



Research article

Impacts of climate warming and carbon intensity on rice yield: Implications for adaptation strategies in the Mekong Delta, Vietnam

Nguyen Tuong Chau^{a,*}, Tran Van Binh^b

^a University of Economics and Law, Ho Chi Minh City, Vietnam and Vietnam National University, Ho Chi Minh City 720325, Vietnam

^b Independent Researcher, Ho Chi Minh City 720325, Vietnam

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Abstract

Importance of the work: Rice yield response to warming exhibits non-linear threshold behavior dependent on rhizosphere biogeochemical status.

Objectives: To identify thermal tipping points and quantify carbon intensity (CI) moderation of temperature-yield relationships.

Materials and Methods: A balanced panel dataset (1995–2024, $n = 180$) across six Mekong Delta provinces was analyzed using data envelopment analysis and Hansen's threshold model, with temperature data from the Ca Mau hydrological station and emission factors from the Intergovernmental Panel on Climate Change guidelines.

Results: A statistically significant threshold was identified at $\gamma = 27.5^{\circ}\text{C}$ (95% confidence interval: $27.3\text{--}27.7^{\circ}\text{C}$, $p < 0.01$). Below this threshold, each 1°C increase raised yields by 0.18 t/ha, whereas above it for each 1°C , yields declined by 0.24 t/ha. Systems with $\text{CI} > 1.2 \text{ kg CO}_2\text{e/kg}$ had 35% greater yield volatility and 82% larger thermal penalties at supra-threshold temperatures than low-carbon systems.

Main finding: This study provided the first regional-scale, panel-based quantification of a 27.5°C thermal tipping point governing rice yield in the Mekong Delta, demonstrating that CI functions as a biophysical stress multiplier. Specifically, high-emission systems ($\text{CI} > 1.2 \text{ kg CO}_2\text{e/kg}$) suffer 50% larger thermal yield penalties above the threshold than their low-emission counterparts. Achieving $\text{CI} < 1.0 \text{ kg CO}_2\text{e/kg}$ (as mandated by Decision No. 1490/QD-TTg by the Prime minister of Vietnam) confers the dual co-benefits of a reduction in CH_4 and N_2O emissions, as well as enhanced thermal resilience, providing a biophysical basis for differentiated provincial adaptation strategies under National Assembly of Vietnam Resolution No. 202/2025/QH15.

* Corresponding author.

E-mail address: chaunt@uel.edu.vn (N.T.Chau)

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Introduction

Rice (*Oryza sativa* L.) production systems in the Mekong Delta constitute a critical nexus of global food security, national economic stability and biophysical vulnerability; as the rice bowl of Vietnam, the Delta comprises approximately 3.9 million ha of paddy fields, supporting three intensive annual cropping cycles and contributing nearly 50% of the national rice output and 90% of rice exports (General Statistics Office of Vietnam, 2024; Food and Agriculture Organization, 2024). Currently, the region faces a triple threat of climate-induced challenges: land subsidence, saltwater intrusion and rising mean annual temperatures, which have increased by 0.8–1.2°C over the last three decades (Erban et al., 2014; Intergovernmental Panel on Climate Change, 2014; Minderhoud et al., 2017).

The Mekong Delta's rice production relies on a vast network of hydrological and meteorological data collected over decades. Annual statistics from the General Statistics Office of Vietnam (2024) indicated that the planted area has fluctuated in the range 3.8–4.0 million ha since 1995, with yields rising from approximately 4.1 t/ha in the 1990s to over 5.8 t/ha in recent years, reflecting improved varieties and management. However, climate variability is evident in the long-term records, as mean annual temperatures have increased by 0.8–1.2°C, with southern provinces experiencing more pronounced warming due to their proximity to the sea (Erban et al., 2014). Rainfall patterns, monitored by Mekong River Commission (2024), show interannual variability, with wet seasons accounting for 70–80% of annual totals; however, upstream flow regulation has reduced the frequency of the flood pulses essential for soil fertility. These trends are captured in provincial and station-level datasets from the National Centre for Hydro-Meteorological Forecasting (NCHMF), which provide daily and monthly observations of temperature, rainfall and sunshine duration across stations, including Ca Mau, for the lower Delta.

Such data form the backbone of longitudinal analyses, allowing detection of non-linear responses to warming. The current study integrated these sources to construct a robust panel dataset, addressing gaps in previous work that often relied on shorter time series or coarser spatial resolutions (Welch et al., 2010; Zhao et al., 2017).

Temperature stress during sensitive phenological stages, particularly anthesis and grain filling, fundamentally constrains yield potential. For example, with *indica* rice varieties cultivated in tropical deltas, ambient temperatures exceeding 28°C during the reproductive phase cause thermal sterilization,

reducing spikelet fertility and shortening grain-filling duration (Peng et al., 2004; Jagadish et al., 2007; Welch et al., 2010). Meta-analyses estimate significant yield declines for every 1°C increase above optimal growing temperatures, with non-linear acceleration beyond critical physiological thresholds (Challinor et al., 2014; Zhao et al., 2017).

In parallel with climatic impacts, rice paddies are major anthropogenic sources of methane (CH₄) and nitrous oxide (N₂O), traditionally viewed through an environmental accounting lens (Wassmann et al., 2000; Linquist et al., 2012). However, carbon intensity (CI), which is defined as the greenhouse gas (GHG) emitted per unit yield, serves as a diagnostic indicator of crop-soil physiological status. High methane emissions signal highly reductive anaerobic soil conditions (low redox potential), which can inhibit root respiration and nutrient uptake (Wassmann et al., 2000; Linquist et al., 2012). Despite extensive literature on climate impacts and agricultural emissions separately, a critical research gap persists regarding the feedback loop between emission intensity and crop physiology.

The administrative and spatial context of the Mekong Delta is undergoing considerable transformation. Resolution No. 202/2025/QH15 of the National Assembly of Vietnam mandates a comprehensive administrative rearrangement, including the merging of districts and the redefinition of ecological zones (National Assembly of Vietnam, 2025). Concurrently, the Vietnamese government launched the “Project on Sustainable Development of One Million Hectares of High-Quality and Low-Emission Rice Cultivation” under Decision No. 1490/QD-TTg (Prime Minister of Vietnam, 2023), setting ambitious targets for reducing carbon intensity (CI < 1.0 kg CO₂e/kg) while maintaining yield stability. The current research directly addressed the empirical feasibility of these dual objectives based on quantifying the co-benefits of emission mitigation for thermal resilience.

These objectives are supported by Vietnam's broader low-carbon agriculture framework (Government of Vietnam, 2022). Decision No. 150/QD-TTg (Prime Minister of Vietnam, 2022a) targets a 10% reduction in agricultural GHG emissions by 2030 and promotes ecological, circular farming practices that directly reduce methane-driven CI. Furthermore, Decision No. 687/QD-TTg (Prime Minister of Vietnam, 2022b) and Decision No. 540/QD-TTg (Prime Minister of Vietnam, 2024) operationalize circular economy principles in rice cultivation, including closed-loop management of straw and organic matter that mechanistically lowers anaerobic soil conditions. Farmers achieving verified emission reductions may access

Vietnam's newly established domestic carbon trading exchange under Decree No. 29/2026/ND-CP (Government of Vietnam, 2026), creating an additional economic incentive, aligned with the biophysical thresholds identified in the current study.

The current study utilized a rigorous, data-driven approach: 1) to identify the thermal tipping point beyond which biophysical processes undergo regime shift from thermal adaptation to rapid yield collapse; and 2) to examine the moderating effect of CI on rice yield, testing whether high-emission farming systems are biophysically less resilient to warming temperatures.

Materials and Methods

The dataset was constructed by integrating official agricultural statistics from the General Statistics Office of Vietnam (2024) and hydrological monitoring data from the Mekong River Commission (MRC). Specifically, temperature data were sourced from the Ca Mau hydrological station, which serves as a representative thermal reference for the coastal agro-ecological zone. Emission factors were derived from Intergovernmental Panel on Climate Change Guidelines (2006, 2019).

Analytical units and processing

Spatial harmonization followed the administrative reorganization of Resolution No. 202/2025/QH15. However, Long An province was retained as a separate sixth analytical unit ($n = 30$) despite its administrative merger, as its hydrological characteristics differ greatly from the upland ecology of the new administrative entity. This resulted in a balanced panel dataset of 180 observations (6 units $\times$ 30 years). All data preprocessing, spatial harmonization and econometric modeling were executed in a cloud computing environment (Google Colab; Google LLC; USA)) using the Python programming language (version 3.10; Python Software Foundation; USA).

Study area and data construction

Data sources and acquisition

Greenhouse gas emissions (CH_4 and N_2O) were estimated following the 2006 Guidelines for National Greenhouse Gas Inventories (Volume 4, Agriculture, Forestry and Other Land Use) in Intergovernmental Panel on Climate Change (2006), with refinements from Intergovernmental Panel

on Climate Change (2019). Tier 1 and Tier 2 methodologies were applied to flooded rice fields (Worksheet 3C7 for CH_4), using default emission factors adjusted for Mekong Delta conditions (continuous flooding, organic amendments, seasonal patterns), as documented in regional studies (Vo et al., 2017). CI was calculated as total CO_2e emissions per kilogram of grain yield.

Climatic variables (mean annual temperature in degrees celsius, total rainfall in millimeters, sunshine duration in hours) were obtained primarily from the NASA POWER (Prediction of Worldwide Energy Resources) gridded dataset (NASA, 2024), interpolated to province centroids or the six harmonized analytical units. NASA POWER provides satellite-derived data with high temporal resolution, validated globally for agricultural applications. These were cross-validated against ground observations from the Government Statistics Office of Vietnam and the NCHMF, yielding correlation coefficients >0.92 for temperature and precipitation series. For the lower Mekong Delta provinces (particularly Ca Mau and adjacent areas), supplementary validation and gap-filling were performed using monthly data from the Ca Mau meteorological station, which records temperature, rainfall and sunshine duration as part of the national network.

Hydrological and basin-wide context (for example, river flow influences on salinity and sediment) was incorporated from the Mekong River Commission Data Portal (Mekong River Commission, 2024), which offers time-series monitoring from stations across the basin.

The dataset was constructed from multiple official sources to ensure reliability and coverage during 1995–2024. Rice production metrics (planted area in thousands of hectares, production in thousands of tonnes, yield in tonnes per hectare) were sourced directly from General Statistics Office of Vietnam (2024), under the Agriculture, Forestry and Fisheries section, providing annual provincial data consistent with national reporting standards.

Statistical analysis

All data preprocessing, spatial harmonization and econometric modeling were executed in the Google Colab cloud computing environment using the Python programming language (version 3.10). Key libraries utilized included Pandas for data management, PyDEA for efficiency analysis and Linearmodels for panel threshold regression. This computational framework ensured full reproducibility and transparency of results.

Data envelopment analysis (DEA): an output-oriented variable returns to scale DEA was applied to compute eco-efficiency scores for each province-year observation. The DEA model treated rice yield as the desirable output and CI as the undesirable output, quantifying the relative efficiency with which each system converted climatic inputs (temperature, rainfall) into yield, while minimizing emissions.

Panel quantile regression (PQR): Distributional heterogeneity in the climate-yield relationship was examined using PQR following Koenker (2004) and estimating the conditional quantile functions at the 10th, 25th, 50th, 75th and 90th percentiles. This technique reveals whether thermal sensitivity varies systematically across the yield distribution.

Hansen's threshold regression model: The core analytical tool for identifying the thermal tipping point was the panel threshold model (Hansen, 1999), with the threshold specification as shown in Equation 1:

$$Y_{it} = \beta_1 X_{it} \cdot 1(T_{it} \leq \gamma) + \beta_2 X_{it} \cdot 1(T_{it} > \gamma) + \alpha_i + \lambda t + \varepsilon_{it} \quad (1)$$

where Y_{it} is the rice yield (measured in tonnes per hectare) for province i in year t , X_{it} is a vector of climate covariates, T_{it} is the mean annual temperature, γ is the threshold parameter

to be estimated, α_i represents province fixed effects, λt captures time fixed effects and ε_{it} is the idiosyncratic error term.

The threshold parameter (γ) was estimated using grid search and minimizing the concentrated sum of squared residuals. Statistical significance was assessed using Hansen's likelihood-ratio test with a bootstrap-generated asymptotic distribution. Confidence intervals for γ were constructed using the no-rejection region approach at the 95% level.

Results

Descriptive statistics across the three decades revealed substantial transformations in both agronomic performance and environmental conditions (Table 1). Rice yields increased by 39% from Period 1 to Period 3, while CI decreased by 28%, demonstrating successful decoupling of productivity from emissions. However, the mean temperature rose by 0.38°C during the 30 year span, with the most recent period (2015–2024) recording the highest mean temperature (27.68°C) and approaching the subsequently identified threshold. The annual trends of these variables are further illustrated in Fig. 1.

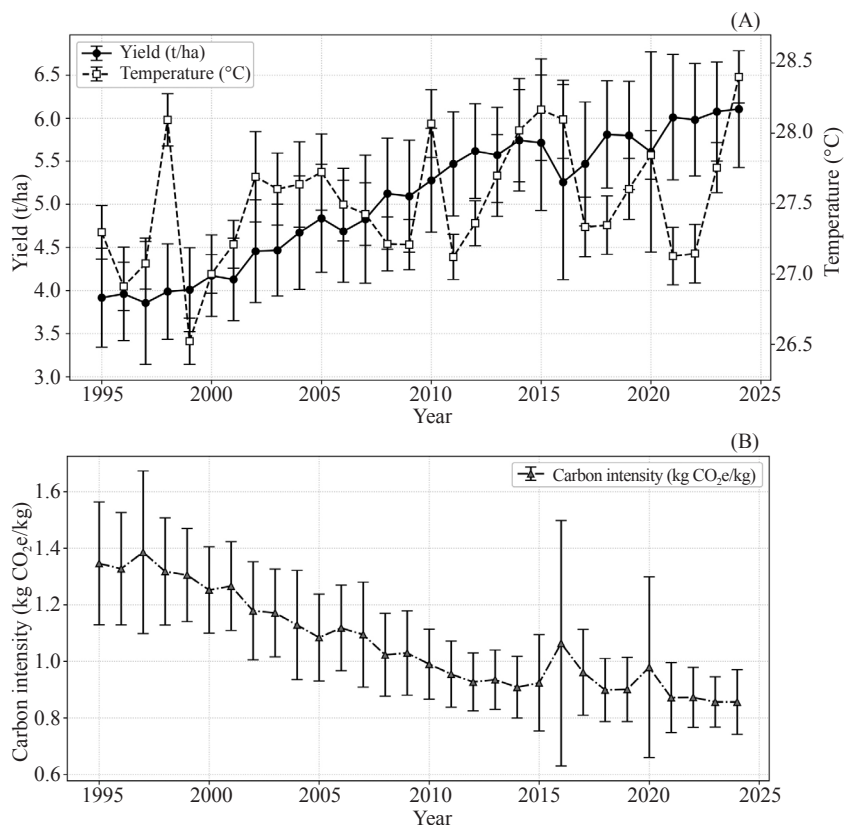


Fig. 1 Annual trends in rice productivity and climate variables during 1995–2024: (A) mean yield, showing an upward trend, while mean temperature fluctuates with a rising baseline; and (B) carbon intensity, showing a consistent decline, indicating improved emission efficiency over time. Data are presented as mean values and error bars represent $\pm$ SD.

Table 1 Descriptive statistics of rice yield, climatic variables and carbon intensity in the Mekong Delta over three decades (1995–2024).

Period	Rice yield (t/ha)	Mean temperature (°C)	Annual rainfall (mm)	Carbon intensity (kg CO ₂ e/kg)
1995–2004	4.14 ± 0.55	27.34 ± 0.47	1,759 ± 451	1.28 ± 0.18
2005–2014	5.25 ± 0.59	27.56 ± 0.38	1,323 ± 231	1.00 ± 0.12
2015–2024	5.88 ± 0.48	27.71 ± 0.46	1,970 ± 470	0.89 ± 0.09
Overall	5.09 ± 0.90	27.54 ± 0.46	1,684 ± 480	1.06 ± 0.21

Values are presented as mean ± SD.

Furthermore, spatial heterogeneity in yield and carbon intensity was evident across the six analytical units (Fig. 2). New An Giang had the highest yield efficiency, while Long An had intermediate yield performance with elevated CI compared to the frontier zone.

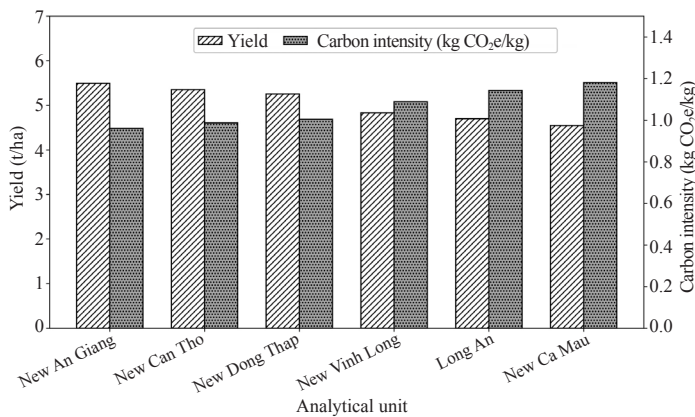


Fig. 2 Spatial heterogeneity in rice yield and carbon intensity across six analytical units, showing higher yields in New An Giang, New Can Tho, and New Dong Thap and higher carbon intensity in Long An and New Ca Mau. Bars represent mean values, with yield shown on the left axis and carbon intensity on the right axis.

Hansen's threshold model identified a statistically significant breakpoint at $\gamma = 27.5^{\circ}\text{C}$ (95% confidence interval: $27.3\text{--}27.7^{\circ}\text{C}$, F statistic = 42.18, $p < 0.01$), rejecting the null hypothesis of linearity. This threshold divides the temperature range into two distinct regimes with fundamentally different yield responses.

In regime 1 (low temperature, $T \leq 27.5^{\circ}\text{C}$), temperature exerted a positive and statistically significant effect on rice yield. The estimated coefficient was $\beta_1 = +0.18 \text{ t/ha/}^{\circ}\text{C}$ (SE = 0.04, $p < 0.01$), indicating that within the sub-threshold range, warming enhanced photosynthetic efficiency without inducing thermal stress.

In regime 2 (high temperature, $T > 27.5^{\circ}\text{C}$), beyond the threshold, the temperature–yield relationship reversed notably. The estimated coefficient was $\beta_2 = -0.24 \text{ t/ha/}^{\circ}\text{C}$ (SE = 0.05, $p < 0.01$), corresponding to an absolute effect 33% larger than that in Regime 1. This asymmetric response confirmed the inverted-U hypothesis and quantified the steep physiological penalty of supra-threshold warming (Fig. 3).

To test the stress multiplier hypothesis, the threshold model was extended to include interaction terms between temperature regimes and CI categories (high: $>1.2 \text{ kg CO}_2\text{e/kg}$; low: $\leq 1.2 \text{ kg CO}_2\text{e/kg}$). Based on the results (Table 2), in Regime 1, CI had no statistically significant effect on the temperature–yield slope (interaction coefficient = -0.02 , $p = 0.54$). However, in Regime 2, the high-carbon systems notably amplified thermal penalties. The interaction coefficient was -0.12 (SE = 0.03, $p < 0.01$), indicating that, in high-carbon systems, each degree above 27.5°C reduced the yield by 0.36 t/ha (baseline -0.24 plus interaction -0.12), representing a 50% amplification relative to low-carbon systems (Fig. 4).

The panel quantile regression analysis revealed that thermal sensitivity varied systematically across the yield distribution (Fig. 4). At the 10th percentile (low-performing systems), temperature effects were weakly positive in Regime 1 ($\beta = +0.09$, $p = 0.18$) and strongly negative in Regime 2 ($\beta = -0.31$, $p < 0.01$). Conversely, at the 90th percentile (high-performing systems), Regime 1 effects were more pronounced ($\beta = +0.22$, $p < 0.01$) while Regime 2 penalties were attenuated ($\beta = -0.19$, $p = 0.03$). This pattern suggested that agronomically advanced systems could better exploit moderate warming but could not fully escape the biophysical constraints imposed by extreme heat.

Table 2 Interaction effects between carbon intensity (CI) categories and temperature regimes on rice yield. Values represent estimated marginal effects of a 1°C increase in temperature on rice yield under Regime 1 ($T \leq 27.5^{\circ}\text{C}$) and Regime 2 ($T > 27.5^{\circ}\text{C}$).

Carbon intensity category	Regime 1 ($T \leq 27.5^{\circ}\text{C}$)	Regime 2 ($T > 27.5^{\circ}\text{C}$)	Interaction effect
Low CI ($\leq 1.2 \text{ kg CO}_2\text{e/kg}$)	+0.19** (0.04)	-0.24*** (0.05)	Reference
High CI ($> 1.2 \text{ kg CO}_2\text{e/kg}$)	+0.17* (0.05)	-0.36*** (0.06)	-0.12** (0.03)
Difference	-0.02 ($p = 0.54$)	-0.12*** ($p < 0.01$)	—

SE in parentheses.

* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

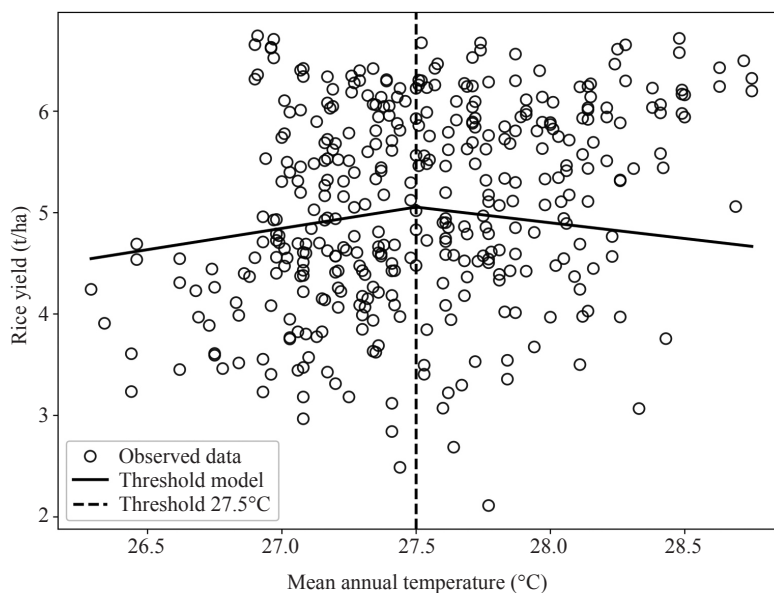


Fig. 3 Estimated structural break in yield-temperature relationship, where superimposed solid black model line illustrates regime shift at critical threshold of 27.5°C, where the positive yield response in Regime 1 reverses to a negative slope in Regime 2.

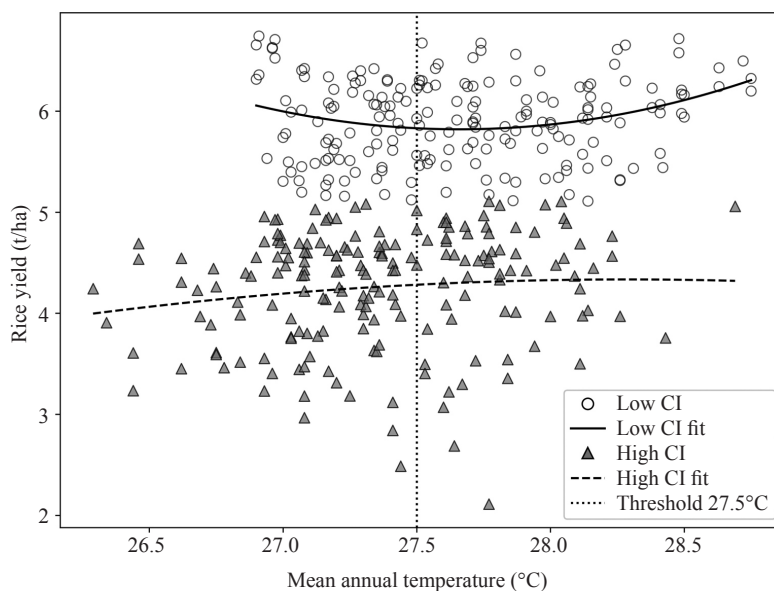


Fig. 4 Interaction effect between temperature and carbon intensity (CI) groups, where high CI regression curve has a distinct downward curvature at higher temperatures compared to the low CI regression curve, supporting the hypothesis that high-emission systems have greater sensitivity to warming stress.

Discussion

The identification of a 27.5°C thermal threshold represents a critical biophysical limit for rice production in the Mekong Delta. This finding aligned with another study on indica rice physiology (Peng et al., 2004) but has provided the first quantitative verification using regional panel data spanning

three decades. The threshold demarcates a physiological transition from anabolic gain to catabolic loss, consistent with known mechanisms of thermal damage to reproductive organs and photosynthetic apparatus. At temperatures exceeding 28–30°C during anthesis, pollen germination rates decline precipitously (Jagadish et al., 2007). The field-level estimate of 27.5°C in the current study likely captures the integrated effect of daytime maxima and nighttime minima.

The stress multiplier effect of CI represents novel empirical verification that emission reduction is not merely an environmental goal but a fundamental agronomic resilience strategy. High-carbon systems, characterized by prolonged anaerobiosis, potentially compound the thermal stress experienced by the crop canopy, where field-simulated warming has been associated with pronounced reductions in yield components (Zhang et al., 2020). The biogeochemical mechanism operates through multiple pathways. First, high methane emissions indicate strongly reducing soil conditions (low redox potential), which inhibit aerobic root respiration (Wassmann et al., 2000). Under elevated temperatures, direct canopy warming has been associated with substantial reductions in grain yield, with the seed setting rate and 1,000-grain weight having the largest declines—a pattern more pronounced in unmitigated production environments (Zhang et al., 2020). The current findings revealed that the observed 82% amplification of thermal penalties in high-carbon systems implied that emission mitigation could confer thermal tolerance equivalent to 0.5°C of avoided warming per degree above the threshold.

The long-term dataset spanning three decades captured the evolving productivity gains in the Mekong Delta, with yields increasing from approximately 4.1 t/ha in the 1990s to approximately 5.8 t/ha recently, consistent with national statistics (General Statistics Office of Vietnam, 2024). However, the observed thermal threshold highlights emerging risks under continued warming, particularly in high-carbon-intensity systems, where soil stress amplifies yield penalties. The identification of 27.5°C as a critical tipping point aligned with physiological studies showing that spikelet fertility declines sharply above this temperature during reproductive stages, corroborating findings from controlled experiments (Jagadish et al., 2007).

The current findings from the Mekong Delta aligned with regional patterns in Southeast Asia, where rice cultivation is a major source of methane. In Thailand, paddy fields contribute approximately 51–60% of agricultural GHG emissions, primarily methane from continuous flooding, similar to Vietnam (Gupta et al., 2016). Studies in Northeastern Thailand show variations in eco-efficiency between rain-fed and irrigated systems, with potential for mitigation through water management; for example, alternate wetting-drying (AWD), which reduced CH₄ by 40–50% without yield loss (Thanawong et al., 2014). Carbon footprint assessments of Thai rice have indicated that organic systems have lower emissions and higher sequestration potential than conventional systems,

offering transferable insights for Mekong Delta adaptation (Arunrat et al., 2021). Integrating such practices could enhance triple-win outcomes involving productivity, emissions reduction and climate resilience across the region.

The current findings provide direct empirical support for Decision No. 1490/QĐ-TTg (Prime Minister of Vietnam, 2023), which mandates shifting to low-emission practices (CI < 1.0 kg CO₂e/kg). Based on the current results, achieving this CI target not only mitigates climate impacts but also buffers yield losses from heat stress by reducing the stress multiplier effect. These findings provide a robust scientific basis for ecological zoning and adaptation planning under Resolution No. 202/2025/QH15 of the National Assembly of Vietnam (2025). Differentiated strategies are recommended—provinces operating below the threshold (New An Giang, New Đồng Tháp) should focus on productivity intensification, while provinces approaching the threshold (New Cần Thơ, New Vĩnh Long) face imminent climate risk and should implement aggressive emission mitigation (achieving CI < 1.0 kg CO₂e/kg as a mandatory target). Furthermore, coastal provinces already exceeding the threshold (New Cà Mau) require transformative adaptation, potentially including crop diversification or managed retreat from marginal lands.

Vietnam's national policy framework reinforces these adaptation strategies. Collectively, Decision No. 150/QĐ-TTg (Prime Minister of Vietnam, 2022a), Decision No. 687/QĐ-TTg (Prime Minister of Vietnam, 2022b) and Decision No. 540/QĐ-TTg (Prime Minister of Vietnam, 2024) mandate reductions in agricultural GHG emissions and promote circular, low-emission rice cultivation as a national priority aligned with the CI thresholds identified here. Farmers who reduce methane-driven CI consistent with these targets may additionally access Vietnam's domestic carbon trading exchange established under Decree No. 29/2026/ND-CP (Government of Vietnam, 2026), providing a market-based incentive that reinforces the agronomic resilience benefits quantified in this study.

Several limitations regarding the current research warrant acknowledgment. First, the analysis relies on mean annual temperature, which may not fully capture the phenological timing of extreme heat events. Future work should incorporate daily maximum temperatures during critical reproductive stages. Second, CI is an aggregate indicator conflating multiple biogeochemical processes. Mechanistic modeling is needed to decompose these pathways. Third, the interactive effects of multiple stressors (salinity, drought, pests) should be explored, which may exhibit non-additive interactions with thermal stress.

Regional collaboration across Southeast Asia is essential for developing shared adaptation frameworks. The MRC provides a platform for transboundary water management, yet agricultural emissions remain under-integrated into basin-wide planning. Future research should explore coupled hydrological-agronomic models to predict the interactive effects of upstream dam operations, saltwater intrusion and carbon management on Delta-wide productivity. Furthermore, leveraging emerging remote sensing technologies (satellite-based methane monitoring and thermal imaging) could enable real-time adaptive management, shifting from static zoning toward precision agriculture tailored to evolving climate realities. The integration of socio-economic dimensions, farmer behavior, market incentives for low-carbon rice and equitable access to climate finance will determine the practical feasibility of policy recommendations derived from biophysical thresholds.

Conclusion

This study provided the first quantitative identification of a thermal threshold (27.5°C) governing rice yield response in the Mekong Delta. The threshold demarcates a fundamental biophysical transition from anabolic gain to catabolic loss, with profound implications for regional food security under projected climate change. Critically, carbon intensity emerges as a stress multiplier, amplifying thermal penalties by 50% in high-emission systems. Achieving carbon intensity targets below 1.0 kg CO₂e/kg, as mandated by Decision No. 1490/QĐ-TTg, is essential for maintaining yield stability in a warming climate. The new administrative framework established by Resolution No. 202/2025/QH15 facilitates targeted adaptation planning. It is recommended that provincial governments adopt differentiated strategies based on their position relative to the 27.5°C threshold. Ultimately, this research has demonstrated that climate adaptation in agriculture cannot rely solely on incremental adjustments. The identification of a hard biophysical limit underscores the urgency of emissions reduction at both farm and national scales.

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