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Climate change and rice production: Empirical evidence from Vietnam

Vietnam has been one of the three largest exporting countries in the global rice market in the recent decades. This study conducts an in-depth analysis of the impact of climate change on rice production in Vietnam from 2002 to 2022, focusing on key climatic variables such as temperature, rainfall, sunshine, and humidity. Located in the tropical and subtropical monsoon climate, Vietnam's agricultural sector is acutely vulnerable to the growing challenges posed by climate variability. Employing robust empirical techniques, the research reveals significant correlations between climatic factors and rice yields. The findings demonstrate that rising maximum temperatures contribute positively to rice production while lowering minimum temperatures lead to reduced yields. Rainfall is shown to play a critical role in boosting productivity, whereas elevated humidity levels exert a detrimental effect. These results highlight the profound sensitivity of rice production to climatic changes, reinforcing the urgency for implementing adaptive measures and climate-resilient strategies to ensure the sustainability and stability of rice production in the face of a changing climate.

Keywords: rice production, agricultural output, climate change, cointegration test, Vietnam

JEL classifications: Q10, Q54.

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Introduction

Vietnam, centrally located in Southeast Asia and classified as an emerging economy, is already experiencing the harmful effects of climate change (Vo and Tran, 2022). With its large extent of coastline, heavy dependence on agriculture - especially in the Mekong Delta region - and situated in the Southeast Asian tropical monsoon belt, it is exposed to high precipitation and storms (Cullen and Anderson, 2017). More frequent natural disasters will shortly influence crop productivity, food security, and livelihood vulnerability. Climate change is significantly impacting livelihoods in Vietnam, affecting agriculture, tourism, health, fisheries, natural resources, and vulnerable groups. Changes in water temperatures and ocean conditions pose risks to fisheries and aquaculture, affecting fish populations and distribution (Tchonkouang *et al.,* 2024). Extreme weather events and environmental degradation harm tourist destinations, leading to increased heat-related illnesses and healthcare costs due to extreme temperatures (Effiong *et al.,* 2024) and might reduce GDP by 0.7%–2.4% by 2050 (Trinh *et al.,* 2021). Within the last two decades, the average temperature has been 0.72°C higher than in the period 1962–1990 for Northeast Vietnam (Kawagoe *et al.,* 2019). This increase in temperature could lead to a reduction in the rice growth period, which will negatively affect the absorption of some major nutrients. A 1% increase in temperature will cause a short-run drop of approximately 0.67% in rice production and 2.74% in the long run (Chandio *et al.,* 2024). In Vietnam's Mekong Delta, saltwater intrusion could harm 1.1 million hectares, or 70% of cultivated land, by 2030. A 30 cm sea level rise by 2050 might inundate 193,000 ha of rice cultivation area and salinity incursion 294,000 ha, reducing rice production by 2.6 million metric tons (Trinh *et al.,* 2021). Given Vietnam's major share in the global rice market, a drop in agricultural output could result in deteriorating regional and worldwide food shortages.

Rice cultivation faces two major challenges: feeding an ever-increasing population and adopting mitigation measures against the adverse effects of climate change through sustainable agriculture (Hussain *et al.,* 2020). As the population increases and the climate changes, the interaction between rice cultivation and climate becomes increasingly relevant, influencing arable land and crop productivity (Taniushkina *et al.,* 2024). To address these challenges, it is essential to understand how climate conditions affect rice growth and yields to design effective measures for sustaining rice production. Crop yield increment is on the main agenda for most local rice growers. This is attained by the introduction of new cultivars and reviewing existing practices in the areas of planting with a view to optimising the use of fertilisers and pesticides (Shabbir *et al.,* 2020; Nhat Lam Duyen *et al.,* 2021). However, high yields in rice cultivation require suitable natural conditions relating to humidity, temperature, sunshine, and rainfall (Firdaus *et al.,* 2020; Ding *et al.,* 2020).

In high-latitude regions, rising temperatures have improved rice yields by creating better thermal conditions in areas where low temperatures previously limited production (Liu *et al.,* 2022). In contrast, low-latitude regions, such as Vietnam, have experienced negative impacts as crops in these areas are closer to their temperature tolerance limits (Chen *et al.,* 2020). The effects of rainfall variability on rice production vary significantly across different regions and even within specific geographical areas. This can, to a very large extent, be explained by local climate, water management, and farmers' adaptation strategies and these aspects, however, require more attention with further research (Chandrasiri *et al.,* 2020;

Firdaus *et al.,* 2020). As such, there is a greater call for experimental studies conducted in various regions, especially in low-latitude regions like Vietnam, in order to understand how climatic change impinges on rice productivity.

Numerous studies have examined the impact of climate change on rice production (Wassmann *et al.,* 2009a; Yang *et al.,* 2017; Tan *et al.,* 2021; Zhou *et al.,* 2021; Yin *et al.,* 2022; Wei *et al.,* 2023), where most concentrate on specific regions and often neglect critical variables. While temperature and rainfall are frequently analysed (Chandio *et al.,* 2021), there are very few studies investigating the influence of climatic factors such as sunshine, wind, CO2, and humidity on crop yields (Tchonkouang *et al.,* 2024). Moreover, much research has employed crop simulation models and field trials (Ding *et al.,* 2020; Chandio *et al.,* 2021); nevertheless, econometric methods have largely been overlooked. For Vietnam, some studies have examined the influence of climatic changes on rice production (Ho *et al.,* 2022; Vo and Tran, 2022), food security (Taniushkina *et al.,* 2024), adoption of climate-smart agriculture technologies (Tran *et al.,* 2022; Chandio *et al.,* 2024) and rice farmers' perceptions (Do Thi and Dombroski, 2022). To the best of the authors' knowledge, however, none of the available studies have examined the combined effects of climatic factors, including sunshine, rainfall, humidity, and temperature, on rice productivity in the country. Accordingly, the present study aims to examine the combined influences of climate change on rice production in Vietnam.

This study addresses two key questions. First, how does climate change impact rice production? Second, what role do climatic factors – such as temperature, sunshine, rainfall, and humidity – play in enhancing rice production in Vietnam? The findings can serve as a reference for developing countries with similar economic and climatic conditions.

This study makes three important contributions. First, the study is the first of its kind to measure the impacts of climatic factors – temperature, sunshine, rainfall, and humidity – on the rice yield of Vietnam. Second, using the cointegration test method, the study provides valuable insights for Vietnamese policymakers to boost rice exports and enhance domestic production by applying the findings. Lastly, the current study delivers an in-depth investigation into the subject and some relevant policy implications to guarantee food security and prepare farmers for the constantly changing climate.

The following sections are organised as follows: Section 2 provides a critical review of the literature. Section 3 discusses methodology and data sources. Sections 4 and 5 present the empirical findings and their interpretation. Finally, Sections 6 and 7 conclude the study with discussions and policy implications.

A brief literature review of climate change and rice production

Climate change is defined as the shift in climate patterns primarily caused by greenhouse gas emissions (Fawzy *et al.,* 2020). The impact of global warming would be an increase in the average surface temperature worldwide. This rise in temperature will then affect the hydrological cycle shifting precipitation amounts, intensity, frequency, and type of precipitation. It will also affect the amount of water vapour available within the atmosphere, thereby affecting humidity. Additionally, global warming would change atmospheric circulation and could alter wind speeds. Therefore, the climatic effects of global warming involve a much larger set of variables than just temperature and precipitation (Zhang *et al.,* 2017). The causes of climate change range from natural factors to anthropogenic factors. Natural sources encompass or linked to forest fires, earthquakes, oceans, permafrost, wetlands and volcanoes (Xi-Liu *et al.,* 2018). In contrast, human activities are mainly related to energy production, industrial processes, forestry, land use and land-use change (Yadav *et al.,* 2021).

Ninety percent of the world's rice is produced and consumed in Asia, where both irrigated and rain-fed rice ecosystems are vital for food security (Wassmann *et al.,* 2009b). Climatic changes are already affecting agriculture, but there are still major lacunae in the understanding of how both short- and long-term climatic changes influence agricultural systems and rural livelihoods, especially for the most vulnerable populations (Yadav *et al.,* 2021). Although climate change is very likely to create some opportunities for increased production in certain regions and for specific crops, the overall impact is expected to be that of decreased agricultural outputs (Chandio *et al.,* 2021).

Pattern changes in precipitation and temperature, as reported globally, affect crop production to a great extent. This is especially so in developing regions, where economies are based on agriculture, as unprecedented climate change disrupts the economic and social sectors (Firdaus *et al.,* 2020). Dependence on climate-sensitive agriculture, coupled with limited adaptive capacity and existing socioeconomic inequalities, amplifies the impacts of climate change on nations, and those countries in lower latitudes with agrarian economies are facing especially increased vulnerability (Chakravarty *et al.,* 2020). This arises from a combination of factors, including the susceptibility of agriculture to climate change (Trinh *et al.,* 2021). Coastal erosion, increased flooding from storm surges, and saltwater intrusion into freshwater sources are major risks that further threaten livelihoods, infrastructure, and freshwater availability (Taniushkina *et al.,* 2024). This sensitivity to temperature changes is especially pronounced in regions where temperatures are already approaching the tolerance levels of staple crops, exacerbating the impacts of global warming (Firdaus *et al.,* 2020). Climate change disproportionately impacts vulnerable populations, pushing them further into poverty and food insecurity. These populations often lack the resources and capacity to adapt to climate change and make them more susceptible to displacement, food shortages, and economic hardship (Aryal *et al.,* 2020).

The effect of temperature increases on crop growth has been estimated from crop simulation and statistical analysis. A rise in temperature of 1% in both time horizons decreases rice yield by 1.01% and 2.99%, respectively (Anh *et al.,* 2023). High temperatures each day reduces rice yields by about 6% per °C if they deviate away from the ideal 28 °C. High temperatures every night have an even more significant negative influence as decreasing the yield with approximately 7% per °C if deviating from the ideal 22 °C of night-time temperature. The minimum temperature positively affects rice plants at the vegetative stage of replanting, while the maximum temperature hurts rice plants at the tillering and stem elongation stages (Abbas and Mayo, 2021). Besides this, high night-time temperatures are also related to adverse spill-over effects like milling yield and grain quality, decreasing the percentage of milled, head, and brown rice and increasing chalkiness, with the latter also coinciding with decreased contents of amylose and protein (Su *et al.,* 2023). In contrast, other studies have found that in some regions even the net effect was positive due to a moderate increase in temperature like that Northeast China faced until recently (Liu *et al.,* 2022). This distinction is very important because in most of the rice-growing areas across the world, the pace of increment in night-time temperature is very fast compared to that of the daytime temperature (Su *et al.,* 2023).

The effect of sunshine on rice yield varies over geographical areas and latitudes. Sunshine is an important weather variable in a tropical country, while changes in sunshine significantly influence crops and yields throughout the growing seasons (Firdaus *et al.,* 2020). More sunshine in north-eastern China might lead to an expansion of rice cultivation because of the increased thermal resources in colder climates like this part of China (Chen *et al.,* 2020). On the other hand, in places where the climate is hot, too much sunshine doesn't guarantee increased yield and could even have detrimental effects (Anh *et al.,* 2023). This variation underscores the importance of considering regional specificity when assessing the impact of sunshine on rice production. Solar radiation is one of the most crucial energy sources affecting crops, significantly influencing rice yields, especially during the final 35–45 days of grain ripening (Lee *et al.,* 2021). This effect is more prominent when other factors like water, temperature, and nutrients are not limited. At the ripening stage, rice needs sufficient radiation and low temperatures (Hussain *et al.,* 2020). There is a positive correlation between increased sunshine, net solar radiation and potential rice yields. In some cases, a lower average shortwave solar radiation during the growing season might increase rice yields by approximately 3% (Chen *et al.,* 2020).

One of the most important indicators for the change in climate is rainfall as it highly affects the production of rice. On the other hand, increased precipitation often leads to frequent and heavy flooding. This has been experienced in some of the most extensive rice-growing regions, such as the Mekong Delta, where the frequency of rainfall is more erratic towards the end of the wet season, which increases the chance of inundation (Ho *et al.,* 2022). The damage caused by such floods to crops and overall production is immense, as observed in Malaysia, where the floods in 2003, 2005, and 2017 resulted in significant losses in rice production, impacting farmers' livelihoods and food security at the national level (Firdaus *et al.,* 2020).

In contrast, low rainfall can cause the complete loss of harvest in areas where minor irrigation tanks dependent on rainfall are being used. Changes in rainfall can affect rice production directly due to changed rainfall, mainly reduced rainfall, through the abandonment of fields or a reduction in planting in case of inadequate water supply as was found in a study carried out in Sri Lanka (Firdaus *et al.,* 2020). The impacts of rainfall variability on rice production can vary significantly across different regions and even within specific geographical areas. While this is substantially explained by local conditions of climate, water management practices and adaptation strategies adopted by farmers, further investigation is required on these topics (Chandrasiri *et al.,* 2020; Firdaus *et al.,* 2020). Nevertheless, other research has shown the opposite findings. For example, Abbas and Mayo's study from 2021 found that rainfall negatively affects rice plants throughout the flowering and heading stages. Rainfall's detrimental effects on rice production were also noted during the ripening period when the rice was being milked. During the reproductive stage, rainfall notably affected the per capita gross domestic product (Abbas and Mayo, 2021).

Humidity directly and indirectly affects rice growth. It directly affects the water vapour content in the troposphere which can further influence photochemical reactions and thermal processes and eventually alter plant growth (Yadav *et al.,* 2021). In addition, it also impacts the plant's water content. Indirectly, humidity impacts leaf growth, photosynthesis, pollination, and the likelihood of disease (Zhang *et al.,* 2017). It impacts photosynthesis through changes in transpiration. Excess moisture increasingly co-occurs within a single growing season, impacting crop yields in global rice-growing regions (Lesk *et al.,* 2022). The higher humidity results in a reduction in transpiration and an increase in the turgor pressure, favoured by leaf expansion (Zhang *et al.,* 2017). Low humidity triggers increased transpiration, leading to water deficits that cause stomata to partially or fully close, restricting carbon dioxide intake and consequently hindering the process of photosynthesis (Zhang *et al.,* 2017). Newly harvested rice may contain about 18–26% water, and managing very wet rice at harvest time is a serious issue in most Asian countries, as high humidity can promote excessive mould growth and increase respiration rates in the grain (Tirawanichakul *et al.,* 2004).

Methodology

Climate change is significantly affecting agricultural production in Vietnam, and particularly rice cultivation, one of the country's key export commodities. Beyond its economic importance, rice farming is vital for rural livelihoods and provides extensive employment opportunities across Vietnam's rural areas. To measure the impact of climate change on rice production, several econometric models have been used. These models analyse three main dependent variables representing rice output: spring season yield, winter season yield, and annual yield.

$$\begin{aligned}\text{T\_Rice}_{it} &= \lambda_0 + \lambda_1\text{Temperature\_max}_{it} + \\ &+ \lambda_2\text{Temperature\_min}_{it} + \lambda_3\text{Rainfall}_{it} + \\ &+ \lambda_4\text{Sunshine}_{it} + \lambda_5\text{Humidity}_{it} + \varepsilon_t\end{aligned} \tag{1}$$

$$\begin{aligned}\text{S\_Rice}_{it} &= \beta_0 + \beta_1\text{Temperature\_max}_{it} + \\ &+ \beta_2\text{Temperature\_min}_{it} + \beta_3\text{Rainfall}_{it} + \\ &+ \beta_4\text{Sunshine}_{it} + \beta_5\text{Humidity}_{it} + \xi_t\end{aligned} \tag{2}$$

$$\begin{aligned}\text{W\_Rice}_{it} &= \alpha_0 + \alpha_1\text{Temperature\_max}_{it} + \\ &+ \alpha_2\text{Temperature\_min}_{it} + \alpha_3\text{Rainfall}_{it} + \\ &+ \alpha_4\text{Sunshine}_{it} + \alpha_5\text{Humidity}_{it} + \sigma_t\end{aligned} \tag{3}$$

The econometric models incorporate key climate change variables, including maximum and minimum temperature, rainfall, sunshine, and humidity in order to analyse the effects on rice yield. The estimation process follows three key steps. First, a correlation matrix analysis is conducted to examine the initial relationships among the variables. Second, to test for long-term cointegration between the variables, we employ panel cointegration tests, such as those by Pedroni, Kao, and Westerlund. According to Kao's cointegration test (Kao, 1999), the cointegration vectors in each panel are assumed to be identical. To supplement this, the authors include the Pedroni test, which allows the AR coefficients to differ between panels by permitting specific cointegration vectors. Pedroni (2004) states that tests based on clustering are considered multivariate, whereas tests based on grouping-panel statistics are called univariate.

The Westerlund test is based on the idea that each panel has its own unique slope coefficient and that the cointegration vectors are panel-specific. Models where the AR parameters are either panel-specific or consistent across panels form the foundation for the Westerlund (2005) test statistic. In this instance, the hypothesis of no cointegration is tested against the alternative hypothesis using the panel-specific AR test statistic. In contrast, the null hypothesis of cointegration is tested using the same AR test statistic (Westerlund, 2005), which asserts that all panels are cointegrated. The authors have selected the Pedroni, Westerlund, and Pedroni tests as the primary tests in the econometric models because of their comprehensive approach to cointegration testing. Third, we assess the models for diagnostic issues, including autocorrelation and heteroskedasticity. We apply the Pooled OLS method for estimation. However, if autocorrelation or heteroskedasticity is detected, the Driscoll-Kraay standard errors method is used to address these problems and estimate the functions more robustly (Driscoll and Kraay, 1998).

The data for this study were sourced directly from the official website of the General Statistics Office of Vietnam (GSO, 2024). We compiled a panel dataset from 15 provinces across Vietnam, including Lai Chau, Son La, Tuyen Quang, Hanoi, Quang Ninh, Nam Dinh, Nghe An, Thua Thien-Hue, Da Nang, Binh Dinh, Gia Lai, Lam Dong, Khanh Hoa, Ba Ria - Vung Tau, and Ca Mau. The dataset spans the period from 2002 to 2022. Because GSO has public representative agencies for collecting data in all provinces of Vietnam, this database does not have any issues such as missing data or reporting bias. Detailed definitions and units of the variables used in the analysis are provided in Table 1.

First, we discuss the descriptive statistics of rice yield. The total annual rice yield in 15 provinces has an average value of 103.2 quintals/ha. However, rice yield according to weather characteristics is different for each crop season. Spring and winter rice yields have average values of 95.97 quintals/ha and 39.83 quintals/ha, respectively. This shows that rice yield fluctuates strongly according to weather where the relatively harsh winter climate in some provinces decreases rice yield. Second, related to climate change, the maximum temperature has an average value of 28.57^{0}C and this index also fluctuates during the annual seasons with temperatures between 19.1^{0}C and 32.8^{0}C. The rainfall statistics have an annual average value of 164.4mm/month, but this index fluctuates significantly according to the times of the year from 67.25mm/month to 401.0mm/month. The average sunshine duration is 160.6 hours and this index has also a significant amplitude of fluctuation where the minimum value is 13.84 hours and the maximum value is 244.8 hours. Humidity in the provinces has the lowest value of 2.88%, and the highest is 88.41%, which is close to the average value of 81.21%.

Table 3 shows the correlation values between rice yield and the variables representing climate change in the econometric equations. Based on the Pearson correlation analysis, maximum temperature has a positive relationship with total rice yield (0.274), spring rice yield (0.138) and winter rice yield (0.112) where all the correlations of maximum temperature with rice yield are statistically significant. Minimum temperature is only significantly related to spring rice yield (-0.243) and winter rice yield (-0.125), where both

Table 1: Definition and unit of variables.

Variable	Definition and unit	Unit
T_Rice	Production of rice by province (calculated by total yield)	Quintal/ha
S_Rice	Production of rice by province (calculated by spring rice yield)	Quintal/ha
W_Rice	Production of rice by province (calculated by winter rice yield)	Quintal/ha
Temperature_max	Maximum temperature	^{0}C
Temperature_min	Minimum temperature	^{0}C
Rainfall	Monthly average rainfall	mm
Sunshine	Monthly average sunshine	Hour
Humidity	Monthly average humidity	%

Source: Authors' compilation

Table 2: Descriptive statistics.

Variable	Mean	Std. Dev.	Min.	Max.	Observations
T_Rice	103.2	56.10	1.000	197	315
S_Rice	95.97	50.71	1.000	187	315
W_Rice	39.83	11.95	10.00	65.0	315
Max_temperature	28.57	2.951	19.10	32.8	315
Min_temperature	19.81	4.190	12.40	27.0	315
Rainfall	164.6	52.58	67.25	401.0	315
Sunshine	160.6	39.13	13.84	244.8	315
Humidity	81.21	2.883	2.880	88.41	315

Source: Authors' calculation

Table 3: Correlations among variables.

Variable	*T_Rice*	*Max_T*	*Min_T*	*Rainfall*	*Sunshine*	*Humidity*
T-Rice	1.000					
Max_T	0.274*	1.000				
Min_T	-0.042	0.318*	1.000			
Rainfall	0.138*	-0.086	-0.004	1.000		
Sunshine	-0.181*	-0.363*	0.530*	-0.085	1.000	
Humidity	-0.022	0.011	-0.052	0.439*	-0.240*	1.000
Variable	*S_rice*	*Tmax*	*Tmin*	*Rainfall*	*Sunshine*	*Humidity*
S-Rice	1.000					
Max_T	0.138*	1.000				
Min_T	-0.243*	0.318*	1.000			
Rainfall	-0.019	-0.086	-0.004	1.000		
Sunshine	-0.136*	-0.363*	0.530*	-0.085	1.000	
Humidity	-0.165*	0.011	-0.052	0.439*	-0.240*	1.000
Variable	*W_rice*	*Tmax*	*Tmin*	*Rainfall*	*Sunshine*	*Humidity*
W-Rice	1.000					
Max_T	0.112*	1.000				
Min_T	-0.125*	0.318*	1.000			
Rainfall	-0.226*	-0.086	-0.004	1.000		
Sunshine	-0.188*	-0.363*	0.530*	-0.085	1.000	
Humidity	-0.253*	0.011	-0.052	0.439*	-0.240*	1.000

Note: adenotes statistical significance at the 5% level. Max_T is the Maximum temperature, Min_T is the Minimum temperature.
Source: Authors' calculation.

coefficients are negative. Rainfall has a positive and statistically significant relationship with total annual rice yield (0.138). However, rainfall has a statistically significant negative relationship with winter rice yield (-0.226), while spring rice has a negative insignificant relationship (-0.019). Sunshine has a negative and significant relationship with rice yield and this holds for total rice yield (-0.181), spring rice (-0.136) and also winter rice (-0.188). Finally, the correlation between humidity and total rice yield is negative and insignificant (-0.022), but significant in the cases of spring rice (-0.165) and winter rice (-0.253). The absolute values of the correlation coefficients in the table are not very high, but all variance inflation factors (VIF) are below 5, which indicate that the problem of multicollinearity does not appear to be a major problem in the estimations.

Results

The dataset includes numerous socioeconomic variables, some of which may exhibit stochastic trends, potentially leading to spurious inferences if not properly addressed. To ensure reliability, we check whether the panel data are stationary - that is, whether its statistical properties, such as mean and variance, remain constant over time. If the data are non-stationary, it contains a unit root, which can affect the validity of the results. Before estimation of the agricultural yield equations, we test all variables for stationarity to identify whether they are stationary at the original level (denoted as I(0)) or become stationary after differencing once (denoted as I(1)). There are two hypotheses in the testing exercises; the null hypothesis (H0) of the existence of a unit root is tested against the alternative hypothesis of no unit roots (H1). We conduct three unit root tests, which are the Breitung test, the Harris–Tzavalis test, and the PP—Fisher Chi-square test. These tests evaluate the null hypothesis (H_0) that a unit root exists (i.e., the data is non-stationary) against the alternative hypothesis (H_1) that the data are stationary.

Table 4 shows that the variables are stationary at their first differences, with significance levels of 1% or 5%. This confirms that the variables are integrated of order one, I(1), and supports the use of cointegration tests to examine long-term relationships between variables. Cointegration refers to a statistical property where non-stationary variables move together over time, maintaining a stable long-term relationship despite short-term fluctuations.

Table 4: The panel unit root test for the variables.

Variable	**Im–Pesaran–Shin test**		**Levin–Lin–Chu test**		**Breitung test**	
	Level I(0)	**First difference I(1)**	**Level I(0)**	**First difference I(1)**	**Level I(0)**	**First difference I(1)**
T_Rice	2.4361	-6.6326^{a}	-3.6653^{a}	-19.6970^{a}	2.3169	-2.0864^{b}
S_Rice	1.0957	-6.0295^{a}	-1.7815^{b}	-19.6837^{a}	2.2177	-2.1567^{b}
W_Rice	-0.0727	-9.3365^{a}	-7.9550^{a}	-17.8898^{a}	1.5390	-2.4441^{a}
Max_temperature	-0.2710	-7.0987^{a}	-2.6397^{a}	-9.7565^{a}	-1.4969^{c}	-2.5238^{a}
Min_temperature	-1.2472	-7.0638^{a}	-4.5619^{a}	-9.8534^{a}	-3.7752^{a}	-6.2562^{a}
Rainfall	-2.8225^{a}	-7.5629^{a}	-10.6426^{a}	-24.4091^{a}	-1.3324^{c}	-3.5474^{a}
Sunshine	-2.7564^{a}	-7.0628^{a}	-10.0847^{a}	-22.2293^{a}	-3.0135^{a}	-4.0091^{a}
Humidity	-1.9694^{b}	-7.4629^{a}	-7.4666^{a}	-20.0299^{a}	-2.8399^{a}	-2.3545^{a}

Notes: ^{a} , ^{b} and ^{c} indicate significance at 1%, 5%, and 10%, respectively.
Source: Authors' calculation

The panel unit root tests confirmed that all the variables in equations (1), (2), (3), and (4) are integrated at the same order, specifically I(1). In the next step, we will test whether there is a cointegration relationship between the variables in the above equations. For this purpose, cointegration tests are used to test the long-run relationship between the variables. We use Pedroni (1999), Kao (1999), and Westerlund and Edgerton (2007) cointegration tests for checking the long-run relationship between the variables. Four agricultural productivity equations will be tested in this section where all the equations are tested step by step. Table 5 shows the results of the cointegration tests. The null hypothesis (H_0) of no long-run cointegration is rejected when these statistics are significant at the 1% level. The results provide strong evidence supporting the existence of long-run relationships among the variables in all four equations, confirming their interconnectedness over time.

The cointegration test results reported in Table 5 conclude that all variables in the research equations are cointegrated. In the next step, we will determine the quantitative relationship between climate change variables (rainfall, sunshine, temperature and humidity) and rice yield (total yield, spring rice yield, winter rice yield) by estimating panel data regression models.

Before initiating the panel estimation process, we first check all output equations assessing the impact of climate change on rice yield for heteroscedasticity (unequal variance in the error terms) and autocorrelation (correlation of error terms across time). If these problems are not detected, the equations will be estimated using Fixed effects and Random effects methods. If the equations suffer from heteroscedasticity and autocorrelation, the Driscoll-Kraay standard error method will be used to estimate the coefficients of the variables. This method is specifically designed to address these issues by adjusting the standard errors, ensuring more reliable estimates. It allows for accurate assessment of the statistical significance of the coefficients, even when the error terms exhibit varying sizes or temporal correlation.

Table 6 shows the results of heteroscedasticity and autocorrelation tests. The Breusch–Pagan/Cook–Weisberg test is used to test heteroscedasticity and the Wooldridge test runs for autocorrelation problems. Based on the test results, the equations of rice yield and climate change are free of heteroscedasticity and autocorrelation. Then, the equations will be estimated using Fixed effects (FEM) and Random effects (REM) methods. The Hausman test is performed to choose between FEM and REM.

After conducting autocorrelation and heteroscedasticity tests, we found no evidence of these issues in the model. The Hausman test confirmed that the REM model provides better explanatory power and the empirical results from the REM estimation on rice yield and climate change effects are presented in Table 7.

Table 5: Panel cointegration test results.

Pedroni cointegration test		
Equation	**Statistics**	**P-value**
f(T_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	4.1154	0.0000
f(S_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	4.2727	0.0000
f(W_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	4.0635	0.0000
Kao cointegration test (Augmented Dickey–Fuller)		
f(T_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	3.3968	0.0003
f(S_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	3.8383	0.0001
f(W_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	2.7132	0.0033
Westerlund cointegration test		
f(T_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	18.0806	0.0000
f(S_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	15.0844	0.0000
f(W_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	13.0845	0.0000

Note: Kao test using the Augmented Dickey-Fuller. Pedroni test using Modified Phillips–Perron.
Source: Calculates from the study data

Table 6: Diagnostic testing results.

Function	**Heteroskedasticity**	**Autocorrelation**
f(T_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	$\chi^2(1) = 0.30$ P-value = 0.5811	F(1,14) = 3.461 P-value = 0.0840
f(S_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	$\chi^2(1) = 2.19$ P-value = 0.1390	F(1,14) = 4.472 P-value = 0.0529
f(W_Rice, Max_temperature, Min_temperature, Rainfall, Sunshine, Humidity)	$\chi^2(1) = 0.68$ P-value = 0.4089	F(1,14) = 3.469 P-value = 0.0837

Notes: Heteroskedasticity was assessed using the Breusch–Pagan/Cook–Weisberg test, while autocorrelation was evaluated using the Wooldridge test.
Source: Authors' calculation.

Table 7: The panel estimates for the models.

Independent variable	Model 1: T_Rice		Model 2: S_Rice		Model 3: W_Rice	
	Fixed effects	Random effects	Fixed effects	Random effects	Fixed effects	Random effects
Max_temperature	5.580[a]	5.740[a]	4.783[b]	5.191[a]	0.677[c]	0.674[b]
Min_temperature	-5.427[a]	-5.063[a]	-4.898[a]	-5.141[a]	-0.850[a]	-0.830[a]
Rainfall	0.163[a]	0.168[a]	0.186[a]	0.182[a]	0.014	0.013
Sunshine	0.177	0.177	0.200[c]	0.197[c]	0.013	0.011
Humidity	-4.590[a]	-4.302[a]	-5.997[a]	-5.736[a]	-0.647[a]	-0.672[a]
Constant	368.7[a]	332.6[b]	480.3[a]	453.4[a]	85.40[a]	87.59[a]
R^2	0.1125	0.1121	0.1348	0.1347	0.0632	0.0630
F test (P value>F)	35.36 (0.000)		22.49 (0.000)		65.11 (0.000)	
Hausman test (P value>χ^2)		1.39 (0.9249)		0.62 (0.9870)		1.63 (0.8976)
Provinces	15	15	15	15	15	15
Observations	315	315	315	315	315	315

Notes: [a], [b] and [c] indicate significance at 1%, 5%, and 10%, respectively.
Source: Authors' calculation.

First, the maximum temperature has a very positive impact on rice yield and is statistically significant for total rice yield (5.740), spring rice (5.191), and winter rice (0.674), respectively, at the significance level of 5% and 1%, which is consistent with the study of Liu *et al.* (2022). The closer the temperature is to the maximum, the better the rice yield. However, this impact will be stronger in spring rice, when warm weather is a favourable factor for rice growth and development.

Second, the minimum temperature has the opposite effect of negatively influencing rice yields. The regression results show that the minimum temperature affects rice yield for total rice (-5.063), spring rice (-5.141), and winter rice (-0.830), at the significance level of 1%. The impact of minimum temperature will be more significant for winter rice, and this shows that the lower the temperature, the lower the rice yield. Winter, when temperatures become more severe, will reduce the rate of photosynthesis, chlorophyll fluorescence, and dry matter characteristics, contributing to reduced rice yield (Siddik *et al.,* 2019).

Third, rainfall is a positive factor in rice yield; the impact level is respectively with total rice yield (0.168), spring rice (0.182), and winter rice (0.013). However, only the impact of rainfall on total rice yield and spring rice yield is statistically significant at the 1% level. Higher rainfall can lead to improved rice yield. Conversely, when rainfall decreases, the impact will be harmful, and insufficient water supply will cause reduced crop yields (Firdaus *et al.,* 2020).

Fourth, the impact of sunshine on total rice yield is (0.177), spring rice (0.197), and winter rice (0.011). Sunshine has a positive effect on rice yields. However, in the experimental results in Table 7, only spring rice is statistically significant at the 10% level. sunshine has a positive impact on rice yield, this result is completely consistent with the study of Chen *et al.* (2020). One of the most important energy sources for crops is solar radiation, which has a major impact on rice yields, particularly in the last 35 to 45 days of grain ripening (Lee *et al.,* 2021).

Finally, humidity has a negative impact on most rice yields. Specifically, humidity reduces total rice yield (-4.302), winter rice (-5.736), and winter rice (coefficient = -0.672). All coefficients of humidity impact on rice yield are significant at the level of 1%. This shows that increasing humidity in the air will be a harmful factor for rice yields. Humidity further affects plants' photochemical reactions and thermotrophic processes and alters plant growth (Yadav *et al.,* 2021).

Discussion

Climate change poses a significant threat to global agriculture with rice production being particularly vulnerable (Gomez-Zavaglia *et al.,* 2020; Wassmann *et al.,* 2009a). As one of the most important staple crops in the world, rice is heavily dependent on specific climate conditions, such as adequate rainfall, stable temperatures, and controlled water availability (Jagadish *et al.,* 2015; Prasad *et al.,* 2017). However, the increasing frequency of extreme weather events, rising temperatures, shifting rainfall patterns, and sea-level rise associated with global climate change are disrupting these essential conditions. It is estimated that nearly 51% of rice cultivation and production could decline over the next century as a result of global climate change (Firdaus *et al.,* 2020). Vietnam, as one of the world's largest rice producers and exporters (Maitah *et al.,* 2020; Yuen *et al.,* 2021), faces significant challenges from climate change, especially in its key rice -growing regions - the Mekong Delta and the Red River Delta. In recent years, Vietnam's climate is increasingly affected by the El Niño phenomenon and broader climate shifts, with 2023 marking the hottest year globally and recording the second-highest temperature in Vietnam's history. The highest recorded temperature in Vietnam, 44.2°C, occurred in the North Central region. Since early 2024, the country has experienced more frequent and severe natural disasters, including unusual cold spells, prolonged heatwaves, and increased salinity intrusion in the Mekong Delta. Projections by the United Nations Intergovernmental Panel on Climate Change and the World Bank suggest that a 1-meter rise in sea level could flood 0.3 to 0.5 million hectares of the Red River Delta and 1.5 to 2.0 million hectares of the Mekong Delta (Nguyen and Hens, 2019). During severe flood years up to 90% of the Mekong Delta could be submerged for four to five months, rendering large areas of rice fields unproductive due to flooding and salinisation. Additionally, the Asian Development Bank warns that a 1°C increase in temperature could result in a 10% decrease in rice productivity, posing a significant threat to national food security and affecting tens of millions of people.

The findings of the paper offer a wealth of insightful perspectives to explore and contemplate. In terms of temperature, the authors indicate a significant positive impact of maximum temperature on rice production across all models, with the effect being particularly strong for total and spring rice production. This suggests that, in the short term, rice production may benefit from warmer temperatures, especially during the growing seasons when heat accelerates crop growth and development (Hussain *et al.,* 2020). However, this positive correlation should be interpreted cautiously in the context of climate change. While moderate increases in temperature can enhance rice growth, extreme and prolonged heat waves pose serious risks to crop yields (Kaushal *et al.,* 2016; Sun *et al.,* 2019). Climate change is expected to bring more frequent and intense heatwaves, which can lead to heat stress, increased water evaporation, and reduced soil moisture (Li *et al.,* 2020; Yin *et al.,* 2022). These conditions may offset the current benefits of warmer temperatures. The spring rice season might experience greater vulnerability as higher temperatures coincide with the most critical growth phases such as flowering and grain-filling where extreme heat could reduce yield significantly (Raoufi and Soufizadeh, 2020; Shimono, 2011). Moreover, high temperatures can increase water demand, stressing irrigation systems and local water resources (Garrote, 2017; Wang *et al.,* 2016). In the long term, rising maximum temperatures could make certain provinces, especially those already experiencing warmer climates, less suitable for rice production without significant adaptation efforts. The results highlight the importance of developing heat-tolerant rice varieties and improving water management to cope with increasing heat risks.

The significant negative effect of minimum temperature on rice production, particularly for spring and total rice yields, highlights the detrimental impact of cooler night-time temperatures. This finding is supported by Lv *et al.* (2018); Peng *et al.* (2004); Shi *et al.* (2017); Yang *et al.* (2017) when they showed that high night-time temperature significantly decreases rice yields. Rice is highly sensitive to temperature fluctuations, and lower night-time temperatures can slow down physiological processes, delay crop maturation, and reduce overall productivity (Fahad *et al.,* 2019; Impa *et al.,* 2021). This negative effect is especially concerning in the context of climate change, where temperature variability is expected to increase, leading to more frequent occurrences of cold nights, even in traditionally warm regions (Freychet *et al.,* 2021; Saleem *et al.,* 2021). The spring rice crop appears to be more vulnerable to these cooler temperatures, as this season often coincides with transitional weather patterns where night temperatures can drop sharply. However, this conclusion contradicts perspective of Tan *et al.* (2021) who stated that while maximum temperature was negatively correlated with yield during the off-season, minimum temperature had a positive impact in both cropping seasons.

In addition, rainfall, sunshine, and humidity are three crucial factors that directly influence rice production. Each plays a vital role in the growth cycle of rice, a water-intensive crop that requires a delicate balance of environmental conditions to thrive. Rainfall is perhaps the most critical factor for rice production as rice is highly water-dependent (Bessah *et al.,* 2021). Rice fields need substantial amounts of water, especially during the initial growth stages, to maintain the flooded conditions essential for proper crop development. Sufficient and timely rainfall ensures that the rice paddies remain inundated, which helps control weeds and maintain soil fertility. However, both excessive and insufficient rainfall can harm rice production (Fu *et al.,* 2023; Rayamajhee *et al.,* 2021). Too much rain can lead to flooding, damaging crops, while too little can cause drought, stunting growth and reducing yields. This reliance on rainfall makes rice production particularly vulnerable to changing precipitation patterns caused by climate change. Maiti *et al.* (2024) indicated that both excessive and insufficient rainfall lead to reductions in rice yield of 33.7% and 19%, respectively. The optimal rainfall threshold across the country is identified as 1621 ± 34 mm; beyond this threshold, rice yield decreases by 6.4 kg per hectare for every additional 100 mm of rainfall.

Sunshine plays a crucial role in rice production, as it directly influences photosynthesis, the process by which rice plants convert light energy into chemical energy for growth and development (Firdaus *et al.,* 2020). The authors argue that sunshine has a positive impact on the production of rice, which aligns with the arguments of Panigrahy *et al.* (2020); Wei *et al.* (2023). Light deficiency alleviates the rice yield and quality. Adequate sunshine exposure is essential for optimal rice yields, as it affects plant height, leaf area, and grain filling (Zhou *et al.,* 2021). During critical growth stages, such as tillering and flowering, sufficient sunshine ensures the healthy development of panicles, leading to higher grain production (Song *et al.,* 2022). However, excessive sunshine, especially during heat waves, can increase plant stress, reduce water retention, and cause rice plants to wither (Semeraro *et al.,* 2023). Thus, balancing sunshine exposure with other factors, such as irrigation and shade management, is vital to ensure consistent yields, particularly in regions experiencing climate variability.

Moreover, high humidity levels can benefit rice during its growth phases by reducing evapotranspiration and helping the soil retain moisture (Fukai and Mitchell, 2022). However, excessive humidity can create favourable conditions for pests and diseases, such as fungal infections and insect infestations, which can significantly reduce yields (Naeem-Ullah *et al.,* 2020). The balance of humidity, particularly in tropical and subtropical regions where rice is commonly grown, is crucial. Managing humidity levels through proper field practices, pest control, and disease prevention measures becomes essential to ensure high productivity in rice farming.

Conclusions and policy implications

This study provides empirical evidence on the impact of climate change on rice production in Vietnam from 2002 to 2022, revealing significant relationships between climatic variables and rice yield outcomes. This study focuses on the impact of climate change on rice production in Vietnam, where there is distinct susceptibility to sea-level rise and salinity intrusion positions, rising temperatures, and extreme weather events. It is a unique case study while also offering valuable lessons for countries experiencing similar climatic challenges. The findings show that when maximum temperatures lie beyond the ideal range, rice yield may suffer. High temperatures can hasten crop development, shortening the growing period and lowering the time for photosynthesis, affecting the yields (Ding *et al.,* 2020). Because they lower seed set rate and grain weight, lower temperatures can limit crop output. Cold spells can also cause loss of winter-spring rice output (Su *et al.,* 2023). The proportion of rice spikelet fertility will be considerably lowered when daily mean temperatures are less than 22°C or average daily maximum temperatures throughout the flowering season are higher than 35°C (Ding *et al.,* 2020). Particularly in rainfed settings, rice farming depends on enough rainfall to provide the required water for plant development and growth (Amnuaylojaroen *et al.,* 2024). By 0.20% in the long run and by 0.19% in the short run, a 1% increase in precipitation will boost rice output (Chandio *et al.,* 2021). In mainland Southeast Asia, rice farming occurs in both the dry and wet seasons. While the rainy season runs from June to December, the dry season is marked by little precipitation. While increasing rainy weather spells could provide ideal conditions for rain-fed crops, they can also cause waterlogging and soil erosion (Amnuaylojaroen *et al.,* 2024). Changing the sowing dates will help to utilise the advantages of solar radiation and prevent too hot conditions (Ding *et al.,* 2020).

Based on these main findings, the following policy implications delineate a strategic framework aimed at strengthening the resilience of Vietnam's rice sector. Firstly, changing cropping patterns and introducing new rice varieties in place of traditional ones that are more sensitive to climate change might also help with adaptation (Aryal *et al.,* 2020). The government should work with research institutions to invest in breeding programs for varieties that can endure higher temperatures, increased salinity, and drought conditions. Besides, promoting sustainable agricultural practices is crucial for enhancing resilience to climate impacts (Usigbe *et al.,* 2024).

This can be done by means of the agro-ecological technique known as System of Rice Intensification (SRI), which enhances the management of water, soil, plants, and nutrients (Aryal *et al.,* 2020). Farmers should be trained in agroecological approaches that improve soil health, enhance biodiversity, and increase resilience to climate extremes (Bezner Kerr *et al.,* 2023). Policymakers should facilitate the dissemination of knowledge about these practices through agricultural extension services. This initiative should be supported by funding for agricultural research and development to ensure that new varieties are rapidly tested and distributed to farmers. The government should cooperate with agricultural research institutes in developing rice varieties that are resilient to climate change, expanding research cooperation models such as collaborating with the Vietnam Academy of Agricultural Sciences (VAAS) to promote research activities to select and breed rice varieties OM6677 and OM5451 that are highly resistant to current salinity and climate change conditions.

Secondly, adjusting planting dates is a common adaptation strategy that can be implemented with low cost using drought- and flood-resistant crop varieties (Ding *et al.,* 2020). Improving irrigation infrastructure is important to ensure a steady water supply for crops, particularly during dry seasons (Trinh *et al.,* 2021). Specially, the implementation of early warning systems for extreme weather events, such as floods, droughts, and typhoons, can significantly mitigate risks (Coughlan de Perez *et al.,* 2022; Neußner, 2021). These systems should provide real-time alerts to farmers and local communities, allowing them to take preventive measures.

Thirdly, the government should also limit cost barriers to rice production, implement appropriate tax policies, and provide preferential financing sources so that farmers have favourable conditions to improve current rice productivity. Infrastructure improvements and capacity building for smallholder farmers should be given top priority. The government also needs to strengthen its collaboration with international organisations and foreign funding sources to enhance cooperation in addressing climate change. Collaborating with organisations like the International Rice Research Institute (IRRI) and the Food and Agriculture Organisation (FAO) offers access to advanced research, best practices, and resources to enhance the nation's agricultural resilience (Byerlee and Lynam, 2020). A prime example of which is funding from the United States, which has provided Vietnam with $4.4 million to implement a project on proper fertiliser use. Climate change is coming and Vietnam is one of the most vulnerable countries in the world, and climate change is a top priority for the United States.

Lastly, the government should boost fundings for agricultural research on climate adaptation and resilience, allocating funding for developing and sharing innovative farming technologies to mitigate climate change impacts on paddy production (Haque *et al.,* 2024). Countries should engage with international research organisations and universities to enhance knowledge exchange and build capacity. Encouraging farmer cooperatives can boost capacity building and resource sharing among farmers. Cooperatives help farmers access training, technology, and financial resources, allowing them to adopt innovative practices together.

However, despite the thorough efforts undertaken, the study does have some limitations. A major one is the omission of socio-economic factors that could affect agricultural outcomes. Although the focus is on climatic variables like temperature, rainfall, and humidity, aspects such as farm size, access to irrigation, credit, and farmers' education are also critical to productivity. Larger farms often have greater access to resources and technology, while smallholders may face challenges in adapting. Future research should incorporate these socio-economic factors to gain a more comprehensive understanding of how climate change interacts with broader socio-economic conditions. Another limitation is the reliance on provincial-level data, which may miss important micro-level variations. Provincial averages reveal general trends but overlook local differences, such as agricultural practices, resource availability, and vulnerability to climate impacts. Future studies should use farm-level or household data to better capture these localised differences, providing insights that lead to more targeted policy recommendations.

Despite these constraints, the study provides valuable insights into the broad impacts of climate change on rice production. These findings can still help shape national and provincial policies, particularly in developing strategies to address climate risks. Future research should expand its scope to include more detailed data and socio-economic factors, improving our understanding of resilience and supporting the development of more inclusive and effective climate adaptation policies.

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