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Original Research Article

Balancing Economy and Ecology: A System Dynamics Analysis of Shrimp Aquaculture and Mangrove Forest Policy

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ABSTRACT

The rapid expansion of shrimp farming in Ca Mau Province, Vietnam since the early 2000s has converted mangrove forests into aquaculture ponds, resulting in deforestation and degraded mangrove ecosystems. A system dynamic model was developed to assess the interactions and temporal changes among various economic, social, and environmental factors. The analysis was conducted under two development scenarios. In the Business as Usual scenario, shrimp farming will expand to 317,037 hectares in 2050, reducing mangrove coverage to 76,484 hectares and carbon storage to 4.8×10^6 MgC. However, this expansion is expected to create jobs, producing an output value of 25,153 billion VND and accounting for 25.13% of the province's workforce. Conversely, the Policy Scenario stabilizes shrimp farming areas at 280,000 hectares, which will have alternative impacts on the environment, society, and economy. By 2050, Ca Mau's mangrove coverage and carbon storage will reach 88,902 hectares and 5.6×10^6 MgC, respectively; the shrimp industry will generate an output value of 22,214 billion VND and account for 23.58% of the province's workforce. Despite yielding lower economic growth and employment generation, policy interventions are expected to support overall positive developmental progress. Furthermore, a shift in the labor structure is anticipated due to restrictions on shrimp farming areas. The findings provide insights for policymakers to anticipate potential consequences of future development and appropriately adjust policy interventions. Several strategies, such as land use management, economic diversification, and alternative livelihood generation, are needed to balance environmental sustainability with social and economic growth in Ca Mau. Moreover, the methodology presented in this study is not limited to Ca Mau but is also applicable to other areas where the expansion of aquaculture endangers mangrove ecosystems.

KEYWORDS

carbon storage, mangrove conservation, shrimp aquaculture, system dynamic modeling, Vietnam.

INTRODUCTION

The global aquaculture, particularly shrimp farming, has seen rapid growth, with shrimp production soaring from 1,600 tons in 1950 to 9.4 million tons in 2022 [1]. However, this growth led to widespread environmental degradation, particularly the conversion of coastal

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ecosystems into shrimp ponds [2]. Between 1980 and 2000, 35% of the world's mangrove forests were lost, with shrimp farming being the major driver [3]. The reduction in the mangrove forest in Sundarbans, India, from 1986-2004 is correlated to the expansion in shrimp cultivation [4]. The concern between shrimp farm expansion and mangrove protection is especially serious in Southeast Asia, where economic growth has often been given priority over environmental protection. This has led to dramatic losses of forests and coastal habitats, with up to 80% of mangrove and seagrass areas disappearing over the past 55 years [5]. Under a "business as usual" scenario, the annual value of lost ecosystem services from Southeast Asian mangroves is projected to be around US$ 2.16 billion in 2050, with Indonesia, Vietnam, and the Philippines bearing the highest costs [6].

Mangrove forests in Vietnam are abundant, diverse, and distributed from north to south over four regions and twelve subregions. By 2014, the mangrove forest area in Vietnam had decreased to 85,000 hectares from 400,000 hectares in the 1940s [7]. Nearly 200,000 ha of mangrove forests contracted to families for preservation and administration became shrimp farms. The U Minh National Forest in Ca Mau is Vietnam's largest mangrove forest [8]. Ca Mau contains extensive mangrove forests, making it ideal for agriculture, forestry, and fisheries development, with a focus on aquaculture.

The aquacultural sector in Ca Mau, bolstered by policies promoting investment in the industry and conversion of land uses to shrimp farming [9], has flourished, transforming the province into Vietnam's leading shrimp producer. Farming areas have expanded 2.44 times, from 121,507 hectares in 1999 to 296,524 hectares in 2022 [10]. This growth has significantly boosted the province's economic output with the shrimp industry alone accounting for 49% of production values, respectively. Additionally, shrimp exports have become a cornerstone of Ca Mau's economy, generating US$ 1.2 billion annually and comprising over 40% of Vietnam's shrimp export revenue [11].

However, this rapid development led to environmental degradation, with Ca Mau's mangrove forests declining by 74% from 1979 to 2013 [12] and further diminishing to 69,846 hectares by 2022 [10]. The accelerated conversion of forests to aquaculture, driven by the weak enforcement of land management policies, was a primary contributing factor to this decline [7]. In certain regions of Ca Mau, shrimp farming led to the complete clearance of mangrove forests [13]. Illegal deforestation driven by shrimp cultivation, along with river dredging, contributed to erosion along the coastline, resulting in the loss of the forest's wave buffering and sheltering effects. Consequently, the region became more susceptible to extreme weather events, posing risks to the sustainability of rural livelihoods [14].

Mangrove forests play a crucial role in complex food webs and profoundly influence aquatic and marine ecosystems. Besides serving as breeding and nursery grounds for coastal fisheries, mangroves offer various benefits such as timber harvesting, fuelwood, carbon sequestration, flood control, and shoreline protection [15]. Consequently, the degradation of mangrove forests adversely affects fish, shrimp, and crab populations, leading to anticipated scarcity of fisheries resources and threatening the welfare of coastal communities. For instance, in Campeche State, Mexico, the loss of mangrove habitat resulted in a decline in shrimp harvest [16]. Achieving a balance between mangrove harvesting and considering interactions among ecosystem components is crucial for optimal management and attaining maximum economic value [17].

Ca Mau Province's strategic plans, including the "Enhancing Efficiency and Sustainable Development of the Shrimp Industry by 2025 with a Vision Towards 2030" [18], and the broader "Sustainable Agricultural and Rural Development Strategy for 2021 - 2030, with a Vision Towards 2050" [19] envision the future growth of shrimp aquaculture by the mid-century. The province aims to solidify its position by producing high-value goods that align with modern processing techniques, sustainable development principles, and climate change adaptation measures. The province seeks to maintain a stable shrimp farming area of 280,000 ha. Shrimp-rice farming, ecological shrimp farming, and organic shrimp farming will be prioritized. Forestry will emphasize careful management, protection, and sustainable use of natural forests, forest regeneration, and improving special-use and protected forests, especially in environmentally sensitive areas [20].

The fulfillment of the policy goal of stabilizing the shrimp aquaculture area in Ca Mau at 280,000 hectares has the potential to have various effects on both the environment and the region's socioeconomic elements. This measure can potentially mitigate the pressures stemming from converting mangrove forests into shrimp ponds. By restricting the expansion of shrimp ponds, the policy contributes to the conservation and preservation of mangrove ecosystems, ensuring their long-term viability. However, the policy's constraints on the shrimp aquaculture area may hinder or restrict the industry's economic growth. Furthermore, the legislation may impact the industry's capacity for generating employment, potentially harming the rural livelihoods of those dependent on shrimp farming.

Previous studies have explored diverse methodologies to examine the interactions of shrimp aquaculture with other factors within coastal ecosystems. In Ecuador, the conversion of mangroves into shrimp ponds was found to yield short-term benefits but result in long-term reductions in productivity [21]. Similarly, in Pamlico Sound, North Carolina, US, a stepwise model was constructed to assess trade-offs between wetland development and the shrimp fishery, emphasizing the preservation of wetlands as the most viable solution [22]. The shrimp industry in Bangladesh was found to incur higher environmental costs than the temporary employment opportunities it provided [23]. In Thailand, a series of regression models analyzed the relationship between fisheries catch and shrimp farming activities, revealing that the loss of mangrove forests would lead to a decline in the benefits of shrimp farming [2]. The critical role of harmonizing food-energy-water for sustainable development was explored using various sustainability indicators in Germany [24]. Additionally, a predictor-response analysis was employed to examine spatiotemporal changes in mangroves in the United Arab Emirates [25].

In Ca Mau, aerial photographs and satellite images revealed that 40% of the forest loss from 1986-2003 was attributed to shrimp farming [26]. This correlation was further supported by another spatial analysis [12], highlighting the limited impact of afforestation and reforestation efforts in Ca Mau from 1979-2013. Similarly, a study conducted from 1990-2010 revealed a significant interaction between human intervention and deforestation in Ca Mau [14].

These studies primarily focused on understanding the spatial implications and cause-and-effect relationship between aquaculture and the environment. Nevertheless, balancing ecological and economic advantages is crucial for achieving sustainable development in aquaculture. Thus, it is imperative to consider the dynamic and interconnected nature of the environment and economic activities.

Various studies have utilized System Dynamics Modeling (SDM) to gain insights into coastal ecosystems' complexity and temporal dynamics. In Longkou city, Shandong Province, China, a comprehensive SD model was constructed for water management to predict water demands under different scenarios [27]. Similarly, a SD model was proposed for ecologically Sustainable Development in the urban coastal system of the Athens Metropolitan Area, incorporating factors from economics, biology, and engineering [28]. In the Shinduri coastal area, South Korea, the value of ecosystem services was found to increase if a coastal sand dune restoration plan was implemented in the mid-century [29]. Furthermore, a conceptual SD model was developed to capture the complex social-ecological system, including fisheries, shrimp farming, forests, and agriculture in Bangladesh, integrating literature review and participatory approaches [30]. Through dynamic models analyzing interactions between shrimp, water quality, land use, employment, and population, studies in Malaysia have demonstrated that the sustainable development of the shrimp farming industry can be enhanced in an integrated shrimp aquaculture park [31]. However, it is essential for the government to implement stricter policies in managing coastal forest areas and establish regulations on wastewater treatment before discharge into the environment [32].

In Vietnam, there has been a lack of comprehensive studies simultaneously considering multiple aspects of coastal development. Adopting a holistic management approach that considers all factors influencing long-term development is essential to achieving the government's development objectives and ensuring long-term growth for the shrimp farming and mangrove forest sectors in Ca Mau Province. Furthermore, it is crucial to analyze social and economic welfare fluctuations when market conditions, the environment, and institutional frameworks change [33]. Therefore, this research aims to establish a model capable of quantifying the diverse and dynamic interactions of economic, social, and environmental factors in policy-driven shrimp aquaculture and mangrove forest development in Ca Mau province.

This research endeavor's findings are designed to provide valuable insights for policy formulation, aiding in the design and implementation of effective measures that promote sustainable development. Furthermore, this is the first study in Vietnam to construct a dynamic model for analyzing shrimp aquaculture, thereby contributing to the existing literature.

MATERIALS AND METHODS

Given the complex dynamics of shrimp aquaculture and mangrove conservation, System Dynamic Modeling was adopted for this exploratory research. J.W. Forrester developed this system at the Massachusetts Institute of Technology (MIT) in 1950. SDM is a methodology that allows for the simultaneous evaluation of multiple modules as well as stock and flow variables within a system through a set of simultaneous difference equations [34]. The SDM model is segmented into sectors encompassing mangrove areas, carbon sink, shrimp farming area expansion, and socio-economics (Figure 1). Within the scale and limited resources of this study, some assumptions are made to formulate the model: (1) no unexpected climatic or economic events, or trade disputes, occurred during the analysis period; (2) the shrimp industry's output value is calculated based solely on the output value per hectare; (3) the demand for labor per unit area and other market factors remain constant over time.

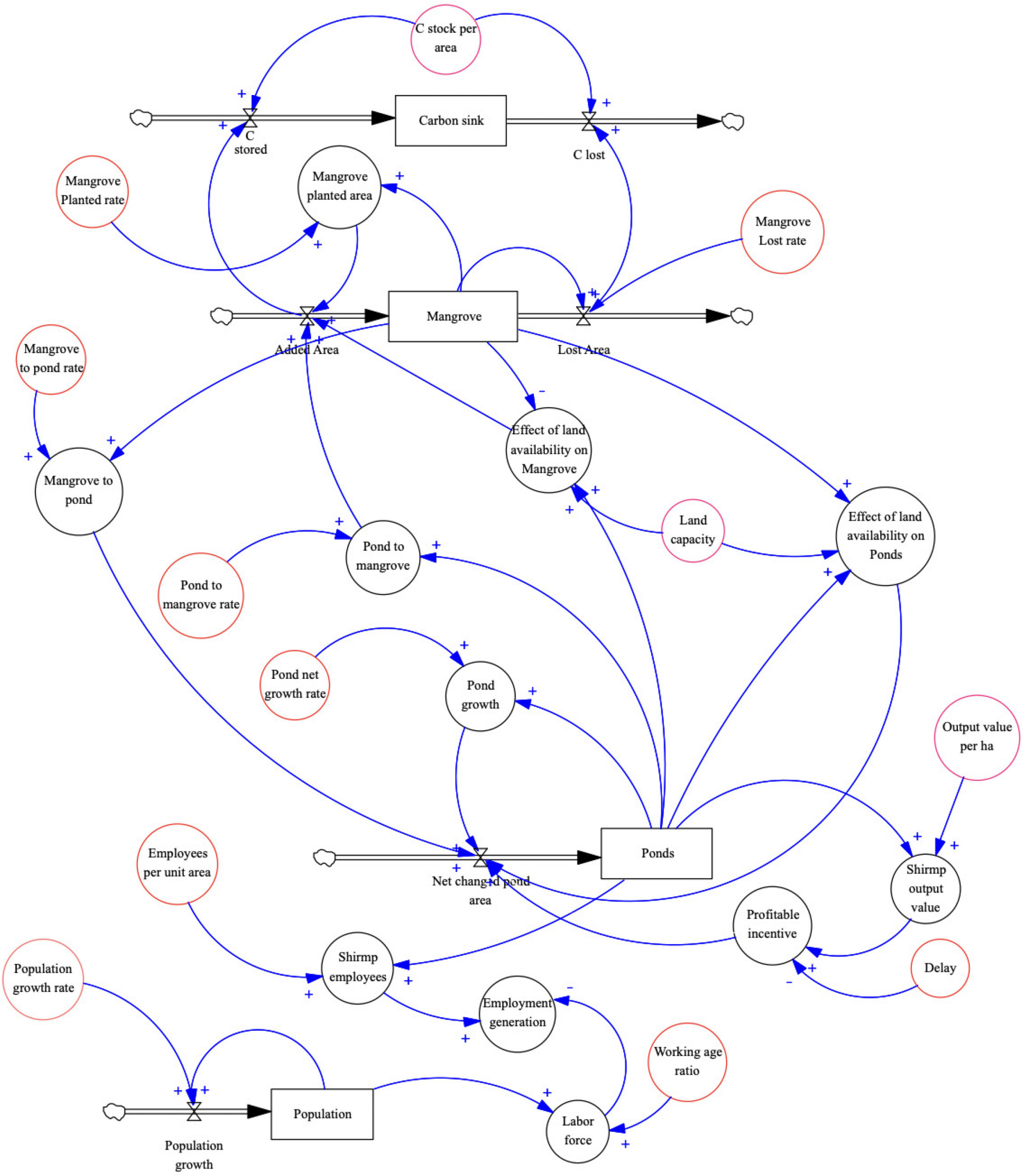

Figure 1. Proposed dynamic model for shrimp aquaculture expansion and mangrove conservation

The feedback model and stock-flow model were first conceptualized and visualized in Vensim [35], and all of the equations within the model and analyses were conducted in R using the packages “deSolve” [36] and “ggplot2” [37].

Mangrove sector. The mangrove forest is modeled as a renewable resource. The mangrove sector contains the stock Mangrove, which represents the mangrove area. The model captures the rates of mangrove planting and loss to determine the change in mangrove area over time. This feedback loop allows us to better understand the effects of mangrove restoration and degradation on the overall system dynamics.

The net change in mangrove area over time is determined by subtracting the area of mangroves lost from the area of mangroves added. This equation reflects the balance between mangrove restoration and degradation within the system. If the net change is positive, it indicates a growth in mangrove area, while a negative net change implies a decline in mangrove area. Furthermore, we assume that a certain part of abandoned shrimp ponds will eventually revert to mangrove habitat [38]. In fact, Landsat imagery from 1999 to 2022 showed a shift in land use from shrimp ponds to mangroves [10].

Policy makers and authorities often overlook the dependence of the shrimp industry on ecological services and fail to implement measures to limit its expansion and preserve natural capital. As a result, shrimp ponds may expand beyond ecological carrying capacity, especially within mangrove areas, with substantial environmental repercussions and potential system collapse [38]. The variable Effect of land availability on Mangrove represents the impact of land availability on the mangrove group. It estimates the extent to which land availability influences the growth or decline of mangrove areas over time. This variable captures the competition for land between mangroves and ponds within the system. As the pond area expands, it reduces the available land for mangroves, potentially constraining their growth. Conversely, if the pond area decreases, it frees up more land for mangrove expansion. Competition between anthropogenic activities and mangrove areas were studied not only in Vietnam but also in international coastal areas such as Indonesia [39], India [40] or Mexico [41].

By incorporating the Effect of land availability on mangroves into the model, it accounts for the feedback between mangrove and pond dynamics. The availability of land for mangrove growth influences the net change in mangrove area by adjusting the planting and loss rates based on the proportion of available land. This feedback mechanism allows researchers and policymakers to explore the interplay between mangrove and pond areas and understand how changes in land availability can impact the growth or decline of mangroves within the system.

Understanding the dynamics of the mangrove sector is critical since mangroves are essential to coastal ecosystems. They provide habitat for a variety of animals, aid in carbon sequestration, help stabilize shorelines, and support local livelihoods. The model allows researchers and policymakers to examine the impacts of mangrove restoration or degradation on overall system dynamics and explore options for sustainable mangrove management by evaluating the feedback loops connected with the mangrove sector.

<u>Carbon sector</u>. The carbon sector comprises the stock Carbon sink, representing the amount of carbon stored in the mangrove ecosystem. The model calculates the change in carbon storage over time by considering the change in mangrove area and the aboveground carbon stock per hectare value [42]. This feedback loop sheds light on the role of mangroves as carbon sinks and the potential implications for climate change mitigation.

<u>Shrimp ponds sector.</u> The ponds sector focuses on the stock Ponds**,** which represents the dynamics of shrimp ponds within the system. Ponds are areas dedicated to shrimp farming or aquaculture. The model accounts for the rise or fall of shrimp aquaculture area over time and explores the factors influencing this process. The model calculates the net change in pond area over time based on auxiliary variables such as net growth rate, profit incentives, and conversion from mangrove area to ponds.

The variable Effect of land availability on ponds is critical for understanding the dynamics of the pond group. It measures the impact of land availability on the net pond change over time. Similar to the Effect of land availability on mangroves, it considers the competition for land between mangroves and ponds within the system [40, 41]. When land availability is limited due to a large mangrove area, it reduces the space for pond expansion, potentially slowing the net growth of pond areas. On the other hand, if the mangrove area decreases, more land becomes available for pond expansion, promoting the net growth of pond areas [43].

<u>Socio-economics sector</u>. The socio-economic sector revolves around the contribution of shrimp industry on output value and employment generation. Typically, the shrimp industry's output value is determined by its yield or productivity, number of seasons, and market considerations such as prices, demand, and exporting. However, these variables change depending on the type of shrimp, such as black tiger shrimp and white shrimp, as well as their

different sizes. All of these factors require substantial effort and go beyond this study's scope. Given that the purpose of this article is to examine the shrimp aquaculture area and its associated consequences, the economic sector was simplified and assumed that the production value from shrimp farming can be interpreted via the generated output value per unit area. This approach was also applied by to estimate agricultural output value in Sichuan, China [44].

The model estimates the Shrimp output value calculated from the Pond area and Output value per hectare. This feedback loop explains the relationship between shrimp production, wealth generation, and economic sustainability. The Vietnamese shrimp industry benefits local farmers financially and creates jobs in the shrimp industry. In 2010, Vietnam's aquatic products contributed 4.6% to the Gross domestic product (GDP), equivalent to US$ 4.8 billion, with shrimp production playing a significant role and providing jobs for over 4 million people [45]. Consequently, the profit gained from shrimp farming serves as an incentive for farmers to further convert more mangrove areas to shrimp ponds [38, 46].

In addition to economic benefits, shrimp farming creates employment opportunities [45, 47]. According to the Sustainable Agricultural and Rural Development Strategy of Ca Mau, the provincial government aims to reduce the proportion of agricultural and fishery employees within the total labor force to 20% by 2030. To assess the feasibility of achieving this policy target, we projected the future number of shrimp farming employees and the overall labor force.

Our model estimates the number of shrimp farming employees based on the Pond area and the standard employment density (Employees per hectare). This method assumes that the employment density remains constant, implying that any changes in the number of shrimp farming employees are directly related to variations in pond areas over time. The population sub-sector accounts for the total population in Ca Mau. The model projects population changes over time based on the population growth rate. The labor force is then derived from the total population size, factoring in the proportion of people of working age [48]. Ultimately, the impact of the shrimp farming industry on employment generation in the province is expressed as the ratio of shrimp farming employees to the total labor force.

All of the variables and equations are presented in Table 1.

Table 1. Variables and equations in the model

Variables	Description	Type	Equations	Units
MPLR	Mangrove planted rate	auxiliary	Table function((2007, 0.025), (2014, 0.0225), (2019, 0.0133), (2020, 0.012), (2021, 0.0108), (2050, 0.0202))	%
MLR	Mangrove lost rate	auxiliary	Table function((2007, 0.0047), (2014, 0.0252), (2019, 0.0246), (2020, 0.0233), (2021, 0.0472), (2050, 0.0161))	%
MPL	Mangrove planted area	auxiliary	$MANGROVE * MPLR$	ha
ELM	Effect of land availability on mangrove	auxiliary	$1 - (MANGROVE/LC - PONDS)$	
ELP	Effect of land availability on ponds	auxiliary	$1 - (PONDS/LC - MANGROVE)$	
PMA	Pond to mangrove area	auxiliary	$PONDS * PMR$	ha
MPA	Mangrove to pond area	auxiliary	$MANGROVE * MPR$	ha
PGR	Pond net growth rate	auxiliary	Table function((2007, 0.0089), (2010, -0.0013), (2015, 0.0101), (2020, 0.0038), (2021, 0.0025), (2050, 0.0025))	%
PI	Profitable incentive	auxiliary	$(0.0005569 * SOV)/DELAY$	ha
POPGR	Population growth rate	auxiliary	Table function((2007, 0.0055), (2010, -0.0017), (2015, 0.0030), (2020, 0.0124), (2021, -0.0009),	%

Variables	Description	Type	Equations	Units
			(2030, 0.0021), (2040, 0.0014), (2050, 0.0006))	
EG	Employment generation	auxiliary	SE/LF	%
CARBON	Carbon sink	level	$INTEG(CS - CL, 59140908.7)$	MgC
MANGROVE	Mangrove area	level	$INTER(MA - ML, 70072)$	ha
PONDS	Shrimp pond area	level	$INTER(NCP, 262177)$	ha
POP	Total population	level	$INTEG(POPG, 1195161)$	people
CS	C stored	rate	$CPH * MA$	MgC
CL	C lost	rate	$CPH * ML$	MgC
MA	Mangrove added area	rate	$(MPL + PMA) * ELM$	ha
ML	Mangrove lost area	rate	$MANGROVE * MLR$	ha
NCP	Net changed pond area	rate	$(PG + MPA + PI) * ELP$	ha
PG	Pond growth	rate	$PONDS * PGR$	rate
SOV	Shrimp output value	rate	$PONDS * OVH$	Million VND
SE	Net change in shrimp employees	rate	$PONDS * EPH$	people
POPG	Population growth	rate	$POP * POPGR$	people
LF	Labor force	rate	$POP * WAR$	people
WAR	Working age ratio	rate	Table function((2007, 0.5234), (2010, 0.5549), (2015, 0.5598), (2020, 0.5619), (2021, 0.49), (2030, 0.6369), (2040, 0.5782), (2050, 0.5287))	%
CPH	C stock per ha	constant	69	MgC
EPH	Employees per ha	constant	0.54147	people
DELAY	Delay	constant	2	
LC	Land capacity	constant	464105	ha
MPR	Mangrove to pond conversion rate	constant	0.01197	%
PMR	Pond to mangrove conversion rate	constant	0.00305	%
OVH	Output value per ha	constant	45.8353	Million VND

Scenarios

The model was estimated using historical data from 2007 to 2021 and predicted from 2022 to 2050 with a time step of 1. Two scenarios regarding the balance between mangrove conservation and shrimp pond expansion in Ca Mau were analyzed (Table 2).

The first scenario, known as the 'business-as-usual' (BAU) or baseline scenario, extrapolates the trends of all variables observed from 2007 to 2021 to predict future developments until 2050, without imposing any policy constraints on the expansion of shrimp aquaculture. Besides, the auxiliary variable "land capacity" imposed a constraint on the expansion of both shrimp ponds and mangrove areas. This growth limitation was set at 464,105 hectares, representing the total area designated for agriculture, forestry and aquaculture in Ca Mau province [11].Table 2. Scenarios summary

Parameters	BAU	Policy
Shrimp ponds	Change at historical pace 2007-2021	Capped at 280,000 hectares from 2030 onwards
Mangrove		Recover and increase
Population		Reach 1,216,070 people in 2050
Mangrove to pond conversion		Reduce by half
Pond to mangrove conversion		Double
Employment generation		Reduce the percentage of the workforce in agriculture and fisheries to 40% in 2025 and 20% in 2030

The second scenario, termed the 'Policy scenario', incorporates the policy objectives stated in the “Enhancing Efficiency and Sustainable Development of the Shrimp Industry in Ca Mau Province by 2025 and Vision towards 2030 Project”, and the “Sustainable Agricultural and

Rural Development Strategy in Ca Mau Province for the Period 2021 - 2030, with a Vision Towards 2050 Plan" into the model. As per the policy measures, the area designated for shrimp aquaculture in Ca Mau is capped at 280,000 hectares. This limit is enforced by adjusting the net change in pond area flow within the model, ensuring that the total pond area does not exceed this limit once it is reached. Consequently, by stabilizing the shrimp farming area at 280,000 hectares, the model predicts a reduction in the conversion of mangrove areas to shrimp ponds and anticipates a rehabilitation of abandoned or inefficient ponds back to mangroves. Additionally, the objective of decreasing the percentage of the workforce in agriculture and fisheries acts as a benchmark for evaluating the projected employment generated by the shrimp industry. Projections for Ca Mau's population and labor force growth is collected from the projection data of General Statistics Office [49]. All other variables are projected to follow the patterns established in the baseline scenario.

Data collection

Data was collected from Ca Mau's Statistical Yearbooks from 2007 to 2021 and the Rural, Agricultural and Fishery Census of 2006, 2011, and 2016. Spatial data from Clark Labs [10] was utilized for visualizing and mapping changes in mangroves in Ca Mau. The land cover mapping process utilized Landsat 5 imagery for 1999 and Landsat 8 imagery from 2014 to 2022. All Landsat data were resampled to a spatial resolution of 15 meters and, when necessary, substituted with panmerged bands. In addition to the Landsat data, supplementary data were incorporated into the analysis, including SRTM elevations, Tasseled Cap transformed images, and various convolutions of reflectance data. Classification techniques involved using a multilayer perceptron neural network for classifying pond aquaculture and open water, while Mahalanobis typicality was employed to classify the remaining land cover classes [10].

Model calibration and validation

The model's validation depends on both its structural and behavioral validity [50]. In this study, the model was calibrated and validated using key variables from 2007 to 2021. The process began with the initial year of 2007, where a series of trial and error simulations were conducted by adjusting individual parameter values. The goal was to minimize the error between the simulation results and the actual values until an acceptable level was reached, without any significant increase in the error. The historical test involved comparing the simulation values with the real values. If the error between the two fell within an acceptable range, it indicated that the model had high credibility and was suitable for subsequent analysis [48]. Additionally, behavior tests were performed using extreme-condition testing based on instructions from Duggan [51] and the "RUnit" package [52]. Table 3 presents each simulation value's relative errors, confirming the model's capability to predict and analyze future scenarios.

Table 3. Comparison of historical and simulation values

		2007	**2015**	**2021**
Shrimp ponds	Historical value	262177	275858	271080
	Simulated value	262177	275858	271080
	Relative error	0.000	0.000	0.000
Mangrove	Historical value	70072.167	77635.900	72524.200
	Simulated value	70072.000	78882.200	75581.730
	Relative error	0.000	0.016	0.042
Population	Historical value	1195161	1218900	1208750
	Simulated value	1195161	1218900	1208750
	Relative error	0.000	0.000	0.000

RESULTS AND DISCUSSION

The model estimation indicates that the BAU Scenario will lead to continuous expansion of shrimp pond areas, resulting in high production output value and significant employment generation. However, this comes at the expense of slow growth in mangrove area and carbon storage. In contrast, the Policy Scenario, which constrains shrimp cultivation area, promotes a more robust growth of mangrove area and carbon storage, but leads to lower shrimp output value and employment generation. The results of both scenarios are summarized in Table 4, with detailed findings presented in the subsequent sections.

Table 4. Estimated results in the BAU Scenario and the Policy Scenario

Variables	Unit	2007	BAU Scenario 2050	Policy Scenario 2050	Differences (%)
Mangroves	Hectares	70,072	76,484	88,902	16.236
Shrimp ponds	Hectares	262,177	317,037	280,000	-11.682
Carbon sink	MgC	4,387,710	4,830,107	5,686,965	17.740
Output value	Billion VND	9,227	25,153	22,214	-11.684
Shrimp employees	People	141,961	171,666	151,612	-11.682
Labor force	People	625,500	682,864	642,942	-5.846
Employment generation	%	22.69	25.13	23.58	-6.168

Mangrove forest and shrimp aquaculture

From 1999 to 2022, Ca Mau's aquaculture landscape dramatically expanded (Figure 2), predominantly at the expense of rice fields and mangrove areas, supported by Directive No. 09/CT/TU in 2000 promoting the transformation of low-yield rice fields into shrimp farms [53]. This policy-driven change mirrored trends in coastal Bangladesh, with both regions seeing rice fields converted into shrimp farming (Nasar et al., 2017). Although mangrove areas initially increased until 2014, they subsequently declined, with the majority of the loss attributable to their conversion into aquaculture zones. Nonetheless, some former pond areas have reverted to mangrove forests (Clark Labs, 2022). Furthermore, silt deposition in Ca Mau's northern and northwestern districts has encouraged fresh mangrove colonization [54].

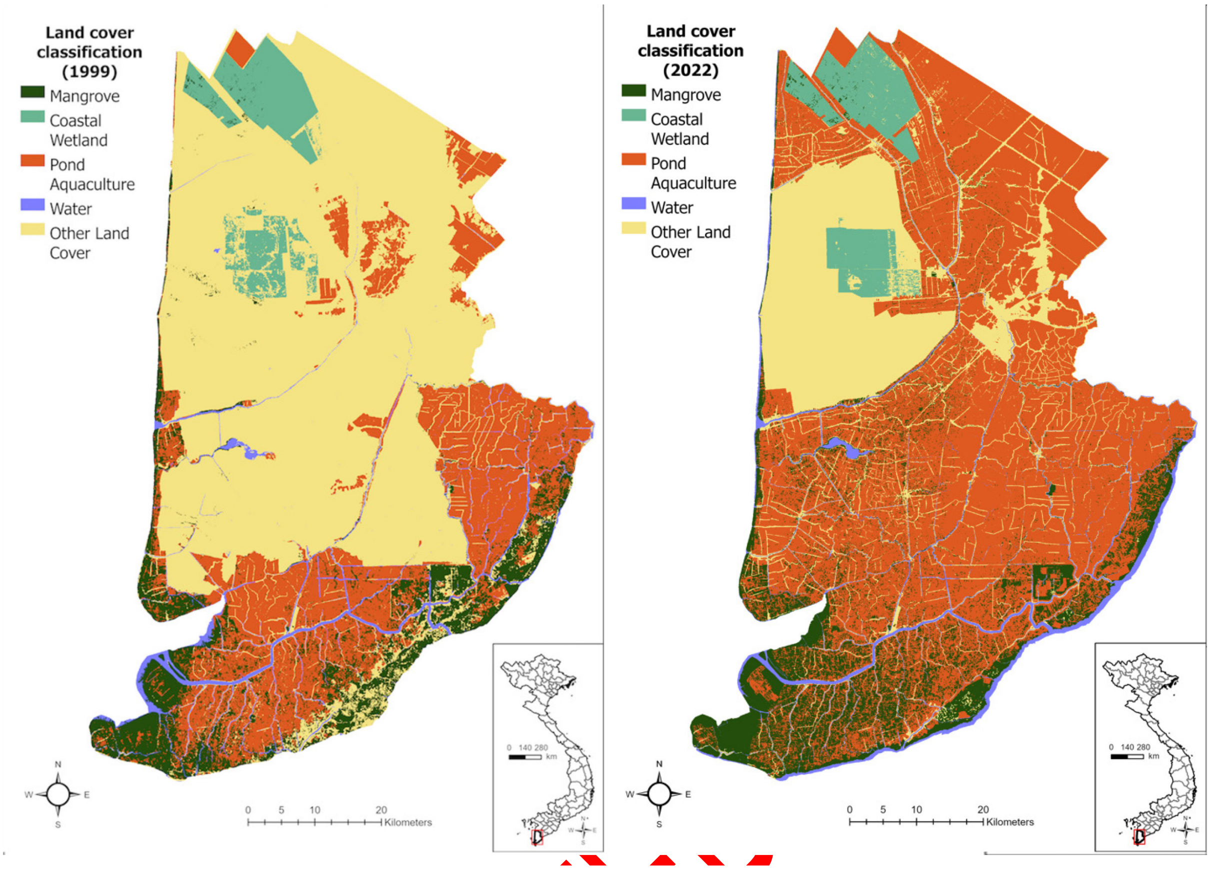

Figure 2. Land covers in Ca Mau 1999-2022 (Clark Labs, 2022)

In Ca Mau, there are currently five main shrimp farming models, including industrial shrimp farming, improved extensive shrimp farming, shrimp-rice farming, shrimp-mangrove farming, and a combination of extensive farming methods. With increasing cultivation areas and yields over the years, shrimp production in Ca Mau Province has increased from 35,000 tons in 1997 to 158,887 tons in 2016 and 205,290 tons in 2021 [11].

In 2022, the area of combined extensive shrimp farming was 96,264.68 hectares, including 20,486 hectares of giant river prawn with a yield of 240-250 kg/ha and a production of 5,050 tons. The area of improved extensive shrimp farming was 176,276 hectares, exceeding the anticipated aim by 2.49% and increasing by 8.53% over 2021. The area of intensive and super-intensive shrimp farming reached 6,317 hectares; super-intensive farming accounted for 4,352 hectares, reaching 117.6% of the planned target and increasing by 18.2% compared to 2021, with a yield ranging from 40 to 50 tons per hectare per crop; intensive farming accounted for 1,965 hectares, with an average yield of 5 tons per hectare per year for tiger shrimp and 8 tons per hectare per year for whiteleg shrimp [20].

In the baseline period 2007-2021, shrimp pond area gradually increased between 2007 and 2016 (Figure 3). The most significant growth in aquaculture was recorded between 2014 and 2016 when the area jumped from 268,600 hectares to 278,642 hectares . These figures indicate a period of aggressive expansion, driven by the promotion of the large-scale transformation of low-yield rice cultivation into shrimp farming [53]. In this period, "aquaculture development" was documented as a favorable policy, and "economic opportunities" were the most relevant factor in the expansion of shrimp aquaculture [55]. From 2016 to 2021, the area of shrimp ponds experienced fluctuations, alternating between reductions and growth, indicating variability in the expansion of shrimp farming.

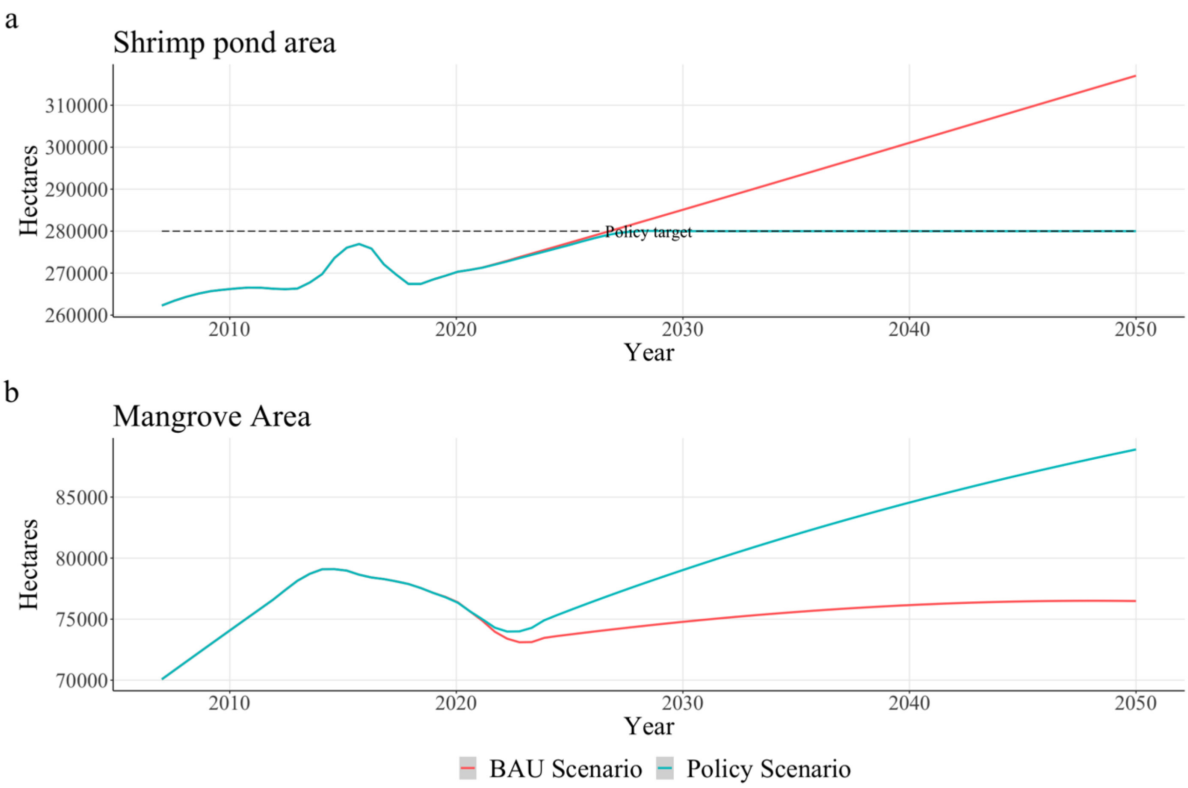

Figure 3. Comparison of Shrimp pond area (a) and Mangrove area (b)

After 2021, distinct trends emerged between the two scenarios. Throughout the simulation period, the BAU Scenario showed that shrimp area ranged from a minimum of 262,177 hectares in 2007 to a maximum of 317,038 hectares in 2050. The BAU shrimp areas exhibited a pattern of growth consistent with past trends, with fluctuations in shrimp pond expansion reflecting historical variability. A similar expansion trajectory was forecasted for Malaysian shrimp farms over the next three decades [32]. In contrast, the Policy Scenario showed that annual changes in shrimp pond area were consistently smaller and decreased over time, implying a controlled and deliberate expansion rate that diverged from the more erratic pattern seen in the BAU Scenario. This shift aligns with policy goals, which aim to cap shrimp farming area at 280,000 hectares from 2028 onwards, thereby fostering the sustainable development of the sector through regulated land-use changes.

A comparison of the two scenarios clearly illustrates that the policy-driven approach would alter the trajectory of shrimp pond area from those projected in the BAU scenario. These diverging paths are likely to result in different implications on environmental-social-economic aspects in the analyses.

Regarding mangrove area, from 2007 to 2014, Ca Mau's mangrove area continuously increased from 70,072 hectares to 79,310 before decreasing to 72,524 hectares in 2021 [10]. The consistent growth from 2007 to 2014 may be attributed to the efforts to meet the objectives outlined in the National Biodiversity Strategy to 2010 and Vision to 2020 [56]. Additionally, diseases and water pollution were found to negatively impacted shrimp aquaculture during this period [39].

Most critically, the enormous expansion in shrimp aquaculture beginning in 2014 coincides with the intensive destruction of Ca Mau's mangrove forests (Figure 3). This highlights a direct correlation between these two land uses. Due to the tremendous economic prospects of the shrimp industry, a portion of Ca Mau's mangrove area was converted into shrimp ponds. Despite conservation efforts, the mangrove forests in Ca Mau have not recovered from the significant losses experienced after reaching their peak in 2014. Previous studies indicated that the major loss of Ca Mau mangrove forest is mostly due to shrimp cultivation expansion [12, 57]. Similarly, on the southern coast of Tamil Nadu, India, meticulous planning and strategic actions are essential to prevent the degradation of mangrove habitats due to the growth of aquaculture operations [58].

From 2022 to 2050, the BAU Scenario's projection data indicated a gradual increase in mangrove area, starting at 73,015 hectares and culminating in 76,484 hectares by the mid-century. This represented a moderate growth of approximately 4.7%. Throughout these years, the increase was not uniform, displaying slight fluctuations, which suggest a degree of variability in mangrove expansion due to unregulated shrimp farming development. A slight reduction was observed in 2049, hinting at a potential leveling off in the growth of mangrove areas as the scenario approached mid-century.

In contrast, the Policy Scenario showed a more robust growth pattern, starting from 73,518 hectares in 2022 and exhibited a more consistent and significant increase. By 2050, the mangrove area under this scenario is expected to reach 88,901 hectares, marking an increase of roughly 20.9% from the initial area. This trend indicates a proactive policy effect that not only promotes but also likely incentivizes the expansion of mangroves, resulting in a more pronounced increase.

The difference in projected shrimp pond and mangrove area in 2050 between the two scenarios is 37,037 hectares and 12,418 hectares, respectively. This implies that for every 37,037 hectares decrease in shrimp ponds, there is a corresponding increase of 12,418 hectares in mangrove area by 2050. Therefore, the stabilization of the shrimp farming area has indirect positive consequences for mangrove protection. The Policy Scenario's trajectory suggests that the policy measures implemented are effective in promoting mangrove conservation and expansion, as compared to the BAU Scenario where the growth in mangrove area is more conservative and subject to fluctuations that could be indicative of less stringent conservation efforts. The Policy Scenario's proactive stance on environmental conservation seems to create a more favorable condition for mangrove expansion, which could contribute to enhanced ecosystem services and coastal protection in the long term. In Thailand, one of the world's leading shrimp producers, "feebate" policy action also has a balancing effect on mangrove regions [46].

However, given the current pressures on mangroves resulting from the rapid expansion of shrimp aquaculture in Ca Mau, it is crucial to implement better-adjusted land use management plans. This involves balancing the needs of shrimp farming with the preservation and restoration of mangrove forests to ensure their long-term sustainability. In fact, there have been efforts made to reduce deforestation, such as the introduction of Decision No. 19/2010/QĐ-UBND in 2010 [59], authorizing recipients of mangrove forest land to use up to 40% of it for combined agriculture and aquaculture, preserving the ecosystem. Following this, the International Union for Conservation of Nature and the Netherlands Development Organization launched the Mangroves and Markets (MAM) project in 2012, which instructed 5,500 Ca Mau residents in sustainable shrimp farming safeguarded 12,600 hectares of mangroves [60]. Continuing these efforts, since 2021, the "Mangrove and climate protection with income generation for vulnerable communities (VM069)" project has been operational, spearheaded by the SRD in Mui Ca Mau National Park and Tam Giang Protection Management Board, aiming to enhance biodiversity and develop mangroves to bolster carbon sequestration [61]. Unfortunately, the conversion of mangroves into shrimp ponds still occurred. Therefore, there is a demand for more effective measures to be implemented to prevent further deforestation.

Carbon sink

The potential carbon stock per ha was represented by a constant auxiliary [42], the shape of the stock variable *Carbon sink* followed the shape of *Mangrove area* in both the BAU and

Policy scenarios (Figure 4). Under the BAU Scenario, the carbon sink values varied from 4.59×10^6 MgC in 2022 to 4.83×10^6 MgC in 2050. This variation occurred with an initial increase until 2023, when carbon sinks reached 4.608×10^6 MgC, followed by a fluctuating decline over the subsequent years. The decline steadied towards 2030 and then showed upsurges till 2050.

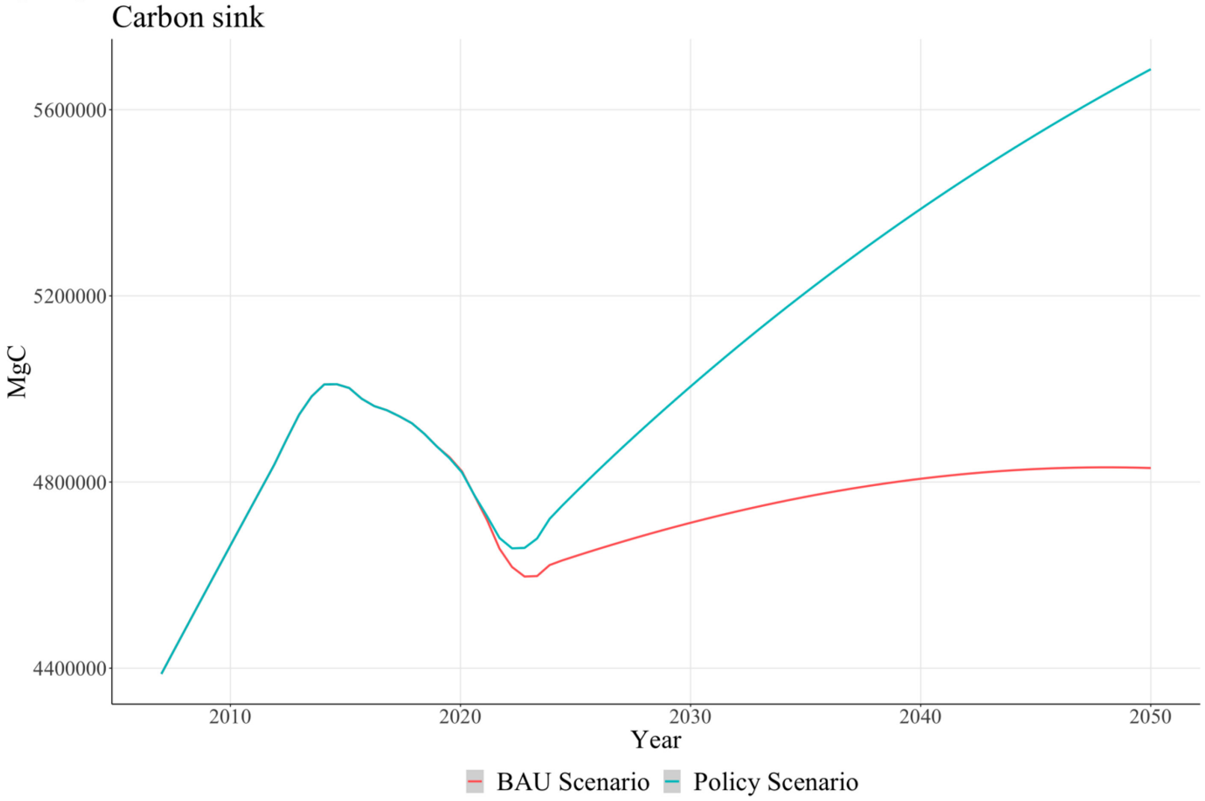

Figure 4. Carbon sink from Ca Mau mangrove forest 2007-2050

Contrastingly, in the Policy Scenario, the carbon sink capacity showed an upward trend, starting from 4.625×10^6 MgC in 2022 and increasing each year to reach 5.686×10^6 MgC by 2050. This consistent rise reflects the potential effectiveness of policy interventions aimed at enhancing carbon sequestration. The increase was steady and did not exhibit the volatility seen in the BAU Scenario, indicating a robust and sustained enhancement of the carbon sink capacity over time.

Presently, these projections suggest that under the Policy Scenario, the carbon sinks in the area are likely to improve significantly, assuming that the policies continue to support activities that enhance carbon sequestration. The increasing trend in the Policy Scenario underscores the potential benefits of targeted environmental policies. In contrast, the BAU Scenario indicates that without targeted interventions, carbon sink capacities may not maintain their initial levels and could potentially decrease, which highlights the importance of policy measures in sustaining environmental health and combating climate change.

Our analysis examined the potential contribution of carbon sinks within the context of Vietnam's National Climate Change Strategy and the commitment to a net zero emission target by 2050. For the year 2050, the BAU Scenario showed a carbon sink capacity of 4.83×10^6 MgC. When converted to CO2e, this capacity translates to a contribution of 17.7261×10^6 MtCO2e. This figure equals 9.6% of Vietnam's total emission cap of 185 MtCO2e as stipulated by the government [62]. On the other hand, the Policy Scenario indicated a more substantial carbon sink capacity of 5.686×10^6 MgC in 2050. This capacity contributes to 20.867×10^6 MtCO2e, mitigating 11.2% of the national emission cap.

These projections suggest that the Policy Scenario's enhanced carbon sequestration efforts could yield a more significant impact in terms of meeting the country's emission reduction targets. The increase from 9.6% to 11.2% of the total allowed emissions underlines the critical role of policy-driven environmental management. It implies that adopting and implementing the proposed policies can amplify the effectiveness of natural carbon sinks, which is a crucial factor in the broader strategy to mitigate climate change. The discussion underscores the importance of strategic policy interventions in achieving Vietnam's climate goals and contributing to global emission reduction efforts.

It is worth noting that the estimation of carbon stocks serves as a rough indicator for the potential of climate change mitigation via carbon storage of Ca Mau mangrove forests because determining carbon sequestration or carbon storage is extremely complicated and beyond the scope of this study. Mangrove forests are the most important carbon sinks in the tropics [63]. The quantification of carbon storage in mangrove forests is essential for the development of climate change mitigation strategies and the implementation of REDD+ schemes in Vietnam [64]. It also contributes to the larger puzzle of addressing climate change and planning for a sustainable future. By assessing the carbon storage capacity of mangrove ecosystems, we can better incorporate their conservation and restoration into broader climate action efforts [65]. In terms of monetary value, the carbon sequestration value of the Ca Mau mangrove is approximately US$ 136.64 per ha per year [66]. In addition to carbon sequestration, effective management of coastal ecosystems can generate beneficial ecosystem services, including protection against tropical cyclones [67].

Shrimp production output value

During the analysis period, Ca Mau agriculture concentrated its efforts on implementing the Agricultural Restructuring Project, particularly from 2016 to 2020. From 2007 to 2021, the total output value of the agricultural, forestry, and fisheries sector rose from US$ 493,710,000 to US$ 940,128,000, contributing nearly 34% to the province's total output value. Laborers in the agricultural, forestry, and fisheries sector earned US$ 1680/person/year, contributing to economic prosperity, political stability, and social stability [11, 68, 69]. Ca Mau is the largest producer in black tiger shrimp production and operates farms with the highest cost efficiency but low environmental efficiency [70].

The shrimp farming industry is identified as a key economic sector and plays an important role in the economic development of Ca Mau province. The production value of the shrimp industry in Ca Mau accounts for 80% of the total production value in the aquaculture sector and 49% of the total production value in the agricultural sector. The output value of the shrimp farming area is approximately 45 million VND/ha (US$ 1890/ha). The province's seafood export turnover, mainly driven by shrimp, reaches US$ 1.2 billion per year, accounting for more than 40% of the country's shrimp export turnover, with processing volume exceeding 138,000 tons per year [11, 68, 69].

Under the BAU Scenario, the Shrimp output value experienced a consistent upward trend, beginning at 12,733 billion VND in 2022 and projected to reach 25,153 billion VND by 2050 (Figure 5). The growth was continuous, reflecting an overall positive trajectory for the shrimp industry in the absence of additional policy interventions. A steady income increase for farmers was also projected in Malaysia due to the expansion of the aquaculture area [32].

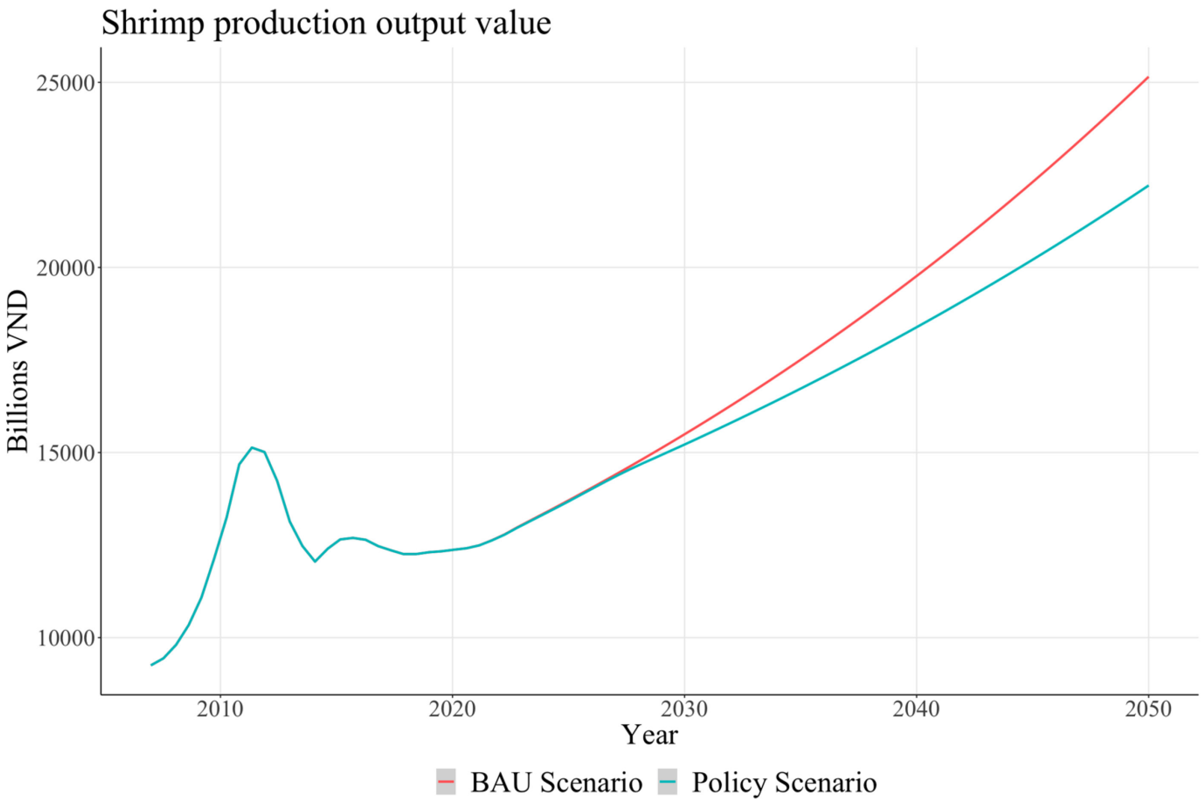

Figure 5. Shrimp production output value in Ca Mau 2007-2050

Comparatively, the Policy Scenario began with a Shrimp output value slightly lower than the BAU at 12,727 billion VND in 2022. However, this scenario projected an ascent to 22,214 billion VND by 2050, indicating a substantial increase, although at a lower ending point than the BAU Scenario. This suggests that while policy interventions may promote more sustainable or regulated growth, they do not necessarily inhibit the economic output of the shrimp industry; instead, they seem to guide it towards a sustainable path.

From the prediction, both scenarios indicated growth in the shrimp sector's output value. The BAU Scenario assumes an unrestrained industry expansion, whereas the Policy Scenario incorporates sustainable growth practices that may slightly temper economic output but still potentially offer long-term benefits. These findings underscore the need to balance economic development with sustainable practices in the shrimp industry, aligning with Vietnam's broader economic and environmental goals. Moreover, in developing countries, it is important to consider the scale of farming operations and the livelihoods of individuals. Shrimp farming, being capital-intensive, allows larger entrepreneurs to easily engage in high-profit activities, while small-scale producers would require institutional, technical, and financial assistance to comply with enhanced regulations aimed at promoting mangrove conservation [55].

To further bolster the shrimp industry’s economic growth in the Policy Scenario, various strategies should be implemented. These strategies encompass improving productivity, enhancing production quality, adopting advanced and high-tech farming models, and strengthening production linkages. Through careful consideration of these factors and the implementation of appropriate measures, Ca Mau may secure the long-term success and development of its shrimp industry. One emerging solution in Vietnam and Indonesia is adoption of mangrove silvo-aquaculture farming systems (particularly integrated mangrove-shrimp farming). The adoption of these systems holds promise in enhancing resilience in coastal aquaculture landscapes by offering opportunities for livelihoods, restoring mangroves, sequestering blue carbon, reducing disease risks, improving water quality, generating additional income through diversified aquatic products and timber production, and providing coastal protection [71].

Furthermore, while shrimp aquaculture significantly bolsters Ca Mau's economy, diversifying its economic activities remains essential. Encouraging the growth of other sectors such as agriculture, tourism, manufacturing, and services can reduce reliance on shrimp farming and mitigate risks associated with capped aquaculture growth. Relying solely on shrimp farming is unsustainable due to its high investment costs and risks, particularly for small rural households. Additionally, promoting diverse economic sectors will aid in redistributing the labor force, attracting more employees to alternative employment opportunities. By fostering various economic sectors, Ca Mau can create new income sources, jobs, and economic resilience, thereby promoting economic development and stability. This aligns with the future plan for restructuring agriculture and rural development in Ca Mau towards 2050 [19].

Shrimp employees and their contribution to rural employment generation

Under the BAU Scenario, shrimp industry employment is projected to increase steadily from 147,605 people in 2022 to 171,666 in 2050 (Figure 6) . Meanwhile, the share of shrimp employees within the total labor force shows a gradual rise from 22.06% to 25.14% over the same period. This trend suggests that, without policy intervention, the shrimp industry's share of the total labor force will continue to grow, potentially exceeding the government's target of reducing the combined share of agricultural, fishery, and forestry employees to 40% by 2025 and to 20% by 2030.

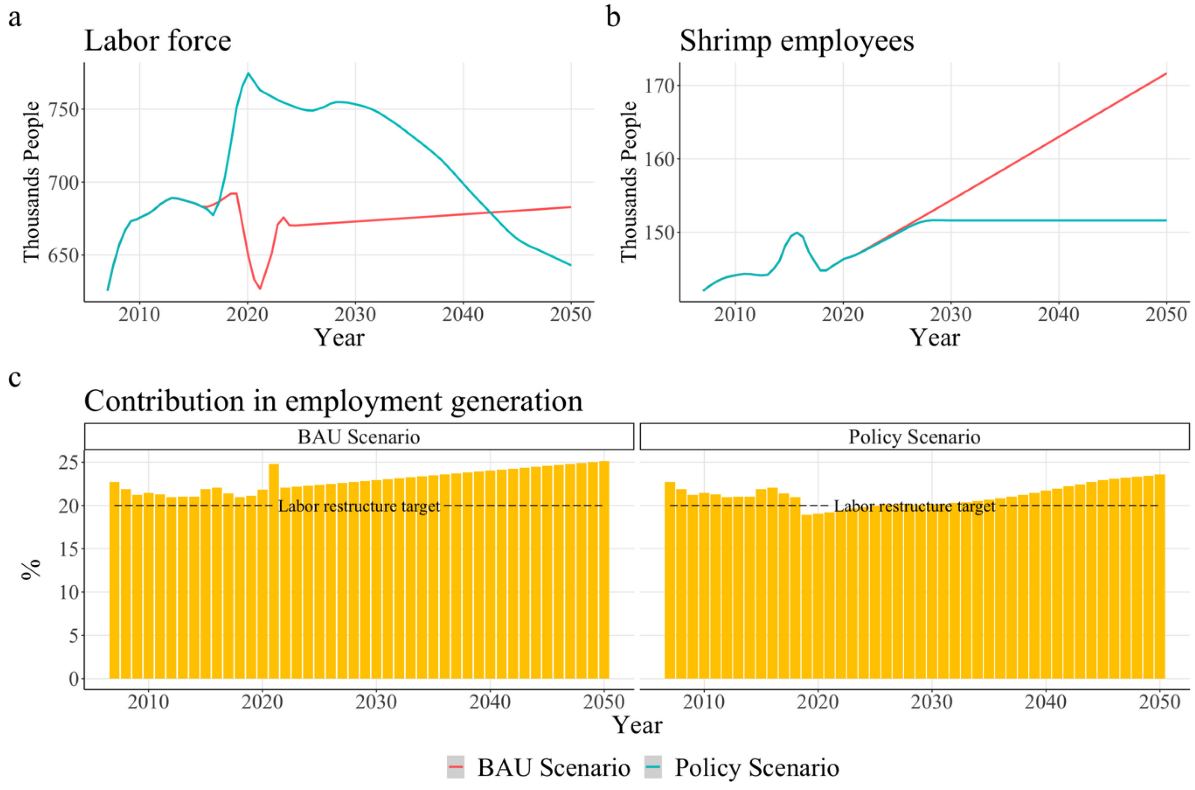

Figure 6. Labor force (a), Shrimp employees (b) and shrimp industry's contribution to employment generation in Ca Mau 2007-2050 (c)

In contrast, the Policy Scenario reveals a different trajectory. The number of shrimp industry employees starts at a comparable level to the BAU Scenario in 2022 but reaches an early plateau at 151,611 people from 2028 onwards due to the stabilized shrimp farming area, maintaining this level through to 2050 (Figure 6). The share of employment generation in the shrimp industry begins at 19.42% in 2022 and shows a subtle increase to 23.58% by 2050. This trend indicates that the Policy Scenario is more closely aligned with Ca Mau government's labor force targets. These projections illustrate that the Policy Scenario is in closer adherence to the government's aim of restructuring the labor force. While the BAU Scenario implies growth beyond the set targets, potentially challenging the government's strategic labor force composition, the Policy Scenario demonstrates a controlled approach, stabilizing the number of employees in the shrimp industry. This stabilization, along with the incremental increase in the industry's labor share, supports the targeted reduction of the workforce in agriculture, fishery, and forestry, thus contributing to the overall objective of diversifying Vietnam's labor force and economic activities.

Shrimp farming, as the predominant industry in the rural regions of Ca Mau, significantly influences local livelihoods, accounting for 60%-70% of annual rural employment [72]. Within the BAU scenario, the projected expansion of shrimp ponds up to 2050 is expected to create additional employment opportunities, reinforcing this sector's role in job creation. However, it is important to recognize that intensive shrimp culture can lead to socioeconomic challenges, as the industry is susceptible to high risks, including potential economic losses due to diseases and environmental degradation, such as water pollution [73].

Contrastingly, the Policy Scenario maintains a significant contribution to rural employment, although the number of shrimp farming jobs is anticipated to stabilize. Despite this, its employment impact is projected to be less than that of the BAU scenario. A cap on shrimp pond expansion could shift the dynamics of the rural labor market, possibly resulting in increased migration of workers from rural areas to urban centers in search of alternative employment. Such a transition underscores the need for policymakers and stakeholders to develop strategies that balance the shrimp industry's role in rural job provision with the pursuit of sustainable employment options.

Moreover, conservation efforts to protect regions rich in biodiversity must consider the economic needs of local communities [74]. The predicted difference in the number of shrimp employees between the BAU and Policy Scenario in 2050 is 20 thousand people, indicating that there would be a potential loss of employment opportunities in rural areas resulting from capped shrimp aquaculture. The implementation of policies in Ca Mau should be phased and should include the promotion of alternative livelihood options to mitigate any adverse effects on local employment [55]. This approach helps ensure that environmental conservation efforts do not undermine the economic stability of the local communities. Promoting alternative livelihoods includes supporting the development of other agricultural sectors, promoting rural entrepreneurship, and facilitating skill development programs to ensure a smooth transition for affected workers. The government can play a pivotal role by building on existing initiatives by allowing rural households with access to mangrove forests to engage in various agricultural and fishery activities, while also being eligible for capital support from programs like the Payments for Forest Ecosystem Services (PFES) Program [75]. Additionally, exploring alternative economic activities such as beekeeping and ecotourism can reduce households' reliance on shrimp farming for income. Furthermore, implementing a payment for carbon services mechanism in Ca Mau's mangrove forests could promote forest conservation and enhance the livelihoods of local communities in the province [76].

CONCLUSIONS

The study provides insight into the dynamic relationship between mangrove ecosystems and shrimp aquaculture in Ca Mau, projecting future developments under various scenarios. In the BAU Scenarios, if current trends continue without intervention, the expansion of shrimp farming will likely lead to further mangrove reduction by 2050, impacting carbon storage potential. However, this growth could bolster the economy and support rural jobs. In the Policy Scenario, where policy interventions promote mangrove conservation, projects positive environmental outcomes without sacrificing economic stability. A policy capping shrimp farming areas could allow mangroves to recover, potentially surpassing their historical peak levels and contributing significantly to national carbon sequestration efforts.

However, there are concerns about the social and economic consequences that authorities must consider. First, assuming all other economic factors remain constant, restricting shrimp aquaculture may result in lower economic growth and potential conflicts with other provincial economic development goals. Second, the shrimp farming sector generates fewer extra employment possibilities in rural regions, potentially leading to indirect consequences such as unemployment, migration, and insecure rural livelihoods. Finally, to achieve sustainable development in managing mangrove forests and shrimp aquaculture in Ca Mau, local authorities must consider various socioeconomic and environmental factors beyond simply capping shrimp pond areas at 280,000 hectares in the near future.

The study's findings underscore the potential impacts of implementing existing plans and policies. These insights are valuable for policymakers in Ca Mau, particularly the Department of Rural Development and Agriculture, tasked with aquaculture and forestry planning and management. Given the projected timeline extending to the mid-century, policymakers have the opportunity to make timely adjustments to mitigate any unintended policy consequences.

The model introduced in this study extends beyond Ca Mau, Vietnam's leading shrimp producer and home to extensive mangrove forests, to other regions facing similar threats from aquaculture expansion. These areas include the Mekong River Delta, the Red River Delta, and specific provinces such as Hai Phong, Thai Binh, Nam Dinh, Thanh Hoa, Quang Nam, Quang Ngai, Phu Yen, Ho Chi Minh City, Bac Lieu, and Kien Giang [77]. Moreover, the model developed in this study can be adapted for international use, particularly in major shrimp-producing countries like Thailand, India, and Malaysia. This is supported by the similar trends observed in the expansion of shrimp cultivation, mangrove coverage, shrimp farmers' income, and policy impacts across previous studies. However, it is important to note that while the approach is transferable, outcomes may vary based on local policy targets.

While the study made efforts to integrate and simulate numerous variables in the intricate system of mangrove and shrimp farming, it encountered limitations due to the complexity of certain variables and a lack of extensive historical data. Specifically, the model could not account for variables like unforeseen economic events or extreme incidents, which could significantly influence the results of shrimp production and the growth of mangrove forests.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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