the loss of approximately two million hectares of rice-growing land or 50% of the country's total rice production area. Besides, the increase in salinity intrusion in some agriculture hotspots is another major concern. According to Global Facility for Disaster Reduction and Recovery [21], rising salinity levels in coastal regions like the Mekong Delta and Red River Delta could reduce agricultural productivity by 3.4% to 6.7% by 2025. Since climate change is anticipated to continue devastating Vietnam's rice productivity, threatening national food security and rural livelihoods, therefore studying its effects on rice production has become an essential concern.

In recent years, a growing body of literature on the impacts of climate change on rice production has been explored. Numerous studies have considered this relationship in China [22–25], Nepal [26–28], and other countries [29–31]. In Vietnam, many studies have examined the impact of climate change on rice production in Vietnam, most rely on either national or regional data, which may overlook substantial heterogeneity across locations [1, 2, 5, 15, 32–38]. Vietnam's provinces differ greatly not only in economic and social conditions but also in geography, climate exposure, and adaptive capacity, so aggregated analysis risks overlooking important local patterns. In addition, much of the existing literature concentrates on specific regions such as the Mekong Delta or Central Coast regions, providing valuable insights but limiting the generalizability of findings to the whole country. By using panel data from all 63 provinces, our study provides a more comprehensive and representative assessment. This approach enables us to capture variations in the impacts of climate change across ecological and socio-economic contexts, thereby offering new empirical evidence and more nuanced policy implications for both local and national adaptation strategies to mitigate the adverse effects of climate change, thereby enhancing the resilience of rice production systems, and ensuring national food security.

The research is organized as follows: Section 2 reviews the literature. Section 3 describes data and methodology while Section 4 discusses the main findings. The conclusion and policy recommendations are presented in Section 5.

2. Literature Review

In existing literature, the relationship between climate change and rice production has been extensively studied by scholars worldwide, even though it remains a controversial topic. Utilizing a panel data from 1984 to 2008, Karn [27] examined the effects of three main factors of climate change (temperature, precipitation and humidity) on different stages of rice production in 20 major rice-growing districts in Nepal. The author identified a non-linear relationship between maximum daily temperature and rice yields. More specifically, an increase in maximum temperature during the ripening phase enhances rice yields up to a critical threshold of 29.9°C. However, beyond this threshold, further increases in temperature could reduce rice yields. Notably, the average maximum temperature in Nepal during this period was estimated at 30.8°C, emphasizing the adverse impact of rising temperature on rice production. Additionally, the excessive rainfall pattern during the nursery stage negatively influences rice growth. Likewise, higher morning humidity was found to impair rice development, whereas afternoon humidity contributed positively to its growth. These findings supported earlier research by Rai, Ale, and Alam [39], who used CERES-Rice model to simulate the rice yield under different climate change scenarios. Sharing the line of research, Devkota and Paija [26] explored the long-run relationship and short-run dynamics between paddy yields and climate variables employing Autoregressive Distributed Lag (ARDL) model. Their research provides strong evidence of a long-term relationship among the variables. Moreover, rainfall plays an important role in improving Nepalese rice productivity, with a 1 mm increase in rainfall enhancing rice yields by 0.65%. Meanwhile, no visible effects of maximum and minimum temperature on rice productivity have been observed. More recently, Rayamajhee, Guo, and Bohara [28] found that a 1°C increase in average summer temperature leads to a decline of 4183 kg in rice yield. Besides, the high frequency of extreme precipitation severely impacts the production capacity of rural households in Nepal.

Considering the case of China, Chen, Zhou, and Zhou [22] analyzed provincial data spanning 1961 to 2010 and revealed a positive relationship between average temperature and single cropping rice production. However, the opposite pattern has been observed for double cropping rice. Interestingly, a drop in the diurnal temperature range has a more profound impact on single cropping rice production, reducing it by approximately 3.0% compared to a 2.0% loss for double cropping rice. In addition, the increase in rainfall might boost single cropping rice production. Similar outcomes could be found in a study by Chen, Zhang, and Tao [40]. Expanding the scope of research, Pickson, He, and Boateng [25] investigated the long term and short-term impacts of climate change on rice production in 30 Chinese provinces. The empirical findings showed that in the long run, average temperature has a negative effect on rice production, whereas average rainfall positively influences rice yields. In contrast, average rainfall has no substantial effect on national rice production in the short run. Furthermore, cultivated area and fertilizer usage serve as key drivers of rice production in the long term. Nevertheless, in the short term, cultivated areas remained a significant positive contributor, while the effect of fertilizer usage on rice production was negligible. Besides, the different effects of climate change on rice yield among regions have been thoroughly explored in numerous studies [41–44].

Applying the Ricardian model and farm household data, Masud et al. [31] examined how climatic factors including temperature and precipitation influence Malaysian rice production during main and off seasons. They demonstrated that temperature, rainfall, farm size, educational knowledge, land area and value of labour input significantly affect rice productivity. Additionally, the research also revealed heterogeneous effects of climate change on household net income among seasons. Specifically, a slight increase in temperature could raise household net revenue during the main season while decreasing revenue during the off-season. Conversely, precipitation positively impacted household revenue in the off-season but had a negative effect during the main season. Another study conducted by Zainal et al.[45] strengthened these outcomes, emphasizing the vulnerability of Malaysia's agricultural systems to climate change.

Focusing on Pakistan, Chandio, Magsi, and Ozturk[46] used time series data to investigate the effects of changing climatic conditions on rice yields from 1968 to 2014 and demonstrated that carbon dioxide emissions (CO2) and the average temperature have a positive impact on rice crops in both the long and short run. Similarly, the area under cultivation has a favorable impact on rice productivity over both timeframes. Meanwhile, the effects of fertilizer use differed. Fertilizers used improved rice output in the long run but had a detrimental impact in the short term. In contrast, the negative influence of temperature has been seen in the case of Thailand[47].

In Vietnam, many studies have employed simulation methods to anticipate changes in rice yield under different climate scenarios in a single province or agriculture zone[5, 15, 32–38, 48]. Meanwhile, other studies use panel data to investigate this relationship. For example, Chung, Jintrawet, and Promburom[19] applied Ordinary Least Square model (OLS) to explore the impact of seasonal climatic factors on rice production in two different growing seasons in the Nam Dong District, Central Highland of Vietnam from 1986 to 2012. They found that seasonal average rainfall positively influenced rice yields, while seasonal average maximum temperatures adversely affected yields in both the winter-spring (WS) and summer-autumn (SA) seasons. In contrast, seasonal average minimum temperatures positively impacted WS rice yields but had no visible effect on SA rice production. Lately, Nguyen, Ho, and Pham[49] examined how seasonal climate change impact rice production in nine districts of Thua Thien Hue province utilizing a Feasible Generalized Least Squares (FGLS) model. Their findings indicated that a 1% increase in maximum temperature improved WS yields by 1.66% while reducing SA yields by 1.01%. Likewise, a 1% increase in minimum temperature lowered WS yields by 0.30% but significantly enhanced SA yields by 3.32%. In addition, there exists a positive relationship between maximum and minimum humidity and rice productivity in these areas. However, maximum precipitation had an adverse impact on SA yields.

Despite the growing body of literature on the relationship between climate change and rice production in Vietnam, no empirical study has comprehensively investigated this relationship across all 63 provinces. Our research aims to address this gap by examining the effect of climatic factors such as temperature and precipitation on rice production in 63 Vietnamese provinces, providing valuable insights to policymakers and households on how to mitigate climate risks, contributing to the sustainable development of agriculture sector while maintaining food security in Vietnam.

3. Methodology and Data

3.1. Data

To scrutinize the relationship between the climate change factors and rice production at the provincial level in Vietnam, data are mainly collected from the provincial annual yearbooks that are published annually by the provincial statistics offices of Vietnam from 2010 to 2023. In cases, local data are missing, we cross-check with the statistical data from the General Statistics Office of Vietnam (GSO) and Ministry of Agriculture and Environment (MAE) to guarantee the credibility and validity of dataset. Similarly, outliers, particularly in precipitation and temperature were also cross-checked with statistical data from GSO and MAE. Noted that if the extreme figures were consistent with official data such as unusually high rainfall during typhoon years, we retained them, as they reflect genuine climate shocks rather than data errors. As is common in the existing literature, two climate change factors used for analysis are average temperature and rainfall, while three indicators of rice production are aggregate rice output, wet-season rice output, and dry-season rice output. Noted that the choice of rural labour as the main production factor, this decision is primarily driven by data availability and the central role of labour in rice cultivation in Vietnam.

After handling data issues, we have balanced panel data for all 63 provinces and six economic regions for the period of 2010–2023.

3.2. Econometric Specification

In this paper, to examine the effects of climate change factors on the rice production at the provincial level in Vietnam, we employ the error-correction model (ECM) for estimation. Of course, this approach has some advantages compared to other dynamic models. First, the ECM approach allows us to examine the short- and long-run effects of climate change factors on rice production, to determine the speed of temporary adjustment towards long-run equilibrium and handle the cointegration. Second, the ECM approach can work well even in the case of different orders of integration. Last but not least, as indicated by Pesaran, Shin, and Smith[50], the ECM approach deals well with small samples. Also noted that the ECM approach has been widely applied in recent literature on climate change and agriculture such as Kilicarslan and Dumrul; Sequeira, Santos, and Magalhães; and Ghosh, Eyasmin and Adeleye[51–53].

Following the seminal works such as Dell, Jones, and Olken; Bond, Leblebicioğlu, and Schiantarelli[54–56], we consider an aggregated production function of the simple agriculture industry, say rice industry, which depends on labor and climate change factors, and is formed as follows:

$$Y_{it} = e^{\alpha_1 TEMP_{it} * \alpha_2 RAIN_{it}} RULA_{it}^{\alpha_3} \tag{1}$$

Where *i* and *t* are provincial individuals and time periods respectively; Y is vector of rice production, including annual average aggregate rice output (*AGRI*), and the rice outputs of its two main rice seasons: the Winter-Spring Season or wet-season (*WET*) and the Summer-Autumn Season or dry-season (*DRY*). Noted that these two seasons define the main rice cultivation periods in Vietnam, with variations depending on geographical location and climate conditions. $RULA$ is a rice production factor, proxied by total number of rural labors; TEMP and RAIN, two common climate change factors, are average temperature and average rainfall, respectively. We noted that the exponential forms of climate change factors and the linear form of physical production factors in the aggregate production function are similar to the contribution by Sequeira, Santos, and Magalhães[52] and Dell, Jones, and Olken[55]. However, our approach differs in several ways. First, we proxy physical production factors by rural labor instead of population in Dell, Jones, and Olken[55] and capital in Sequeira, Santos, and Magalhães[52]. It is more meaningful to consider rural labor in the production function of the rice industry, as it is a key determinant of agricultural production growth, especially in developing countries like Vietnam, where physical labor plays a crucial role. In addition, we analyze a dynamic model that rice output changes over time. Last but not least, we consider cross-provincial data rather than cross-national data. The weather and geography vary significantly among countries, which could lead to biased results with cross-national data. By considering cross-provincial data, our approach can better distinguish the unique differences in the effects of weather and geography on rice production between provinces. These differences make the contributions of the paper to the economic effects of climate change more significant in literature.

Taking a logarithmic form, equation (1) can be expressed explicitly as follows:

$$\begin{aligned} LnAGRI_{it} = \alpha_0 + \alpha_1 TEMP_{it} + \alpha_2 RAIN_{it} \\ + \alpha_3 LnRULA_{it} + \gamma_i^{'} \theta_t + \varepsilon_{it}, \end{aligned} \tag{2}$$

Where, θ_t is characteristics of province that commonly affect the rice production, and γ_i refers to province-specific effects. The ECM specification of equation (2) for estimation then is exhibited as follows:

$$\begin{aligned} \Delta LnAGRI_{i,t} = \alpha_0 + \rho_i[\delta_1 LnAGRI_{i,t-1} \\ -(\delta_2 TEMP_{i,t-1} + \delta_3 RAIN_{i,t-1} \\ + \delta_4 LnRULA_{i,t-1} + \gamma_i^{'} \theta_{t-1})] \\ + \sum_{j=0}^{h} \varPhi_{2i} \Delta TEMP_{i,t-j} \\ + \sum_{j=0}^{k} \varPhi_{3i} \Delta RAIN_{i,t-j} \\ + \sum_{j=0}^{r} \varPhi_{4i} \Delta LnRULA_{i,t-j} \\ + \sum_{j=0}^{s} \lambda_i^{'} \Delta \theta_{t-j} + \epsilon_{it} \end{aligned} \tag{3}$$

where δ and $\varPhi$ represent the long-run and short-run effects between rice production, climate change factors (temperature and precipitation), and physical rural labor of provinces. ρ_i is the speed of adjustment parameter towards to the long-run equilibrium. Note that the

ECM requires $\rho_i < 0$, otherwise there is no error correction model. h, k, r, s are the optimal lags of each variable. From a theoretical perspective, the short-run adjustment of rice production to climate shocks is expected to materialize within one period, making a single lag sufficient. Empirically, we tested longer lag specifications, but they yielded no additional explanatory power and introduced potential multicollinearity. Therefore, we use the most common lag across the provinces, say $h, k, r, s =$ 1, 0, 0, 0 that provides a parsimonious representation to balance explanatory adequacy and model efficiency [52]. γ and λ are province-specific effects.

4. Empirical Results

4.1. Descriptive Statistics

The summary of descriptive statistics in **Table 1**. The figures show that the provincial average rice yields for the aggregate, wet season, and dry season are 687.32, 148.99, and 322.13 thousand tons, respectively. The highest rice yields are 4643, 716.4, and 2224.5 thousand tons, while the lowest are 25, 0.2, and 0.2 thousand tons, respectively. These figures indicate a huge gap in rice production among provinces in Vietnam.

Table 1. Summary of descriptive statistics.

Variable	Obs	Mean	Std. dev.	Min	Max	Variable	Obs	Mean	Std. dev.	Min	Max
Country											
AGRI	819	687.32	869.44	25.00	4643.00						
WET	819	148.99	134.53	0.20	716.40						
DRY	819	322.13	414.48	0.20	2224.50						
TEMP	819	25.11	2.18	15.70	30.30						
RAIN	819	1898.82	769.67	1.24	6965.70						
RULA	819	977.96	644.54	122.88	4297.15						
Region 1						Region 4					
AGRI	143	586.02	291.83	194.30	1220.30	AGRI	65	253.91	210.61	61.80	780.70
WET	143	265.49	131.41	105.50	581.50	WET	65	145.02	121.81	37.60	438.70
DRY	143	320.41	162.17	84.50	638.80	DRY	65	102.83	92.55	24.20	342.00
TEMP	143	24.22	1.30	16.70	25.40	TEMP	65	23.14	2.44	18.10	26.10
RAIN	143	1736.37	337.71	699.00	2724.30	RAIN	65	1988.03	266.46	1471.10	2722.80
RULA	143	1298.81	921.64	434.17	4297.15	RULA	65	806.79	377.90	294.63	1440.12
Region 2						Region 5					
AGRI	182	237.68	127.55	93.70	629.10	AGRI	78	230.55	265.90	25.00	813.00
WET	182	137.03	56.06	57.40	314.50	WET	78	84.24	87.68	10.80	272.90
DRY	182	100.65	77.00	15.20	320.00	DRY	78	72.40	88.03	9.20	281.10
TEMP	182	23.37	2.11	15.70	30.30	TEMP	78	26.88	1.27	25.11	28.80
RAIN	182	1970.69	1206.02	1.24	6965.70	RAIN	78	2025.16	410.12	1198.70	3243.00
RULA	182	705.02	325.34	246.01	1603.10	RULA	78	1032.19	547.31	402.38	2091.87
Region 3						Region 6					
AGRI	182	485.93	348.14	28.10	1516.50	AGRI	169	1851.65	1267.38	59.10	4643.00
WET	182	100.36	173.28	0.20	716.40	WET	169	147.05	111.30	0.30	473.70
DRY	182	254.88	194.70	14.90	800.10	DRY	169	834.15	625.20	0.20	2224.50
TEMP	182	25.89	1.13	23.00	28.10	TEMP	169	26.85	1.38	19.50	28.40
RAIN	182	2105.54	844.61	513.00	6319.90	RAIN	169	1643.63	444.85	120.20	2916.90
RULA	182	1016.05	806.99	122.88	3107.50	RULA	169	1000.20	338.136	369.49	1525.77

Note: Region 1: Red River Delta, Region 2: Northern Midland and Mountain, Region 3: North-Central Coast and South-Central Coast, Region 4: Central Highlands, Region 5: Southeast, and Region 6: Mekong River Delta.
Source: Authors' calculations.

Regarding climate change factors, the average temperature and rainfall in the provinces are 25.11 °C and 1898.82 mm, respectively. The lowest and highest temperatures are 15.7 °C and 30.03 °C, while the lowest and highest rainfalls are 1.24 mm and 6665.7 mm, respectively. For the rural population, the average, highest, and lowest rural populations are 977.96, 4297.15, and 122.88 thousand people, respectively. It is worth noting that some descriptive statistics in rice outputs, temperature and rainfall show unusually large ranges between provinces, these reflect Vietnam's considerable geographic diversity.

Next, we report the pairwise correlation matrix for all variables used in the regression models. The results for correlations are expressed in **Table 2**. The results show that all correlation coefficients are lower than the critical value of 0.8, suggesting that multicollinearity is not problematic in the models [57]. Given that data are ready for further analysis.

Table 2. Correlation matrix.

Variable	AGRI	WET	DRY	TEMP	RAIN	RULA	Variable	AGRI	WET	DRY	TEMP	RAIN	RULA
AGRI	1												
WET	-	1											
DRY	-	-	1										
TEMP	0.294	−0.093	0.265	1									
RAIN	−0.172	−0.176	−0.154	−0.152	1								
RULA	0.325	0.589	0.372	0.059	−0.095	1							
Region 1							Region 4						
AGRI	1						AGRI	1					
WET	-	1					WET	-	1				
DRY	-	-	1				DRY	-	-	1			
TEMP	−0.003	−0.010	0.003	1			TEMP	0.230	0.287	0.258	1		
RAIN	−0.300	−0.302	−0.296	−0.112	1		RAIN	−0.468	−0.449	−0.462	0.005	1	
RULA	0.784	0.796	0.765	0.018	−0.051	1	RULA	0.738	0.727	0.720	0.005	−0.433	1
Region 2							Region 5						
AGRI	1						AGRI	1					
WET	-	1					WET	-	1				
DRY	-	-	1				DRY	-	-	1			
TEMP	0.325	0.287	0.329	1			TEMP	−0.184	−0.178	−0.178	1		
RAIN	−0.182	−0.176	−0.173	−0.238	1		RAIN	−0.087	−0.062	−0.099	−0.048	1	
RULA	0.775	0.788	0.776	0.311	−0.167	1	RULA	0.150	0.159	0.100	−0.206	0.284	1
Region 3							Region 6						
AGRI	1						AGRI	1					
WET	-	1					WET	-	1				
DRY	-	-	1				DRY	-	-	1			
TEMP	−0.324	−0.253	−0.414	1			TEMP	−0.006	0.148	−0.034	1		
RAIN	−0.202	−0.238	−0.094	−0.344	1		RAIN	−0.033	0.225	0.001	0.104	1	
RULA	0.729	0.723	0.772	−0.398	−0.088	1	RULA	0.489	−0.241	0.485	0.202	−0.178	1

Note: Region 1: Red River Delta, Region 2: Northern Midland and Mountain, Region 3: North-Central Coast and South-Central Coast, Region 4: Central Highlands, Region 5: Southeast, and Region 6: Mekong River Delta.
Source: Authors' calculations.

4.2. Cross-Province Dependency

Working with a panel time series, the characteristics of cross-province dependency strongly affect subsequent tests and analyses, as this attribute potentially influences the identification of empirical specifications and the economic inferences of estimated results [58]. Thus, we first perform the Pesaran test (CD test) to check whether cross-province dependency exists when considering the impact of climate change factors on rice production in Vietnam. The results of the cross-province dependency test are shown in **Table 3**. The statistical values of the CD tests for all three models, including aggregate rice production (AGRI), wet-season rice production (WET), and dry-season rice production (DRY), present strong evidence of cross-province dependency. Further tests and analyses in this paper are based on the characteristics of cross-province dependency.

4.3. Unit Root Tests

Theoretically, checking the stationarity of variables is necessary to determine the presence of cointegration. As is common in the time series literature, the ECM model requires the series to be integrated at level I(0) or at first difference I(1), or both. As indicated in the previous section, the data used in this paper exhibits characteristics of cross-province dependence. Therefore, to identify the order of the series, we perform Pesaran Panel Unit Root Test with cross-sectional dependency, so-called the Pesaran's CIPS test, to check the stationarity of the time series in the regression models [59]. The results of the unit root tests are presented in **Table 4**. The results show that all variables are stationary at either the level or at the first difference, suggesting that the ECM models are appropriate for use in this paper.

Table 3. Cross-dependency test.

Model	CD Test	*p*-Value
Aggregate rice production	17.659	0.000
Wet-season rice production	15.531	0.000

Table 3. *Cont.*

Model	CD Test	*p*-Value
Dry-season rice production	14.457	0.000

Source: Authors' calculations.

Table 4. Unit root test results.

Variable	Test	Pesaran Panel Unit Root Test with Cross-Sectional Dependency						
		Country	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
LnAGRI	Level	−2.72**	−2.35	−3.49***	−2.92**	−2.40	−2.32	−3.10***
	1st difference	−3.93***	−3.61***	−4.21***	−4.22***	−2.57*	−3.30**	−4.05***
LnWET	Level	−2.59***	−2.26***	−2.31***	−2.39***	−3.36***	−2.94***	−3.94***
	1st difference	−4.12***	−3.62***	−4.32***	−3.35***	−5.97***	−4.01***	−4.87***
LnDRY	Level	−2.57	−3.03***	−3.23***	−2.86*	−2.81*	−3.31**	−2.44
	1st difference	−4.01***	−3.85***	−4.11***	−3.98***	−4.06***	−3.32***	−3.60***
TEMP	Level	−2.66**	−2.24	−3.06**	−2.62	−2.73	−3.02**	−3.31**
	1st difference	−3.44***	−4.27***	−4.74***	−2.75*	−3.74***	−4.54***	−3.55***
RAIN	Level	−3.81***	−3.53***	−3.47***	−3.62***	−4.49***	−3.91**	−3.23***
	1st difference	−4.67***	−3.61***	−4.11***	−3.88***	−5.97***	−4.37***	−4.96***
LnRULA	Level	−2.59*	−2.61	−1.86	−2.49	−2.27	−2.55	−3.45***
	1st difference	−3.38***	−4.15***	−1.99*	−3.49***	2.79*	−2.60*	−3.51***

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; Region 1: Red River Delta, Region 2: Northern Midland and Mountain, Region 3: North-Central Coast and South-Central Coast, Region 4: Central Highlands, Region 5: Southeast, and Region 6: Mekong River Delta.
Source: Authors' calculations.

4.4. Cointegration Tests

For panel times series with the characteristics of cross-sectional dependence, we use the Westerlund test to check the long term cointegration between the climate change factors and the rice yields at the provincial level in Vietnam [60]. The Westerlund test was developed by Westerlund [61] and widely applied for testing the presence of cointegration in panel data. Especially, the Westerlund is not only a suitable technique to handle panel data but also robust to cross-sectional dependency [60]. Under the Westerlund test, null hypothesis (H0) is no integration, and alternative hypothesis (H1) is all panes are cointegrated. The Westerlund test results for cointegration are exhibited in **Table 5**. The results show that we reject H0 and accept H1, indicating that all panels are cointegrated. Therefore, there exist long term relationships between the dependent variable of rice production (aggregate rice production, wet-season rice production and dry-season production) and independent variables of climate change factors (temperature and rainfall) and the number of rural populations.

4.5. Estimated Results

The short-run and long-run effects of climate change and rural population factors on the rice production at the provincial level in Vietnam are reported in **Table 6**, where model (1), (2) and (3) are the estimated results for aggregate rice production (AGRI), the dry-season rice production (DRY), and the wet-season rice production (WET), respectively. We first note that the error correction coefficients, ρ-ECM(−1), for all three models are negative and statistically significant at the 1 percent level, verifying the appropriateness of the ECM model for estimation in this paper.

Table 5. Westerlund test for cointegration.

	Statistic	*p*-Value
Aggregate rice production	−2.854	0.002
Wet-season rice production	−1.588	0.046
Dry-season rice production	−5.699	0.000

Table 5. *Cont.*

	Statistic	*p*-Value
Region—Aggregate rice production		
Region 1	−0.227	0.041
Region 2	1.855	0.032
Region 3	−0.317	0.037
Region 4	0.313	0.037
Region 5	−1.479	0.049
Region 6	1.329	0.009

Note: Region 1: Red River Delta, Region 2: Northern Midland and Mountain, Region 3:North-Central Coast and South-Central Coast, Region 4: Central Highlands, Region 5: Southeast, and Region 6: Mekong River Delta.
Source: Authors' calculations.

Table 6. Estimated results.

Variables	(1) AGRI	(2) DRY	(3) WET
Long-run results			
TEMP	−0.010*** (0.002)	−0.007*** (0.002)	−0.007*** (0.002)
RAIN	−0.000** (0.000)	−0.000** (0.000)	0.000*** (0.000)
LnRULA	0.357*** (0.034)	0.654*** (0.042)	0.754*** (0.022)
Short-run results			
D.TEMP	−0.010 (0.008)	−0.006 (0.007)	−0.025 (0.022)
D.RAIN	−0.000* (0.000)	−0.000 (0.000)	0.000 (0.000)
D.LnRULA	−0.951 (0.839)	3.141 (5.871)	−2.494 (2.134)
Constant	1.475*** (0.184)	0.320*** (0.097)	−0.105 (0.122)
ρ-ECM(−1)	−0.404*** (0.049)	−0.427*** (0.051)	−0.420*** (0.054)

Note: Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Model (1), (2) and (3) estimates for the dependent variables of aggregate rice production (AGRI), dry-season rice production (DRY), and wet-season rice production (WET), respectively.
Source: Authors' calculations.

For long-run effects, as shown in the first panel of **Table 6**, the estimated coefficients for temperature (TEMP) in all three models are negative and statistically significant. This suggests that all other things being equal, an increase in temperature could reduce aggregate rice production, dry-season rice production, and wet-season rice production in the provinces of Vietnam. The long-run negative relationship between temperature and rice production can be explained as follows: First, rice is sensitive to temperature, particularly when rainfall exceeds the rice's absorption capacity, leading to lower rice productivity. Second, higher temperatures often lead to water scarcity, which can decrease rice yields, especially in provinces that rely heavily on irrigation for rice farming. Third, elevated temperatures create favorable conditions for the growth of pests and diseases, which negatively impact rice cultivation. These findings align with conclusions from studies on Vietnam and other countries, such as Nguyen and Scrimgeour; Anh, Anh, and Chandio [62, 63], and among others.

Next, the estimated coefficients for rainfall (RAIN) in all three models are statistically significant, but show different signs: negative for aggregate rice production and wet-season rice production, and positive for dry-season rice production. Specifically, an increase in rainfall would lead to a decrease in aggregate rice production and wet-season rice production, but an increase in dry-season rice production. Intuitively, the contradictory effects of precipitation reflect the characteristics of Vietnam's seasonal distinction that during the wet season, excessive rainfall can cause flooding and reduce yields, while in the dry season, precipitation alleviates water shortages and thus benefits rice production. These results are consistent with findings of Nhan, Trung, and Van Sanh; Huong, Bo, and Fahad [64, 65] for Vietnam, as well as with those of Kilicarslan and Dumrul [51] for Turkey.

The estimated coefficients for rural population factor are positive and statistically significant at the 1 percent level, indicating that a larger rural population contributes to greater rice production. Recently, there has been a significant wave of migration from rural to urban areas, leading to a shortage of labor in the agricultural sector in the rural areas of Vietnamese provinces. Therefore, provinces with a higher ratio of rural population have more labor available for rice farming, resulting in increased rice production. Our results are contrary to the findings of Anh, Anh, and Chandio [63] and Xiang and Solaymani [66] for Vietnam and Malaysia, respectively, who explain this negative relationship by stating that Vietnamese agriculture industry is labor-intensive and still relies heavily on low-skilled labor. This suggests that the shortage of agricultural labor may be a more significant issue than the inefficiency of rural workers in Vietnam's agriculture industry in general and rice cultivation in specific.

For the short-run effects, as shown in the second panel of **Table 6**, the relationship between rice production indicators, climate change factors, and rural population varies. Only the estimated coefficient for rainfall in the aggregate rice production estimate is negative and statistically significant, while the coefficients for the other independent variables are statistically insignificant. These short-run results suggest that rainfall has a noticeable impact on rice production, while changes in temperature and the rural population have weaker and more inconsistent effects. The significant ECM term indicates that any short-run deviations from equilibrium are gradually corrected over time.

4.6. Regional Heterogeneous Effect

Rice production in Vietnam differs across provinces due to several factors, including climate, soil fertility, irrigation systems, and agricultural practices. Provinces with favorable conditions, such as the Mekong Delta, benefit from ample rainfall and rich soil, leading to higher yields. In contrast, areas facing water scarcity or extreme weather conditions often experience reduced production. Labor availability also plays a significant role, as rural migration can lead to shortages in the agricultural workforce. Furthermore, variations in government policies, infrastructure, and access to modern farming technologies contribute to disparities in productivity, creating notable regional differences in rice production across the country [67]. Therefore, it is believed that there exist heterogeneous effects of climate change factors and rural population on rice production in different provinces in Vietnam. We provide empirical evidence on regional heterogeneous effects for the aggregate rice production in **Table 7.** Note that all tests were conducted to assess the appropriateness of the ECM approach.

The results in **Table 7** indicate that the long-run relationship between rice production, climate change, and the rural population is confirmed by almost all models, although the estimated results vary significantly. These findings are consistent with Sequeira, Santos, and Magalhães [52], which examines the heterogeneous effects of income levels and climate regimes at the country level. The effects of temperature differ across regions, largely due to variations in agro-ecological conditions, cropping season, and adaptive practices. For example, higher temperatures may accelerate crop growth in cooler northern provinces but exacerbate heat stress in already warm southern regions. We also observed the regional heterogeneous effects of climate change factors on the dry- and wet-season rice yields in Vietnam. To save space, we do not report the estimated results, but they are available upon request.

Table 7. Regional heterogeneous effect: Aggregate rice production.

Variables	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6
Long-run results						
TEMP	−0.050*** (0.004)	0.023*** (0.004)	0.028** (0.012)	−0.1213 (0.000)	0.023** (0.010)	0.014*** (0.004)
RAIN	−0.000*** (0.000)	0.000** (0.000)	0.000 (0.000)	−0.0480 (0.000)	0.000** (0.000)	−0.000*** (0.000)
LnRULA	0.571*** (0.044)	0.089 (0.096)	0.076 (0.077)	−0.8643 (0.000)	−1.080*** (0.208)	0.644*** (0.204)
Short-run results						
D.TEMP	0.006 (0.006)	−0.009*** (0.003)	0.008 (0.006)	0.009 (0.013)	−0.085 (0.075)	−0.002 (0.006)
D.RAIN	0.000* (0.000)	0.000 (0.000)	−0.000*** (0.000)	0.000 (0.000)	−0.000 (0.000)	−0.000 (0.000)
D.LnRULA	−0.340	−0.210	−2.723	−1.573	0.277	−2.101
Constant	2.027*** (0.658)	1.730*** (0.561)	3.137*** (0.478)	1.317 (1.073)	6.441*** (1.661)	0.918*** (0.240)
ρ - ECM(−1)	−0.531*** (0.172)	−0.368*** (0.118)	−0.652*** (0.096)	−0.000 (0.000)	−0.510*** (0.135)	−0.375*** (0.078)

Note: Standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; Region 1: Red River Delta, Region 2: Northern Midland and Mountain, Region 3:North-Central Coast and South-Central Coast, Region 4: Central Highlands, Region 5: Southeast, and Region 6: Mekong River Delta.
Source: Authors' calculations.

5. Conclusion and Recommendations

Applying the error-correction model (ECM), this research investigates the long-term and short-term effects of climate change on rice production across 63 provinces in Vietnam over the period of 2010–2023. The findings demonstrated the existence of a long-term relationship among climatic factors, rural population and rice yields. Higher temperature could reduce rice productivity during the wet and dry seasons, while increasing rainfall pattern negatively affected average annual rice yield and summer-autumn rice yield. Interestingly, no visible effect of precipitation was found during winter-spring season. Besides, the rural population had a positive influence on rice yields, highlighting the vital role of human capital in enhancing rice productivity in the face of climate variability. Additionally, the effects of climate change on rice productivity varied by region.

Based on above findings, several policy recommendations have been proposed to address the challenges posed by climate change while strengthening the sustainability of rice production in Vietnam. First, the government should provide financial incentives and technical support to encourage farmers to adopt modern water management practices such as drip irrigation, automated irrigation systems, and groundwater recharge supplies. These innovations could optimize water use, ensuring the efficient management of freshwater resources needed for rice cultivation, particularly during drought seasons. Moreover, upgrading drainage infrastructure is necessary to mitigate waterlogging in low-lying regions, preserving ideal conditions for rice farming to cope with the negative effects of excessive rainfall. In addition, the government should prioritize investments in research and development to generate rice varieties that are resistant to temperature extremes, flooding, drought, and pests, reducing the vulnerability of rice production. Finally, the government should implement strategic programs aimed at diversifying agricultural production, promoting crop rotation and encouraging the cultivation of alternative crops alongside rice, maximizing agricultural productivity and safeguarding national food security.

Given the heterogeneous effects observed across regions, the government should implement climate change adaptation strategies that are not only tailored to the specific development conditions of each region in terms of infrastructure, environment, and socio-economic contexts but also aligned with national agricultural development goals. By adopting region-specific solutions, the government could support farmers dealing with climate change challenges and promote long-term agricultural sustainability. In particular, temperature increases have a significantly negative long-run effect in the Red River Delta (Region 1), while precipitation shocks are particularly detrimental in the North-Central and South-Central Coast (Region 3). These regions would benefit most from improved irrigation systems and climate-resilient water management strategies. In contrast, the Southeast (Region 5) shows vulnerability due to both rainfall variation and labor constraints, suggesting that mechanization and labor-saving technologies should be prioritized there to address shortages. At the same time, the Mekong River Delta (Region 6) continues to depend heavily on rural labor, implying that policies to stabilize the agricultural workforce are also critical.

In general, although the study has achieved its objective and could be used as a case study for other developing countries in Asia with similar climate conditions, it is not free from limitations. First, the study period is relatively short (2009–2024), which may not fully capture long-term climate dynamics. Second, the use of annual averages may overlook important seasonal variations in temperature and precipitation that are critical for rice growth. Third, while the analysis concentrates on the relationship between climate variables and rice production, it does not explicitly account for socio-economic and technological factors such as mechanization, the adoption of drought-resistant varieties, labor migration, or market dynamics. Moreover, issues related to rice prices, quality, yield variations, and different rice types were beyond the scope of this study. These limitations suggest directions for future research to provide a more comprehensive assessment of climate impacts on rice production in Vietnam.

Author Contributions

All authors contribute equally to all parts of the manuscript, including conceptualization, methodology, validation, formal analysis, writing, reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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The data presented in this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflict of interest.

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