ASSESSING VULNERABILITY TO CLIMATE CHANGE IN RICE CULTIVATION IN THANH HOA PROVINCE, VIETNAM

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Abstract. Thanh Hoa Province, situated in the North Central region of Vietnam, is distinguished by its varied landscape, including mountainous, midland, and delta terrains. This diverse geography collectively fosters an environment suitable for agricultural activities, especially rice cultivation. However, the onset of climate change and the increased frequency of natural disasters in recent years have significantly reduced rice productivity and yields in the province. This study employs an index-based vulnerability assessment method, incorporating exposure, sensitivity, and adaptive capacity indices, to systematically evaluate the impact of these environmental challenges on rice cultivation. These indices categorize vulnerability into four distinct levels: low, medium, high, and very high. Our analysis indicates that across all 27 districts in Thanh Hoa Province, there is a moderate to high vulnerability to climate change and natural disasters, with 12 districts showing a high vulnerability level. This high vulnerability is particularly pronounced in delta regions (Yen Dinh, Tho Xuan, Thieu Hoa, Trieu Son, Nong Cong) and coastal areas (Hoang Hoa), along with midland and mountainous districts (Ba Thuoc, Lang Chanh, Ngoc Lac, Thuong Xuan, Nhu Xuan, Nhu Thanh). The districts within delta and coastal zones are notably more sensitive, while those in midland and mountainous regions exhibit lower adaptive capacities, further increasing their vulnerability. This research provides crucial insights for local policymakers in Thanh Hoa Province, emphasizing the need for strategic interventions to improve resilience and response strategies, thus ensuring the sustainable development of rice cultivation and food security in the context of climate change.
Keywords: *exposure, sensitivity, adaptive capacity, vulnerability index, rice cultivation, Vietnam*

Introduction

Vietnam is identified by the Intergovernmental Panel on Climate Change (IPCC) as one of the countries severely affected by climate change (IPCC, 2014). According to the Vietnam Country Climate and Development Report (CCDR) published by the World Bank in 2022, the country incurred losses of approximately 10 billion USD in 2020, equivalent to 3.2% of its Gross Domestic Product (GDP), as a direct consequence of climate change. By 2050, without the implementation of appropriate adaptation and mitigation strategies, climate change is projected to cost Vietnam an estimated 12% to 14.5% of its GDP and could result in up to one million people facing extreme poverty by 2030 (World Bank Group, 2022).

Vietnam, an agricultural country, derives approximately 20% of its Gross Domestic Product (GDP) from agriculture. According to the Ministry of Industry and Trade (2022), as of 2022, the country holds the sixth position globally in rice production and is the third-largest rice exporter. This underscores the pivotal role of rice production as a traditional industry in Vietnam's economic development. It not only significantly contributes to the

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national economy but also supports the livelihoods of tens of millions of farmers. These agricultural activities are predominantly concentrated in the extensive deltas and coastal plains, underscoring the geographical and economic significance of the sector.

Thanh Hoa Province, located in the North Central region of Vietnam, ranks fifth in size nationwide. Rice is among the thirteen key agricultural products driving the agricultural development of the province (Thanh Hoa Provincial People's Committee, 2021). Predominantly cultivated in lowland areas, the Thanh Hoa plain is the largest in Central Vietnam and ranks third nationwide. The delta, shaped by alluvial deposits from the Ma, Bang, Yen, and Hoat rivers, features a triangular deltaic form with its apex at Bai Thuong (Tho Xuan district) and its base along the coastline from Nga Son to Tinh Gia. The northern edge of the delta is bounded by the Thach Thanh - Bim Son mountain range, and the southwestern edge by the mountains of Nhu Thanh district. The surface of the delta gently slopes towards the East Sea, with an average elevation of 5 to 15 meters, interspersed with low hills and standalone limestone mountains ranging from a few dozen to several hundred meters in height.

In recent years, Thanh Hoa Province has witnessed an escalation in the severity, unpredictability, and frequency of natural disasters due to the adverse effects of climate change, leading to pronounced vulnerabilities. These calamities have not only caused damage to the population, property, and ecological environment but have also significantly impacted the socio-economic fabric of various sectors within the province, particularly affecting the agricultural domain and, more specifically, rice cultivation. From 2010 to 2020, the province was hit by 151 water-related natural disasters, including 25 typhoons, one tropical depression, one flash flood, and 122 episodes of thunderstorms and tornadoes, often accompanied by heavy rain and hail. Historical records over the period from 1970 to 2020 highlight that Thanh Hoa Province has endured direct impacts from 51 typhoons and tropical depressions, averaging one significant storm annually with wind speeds fluctuating between levels 8 and 11 (corresponding to wind speeds from 62-74 km/h to 103-117 km/h). Notably, the region has experienced extreme typhoons reaching level 12 or higher (wind speeds >118 km/h) such as Typhoon No. 8 in September 1973, Typhoon No. 6 in September 1975, Typhoon No. 6 in September 1980, Typhoon No. 6 in July 1989, and Typhoon No. 7 in September 2005. These intense typhoons, characterized by level 12 wind speeds and higher gusts, along with accompanying tidal surges, have led to sea level rises between 4.5 and 5.5 meters, further exacerbating the vulnerability of the province to climate-induced phenomena.

Between 2017 and 2022, Thanh Hoa Province experienced significant devastation due to natural disasters, as reported by the Thanh Hoa Provincial Command of Natural Disaster Prevention and Control, Search and Rescue (2020). Over this six-year period, the disasters resulted in 114 people either losing their lives or going missing and left 25 others with sustaining injuries. Residential damage was widespread, with 9,426 houses being damaged and 52,567 flooded. The educational and healthcare infrastructures also faced severe impacts, with 66 medical facilities and 162 schools suffering from flood damage. The agricultural sector was notably affected, with 57,678 hectares of various crops, including vegetables and annual plants, being damaged. The livestock industry saw substantial losses, with 32,143 cattle and 871,395 poultry perishing. The province's infrastructure was significantly compromised, with damages reported to 4,674 meters of dikes, 79 reservoirs, 69,761 meters of canals, and 123 pumping stations. Additionally, there were 2,787,039 cubic meters of road collapses among other property damages.

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Specifically, 46,955 hectares of rice fields were damaged, resulting in an estimated financial loss of approximately 9,957 billion VND.

In light of these circumstances, it is essential to assess the vulnerability of rice cultivation in Thanh Hoa Province to climate change. This analysis will equip policymakers with reliable information, which is vital for developing strategies to mitigate current vulnerabilities and crafting response plans for the increasing effects of climate change and natural disasters expected in the coming years.

According to the Intergovernmental Panel on Climate Change (IPCC, 2007), vulnerability to climate change is defined as "the degree to which a species or system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Previously, research on assessing vulnerability to climate change has predominantly utilized two methodologies: the top-down approach and the bottom-up approach (UNFCCC, 2007; Hahn et al., 2009). The top-down approach aims to forecast the potential impacts of climate change over several decades, relying on climate change scenarios that often extend to the year 2100. This method synthesizes existing documents to understand institutional systems and policies for climate change adaptation, local climate trends, and significant development goals pertinent to the area of study. Subsequently, vulnerability assessments are conducted, and adaptation solutions are proposed. Conversely, the bottom-up approach enhances the top-down method by incorporating local response strategies, technology, indigenous knowledge, and the capacity of communities and authorities to adapt to current climate fluctuations. This strategy is instrumental in crafting specific strategies and implementing policies tailored to local needs.

Each approach presents distinct advantages and disadvantages. The top-down method, with its emphasis on the broader impacts of climate change, offers critical insights for strategic decision-making but may fall short in capturing the nuances of local interactions and adaptive capacities. Meanwhile, the bottom-up approach, with its focus on actionable solutions, plays a vital role in the development and implementation of specific strategies and policies. Nonetheless, these studies often rely on secondary data, which can introduce variability in the research structure depending on the data collected (Sullivan and Meigh, 2005). The reliance on secondary data may also lead to potential errors or omissions during the collection process, complicating the analysis of subject sensitivity (Hahn et al., 2009). Moreover, while climate change is projected to intensify and evolve, this methodology tends to concentrate on immediate, short-term solutions (UNFCCC, 2007).

In the context of future trends in climate change, maintaining a strict dichotomy between the top-down and bottom-up approaches to vulnerability assessment is increasingly seen as impractical. The necessity for integrating climate projections and response decisions into vulnerability assessments has become paramount (UNFCCC, 2007). A prevalent method among researchers today is the index-based vulnerability assessment, which amalgamates the strengths of both aforementioned approaches through the development of a comprehensive set of indicators. This approach is lauded for its flexibility, precision, and applicability across various scales—from global analyses, as demonstrated by Welle and Birkmann (2015) and Eckstein et al. (2020), to national studies like those by Hahn et al. (2009) and Namdar et al. (2021), and even local assessments, as seen in the works of Kumar et al. (2016), De Brito et al. (2017), and in urban studies by Tapia et al. (2017), Senapati and Gupta (2017). It is particularly recommended for assessing climate change vulnerability in coastal regions (Bezuijen et al., 2011), with notable contributions to the field by Giannakidou et al. (2020), Addo

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(2013), Ahsan and Warner (2014), Murali et al. (2013), El-Zein et al. (2021), Satta et al. (2015), Zanetti et al. (2016), Balica et al. (2012), Debortoli et al. (2019), McLaughlin and Cooper (2010), Pantusa et al. (2018), and Ietto et al. (2018). In Vietnam, research employing indicator-based vulnerability assessments to climate change remains limited and has only begun to emerge in recent years, as indicated by the study from Huong et al. (2020). Moreover, vulnerability assessments focusing specifically on rice cultivation in Vietnam are still in their infancy.

Therefore, the aim of this study is to evaluate the vulnerability of rice crops in Thanh Hoa province through the application of an index-based vulnerability assessment method. This approach encompasses a vulnerability index along with component indices, each designed to quantify specific facets of vulnerability. These components include the extent of climate change impacts, the sensitivity of rice crops to these changes, and the efficacy of local adaptation strategies. By integrating these elements, the vulnerability index provides a comprehensive measure of the risk posed by climate change and natural disasters to rice cultivation in the region. This holistic assessment aims to offer valuable insights for policymakers and stakeholders, guiding the development of targeted adaptation measures to enhance the resilience of rice production systems in Thanh Hoa Province.

Materials and methods

Study area

Thanh Hoa Province is situated between 19°18'N to 20°40'N latitude and 104°22'E to 106°05'E longitude, covering an area of 11,120.6 km² with a population of approximately 3.72 million in 2021. The province opens eastward to the central part of the Gulf of Tonkin, the Earth Sea, boasting over 102 km of coastline. The terrain gradually descends from west to east, delineating three distinct regions: the midland-mountainous area, the plain, and the coastal zone (*Fig. 1*). The midland-mountainous region spans 839,037 hectares with mountains averaging 600-700 meters in elevation and slopes over 25°; midlands average 150-200 meters in height with 15-20° slopes. The plain covers 162,341 hectares, forming 14.61% of the provincial area, enriched by alluvial deposits from the Ma, Bang, Yen, and Hoat rivers. The coastal area has a relatively flat terrain spreading over 110,655 hectares, featuring seven estuaries interspersed with bays and offshore islands like Ngu Island and Me Island.

Thanh Hoa’s climate is characterized by a tropical monsoon humidity with hot, rainy summers typically experiencing hot, dry westerly winds; cold, less rainy winters are marked by frost and predominantly northeast monsoon winds, decreasing in intensity from the sea inland and from north to south. Over the period from 1980 to 2020, the region's annual average air temperature hovered around 23-24°C in the lowland and midland areas, with a gradual decrease toward the mountainous regions, reaching 18-20°C in the areas bordering Vietnam and Laos at elevations above 1000 meters. Each year, the months from December to February have an average temperature below 20°C, with January typically being the coldest month, averaging 17-18°C. The overall annual thermal regime is approximately 8600-8700°C in the lowlands, which decreases to 8000°C in the mountainous territories (Vietnam Center of Hydro-Meteorological Data, 2020).

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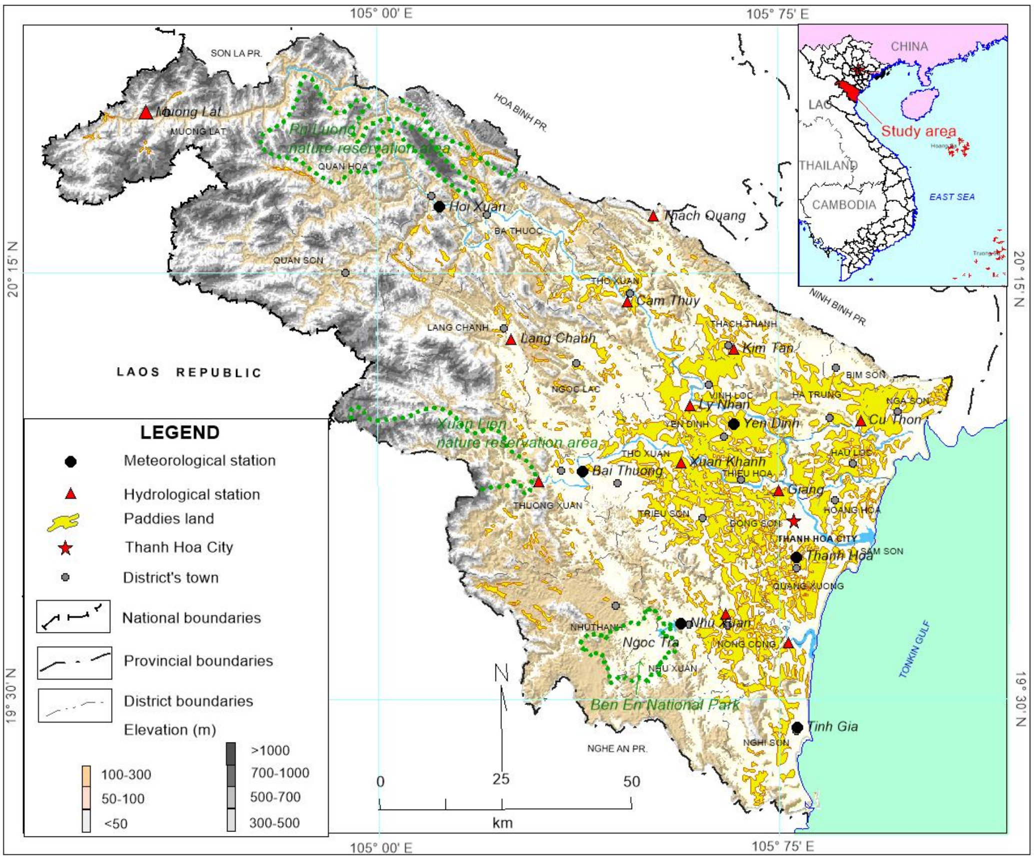

Figure 1. *Distribution of rice area in Thanh Hoa Province in 2020*

The average annual rainfall ranges from 1600-1800 mm/year, with an average of 130-170 rainy days per year. The rainy season lasts six months from May to October, peaking in August, September, and October, accounting for 60-80% of the annual rainfall. The dry season extends from November to the following April. Wind speeds in mountainous areas are relatively constant throughout the year, averaging 1-2 m/s, while coastal and lowland regions may experience significant variations, especially during the typhoon and flood season from June to November. The total annual sunshine hours amount to approximately 2225 hours, correlating with 70-75 sunshine hours per month, providing favorable weather conditions for rice cultivation. The rice-growing plains and coastal areas, covering 77.2% of the provincial rice cultivation area, frequently encounter natural disasters such as typhoons, storm surges, heavy rains leading to flooding, drought, and cold snaps concentrated in September. Drought and severe cold spells occur from December to February. Additionally, tornadoes and hail can occur in this region with low frequency. The midland-mountain region, accounting for 22.8% of the provincial rice cultivation area, primarily experiences heavy rains, dry hot westerly winds, prolonged cold spells, flash floods, mudslides, and sudden floods. High rainfall in July and August can trigger flash floods and debris flows. Thanh Hoa also boasts the Pu Luong Nature Reserve, Xuan Lien Nature Reserve, and Ben En National Park, which function as water regulation areas, facilitating rice cultivation. Specifically, Ben En National Park's ecosystem services help maintain the water level of the Song Muc Lake with a capacity of 174 million m³, significantly contributing to rice cultivation in Nhu Thanh and Nhu Xuan districts.

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In 2020, Thanh Hoa Province dedicated a total of 231,205 hectares to rice cultivation, engaging in the planting of two principal rice crops annually: the winter-spring and the seasonal crops (*Table 1*). The winter-spring crop is typically sown in late October or early November and harvested by the end of May the following year, while the seasonal crop is planted towards the end of May and harvested by mid-November. Recent years have seen the cultivation of various rice varieties in the province, including hybrid types such as Thai Xuyen 111, MHC2, Phu Uu 978, Quoc te 1, VT404, C uu da he so 1, Nhi Uu 986, Huong Uu 98, alongside pure rice varieties like Bac Thinh, TBR225, ADI168, ADI28, Thien Uu 8, Dai Thom 8, Lam Son 8, Mutant Khang Dan, TBR279, Bac Thom No. 7, J02, VNR 20, Ha Phat 3, among others. These varieties are predominantly chosen for their adaptability to high temperatures and resistance to common pests, including rice blasts and brown planthoppers. The employment of hybrid rice varieties, in particular, has been instrumental in achieving higher yields compared to those obtained from traditional pure rice varieties, demonstrating enhanced resilience to climatic and environmental variations.

Table 1. *Annual rice growing area by district/town/city in Thanh Hoa Province in 2020 (Thanh Hoa Provincial Statistics Office, 2021)*

No	District	Area (ha)	No	District	Area (ha)
	Lowland	178,602.4		Highland	52,602.3
1	Thanh Hoa[1]	6,658.4	15	Nghi Son[2]	9,602.0
2	Sam Son[1]	1,548.8	16	Vinh Loc[3]	9,143.0
3	Bim Son[2]	813.5	17	Thach Thanh[3]	8,718.8
4	Tho Xuan[3]	15,634.4	18	Cam Thuy[3]	7,269.0
5	Dong Son[3]	7,741.9	19	Ngoc Lac[3]	6,835.2
6	Nong Cong[3]	20,079.2	20	Lang Chanh[3]	2,509.7
7	Trieu Son[3]	18,855.4	21	Nhu Xuan[3]	4,344.1
8	Quang Xuong[3]	12,987.5	22	Nhu Thanh[3]	5,224.9
9	Ha Trung[3]	10,659.2	23	Thuong Xuan[3]	5,056.7
10	Nga Son[3]	8,471.5	24	Ba Thuoc[3]	4,976.7
11	Yen Dinh[3]	18,073.1	25	Quan Hoa[3]	2,303.1
12	Thieu Hoa[3]	15,955.1	26	Quan Son[3]	2,275.7
13	Hoang Hoa[3]	13,081.0	27	Muong Lat[3]	3,088.4
14	Hau Loc[3]	9,298.6			

Note: [1] City; [2] Town; [3] District

Data source

Meteorological data were collected from six weather stations and twelve hydrological stations across Thanh Hoa Province, spanning from 1980 to 2020. The locations of the meteorological and hydrological stations are depicted in Figure 1. Specifically, six meteorological stations measure temperature, precipitation, humidity, wind speed, and sunshine duration, including the following stations: Hoi Xuan (20˚22'; 105˚07'); Bai Thuong (19˚54'; 105˚23'); Yen Đinh (19˚59'; 105˚40'); Thanh Hoa (19˚45'; 105˚47'); Nhu Xuan (19˚38'; 105˚34'); Tinh Gia (19˚27'; 105˚47'). Additionally, twelve hydrological stations are responsible for measuring precipitation. Primary data collected and calculated include temperature, rainfall, humidity, heatwaves, droughts, heavy rainfall, and severe cold events. In particular:

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- The number of hot days is defined as the number of days with a maximum daily temperature (Tx) ≥ 35°C. Consecutive days with Tx ≥ 35°C are considered a heatwave.
- Drought is determined using the Standardized Precipitation Index (SPI), based on the deviation of actual precipitation (R) from the long-term average ($\overline{R}$) divided by the standard deviation (σ).
- The number of heavy rainfall days is defined as the number of days with daily precipitation (R) ≥ 50mm.
- The number of cold days is defined as the number of days with an average daily temperature (Ttb) ≤ 15°C.

Data related to exposure indicators were collected from the meteorological and hydrological data of Thanh Hoa Province for the period 1980-2020. Based on the collected data, several indicators were identified through calculations and synthesis from raw meteorological data.

Methods

Assessment of vulnerability to climate change

According to the IPCC, vulnerability to climate change is a function of the degree of exposure, sensitivity, and adaptive capacity (IPCC, 2007).

Vulnerability (V) = f(exposure (E), sensitivity (S), adaptive capacity (AC)), where:

- Exposure is the nature and degree to which a system is exposed to significant climatic variations.
- Sensitivity is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli.
- Adaptive capacity is the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, exploit opportunities, or cope with the consequences.

The process of calculating the vulnerability index for rice crops due to climate change is detailed in the following steps (World Bank, 2010; Mohan and Sinha, 2010; WWF Vietnam, 2013):

Step 1: Standardize selected indicators of each component/variable

The actual values of the indicators are standardized for all districts according to the formula:

$$X_{ij} = \frac{X_{ij}(t) - MinX_{ij}}{MaxX_{ij} - MinX_{ij}} \qquad \text{(Eq.1)}$$

where,

X_{ij}: Standardized value of indicator j at locality i;

$X_{ij}(t)$: Real value of indicator ij;

Min X_{ij}: Minimum real value of indicator ij(t) in all districts;

Max X_{ij}: Maximum real value of indicator ij(t) in all districts.

The calculation according to formula (1) aims to bring different factors with different units to the same dimensionless unit and result in the values of indicators ranging from 0.0 - 1.0.

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Step 2: Calculate the values/indexes of the component variables

The indices of exposure (E), sensitivity (S), and adaptive capacity (AC) components are calculated using the formula:

$$C = \frac{\sum_{j=1}^{k} X_{ij} * WX_{ij}}{\sum_{j=1}^{k} WX_{ij}} \qquad \text{(Eq.2)}$$

where,

C: Value of index of component variables;

Xij: Standardized value of indicator j at locality i;

WXij*:* Weight of indicator j at locality i (determined by the AHP method).

Step 3: Calculate the vulnerability index

Integrating the values of the three components/variables will yield the vulnerability index. The vulnerability index is calculated according to the formula:

$$V = \frac{E+S+(1-AC)}{3} \qquad \text{(Eq.3)}$$

where,

V: Vulnerability index

E: Exposure index, The higher the E index, the stronger the impact;

S: Sensitivity index, the higher the S index, the greater the sensitivity;

AC: Adaptive capacity index, The higher the AC index, the greater the adaptability.

The vulnerability scale ranges from 0 to 1, indicating low, medium, and high levels of vulnerability. However, for different regions, the scale can be divided into different levels based on the specific vulnerability index of that area.

In the assessment method, the initial step of selecting indicators for evaluating vulnerability is crucial in building the input database for the calculation process of the component indices and the overall vulnerability index. The selection of primary and supplementary indicators for each component should align with the nature of climate change impacts and natural disasters affecting the subject of assessment. An indicator is an independent measurement unit for a characteristic of the affected object, and an index is a composite measurement unit incorporating several indicators. However, vulnerability indicators should also reflect the socio-economic conditions, environmental issues of countries or regions, the processes leading to vulnerability, and available capacities (Handisyde et al., 2006).

In this study, exposure indicators were selected based on climate factors (temperature, humidity, rainfall) and natural phenomena (typhoons, heatwaves, droughts, heavy rainfall, and severe cold) causing damage to rice crops in the context of climate change. These indicators are represented through the frequency, intensity, and variability of climate factors in Thanh Hoa Province. Sensitivity indicators were chosen concerning the impact of climate change and natural disasters on rice cultivation areas and productivity per season. Adaptive capacity indicators related to rice cultivation were selected regarding the development of infrastructure, the economic capability of households, and state policies implemented to enhance adaptability to climate change, mitigate damages caused by climate change, and utilize opportunities for adaptation.

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Each indicator of the variables was collected, calculated, and synthesized into a set of indicators for assessing vulnerability. Due to the differing units of the indicators, direct evaluation and comparison are not feasible. Therefore, the indicators were normalized using formula (1) to allow for the assessment of the impact level of each indicator across different areas. After normalization, formulas (2) and (3) were applied to determine the impact levels of the component variables and the vulnerability levels in various regions. *Table 2* presents a set of selected indicators to assess the vulnerability of rice crops in Thanh Hoa Province. The weights of the indicators presented in *Table 2* were determined using the Analytic Hierarchy Process (AHP) method, as detailed in the AHP analytical hierarchy method section.

***Table 2**. Set of indicators to assess vulnerability to the rice growing field due to the impacts of climate change and natural disasters in Thanh Hoa Province*

Indicator groups	Main indicators	Sub-indicators	Indicator weights	Indicator unit	Data source
Exposure indicators	Natural disasters and climatic factors affect crops throughout the year	Frequency of storms	0.126	Average number of storms/year	
		Number of months the drought occurred	0.124	Months of drought	
		Variation of mean annual temperature	0.073	%	
		Variation of mean annual maximum temperature	0.056	%	
		Variation of mean annual minimum temperature	0.056	%	
		Number of hot days (Tx ≥ 35°C)	0.098	Day	
		The number of severe cold days (Ttb ≤ 15°C)	0.108	Day	
		Number of heavy rain days (R ≥ 50mm)	0.096	mm	
		Variation of annual rainfall	0.084	Day	
	Climatic conditions affect the winter-spring rice crop and the seasonal rice crop	Minimum temperature during the sprouting stage	0.178	˚C	Hydrometeorological data of Thanh Hoa province for the period 1980-2020
		Temperature during the growth period		˚C	
		Temperature of harvest month		˚C	
		Rainfall of the 1st month		mm	
		Rainfall of the 2nd month		mm	
		Rainfall of the 3rd month		mm	
		Rainfall of the 4th month		mm	
		Relative humidity during the sprouting stage		%	
		Relative humidity during the development period		%	
Sensitive indicators	Area	Area of winter-spring rice crop	0.167	Ha	Statistical Yearbook of Thanh Hoa in 2020
		Area of seasonal rice crop	0.167	Ha	
	Productivity	Productivity of winter-spring rice crop	0.333	Quintal/ha	
		Productivity of seasonal rice crop	0.333	Quintal/ha	
Adaptive capacity indicators	Infrastructure Adaptation	Percentage of villages with national grid electricity	0.172	%	Statistical Yearbook of Thanh Hoa in 2020
		Percentage of households with hygienic water	0.145	%	
		Percentage of communes and wards with 100% asphalt and concrete roads	0.118	%	
		Percentage of communes and wards meeting national health standards	0.038	%	
	Socioeconomic	Average income per capita per year	0.104	Million VND	Report on the socio-economic situation of Thanh Hoa province and districts of Thanh Hoa Province in 2020
		Percentage of trained workers with elementary degrees or higher working in the economy	0.064	%	
		Percentage of households with medium living standard or higher	0.087	%	
	Policy mechanisms	Budget spent on environmental careers and climate change	0.273	Million VND	

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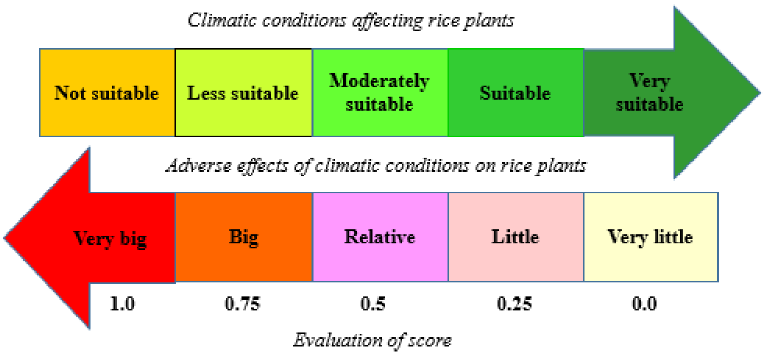
The critical climatic thresholds impacting rice cultivation were outlined in the study by Oldeman and Frere (1982) (*Table 3*). In our study, the phenological stages of the rice plant are as follows: For the winter-spring crop, the germination phase occurs between late October and early November. This phase is followed by a growth period lasting five months, from December through April of the subsequent year, culminating in a harvest at the end of May. In the case of seasonal rice crops, germination is set towards the end of May and the beginning of June. The vegetative growth spans the months of July, August, September, and October, with the harvest scheduled for mid-November.

Table 3. *Climatic conditions affecting rice cultivation (Oldeman and Frere, 1982)*

Climatic conditions	Very suitable	Suitable	Moderately suitable	Less suitable	Not suitable
Minimum temperature during the sprouting stage (°C)	22-18	18-14 22-25	14-10 25-28	10-7 28-30	< 7 > 30
Temperature during the growth period (°C)	32-30	30-24 32-26	24-18	18-10	< 10
Temperature of harvest month (°C)	36-33	33-30 > 36	30-26	26-21	< 21
Rainfall of the 1^{st} month (mm)	400-200	200-175 400-500	175-125 500-650	125-100 650-750	< 100 > 1500
Rainfall of the 2^{nd} month (mm)	400-200	200-175 400-500	175-125 500-650	125-100 650-750	< 100 > 1500
Rainfall of the 3^{rd} month (mm)	400-200	200-175 400-500	175-125 500-650	125-100 650-750	< 100 > 1500
Rainfall of the 4^{th} month (mm)	50-200	200-300	300-500 50-30	500-600 < 30	> 600
Relative humidity during the sprouting stage (%)	75-60	60-50 > 75	50-40	40-30	< 30
Relative humidity during the development period (%)	65-37	37-33 65-80	33-30	< 30	

The standardization of these indicators deviates from the conventional application of formula (1), opting instead for a scoring system that ranges from "Not suitable" to "Very suitable," with scores transitioning from 1 to 0. This methodological choice aims to remove unit-based discrepancies, thereby ensuring that the numerical scoring aligns with the principles underlying formula (1). In this context, a score of 0 signifies minimal impact, whereas a score of 1 indicates maximal impact.



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AHP analytical hierarchy method

The determination of the weights for the indicators of component variables employs the Analytical Hierarchy Process (AHP) as proposed by Saaty (1980), encapsulated in three primary stages: analysis, evaluation, and synthesis. The initial stage of analysis entails the delineation of objectives, criteria, and alternatives within a structured hierarchy. Subsequently, the evaluation phase utilizes a pairwise comparison matrix, employing a ratio scale from 1 to 9 to ascertain weights based on the priority vector which aligns with the scores of alternatives, followed by an assessment of the consistency ratio. In the final stage, these weights are amalgamated to facilitate optimal decision-making.

For the assessment of exposure indicators, criteria for comparison are selected to elucidate the nature and extent of each indicator's impact, categorized under winter-spring and seasonal criteria. Indicators of sensitivity are directly tied to the rice crops, with the comparison based on the level of vulnerability attributable to the ramifications of climate change and natural disasters on each cropping cycle. The comparative criteria for adaptive capacity indicators focus on the mitigation and minimization of adverse impacts stemming from natural disasters and extreme weather conditions on rice cultivation in Thanh Hoa province. The weights assigned to the indicators range between 0 and 1, ensuring that the cumulative weight of the indicators for each component equals 1. The consistency ratio for the entire weighting process remains below 10%, indicating that the results of the weight calculation are sufficiently reliable for integration into the vulnerability index calculation.

Thiessen partition method

The differentiation of temperature, humidity, and precipitation across the districts of Thanh Hoa was conducted utilizing the Thiessen polygon method via ArcGIS software. This approach facilitated the delineation of distinct zones for temperature and humidity, illustrated in *Figure 2a*, and for precipitation, shown in *Figure 2b*. Within these delineated districts, the values assigned to meteorological factors correspond to the area ratio of each zone, ensuring that local variations in climate conditions are accurately represented in the assessment.

Results and discussion

The vulnerability of rice crops in Thanh Hoa Province to climate change and natural disasters is intricately linked to three key component variables: exposure (E), sensitivity (S), and adaptive capacity (AC). The calculated values for these component indices (E, S, AC) along with the overall vulnerability index (V) fall within a range from 0 to 1. This range is further categorized into four distinct levels of vulnerability: low (0.0-0.25), average (0.26-0.5), high (0.51-0.75), and very high (0.76-1.0). Classifying the indicators into different levels is crucial for comparing and assessing the vulnerability levels across various regions (Mohan and Sinha, 2010).

The exposure index values for rice cultivation in Thanh Hoa Province range from 0.32 to 0.65, indicative of a moderate to high level of exposure to climate change and natural disasters (*Table 4*). Nhu Thanh district exhibits the highest exposure, whereas the lowest levels are found in Dong Son district and Thanh Hoa City. Within the province, four out of twenty-seven districts, specifically Nhu Xuan, Nhu Thanh, Nong Cong, and Nghi Son, are identified with high exposure levels.

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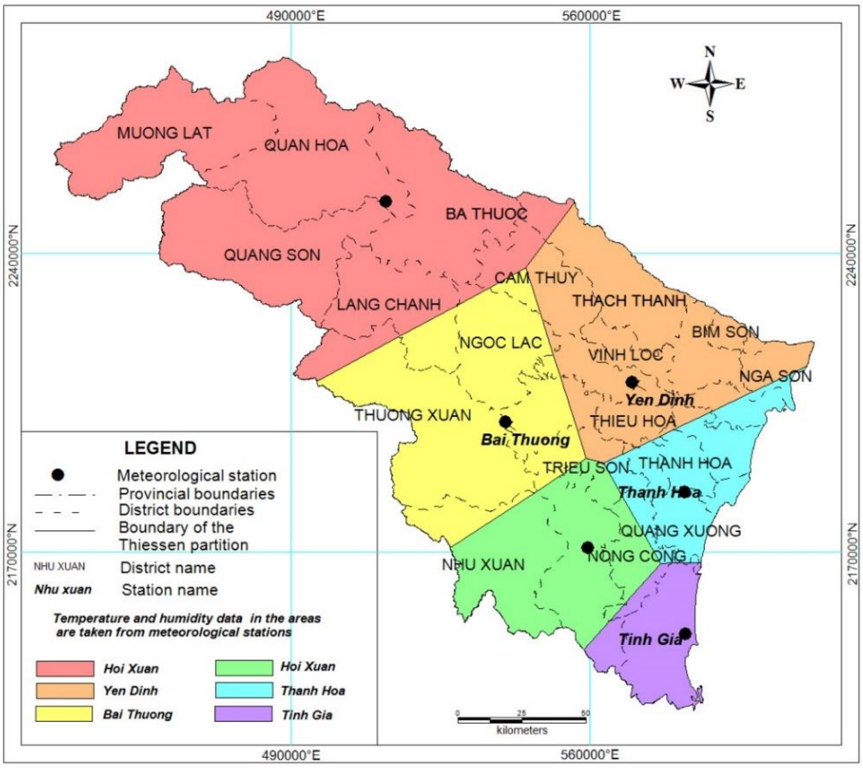
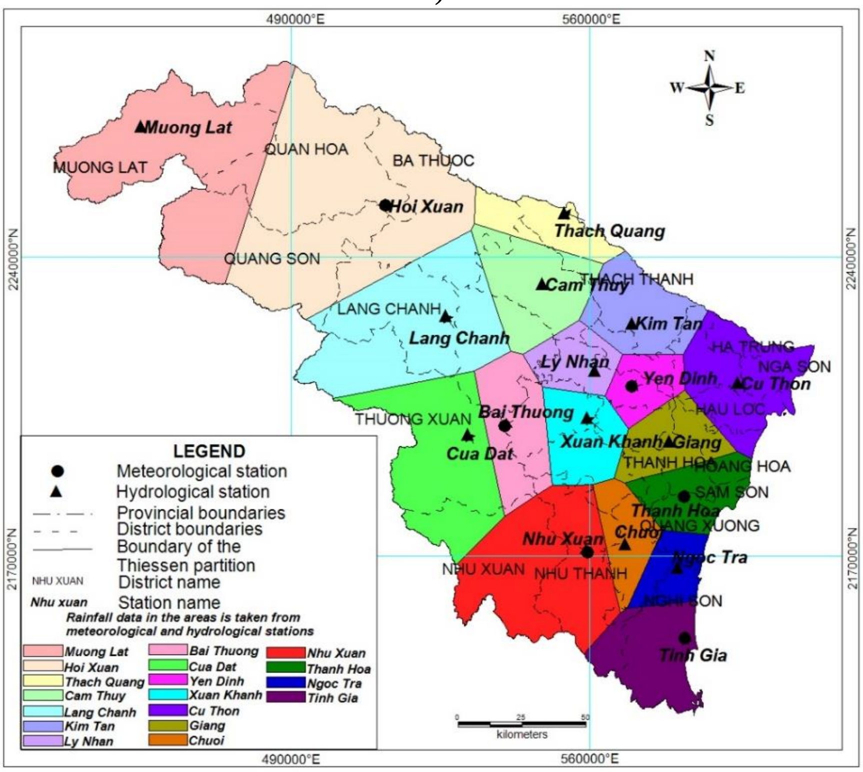


a)



b)

Figure 2. *Distribution diagram of a) temperature, humidity, and b) rain areas in Thanh Hoa Province*

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Table 4. *Values of component indices and vulnerability index due to climate change for rice in Thanh Hoa Province*

No	Districts	E	S	AC	V
1	Muong Lat	0.41	0.08	0.08	0.47
2	Quan Hoa	0.39	0.20	0.20	0.46
3	Quan Son	0.40	0.22	0.20	0.47
4	Ba Thuoc	0.42	0.45	0.28	0.53
5	Lang Chanh	0.46	0.30	0.24	0.51
6	Thach Thanh	0.36	0.51	0.52	0.45
7	Cam Thuy	0.38	0.56	0.53	0.47
8	Ngoc Lac	0.46	0.51	0.35	0.54
9	Thuong Xuan	0.46	0.42	0.35	0.51
10	Vinh Loc	0.37	0.65	0.61	0.47
11	Yen Dinh	0.38	0.96	0.65	0.56
12	Tho Xuan	0.44	0.85	0.61	0.56
13	Bim Son	0.40	0.24	0.78	0.29
14	Ha Trung	0.40	0.59	0.61	0.46
15	Thieu Hoa	0.36	0.89	0.62	0.54
16	Trieu Son	0.48	0.84	0.62	0.57
17	Nhu Xuan	0.62	0.36	0.30	0.56
18	Nhu Thanh	0.65	0.47	0.49	0.55
19	Nga Son	0.43	0.63	0.60	0.48
20	Hau Loc	0.41	0.62	0.58	0.48
21	Hoang Hoa	0.37	0.79	0.62	0.51
22	Dong Son	0.32	0.63	0.68	0.42
23	Thanh Hoa	0.32	0.55	0.99	0.29
24	Quang Xuong	0.36	0.68	0.63	0.47
25	Nong Cong	0.60	0.96	0.61	0.65
26	Nghi Son	0.57	0.41	0.60	0.46
27	Sam Son	0.35	0.30	0.75	0.30

Note: E: exposure; S: sensitivity; AC: adaptive capacity; **V:** vulnerability

These districts, situated in the southern part of the province, encompass various geographical settings including midland (Nhu Xuan, Nhu Thanh), delta (Nong Cong), and coastal areas (Nghi Son), making them particularly vulnerable to environmental hazards such as storms, flooding, sea level rise, and saltwater intrusion. Notably, coastal ecosystems are often directly and indirectly impacted by climate change through changes in precipitation, sea surface temperature, sea level rise, ocean chemistry alterations, and shifts in ocean circulation (Bezuijen et al., 2011). Additionally, these regions experience significant variations in temperature, with an average of 34-39 hot days and 19-20 severe cold days annually, based on climate data from 1980 to 2020.

The observed climatic variability in these districts is notably higher compared to other parts of the province, with mean annual temperature fluctuations ranging from 2.6-3.2%, mean annual maximum temperature variations between 2.8-3.1%, and mean annual minimum temperature shifts from 2.4-2.6%. Average annual rainfall variability is also pronounced, ranging from 21-24%. The remaining districts exhibit moderate levels of

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exposure to climate-related risks. Given its location in the North Central coastal region, Thanh Hoa Province is significantly impacted by the effects of climate change and natural disasters each year. Thus, despite an overall average assessment of exposure for rice plants, the implications of climate variability and disasters remain profound across the identified districts.

For the Winter-Spring rice crop, climatic conditions across Thanh Hoa Province's districts tend to be relatively consistent (*Fig. 3*). During the crucial stages of sprouting and growth, as well as at harvest time, the minimum temperatures and relative humidity levels generally support the healthy development of rice plants. However, the rainfall pattern from the first to the fourth month, along with relative humidity levels throughout the plant's development period, ranges from less suitable to unsuitable. This indicates potential challenges in ensuring adequate water availability for the crops during these critical growth phases. Consequently, it is essential for farmers to accord heightened attention to water management practices for rice cultivation during this season to mitigate any adverse effects on crop yield and health due to suboptimal moisture conditions.

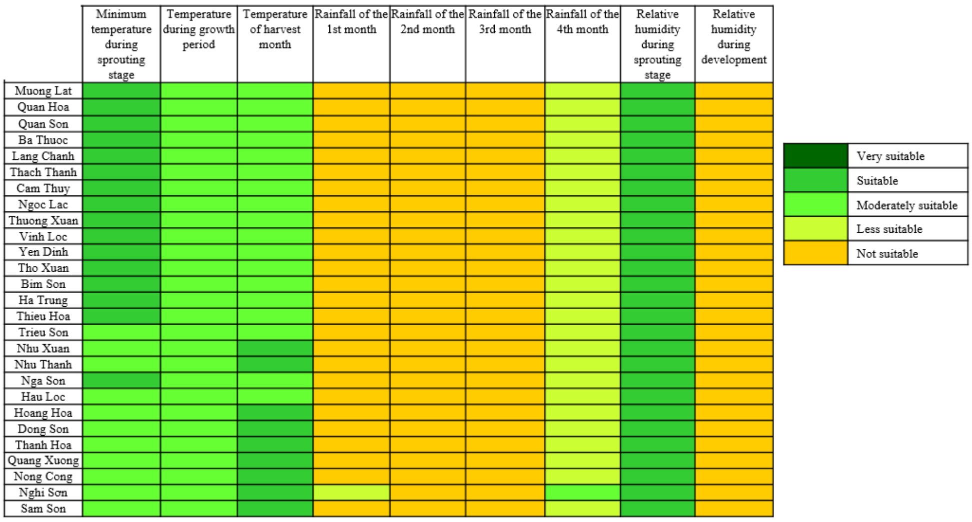

Figure 3. *Impact of climatic conditions on the winter-spring crop in Thanh Hoa Province*

For the seasonal rice crop, the climatic conditions—including temperature during the growing period, rainfall from the first to the fourth month, and relative humidity during the sprouting stage—are generally conducive to the growth of rice plants. Notably, rainfall during the second and third months often reaches levels highly favorable for cultivation (*Fig. 4*). However, the minimum temperature conditions during the sprouting stage present only moderate suitability for certain districts, such as Muong Lat, Quan Hoa, Quan Son, Ba Thuoc, Lang Chanh, Cam Thuy, and Thuong Xuan. In contrast, the remaining districts experience conditions ranging from less suitable to unsuitable. Additionally, the temperature at harvest time and the relative humidity throughout the growth period often fall into the less suitable to unsuitable category.

This analysis indicates that while certain climatic conditions support rice growth, others pose challenges, particularly regarding humidity during the growth stages of both rice crops. Consequently, in areas with suboptimal conditions, it is imperative for farmers to implement targeted interventions to mitigate the potential adverse effects on rice cultivation.

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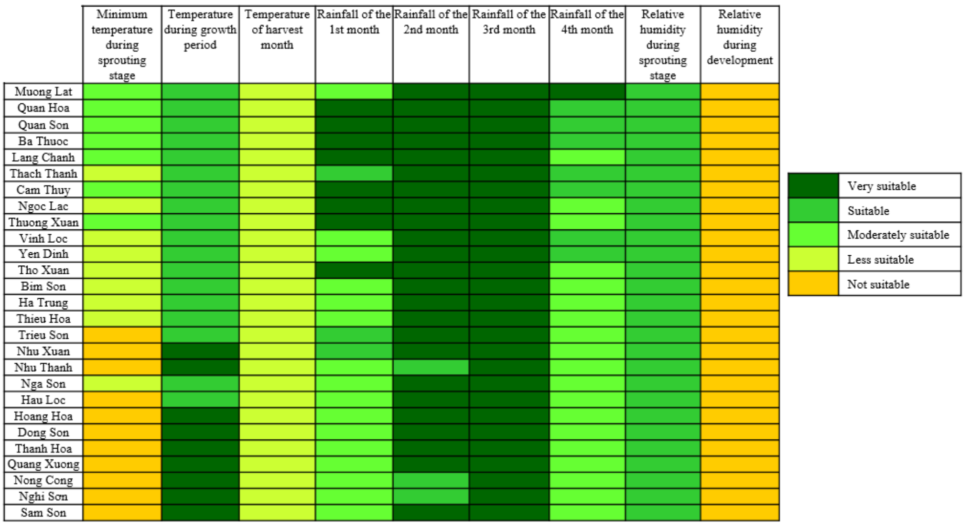

Figure 4. *Impact of climatic conditions on the seasonal rice crop in Thanh Hoa Province*

In Thanh Hoa Province, the sensitivity index values for rice range from 0.08 to 0.96, indicating a spectrum from low to very high sensitivity levels (*Table 4, Fig. 5*). The highest sensitivity is observed in the Nong Cong and Yen Dinh districts, with the lowest in Muong Lat District. Within the province, six out of twenty-seven districts exhibit very high sensitivity levels, namely Yen Dinh, Tho Xuan, Thieu Hoa, Trieu Son, Hoang Hoa, and Nong Cong. An additional ten districts display high sensitivity levels, including Thach Thanh, Cam Thuy, Ngoc Lac, Vinh Loc, Ha Trung, Nga Son, Hau Loc, Dong Son, Thanh Hoa, and Quang Xuong. Seven districts have an average sensitivity level, and four districts are categorized with low sensitivity.

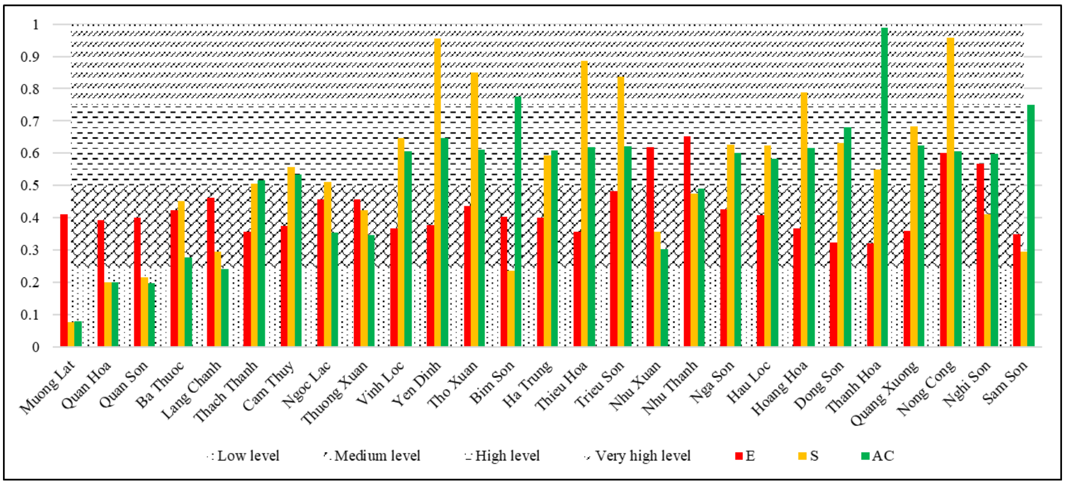

Figure 5. *Comparison of E, S, and AC values between districts in Thanh Hoa Province*

This distribution reveals that districts with very high and high sensitivity levels tend to be those with extensive rice cultivation areas and notable rice productivity. For instance, districts such as Yen Dinh, Trieu Son, and Nong Cong are among those with the largest rice cultivation extents in the province, each exceeding 9,000 hectares per crop, and achieving high yields of approximately 66-71 quintals per hectare for the winter-spring crop and 50-60 quintals per hectare for the seasonal crop. Typically, the yield for the winter-spring rice crop surpasses that of the seasonal crop, with a difference ranging from 1 to 16 quintals per hectare. Conversely, mountainous districts like Muong Lat, Quan Hoa, and Quan Son, characterized by smaller rice-growing areas and lower productivity—ranging from 700 to 1,000 hectares with yields of 47-54 quintals per hectare for the winter-spring crop, and 1,000 to 2,000 hectares with yields of 32-44 quintals per hectare for the seasonal crop—exhibit the least sensitivity to climate change and natural disaster impacts.

The adaptive capacity index values for rice cultivation in Thanh Hoa Province span from 0.08 to 0.99, indicating a range from low to very high levels of adaptive capacity (*Table 4, Fig. 5*). Thanh Hoa City boasts the highest adaptive capacity, whereas Muong Lat District registers the lowest. Within the province, Bim Son Town and Thanh Hoa City are the two out of twenty-seven districts identified with very high adaptive capacity levels. Additionally, sixteen districts are recognized to have high adaptive capacity levels, five districts exhibit average adaptive capacity, and four districts display low adaptive capacity.

The distribution of adaptive capacity levels highlights that districts with very high and high adaptive capacity are predominantly located in the delta-coastal region, which benefits from more favorable economic development conditions compared to the mountainous districts, such as Muong Lat, Quan Hoa, Quan Son, Ba Thuoc, and Lang Chanh. Despite the geographical challenges, concerted efforts by provincial leadership have led to significant improvements in infrastructure adaptability both in the mountainous and delta regions. For instance, the coverage of villages connected to the national grid electricity ranges from 90 to 100%, with the exception of Muong Lat District at 63.6%. Furthermore, the percentage of households with access to hygienic water sources is between 89 to 96%, and the proportion of communes and wards meeting national health standards spans from 71 to 100%. These achievements underscore the concerted efforts to enhance resilience and adaptive capacity across different parts of the province, contributing to a more robust response to the challenges posed by climate change and natural disasters.

The vulnerability index for rice cultivation in Thanh Hoa Province spans from 0.29 to 0.65, signifying a range from moderate to high vulnerability (*Table 4*, *Fig. 5*). Vulnerability assessment results are often presented in the form of vulnerability maps, particularly when using index-based assessments (USAID, 2016). Vulnerability maps provide policymakers with an effective tool to identify the most vulnerable areas (Huong et al., 2020). Consequently, a vulnerability map for rice cultivation in Thanh Hoa Province has been developed to illustrate the impacts of climate change and natural disasters. This map offers an overview of the region's vulnerability status. The results indicate that, across the province, twelve out of twenty-seven districts are categorized under a high vulnerability level. This classification encompasses districts situated in the delta (Yen Dinh, Tho Xuan, Thieu Hoa, Trieu Son, Nong Cong), along the coast (Hoang Hoa), and those located in midland and mountainous regions distant from the sea (Ba Thuoc, Lang Chanh, Ngoc Lac, Thuong Xuan, Nhu Xuan, Nhu Thanh) (*Fig. 6*). Among these areas, Nong Cong District, located in the southeastern part of the province and near the coast, is highly vulnerable due to its exposure to strong storms, heavy rains, and flooding. The district's terrain is primarily flat, accounting for 67.3% of the total area, with two main rivers, the Yen River and the Lang Giang River, flowing through it. Nong

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Cong has the largest rice cultivation area in the province, with a total planting area of 20,079.2 hectares in 2020. However, climate change and natural disasters significantly impact rice production in the district.

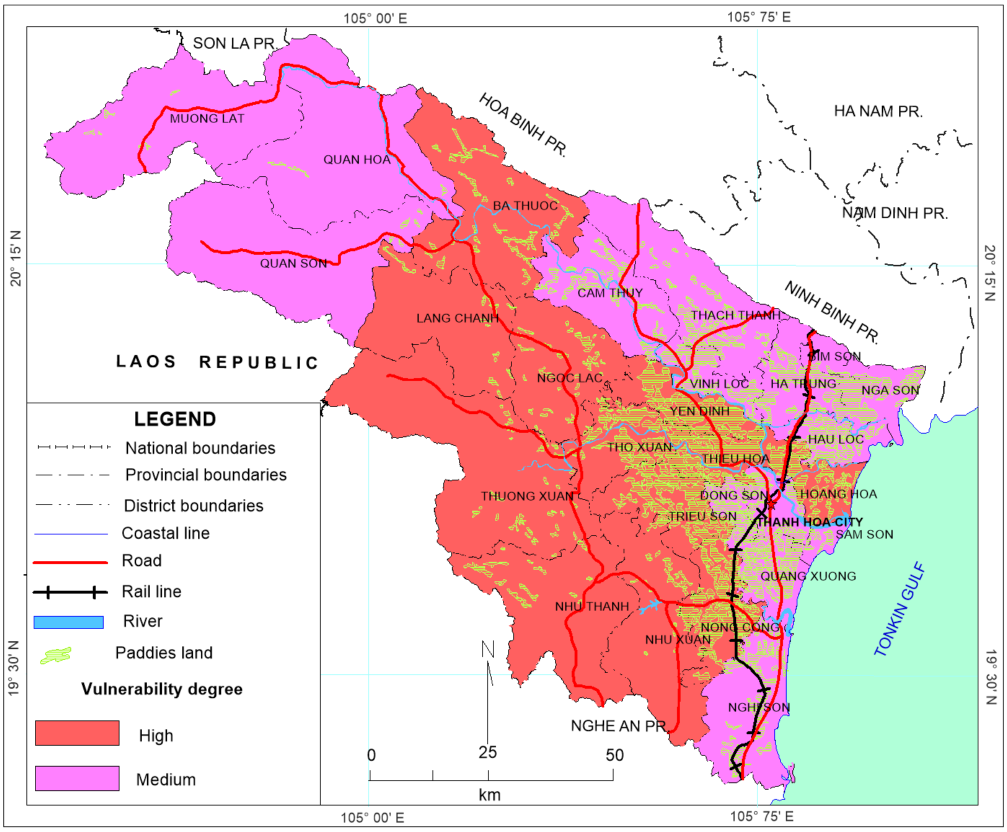

Figure 6. *Level of vulnerability to rice cultivation due to the impact of climate change and natural disasters in Thanh Hoa Province*

Statistical data shows that from 1980 to 2020, the district experienced an average of 35.5 hot days and 20.3 cold days per year, 11.1 days of heavy rainfall, and significant variations in average, maximum, and minimum temperatures ranging from 2.4% to 2.9%. Therefore, areas with high vulnerability levels need appropriate solutions to adapt to increasingly harsh climate conditions. These solutions include following the recommended planting schedules from local authorities, improving water management systems, adopting new rice cultivation models, and using high-yield rice varieties that are more resilient to environmental and climatic changes. For example, using sturdier rice varieties that are less prone to lodging during storms and have increased resistance to pests and diseases. The other districts are identified with a medium level of vulnerability, with Thanh Hoa City and Sam Son City registering the lowest vulnerability indices. These two cities have developed economies, good infrastructure, high per capita income, and high levels of education. As a result, farmers in these areas are better equipped to care for and recover from crop damage. They can use advanced rice varieties, apply biotechnology in cultivation, and incorporate advanced science and technology, as well as modern machinery, into rice production. Therefore, despite being situated in coastal areas prone to natural disasters such as storms, floods, heavy rains, and hot days, and having a medium

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to high sensitivity level, the impact on vulnerability is substantially mitigated due to the rice crops' high to very high adaptive capacity in these areas. This demonstrates how effective adaptation strategies can significantly lower the vulnerability of agricultural practices to the adverse effects of climate change and natural disasters.

Conclusions

In Thanh Hoa Province, Vietnam, climate change, coupled with a susceptibility to various natural disasters, has significantly compromised rice cultivation, affecting both productivity and the economic well-being of farmers. Our comprehensive index-based vulnerability assessment, focusing on exposure, sensitivity, and adaptive capacity, illuminates the acute challenges faced by the rice-producing sectors across the province's 27 districts. Notably, twelve districts are characterized by a high level of vulnerability, a scenario that underscores the urgency for tailored mitigation and adaptation strategies. These critical districts are spread across delta, coastal, and remote midland and mountainous areas, each with distinct challenges posed by climate change and natural disasters.

The study's findings suggest a multi-faceted approach to enhance resilience among these high-risk areas. Key recommendations include adherence to optimized sowing schedules, improvement of water management systems, deployment of advanced rice cultivation models, and the adoption of new rice varieties engineered for higher productivity, weather resilience, and pest resistance.

This research underscores the critical need for strategic planning and resource allocation to reinforce Thanh Hoa's rice cultivation against the threats of climate change. Identifying the most vulnerable districts provides valuable insights for policymakers, agronomists, and local stakeholders, urging collaborative efforts to develop and implement adaptive strategies and policies. Such measures are essential to protect rice production, ensure food security, and maintain the livelihoods of the farming communities in Thanh Hoa Province.

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