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Unravelling the economic impact of climate change in Vietnam's Mekong River Delta and Southeast region

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Abstract
Vietnam faces a heightened susceptibility to natural disasters stemming from climate change, yet the impact of these disasters varies markedly across its regions. Consequently, it is imperative to scrutinize the climatic factors affecting the regional economy, with a particular dearth of research addressing the nexus between natural threats and the economies of the Mekong River Delta and the Southeast region of Vietnam. The primary objective is to investigate how temperature fluctuations, rising sea levels, storms, and forest fires can detrimentally affect agriculture, forestry, and infrastructure in these regions. The present research uses the secondary data from Vietnam's General Statistics Office and the German Agency for International Cooperation. Employing quantitative analysis, the study endeavours to assess and compare the influence of climate change elements on the economic trajectories of the Mekong River Delta and the Southeast region. The findings reveal that the Mekong River Delta is disproportionately impacted by economic losses attributed to rising sea levels when juxtaposed with other regions in Vietnam. Firstly, the escalating sea levels significantly jeopardize residential and agricultural land in the Mekong River Delta (1). Secondly, while wildfires inflict damage on forestry in both the Mekong River Delta and the Southeast area, their overall impact is deemed negligible (2). Thirdly, the study ascertains that houses in the Mekong River Delta and the Southeast region remain relatively unscathed by storms (3). However, it is noted that specific storms have inflicted substantial damage on both regions (4). In light of these findings, future research should delve deeper into the analysis of storm risks in the Mekong River Delta and the Southeast region. Such insights are crucial for enhancing our understanding of the vulnerabilities and devising effective strategies to mitigate the economic repercussions of climate change in these pivotal areas.

Keywords Sea level rise · Climate change · Economic growth · Agriculture · House · Mekong River Delta · Southeast region

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1 Introduction

The exploration of climate change and its ramifications is undergoing a significant expansion.[1] In the absence of efficacious adaptation strategies, climate change is poised to engender profound environmental transformations, exerting adverse effects on nations worldwide [1]. Concurrently, the evolving climate manifests multifaceted repercussions across various socioeconomic domains, spanning agriculture, human health, tourism, labour dynamics, and disease proliferation. Among these realms, climate impacts agriculture and fishing. While rising temperatures and CO_2 levels can boost crop yields in many parts of the world, nutrient levels and soil moisture, as well as water availability and other conditions, will need to be met in order for these benefits to be realized [2]. Drought and flooding events could become more frequent and severe, posing new challenges for farmers, ranchers, and food security [2]. Furthermore, Livestock could also be at risk from heat waves, which are expected to become more frequent as a result of climate change. In 2011, heat-related losses for agricultural producers were estimated at over $1 billion [3]. Also, Climate change is causing marine diseases such as oyster parasite spread, salmon diseases in Bering Sea, and coral, eelgrass, and abalone outbreaks [4]. Higher water temperatures and estuarine salinities contribute to these outbreaks.

As projected by the Intergovernmental Panel on Climate Change (IPCC), the escalating concentration of greenhouse gases globally is anticipated to induce alterations in the worldwide average temperature, sea levels, and the frequency of extreme weather events [5]. This shifting climate landscape is poised to exert an impact on Vietnam's economic trajectory. Extensive research, as documented in studies by [6–8], underscores the vulnerability of long-term economic growth to the perils of climate warming, rising sea levels, and the heightened occurrence of extreme weather phenomena, including hurricanes and droughts. Of noteworthy significance is Vietnam's placement on the list of nations most profoundly affected by climate change, as elucidated by [9]. This underscores the urgency and imperative for comprehensive understanding and strategic intervention in light of the unique challenges posed to Vietnam's economic landscape. Furthermore [10], indicates that Vietnam belongs to the most disaster-stricken regions in the West Pacific. Natural calamities concern millions of Vietnamese citizens, threatening the populations' means of subsistence as well as their lives. The recognition of these risks serves as a compelling call to action, emphasizing the need for proactive measures and informed policies to navigate and mitigate the multifaceted impacts of climate change on Vietnam's socio-economic fabric.

Nevertheless, the impacts of climate change on distinct economic regions in Vietnam are anticipated to vary significantly due to the pronounced geographic diversity across the nation. For example, the prognosis suggests that global warming will lead to more frequent and intensified storms in Vietnam. Historical data spanning the period from 1954 to 2000 reveals an annual average of 7 storms making landfall on Vietnam's coast, with the Southeast and Mekong Delta areas experiencing fewer direct hits [11]. Consequently, the augmented strength of storms induced by climate change is likely to result in more substantial damage concentrated in the central and northern regions of Vietnam. Contrastingly, the elevation of sea levels is expected to inflict comparatively less damage on cities in the Red River Delta when juxtaposed with the Mekong River Delta. The rationale lies in the fact that the majority of cities in the Red River Delta are situated above sea level, ranging from 3 to 8 m [11]. In stark contrast, a significant portion of the land in the Mekong River Delta region is situated at one meter or less above sea level [12], rendering agricultural activities in this region exceptionally susceptible to the adverse impacts of sea level rise and soil salinity [13]. This nuanced understanding underscores the imperative for tailored adaptation and mitigation strategies geared towards the specific vulnerabilities of each region.

An estimated 85% of the population residing in the Mekong River Delta is engaged in the agricultural sector, underlining its pivotal role in the region's socio-economic fabric [13]. Moreover, this area is responsible for a staggering 90% of the country's rice production and 60% of its aquaculture exports, accentuating the susceptibility of the Mekong Delta's economy and the livelihoods of its inhabitants to the adverse impacts of sea level rise. While sea level rise poses a substantial threat to Vietnam as a whole, the Central Highlands, Northern Midlands, and Mountain regions are anticipated to experience relatively minor negative consequences. In light of these regional nuances, it becomes imperative to conduct analyses that consider the specific vulnerabilities of each area. Furthermore, the segmentation of Vietnam into smaller economic regions is deemed essential for the implementation of targeted economic adaptation strategies, aiming to mitigate the deleterious effects of climate change in each unique region. To ensure precision, this paper adopts a classification into six distinct economic regions, facilitating an in-depth examination of the climate change impact on each

[1] https://climate.ec.europa.eu/climate-change/consequences-climate-change_en (Accessed on 17/01/2024).

Fig. 1 Asia base map [17]

area: Red River Delta area, Northern Midlands, Mountain Areas, Central Highlands, North Central and Central Coastal area, Southeast, and Mekong River Delta.

Furthermore, article follows a structure, where the second section offers a brief literature review on the present topic. Section three is more focused on the methodology used in this research followed by section four, where the analysis of present research is done. Section five provides a brief discussion on the findings of the present research and how these findings advances the past literature. Finally, section five offers the conclusion which summarises the present research along with the limitations and future research directions.

2 Literature review

The pervasive effects of global warming and changing climate reverberate across every corner of the planet, ushering in significant disruptions with inevitable repercussions on the economies of various regions in Vietnam, both through direct and indirect channels [14, 15]. Given Vietnam's extensive coastlines, dense population, heavy reliance on agriculture and other natural resources, and vast forested areas, the nation stands as one of the most profoundly impacted by the far-reaching consequences of climate change [16]. Particularly vulnerable are communities with lower incomes, as their livelihoods are intricately tied to agricultural production, heavily contingent upon environmental conditions and weather patterns. Further, we have illustrated an Asia map to present the location of Vietnam in southeast Asia region in Fig. 1.

It is imperative to emphasize that the consequences of climate change in Vietnam, particularly the rise in sea levels, will vary significantly between coastal and non-coastal regions. Consequently, conducting a comprehensive

Table 1 Share of economic sector and regions in GDP [18]

Row labels	Central highlands (%)	Northern Central area and Central coastal area (%)	Northern midlands and mountain areas (%)	Red River Delta (%)	Mekong River Delta (%)	South East (%)	Grand Total (%)
Agriculture excluding rice	0.4	1.6	0.9	1.7	1.4	1.2	7.3
Aquaculture	0.2	0.6	0.3	0.6	0.5	0.5	2.7
Construction	0.3	1.0	0.6	1.0	0.8	0.8	4.5
Energy	0.5	1.8	1.0	1.8	1.5	1.4	8.0
Forestry	0.1	0.3	0.2	0.3	0.3	0.2	1.4
Health	0.1	0.3	0.2	0.3	0.2	0.2	1.3
Manufacturing	1.8	6.4	3.8	6.7	5.6	5.0	29.2
Rice	0.1	0.5	0.3	0.4	1.7	0.1	3.2
Services	1.9	6.8	4.0	7.1	5.9	5.3	31.1
TransportLand	0.6	2.2	1.3	2.3	1.9	1.7	9.9
TransportWater	0.1	0.2	0.1	0.2	0.2	0.1	0.8
Water	0.0	0.1	0.1	0.2	0.1	0.1	0.7
Total	6	22	13	23	20	17	100

Table 2 Regional rice production [18]

Region	Share of planted paddy land (%)
Northern Central area and Central coastal area	16
Northern midlands and mountain areas	9
Centre highlands	3
Red river delta	14
South East	4
Mekong Delta	54

analysis of the overall impact of climate change on Vietnam's economy poses a considerable challenge due to the intricate and diverse nature of these effects. Further, Table 1 offers the share of economic sector in GDP.

In this study, particular emphasis is placed on the analysis of the Southeast region and the Mekong River Delta, as these regions wield significant economic influence, collectively representing a substantial portion of planted paddy land (58%, Table 2), and are home to 70 million of the Vietnamese population [19]. While briefly touching upon the negative repercussions of climate change on other regions' economies, this study delves deeply into the multifaceted challenges posed by climate change. Recognizing that climate change may escalate the frequency and intensity of natural disasters, encompassing storms, rising sea levels, salinization, landslides, higher average summer temperatures, increased floods, and heightened occurrences of forest fires, this research focuses on analysing three specific adverse aspects. Firstly, a meticulous examination is conducted to unravel the negative impact of elevated temperatures and rising sea levels on agriculture in the Mekong River Delta and Southeast regions. Secondly, the paper scrutinizes the influence of sea level rise and forest fires on the forestry industry in the Mekong and Southeast regions. Lastly, the study investigates the structural damage caused by storms and the rising sea levels, providing comprehensive insights into the intricate interactions between climate change and these vital economic sectors.

This paper directs its analytical focus towards agriculture, forestry, and critical infrastructure, recognizing their pivotal roles in sustaining life. It underscores the importance of acknowledging that the impacts of climate change, such as rising sea levels and intensified storms, vary significantly across industries. The effects on agriculture and forestry, for instance, differ markedly from those on construction. Consequently, adaptation measures must be tailored to the unique challenges faced by each industry. For instance, agricultural land loss resulting from rising sea levels can be mitigated through the construction of dams [20]. Implementing storm early-warning systems proves effective in reducing infrastructure damage [21]. Water management solutions address shortages induced by rising temperatures [22], while adapting to extreme heat involves transitioning towards more capital-intensive production processes to replace labour-intensive operations, thereby safeguarding labour productivity [23]. The formulation of adaptation measures necessitates a thorough cost–benefit analysis, recognizing the dynamic nature of the issue [24]. This paper strives for precision by utilizing specific climate variables' data to analyse their impact on distinct economic variables. Such a nuanced approach is crucial for understanding the intricacies of climate change impacts and devising effective adaptation strategies that align with the unique challenges faced by each sector.

2.1 Climate variables

In order to comprehensively capture the impact of climate change on the economy, it is imperative to integrate climate variables into the model. Unlike a small open economy model, the influence of domestic economic activity on climate variables need not be considered. In contrast to the approach taken by [25], our model does not delve into the intricate interactions between business activity and climate change. In this model, climate factors operate independently of other endogenous variables. To investigate the repercussions of climate change on the economy of the Mekong River Delta and Southeast regions, this study employs simulation data for regional annual average temperature (TAS_r), forest fires ($FIRE_t$), storms ($STORM_t$), and sea levels (SL_t). These climate variables are meticulously modelled by region, enabling a nuanced exploration of their individual and collective impacts on the economic dynamics of the specified regions.

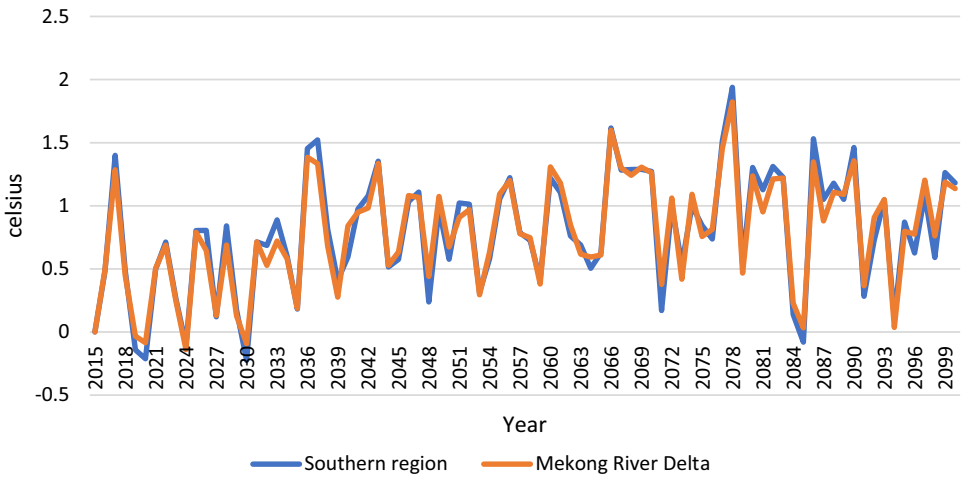

Fig. 2 Regional Average Annual Temperature (Moderate scenario)

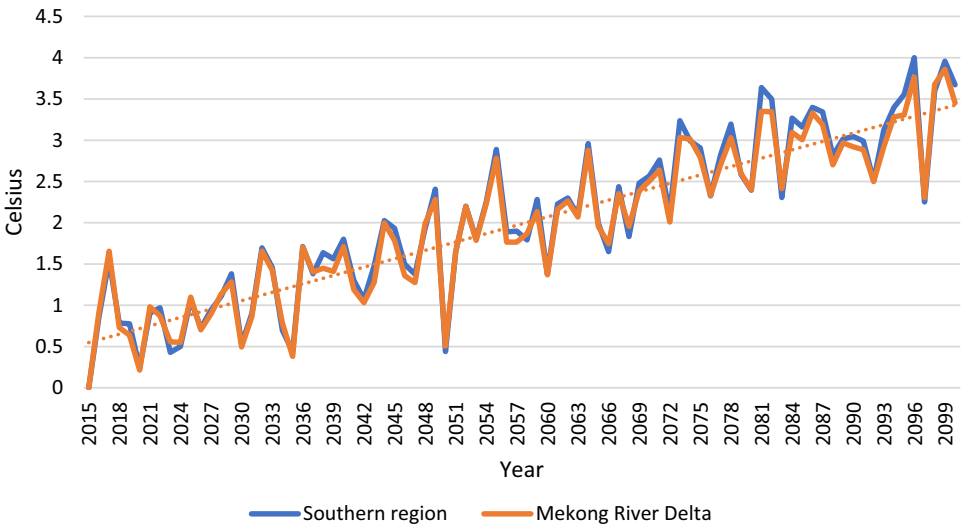

Fig. 3 Regional Average Annual Temperature (extreme scenario)

2.1.1 Temperature

Scientists worldwide, after extensive deliberation, have reached a consensus that socio-economic growth has undergone significant acceleration over the past few decades across various sectors, encompassing energy, industry, transportation, agriculture, and forestry. This surge in growth, however, comes at a cost: escalating greenhouse gas emissions, resulting in a warmer Earth, changes in the climate system, and adverse impacts on the overall environment. Greenhouse gas emissions will continue to cause rapid global warming, and it is likely that "we will exceed 1.5 °C around 2030–2035". We are now at around 1.1 °C and current climate policies are estimated to lead to an increase in warming up to 3.2 °C by 2100 [26]. The rise in sea levels by 2100, expected to be 0.6 m higher than 2000 [27]. Additionally, the intensity and frequency of natural catastrophes such as storms, floods, droughts, and tsunamis are anticipated to rise. These interconnected factors underscore the pervasive impact of climate change on both natural ecosystems and global economic sectors.

This study specifically dissects the average surface temperature (TAS_r) into two scenarios. In the first scenario, it is posited that the increase in the average surface temperature in the Mekong Delta and Southeast area will fluctuate between 0 and 1.5 °C, referred to as the 'moderate' scenario (Fig. 2). Conversely, the second scenario envisions an upward trend in the average surface temperature ranging from 0.5 to 3.5 °C in the Mekong Delta and Southeast area, denoted as the 'extreme' scenario (Fig. 3). Importantly, these two scenarios regarding the increase in average surface temperature have distinct implications for sea level rise, adding a layer of complexity to the multifaceted challenges posed by climate change.

2.1.2 Sea level

The repercussions of sea level rise are prominently marked by saltwater intrusion, erosion, and intermittent or chronic floods, impacting both natural and human systems, both onshore and in coastal wetlands [28]. While various adaptation measures can mitigate some of these effects, improper implementation may exacerbate certain challenges. For instance, well-designed dike systems can shield coastal communities, curtailing floods and minimizing land losses [29]. The rise in sea levels not only threatens agricultural land but also poses risks to real estate and coastal infrastructure. Despite the typically high value of oceanfront properties, it is crucial to recognize that rising sea levels compel coastal populations to migrate inland, impacting overall property values beyond just beachfront properties [30].

The vulnerability to sea level rise is unevenly distributed, with alluvial plains and deltas facing greater risks than highland areas. Particularly noteworthy is the vulnerability of islands, especially atolls, which could face extinction, leading to the loss of entire civilizations and cultures [31]. In the case of the Mekong deltas, characterized by fertile soils and robust transportation networks, even a modest sea level rise could result in a significant loss of land, affecting millions of residents and necessitating substantial protective measures [32, 33].

The potential economic consequences of sea level rise extend beyond direct losses, impacting agricultural productivity and food prices [34]. A 25-cm sea level rise, for instance, could elevate food costs by 0.5%, with repercussions felt globally through shifts in trade patterns [35]. While certain regions may experience reduced production, others like Australia, less directly affected by sea level rise, might benefit from increased exports [36]. This ripple effect extends to increased demand for fertilizers, elevated wages, and impacts on various marketplaces [37]. Utilizing data, this study aims to model the intricate correlation between sea level rise and diverse economic variables in the Mekong and Southeast regions, encompassing aspects such as agricultural and forestry land losses, and damage to infrastructure [38].

2.1.3 Forest fire

The Vietnamese economy encompasses a crucial sector—the forestry industry. Forecasts indicate a substantial increase in timber production, projected to reach 16,314 m^3 by 2020—an impressive surge from 2375.6 thousand m^3 in 2000 and 4,042.6 thousand m^3 in 2010. Over the past 5 years, the volume of wood harvested from planted forests has surged by 33.9%, escalating from 12.6 million m^3 in 2016 to a remarkable 16.9 million m^3 in 2020. Notably, since 2014, mining activities have ceased, and natural forest exploitation is rigorously controlled under sustainable practices [39].

Despite boasting high biodiversity, Vietnam's lumber industry faces susceptibility to environmental degradation. This vulnerability stems from the overexploitation of natural resources coupled with population growth, climate change impacts, rising temperatures, fires, and sea level rise [40]. Vietnam's tropical forests, covering over 30% of the country's land, face degradation, making it a pressing economic and environmental concern. The escalating frequency of wildfires, linked to factors like increased droughts and higher air temperatures, reached nearly 400 incidents in 2015, as reported by the Ministry of Agriculture and Rural Development.

Various environmental elements—such as wood supply, heat, geography, and ignition sources—contribute to the occurrence of forest fires. Optimal conditions, including low humidity, strong winds, terrain, and wind direction, can rapidly facilitate the spread of flames. Wind speed, humidity levels, and average temperature play pivotal roles in influencing the risk of fire. Elevated temperatures lower the ignition threshold, reduced humidity expedites flame spread, and increased wind speeds intensify their severity. Forest fires not only pose threats to lives but also inflict substantial environmental and financial damages. Large-scale forest fires have caused significant economic and environmental harm, contributing to increased environmental pollution in Vietnam in recent years. This study aims to elucidate the mechanism through which forest fires induce land loss in the forestry sector within the Mekong River Delta and Southeast regions.

Deforestation in the Vietnam highland regions of presents a substantial danger of land subsidence and landsliding. The removal of trees on large areas sends the decelerative soils flowing, leading to an accelerated erosion process [41]. Thus, the probability of landsliding increases because such a process happens during heavy rainfall and seismic activity when decelerative substances are already destabilized. Also, deforestation may obstruct water as it is absorbed by the floating soil, increasing risk of land subsidence [41]. Such a phenomenon is a threat not only to local environments and biodiversity by also to the human settlements and infrastructure. This issue indicates an requiring urgent attention and active measures, including sustainable practices and reforestation [41].

2.1.4 Storm

The Vietnamese coast faces several potential coastal hazards, with storm surges and typhoons emerging as the most significant threats originating or traversing through the East Sea [42]. Annually, approximately 12 tropical storms occur in the South China Sea, with approximately 45% originating in the South China Sea and the remaining 55% originating from the Pacific Ocean. Notably, tropical storms account for the majority of Vietnam's disasters, causing around 80% of the country's catastrophic events [43].

Despite this, only an average of 5 out of the 12 storms typically make landfall in Vietnam. Specifically, the central and northern coastal regions of the Northern East Sea experience the highest frequency of storms or tropical depressions. Along the central and northern coastal areas, tropical depressions or storms are more common [44]. Although the overall number of tropical cyclones affecting Vietnam's mainland remains relatively stable, there has been a marginal increase in the number of cyclones in the East Sea. Cyclones heading towards Vietnam tend to shift southward, with an observed increase in the intensity of cyclones and a lengthening of the storm season. In essence, the nation's exposure to hurricanes appears to be on the rise. This paper delves into the investigation of the adverse impact of storms on the construction sector.

3 Research methodology

Utilizing a quantitative methodology that incorporates statistical analysis, synthesis, interpretation, comparison, and inductive reasoning, the study explores and assesses the impact of climate change factors on the economic growth of the Mekong River Delta and Southeast region in Vietnam. In doing so, the present research used the data from different reputable institutions, such as the General Statistics Office (GSO), an entity falling under the Ministry of Planning and Investment (MPI) of Vietnam, and the National Oceanic and Atmospheric Administration (NOAA). Furthermore, crucial support in furnishing regional economic and climate change data was provided by the German Agency for International Cooperation. The data was then classified in different climate change factors, such as storm, forest fire, temperature, and sea level to consider for this study to analyse their influence on financial development of the Mekong River Delta and Southeast region in Vietnam. To carry out the analysis, Matlab software (version 2021) was employed, leveraging its capabilities to process the data and articulate the findings, which are meticulously presented in Sect. 4 of this research. This robust methodological approach ensures a thorough examination of the intricate interplay between climate change and economic dynamics in the specified regions.

The study extends the modelling approach introduced by [25], incorporating damage functions to analyse the impacts of climate change. This involves employing sector- and region-specific damage functions to capture the intricate interplay between the economy and climate, affecting all production factors, including labour productivity and capital formation. The model undergoes careful calibration to accurately represent the current economic landscape, aligning industry classifications with those outlined by the General Statistics Office of Vietnam (GSO). Statistical data is amalgamated to adapt the model's sectors and regions accurately. The model's framework remains flexible for potential expansion to incorporate additional economic factors and replicates long-term trends. It's crucial to note that the simulations are not designed to predict unforeseen events, such as black swan occurrences; for instance, the global economic slowdown caused by the unexpected COVID-19 pandemic in 2020 and 2021.

The climate change scenarios rely on data sourced from the National Oceanic and Atmospheric Administration (NOAA). Two scenarios for the average surface temperature are considered: the moderate scenario and the extreme scenario. In the moderate scenario, it is postulated that the average surface temperature in the Mekong Delta and Southeast area will rise between 0 and 1.5 °C. To elaborate, the average surface temperature in these regions is projected to increase by 0.7 °C in 2031, 0.9 °C in 2050, and 1.5 °C in 2100. In the second scenario, a continual upward trend in the average surface temperature in the Mekong Delta and Southeast area is hypothesized. Specifically, the temperature is anticipated to rise by 0.86 °C in 2031, 1.8 °C in 2050, and 3.5 °C in 2100. The temperature function is defined as follows:

$$\mathrm{Tas}_{rt} = \mathrm{T}_{0,n} + \eta_{\mathrm{tas,nt}}$$

In which:

- $\mathrm{T}_{0,n}$: Initial regional average annual temperature
- $\eta_{\mathrm{tas,nt}}$: exogenous regional average annual temperature

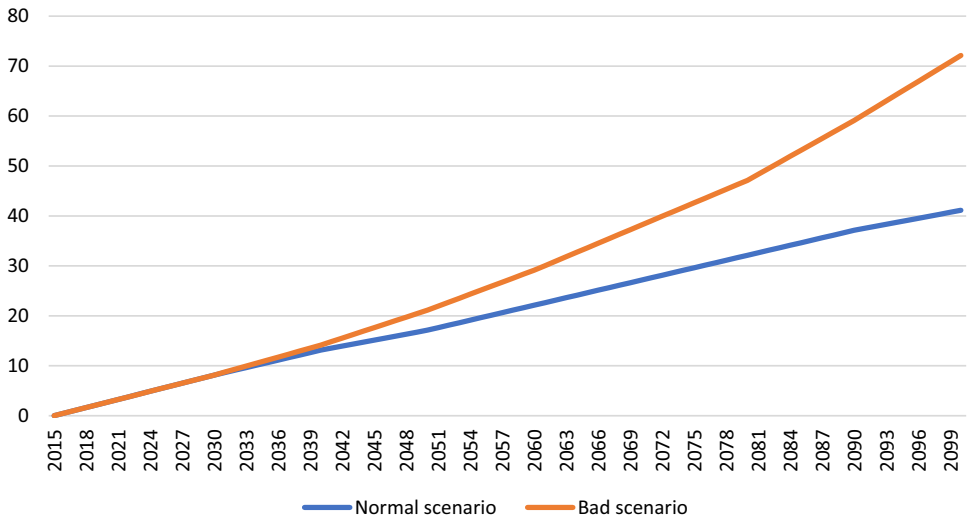

Fig. 4 Sea level rise based on regional average annual temperature

Sea level rise stands as a pivotal proxy variable, reflecting the adverse effects of climate change on the regional economy in Vietnam. This paper adopts a comprehensive approach, aggregating data from the provincial level to a regional scale to simulate climate change dynamics at a subnational level for the respective regions. Additionally, the simulation of sea level increase in this study is intricately linked to average surface temperature scenarios. To elaborate, the 'extreme scenario' temperature is associated with a higher sea level compared to the 'moderate scenario'. Sea level function: $SL_t = SL_0 + \eta_{SL,nt}$.

In which:

- SL_0: Initial sea level
- η^{SL}_t: Exogenous Sea Level

Figure 4 illustrates the sea level rise based on two scenarios of regional average surface temperature.

4 Analysis

The escalating sea level emerges as one of the most imminent threats to the Vietnamese economy. Projections indicate that in the 'extreme scenario,' a surge of 8 cm in sea level is anticipated by 2030, followed by a 21 cm increase by 2050 and a substantial 70 cm rise by 2100 due to global warming. Conversely, under the 'moderate scenario,' the model suggests a more moderate rise, with sea levels increasing by approximately 8 cm by 2030, 17 cm by 2050, and 41 cm by 2100. This underscores the correlation between elevated temperatures and heightened vulnerability to rising sea levels in coastal regions. Furthermore, the ascending sea level poses a threat to the available land for agricultural, forestry, construction, and other commercial activities.

4.1 Rice

This study unveils a negative correlation between available land for agriculture and rising sea levels. Essentially, the expansion of sea levels is anticipated to result in a reduction of land suitable for rice cultivation. The research categorizes sea level rise into two distinct scenarios— [moderate scenario and extreme scenario]. Within each scenario, the authors employ a predictive model to illustrate the percentage of farmland dedicated to rice production that may be lost in the Mekong River Delta and Southeast region. The estimation process follows a systematic approach: Firstly, the study acquires data on crop production land by area. Subsequently, the total national land allocated for rice cultivation is multiplied by the regional share of paddy land production in each area, providing the extent of land utilized for rice production in each province. Thirdly, by subtracting the land utilized for rice production from the agricultural production land per province, the farmland not utilized for rice is determined. Lastly, the paper calculates the proportion of land loss for each sea level rise scenario. ($ll_{b;r}$ for $b \in (5(j—1); 5j)$ for $j \in (1, \ldots 20)$).

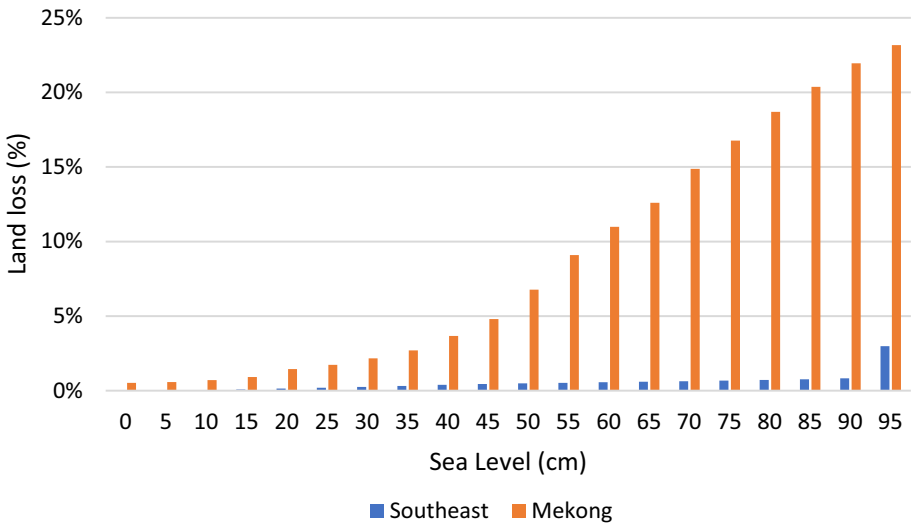

Fig. 5 Land used to raise rice loss due to sea level rise

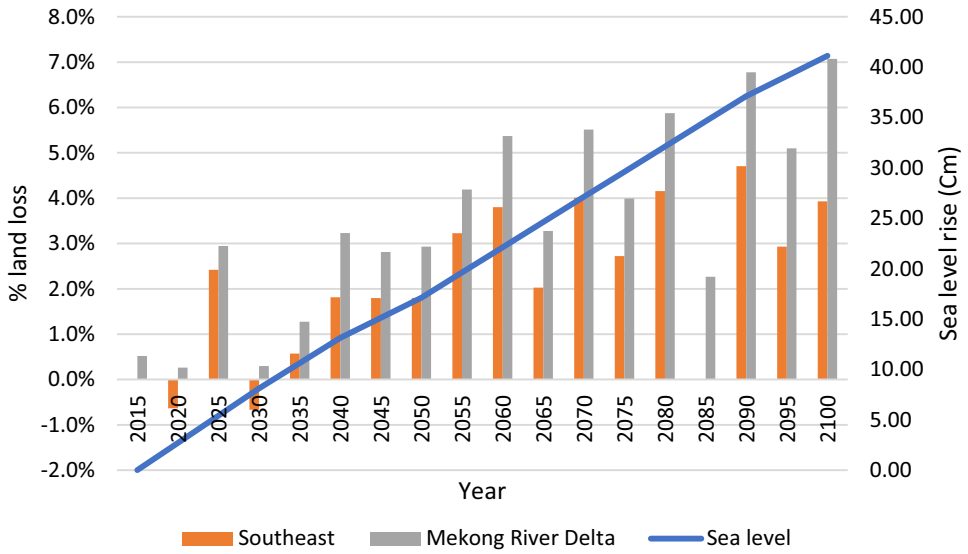

Fig. 6 Land loss due to sea level rise (moderate scenario)

Damage function of rice production due to sea level rise:

$$D_{1,r,t} = \eta^{D}_{1,r,t} = 0.031\eta^{tas}_{r,t} + 1(\eta^{SL}_{t} \in b)\, ll_{b,1,r,}$$

In which:

- $\eta^{D}_{1,r,t}$: Exogenous damage on regional productivity in the rice sector.
- $\eta^{tas}_{r,t}$: Regional temperature increase.
- η^{SL}_{t}: Exogenous Sea Level
- $ll_{b,1,r,}$: The share of land loss for the different levels of sea-level rise

Figure 5 illustrates the calculated land loss represented by the share of land loss attributed to sea level rise concerning available agricultural land dedicated to rice cultivation. The depicted percentages of land loss in Fig. 5 correspond to various sea level rise scenarios. Significantly, the Mekong River Delta demonstrates a considerably higher percentage of land loss for rice cultivation compared to the Southeast region's agricultural land solely dedicated to rice cultivation. This study establishes the Mekong River Delta as the region most vulnerable to sea level rise. In this delta, a sea level rise of 20 cm, 50 cm, 80 cm, and 95 cm results in land losses of approximately 1%, 7%, 19%, and 23%,

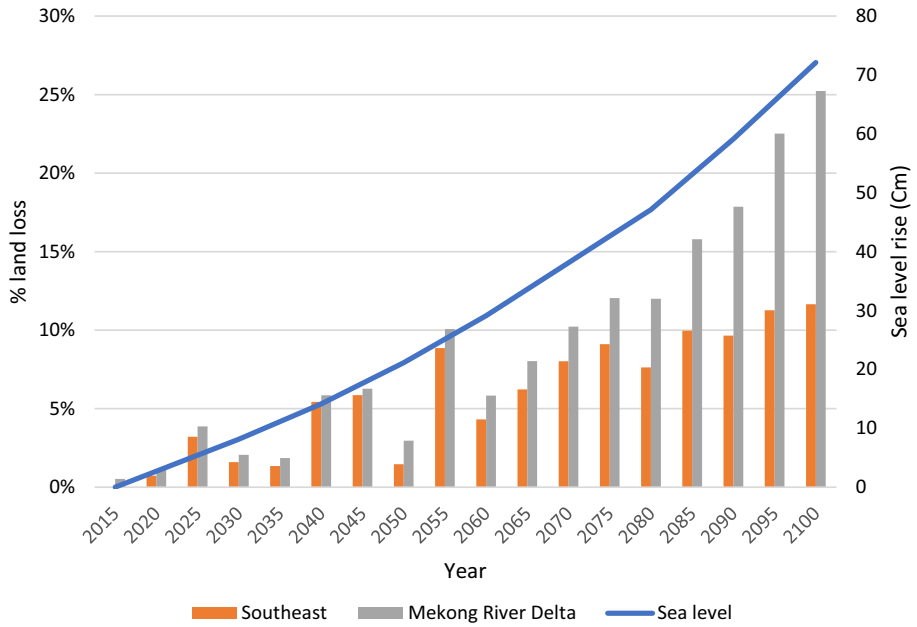

Fig. 7 Land loss due to sea level rise (extreme scenario)

respectively. Conversely, the Southeast region experiences minor land losses (used for rice cultivation) even with a substantial sea level rise of 95 cm, accounting for only a 3% loss.

In the subsequent analysis, the study investigates the correlation between sea level rise projections from 2015 to 2100 and the loss of land dedicated to rice cultivation (Fig. 6). Under the 'moderate' scenario, the data predicts a sea level increase to 8 cm in 2030, 17 cm in 2050, 32 cm in 2080, and 41 cm in 2100. The rise in sea level exhibits a positive correlation with agricultural land loss in both the Mekong River Delta and Southeast regions. Farmland losses in the Mekong Delta region in 2025, 2050, and 2100 are estimated at 2.9%, 2.9%, and 7.1%, respectively. Similarly, the Southeast region experiences farmland losses, but the reduction is comparatively smaller than in the Mekong Delta region, with losses estimated at 2.4%, 1.8%, and 3.9% in 2025, 2050, and 2100, respectively.

It is noteworthy that under the 'extreme' temperature scenario, our model projects a sea level increase to 8 cm in 2030, 21 cm in 2050, 47 cm in 2080, and 72 cm in 2100 (Fig. 7). This substantial rise in sea level results in significant land destruction used for rice cultivation in both the Mekong River Delta and Southeast regions. Specifically, in the 'extreme' scenario, farmland loss in the Mekong Delta region is projected at 2%, 3%, 12%, and 25% for the years 2030, 2050, 2080, and 2100, respectively. Similarly, the Southeast region experiences notable losses, with projected farmland reductions of 1.6%, 1.4%, 8%, and 12% for the corresponding years in the 'extreme' scenario.

4.2 Agriculture excluding rice

In this section, the analysis delves into the repercussions of sea level rise on non-rice agricultural land. The focal point of concern is the negative influence of climate change, with sea level rise serving as the primary variable. The computation of the percentage of land loss attributable to rising sea levels is a key aspect of the study. Two significant factors contribute to this analysis: the first involves a decline in agricultural output resulting from heightened average temperatures, while the second factor is the risk of land loss due to escalating sea levels. The task at hand is to discern the differential impact of these risks across distinct regions in the outlined scenario. Referencing a meta-study by [45], which explores the global impact of climate change on agricultural production, this paper adapts the findings to various crops and extrapolates their direct implications on the Vietnamese economy. It is crucial to underscore that agriculture land, excluding rice, in the Mekong River Delta faces considerable vulnerability to sea level rise. Specifically, if the sea level rises by 50 cm, over 17% of the current area designated for non-rice agriculture production may be at risk of loss. In contrast, the Southeast region encounters comparatively minor land loss for non-rice agriculture due to rising sea levels.

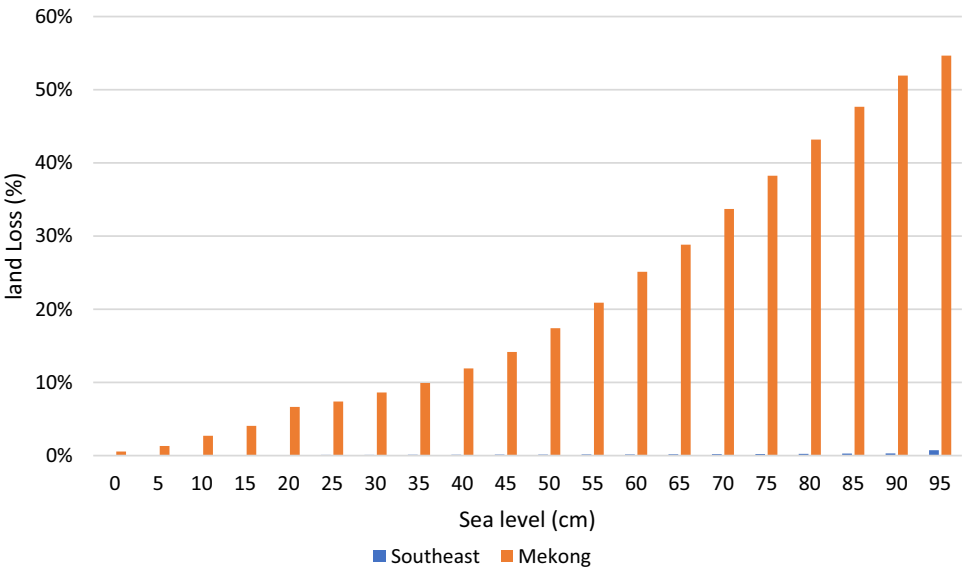

Fig. 8 Land for agriculture loss due to sea level rise (exclude rice)

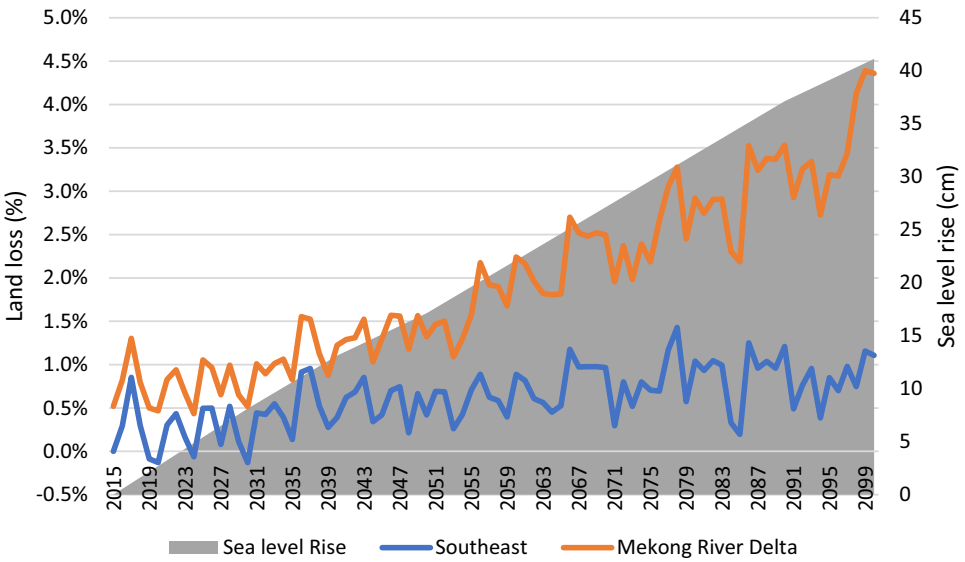

Fig. 9 Agriculture land loss in moderate scenario (exclude rice)

In this ensuing section, the study meticulously scrutinizes the repercussions of sea level rise on agricultural land, specifically excluding rice, by employing two distinct sea level scenarios. Additionally, this segment aims to model the correlation between the escalating sea levels and the ensuing loss of farmland (excluding rice) from the year 2015 to 2100.

Figure 8 serves as an illustrative representation of how sea level rise adversely impacts the land designated for crop cultivation in the 'moderate' scenario. According to the study's data projections, the sea is anticipated to rise by 8 cm, 17 cm, 32 cm, and 41 cm in the years 2030, 2050, 2080, and 2100, respectively. This rise in sea level corresponds to the diminishing agricultural land (excluding rice) in both the Mekong River Delta and Southeast regions. However, it is noteworthy that, on the whole, the Mekong River Delta is expected to undergo more significant land loss compared to the Southeast region. The projected farmland loss in the Mekong Delta region for the years 2030, 2050, 2080, and 2100 is outlined in Fig. 9, excluding rice.

Furthermore, it holds paramount importance to note that in the 'extreme' temperature scenario, our calculations forecast an escalation in sea levels by 8 cm, 21 cm, 47 cm, and 72 cm in the years 2030, 2050, 2080, and 2100, respectively (refer to Fig. 10). The accelerated and heightened rise in sea levels within this adverse scenario leads to severe devastation of the land designated for agriculture (excluding rice) in both the Mekong River Delta and Southeast regions. Specifically, under the 'extreme' scenario, the anticipated farmland loss in the Mekong Delta region is projected to be 2%, 3%, 12%, and 25% in the years 2030, 2050, 2080, and 2100, respectively. While the Southeast region is expected to experience

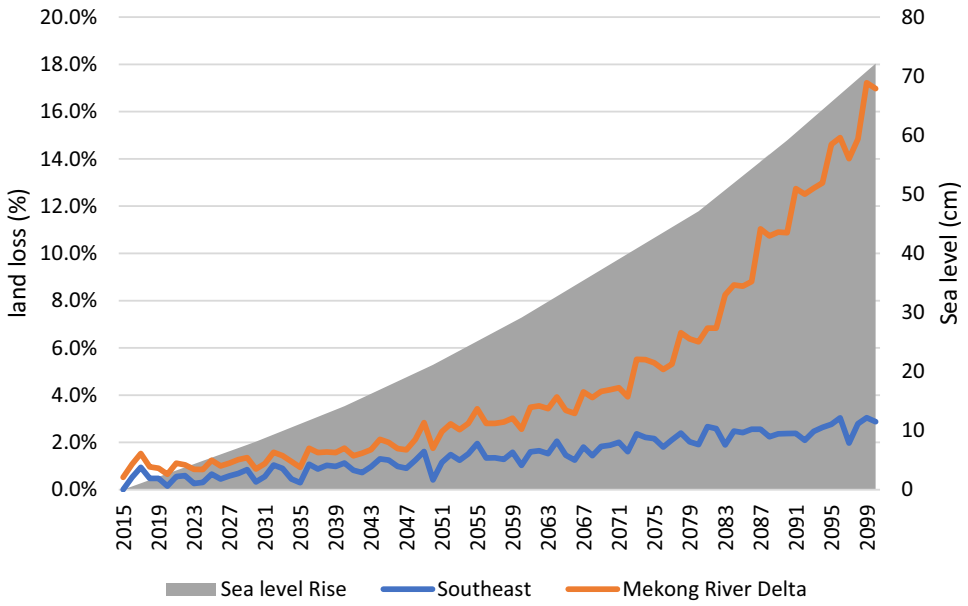

Fig. 10 Agriculture land loss in extreme scenario (excluding rice)

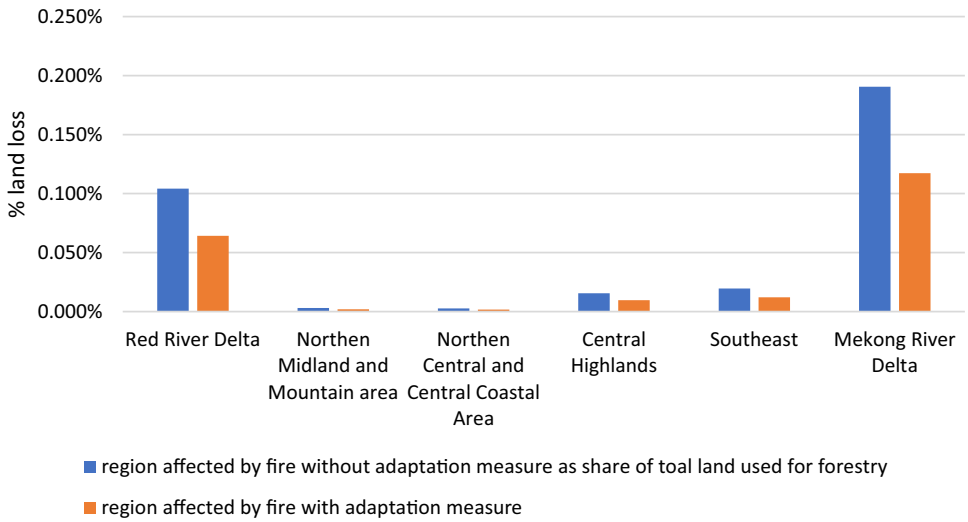

Fig. 11 Forestry land loss due to forest fire

comparatively lower losses than its Mekong River Delta counterpart, the agricultural land in the Southeast, under the 'extreme' scenario, is still projected to suffer more compared to the 'moderate' scenario. The estimated farmland loss in the Southeast region for 2030, 2050, 2080, and 2100 under the 'extreme' scenario is 0.3%, 0.4%, 1.9%, and 2.9%, respectively.

Various strategies exist for adapting the agriculture industry to climate change. In the context of Vietnam, one adaptive strategy involves transitioning manufacturing activities from highly sensitive sectors to less vulnerable ones. This adaptive approach entails reallocating investments, directing resources from sectors highly susceptible to climate change impacts to those with lower vulnerability. Furthermore, augmenting investments in capital stock emerges as a compensatory measure to counterbalance the reduction in total factor productivity.

Presently, predominant adaptation measures in the agricultural sector primarily consider private actions, implicitly incorporating these actions through optimized agent models.

4.3 Forestry

As the climate undergoes changes and the population continues to grow, the threat of wildfires becomes increasingly pronounced for the tropical forests in Vietnam's Southern region. This study delves into the repercussions of forest fires

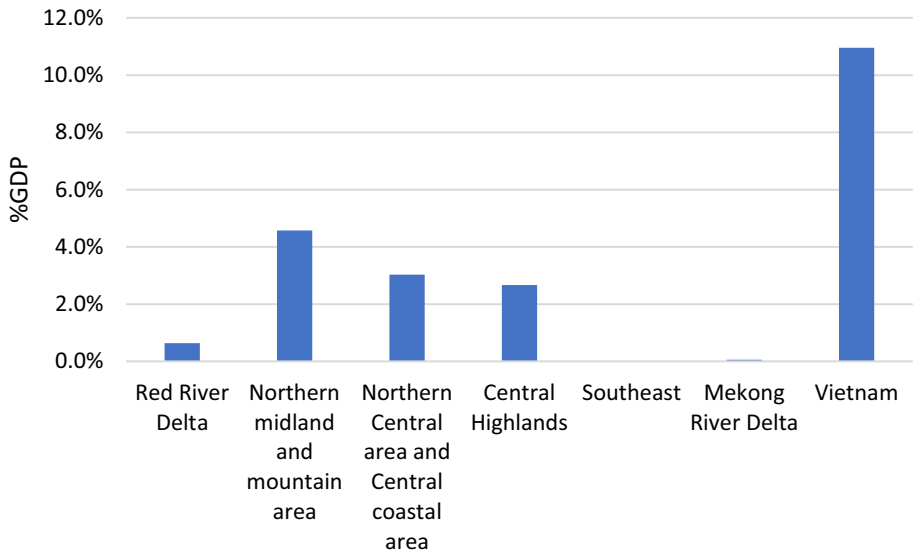

Fig. 12 Houses destroyed by storms in 2014 (% GDP)

on Vietnam's forestry, as illustrated in Fig. 11, which delineates forest loss areas with and without the implementation of adaptation methodologies.

Notably, both the Mekong River Delta and Red River Delta experience more substantial losses in forested areas compared to their counterparts. However, it is crucial to highlight that the overall magnitude of negative consequences remains relatively modest. Without any adaptation efforts, both the Mekong and Red River deltas encounter a mere 0.3% loss in forest area. Conversely, adopting adaptation measures to mitigate the adverse impacts of forest fires holds the potential to curtail damages by as much as 50%.

4.4 Construction

At present, one of the most formidable natural hazards globally is coastal flooding induced by storm surges, surpassing earthquakes in terms of both human casualties and property devastation [46]. With an extensive 3260-km coastline, Vietnam stands as one of the nation's significantly vulnerable to coastal calamities, particularly tropical cyclones. Notably, storms contribute to over 70% of all natural disasters in Vietnam. Furthermore, both the frequency and financial ramifications of storms appear to be on the rise in recent times [47]. Hence, it is imperative to conduct a quantitative analysis to assess the adverse impact of storms on the overall economy of Vietnam, with a specific focus on the Southern region.

After a meticulous calculation and analysis of the data, this study reveals that tropical storms inflict substantial damage on residential infrastructure in Vietnam (Fig. 12). Specifically, storm-related damage to housing infrastructure is estimated to account for approximately 11% of Vietnam's GDP. However, the impact of storms varies significantly across economic regions, with the Northern Midland and Mountain regions experiencing the most significant house destruction, amounting to around 4.6% of GDP. In the Northern Central and Central coastal areas, the damage caused by tropical storms is estimated at 3% of GDP, while the Red River Delta and Central Highlands face approximately 0.6% and 2.7% of GDP in housing infrastructure costs, respectively.

Aligned with the findings of [48], our study indicates that the Southern regions of Vietnam, including the Mekong River Delta and Southeast, generally face minimal damage caused by storms. While historical records show occasional landfalls in the Southeast and Mekong regions, the probability of such occurrences appears significantly lower than in the northern or central coasts.

Despite the relatively lower incidence of tropical cyclones along the southern coast, the study acknowledges that an exceptionally severe storm event in the Southeast and Mekong area could cause substantial damage, especially in low-lying riverfront communities or areas with degraded shorelines [49]. The devastating impact of the 1997 typhoon Linda serves as an illustrative example, resulting in 3111 fatalities, US$385 million in damages, and leaving hundreds of thousands of people homeless [49].

Beyond tropical cyclones, sea-level rise emerges as the second major long-term threat to housing infrastructure in Vietnam. As global warming and climate change progress, the rise in sea level is anticipated to have significant

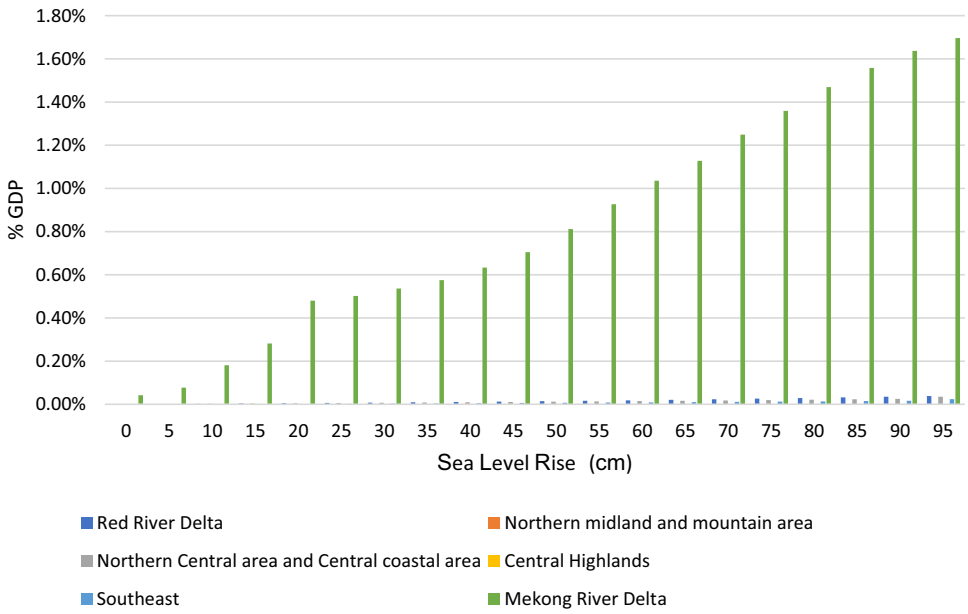

Fig. 13 House destruction by sea-level rise in 2014 (% GDP)

consequences. Research by [50] indicates that residents in Ho Chi Minh City, the largest city in the Southeast region, may face undesirable relocations due to the loss of residential areas caused by sea-level rise. Furthermore, sea-level rise contributes to riverbank and coastline erosion, significantly impacting people's lives. Coastal erosion, estimated at a few meters to 20 m annually, reduces available land for agriculture and damages critical infrastructure. Consequently, in the long term, sea-level rise indirectly contributes to increased poverty and reduced income in affected areas.

Sea-level rise compounds the impact of floods on residential areas and housing infrastructure [51]. Additionally, low-lying regions, such as the Mekong River Delta, are particularly susceptible to the combined effects of floods and sea-level rise [52]. Consequently, this study delves into the analysis of house destruction resulting from sea-level rise.

Our data highlights that houses in the Mekong River Delta bear a disproportionate share of destruction due to rising sea levels compared to other regions. As depicted in Fig. 13, the proportion of houses ravaged by sea-level rise relative to GDP is 0.54%, 0.81%, 1.4%, and 1.7% for sea level increases of 30 cm, 50 cm, 80 cm, and 95 cm, respectively. While housing infrastructure in other regions experiences some damage, the overall expectation is that house destruction due to sea-level rise in other parts of the country will be minor and negligible. This discrepancy can be attributed to the fact that the majority of residential land in the Mekong River Delta lies approximately one meter below sea level [11]. Consequently, this region may bear the brunt of the negative impacts of sea-level rise, flooding, and erosion. This finding aligns with [42] study, which indicates that the Mekong River Delta stands to lose a significant portion of land used for residential and agricultural purposes with rising sea levels. Without the implementation of adaptation strategies or protective measures, an increase in sea level could lead to substantial destruction of houses and adversely affect the lives of the people in this area. To address the detrimental impacts of sea-level rise, the construction of coastal dikes and river embankments is deemed necessary.

5 Discussion and implications

Environmental degradation and global warming have dreadful effects that extend far beyond the environment; they have a massive and expanding impact on the lives of humans, their livelihoods, and the economies of the entire world. These effects are a direct result of climate modification and global warming. Because Vietnam is a country that has a significant coastline, it is also at a significant risk of experiencing the adverse effects of climate change, notably the rise in sea level. This is caused by the fact that Vietnam is a country that has a big coastline. According to the most recent research, the regions of the Southeast and the lower southern sections of the Mekong River Delta are both at a particularly high risk. This can be attributed to the fact that the country is extremely sensitive to the effects of climate change. The Mekong River Delta, which is located between one and two metres above sea level and encompasses a vast range of the most important cities and economic areas in the Southeast, is the most vulnerable due to the vast size of land that

is over one metre above sea level, as demonstrated by studies [13] and [50]. These studies provide strong evidence that the Mekong River Delta is the most vulnerable. The fact that the Mekong River Delta is situated in the middle of these two levels is evidence that this is the case. According to the conclusion of the study, which claims that the rising sea level will have substantial implications on important enterprises such as agricultural and housing infrastructure in both of the places, the concerns that have been stated as a result of this research are backed by the findings of the study. The fact that even if the 'moderate' impact is what would occur in the Southeast, approximately 19% of the land that is utilised for the production of rice will disappear, and 5% of fields that are used for other crops will suffer as a result of the flooding is something that is very notable. In spite of the fact that the Mekong River Delta will only face losses of 5% and 1% for rice and other plants, respectively, the 'moderate' scenario cannot be judged to be acceptable. In each and every situation, the population of the Southeast is the one that is believed to be the most vulnerable to the disease. Those who lived in the lowland Mekong River Delta, on the other hand, would surely be the ones to suffer the largest loss of property. This is due to the fact that their homes are among the sorts of infrastructure that are most likely to be affected by the rise in sea levels.

In the years to come, the Mekong River Delta will be forced to contend with a number of economic issues, and these findings will be of great assistance in reevaluating those challenges. At this point, the information that has been presented serves as the foundation for a conclusion that can be drawn regarding the necessity of developing a series of adaptive long-term activities that are to be carried out in the region in order to reduce the risks that are associated with the rise in sea levels and natural disasters that are caused by climate change. It is essential to emphasise, however, that the rise in sea levels is not the only thing that ought to be of concern in the places that have been described above. Furthermore, the Southeast and the Mekong River Delta are prone to forest fires, tropical storms, and violent typhoons. These natural disasters can be found in the region. The region is prone to experiencing these kinds of natural calamities. Natural catastrophes of this nature are exceedingly rare; nonetheless, throughout history, they have been responsible for a large amount of damage to the economies of the region and have resulted in a significant number of fatalities. This is despite the fact that they are highly unusual. As a result of this, it is of the utmost importance that people who are in charge of making choices in the Mekong Delta and Southeast regions come up with comprehensive and stringent strategies to handle and manage the hundreds of dangers that are related with climate change. The majority of these dangers are situated around coastlines that are vulnerable to the consequences of climate change. Despite the fact that they will be required to address the challenges that are associated with rising sea levels, they will also be required to incorporate measures that are designed to minimise the consequences of natural phenomena that are exacerbated by global warming. These natural phenomena include cyclones, typhoons, and other natural phenomena. The outcomes of this study, taken as a whole, shed light on the enormous negative economic impact that climate change is having on Vietnam, and more notably on the southern regions throughout the country. To enhance the system's resilience to the threats that are associated with processes like as storms and rising sea levels, immediate action is required in order to put adaptation plans into action and strengthen the system's ability to withstand these threats. If this course of action is not adopted, the researchers warn that the health, well-being, and level of living of millions of Vietnamese people who live in the areas that have been discovered will be seriously damaged. This is because the places that have been identified are located in areas that have been specifically recognised.

5.1 Implications

The research emphasizes the local and regional implications of climate change in a country, highlighting that vulnerability and impacts vary between different regions of the country. This contributes to a theoretical understanding of climate change at a local level and reinforces the need for tailored adaptation strategies. From sea-level rise to agricultural impacts to vulnerability to natural hazards, the study integrates evidence from multiple sources to evaluate the multi-faceted risks posed by climate change. This approach provides theoretical value by highlighting the interdependent nature of climate-related issues and the need for robust risk assessment frameworks. The focus on long-term adaptation plans highlights the theoretical need to be proactive and future-oriented in addressing the long-term and changing risks of climate change, which is in line with broader conversations about sustainable development and building resilience to environmental challenges.

The research offers practical recommendations for policymakers, calling on them to tailor adaptation plans to the specific vulnerabilities of each region. For the Mekong River delta and the Southeast, tailored measures are needed to address the unique challenges of rising sea levels, agri-environmental impacts, and other climatic risks. The findings on major agricultural losses call for practical actions such as crop diversification, irrigation improvements, and

climate-resilient agricultural practices. Policymakers and agricultural stakeholders can leverage this information to strengthen the resilience of local agricultural-dependent communities. The study's emphasis on housing infrastructure vulnerability necessitates practical actions regarding infrastructural development and reinforcement. In vulnerable regions, authorities should invest in resilient construction practices, early warning and evacuation plans to protect human life and reduce economic losses. In addition to sea-level rise risks, the research emphasizes forest fires and tropical storm risks. The practical implications include integrated disaster management plans considering multiple climate-related risks. Not only do we need to respond to immediate threats, but we also need to build resilience against recurrent challenges. Practical implications extend to community-level initiatives, highlighting the need for public education campaigns and community involvement. By empowering local communities with climate risk information, they can actively engage in adaptation efforts, creating a sense of collective responsibility for climate resilience.

6 Conclusion

This study highlights (1) climate change's significant economic and social impacts and global warming, especially in vulnerable coastal nations such as Vietnam. The study emphasizes the (2) differentiated vulnerability across different regions, with the Mekong River delta and the Southeast region being particularly vulnerable. (3) The projected losses of agricultural land and housing infrastructures due to rising sea levels call for urgent attention and long-term adaptation planning. However, there are limitations, such as the uncertainty of climate projections and the possibility of socio-economic development. Future research directions include refining predictive models, including dynamic socio-economic factors, and exploring novel adaptation strategies [53]. A more in-depth analysis of the historical impacts of forest fires or tropical storms can also inform more effective risk management plans. In conclusion, this study urges policymakers and stakeholders to focus on region-specific approaches to mitigate the multi-faceted risks of climate change and to build resilient communities in fragile coastal regions.

Furthermore, there needs to be more research examining the risks posed by tropical storms in the Mekong and Southeast regions. This gap can be attributed, in part, to the fact that tropical cyclones more frequently impact Vietnam's northern and central regions, as discussed in the previous section [48]. However, underestimating the negative impact of storms on the economy and communities of the Mekong River Delta and Southeast would be a mistake, given the historical instances of catastrophic destruction in the Southern area. Infrequent occurrences of tropical storms and cyclones in the south result in residents having less experience in preventing potential destruction and managing risks associated with storms. Consequently, when a storm hits the southern regions of Vietnam, particularly in susceptible coastal areas, it can potentially cause significant damage to both lives and infrastructure. Therefore, addressing and managing the risks posed by storms in the southern areas of Vietnam should be a focal point for further research.

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Data availability Data collected in this study will be made available on request to the corresponding authors.

Declarations

Competing interests The authors declare no competing interests.

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