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Economic Valuation and Ecological Thresholds in the Mangrove-Shrimp System

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Abstract: The conversion of mangrove forests into vannamei shrimp ponds has increased aquaculture production, but at the same time triggered the degradation of coastal ecosystems and the loss of environmental services of high economic value. This study aims to analyze the trade-off between economic benefits and ecological sustainability through estimating Total Economic Value (TEV), testing the effect of pond intensity on mangrove health, and identifying ecological thresholds as the basis for sustainable coastal management. The research uses a mixed-methods approach with a sequential explanatory (QUAN→QUAL) design. Quantitative data were obtained from a survey of 212 farmers, analysis of Landsat/Sentinel imagery for the 2020–2024 period, and then deepened through interviews and Focus Group Discussions (FGD). The analysis was conducted using Ordinary Least Squares (OLS) with Robust Standard Errors, as well as Cost–Benefit Analysis (CBA) and Net Present Value (NPV) evaluations. The results of the study show that the TEV of the mangrove ecosystem reaches Rp306.8 million/ha/year, with Indirect Use Value dominating at 71.2%. The intensity of ponds had a negative and significant effect on the NDVI index ($\beta = -0.710$; $p < 0.001$), while the application of silvofishery had a positive effect on mangrove health. Scenario simulation shows that the silvofishery system with a composition of 60% mangroves and 40% ponds produces the highest economic feasibility (NPV of Rp89.7 million/ha; BCR 2.38) while maintaining ecological function. These findings confirm that the integration of economic valuation and ecological thresholds is an important basis for the formulation of coastal management policies that are able to balance aquaculture productivity and mangrove conservation.

Keywoards: Ecological Threshold, Ecosystem Valuation, Mangrove-Pond System, Silvofishery

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INTRODUCTION

Mangrove ecosystems are a form of natural capital that has a strategic role in supporting the sustainability of coastal areas through the provision of various ecosystem services, ranging from coastal protection, blue carbon storage, aquatic biota habitats, to buffering coastal fisheries productivity. In the last two decades, the increasing global demand for vannamei shrimp (Litopenaeus vannamei) has driven the massive expansion of aquaculture in various developing countries, including Indonesia. These developments provide economic benefits in the form of increased production and income for coastal communities, but at the same time create pressure on the sustainability of mangrove ecosystems due to increasingly extensive land conversion (Friess et al., 2020; Boyd et al., 2022). This condition shows that the economic growth of the aquaculture sector does not always go hand in hand with environmental sustainability, so a management approach is needed that is able to balance economic interests and ecosystem conservation.

Indonesia has around 20–25% of the world's total mangrove cover, so it plays an important role in maintaining the sustainability of global coastal ecosystems (Spalding & Parrett, 2019). However, various coastal areas in Indonesia still face a high rate of mangrove conversion due to intensive pond development, settlement expansion, and land use change. The impact caused is not only in the form of a reduction in mangrove cover, but also a decrease in ecological quality, which is characterized by increased coastal abrasion, seawater intrusion, loss of biodiversity, decreased carbon sequestration capacity, and reduced ecosystem ability to reduce aquaculture waste (Alongi, 2014, 2020; Donato et al., 2011; McLeod et al., 2011). This phenomenon suggests that the exploitation of coastal resources without considering the carrying capacity of the environment will result in much greater social and economic costs compared to the short-term financial benefits.

Pasangkayu Regency, West Sulawesi Province, is one of the coastal areas that is experiencing rapid development of vannamei shrimp cultivation while facing increasingly real mangrove degradation pressures. Spatial analysis using Landsat and Sentinel imagery showed that during the 2020–2024 period, the mangrove area decreased from 52.40 ha to 44.60 ha or decreased by 7.80 ha (14.88%). In the same period, the average value of the Normalized Difference Vegetation Index (NDVI) also decreased from 0.71 to 0.53, indicating a change in vegetation conditions from the very dense category to degraded conditions. The decline in cover area that occurs simultaneously with the decline in vegetation quality shows that the ongoing degradation is not only quantitative but also affects the ecological function of mangroves as an environmental service provider for coastal communities.

The destruction of mangroves from an environmental-economic perspective not only means the loss of physical resources but also reduces the economic value of various ecosystem services previously provided to the community. The Total Economic Value (TEV) approach explains that the benefits of mangroves are not limited to direct use values such as fishery or timber products but also include indirect benefits in the form of coastal protection, carbon sequestration, biofiltration functions, choice values, and existential value that are often not taken into account in development decision-making (Costanza et al., 1998; Barbier et al., 2011). Within the framework of Natural Capital Theory, the loss of natural capital due to mangrove conversion will reduce inclusive wealth and long-term prosperity because lost ecosystem services require much greater replacement costs (Schumacher, 2022; Turner & Daily, 2008). Therefore, the evaluation of coastal development should not only be based on the financial gains of the pond but also consider the accompanying depreciation of natural capital.

Various previous studies have proven the importance of mangrove economic valuation and the ecological impact of aquaculture expansion. Barbier et al. (2011) emphasized that mangrove ecosystem services have a much greater economic value compared to the market benefits obtained through land conversion. Ahmed et al. (2018) show that shrimp farming can increase people's income in the short term but has the potential to cause environmental damage if not balanced with mangrove conservation. Boyd et al. (2022), through the Life Cycle Assessment approach, also revealed that intensive cultivation systems have a higher environmental footprint compared to systems that integrate mangrove vegetation. On the other hand, research by Su et al. (2021) shows that silvofishery systems can increase ecological efficiency using mangrove vegetation as a natural biofilter. However, most of these studies still examine economic, environmental, or spatial aspects separately, so they have not been able to explain the relationship between mangrove cover change, ecosystem economic value, and financial feasibility in one integrated analytical framework.

Based on the synthesis of the literature, there are still several research gaps that need to be answered. First, most mangrove valuation studies still focus on one component of ecosystem services, so they do not provide a comprehensive picture of Total Economic Value. Second, research on the impact of pond expansion generally uses a linear approach, so it has not been able to identify an ecological threshold that indicates the point when mangrove degradation begins to cause a drastic decline in ecosystem function. Third, empirical evidence integrating NDVI-based spatial analysis, econometric estimation, and economic feasibility evaluation through Cost-Benefit Analysis (CBA) and Net Present Value (NPV) on a micro scale in Indonesia is still very limited, especially in the coastal areas of West Sulawesi. These gaps show the need to develop an analytical model that can connect the ecological and economic dimensions simultaneously to produce a more comprehensive policy-making basis.

This research offers novelty through the integration of three approaches that have generally been studied separately, namely Total Economic Value valuation, spatial analysis of mangrove quality changes using NDVI, and evaluation of coastal management scenarios based on OLS Robust, CBA, and NPV. Integration allows the identification of relationships between pond utilization intensity, changes in ecosystem quality, and long-term economic implications, so that it can be used to determine ecological thresholds as the basis for sustainable coastal management. Thus, this study not only expands the application of the concepts of Natural Capital and Total Economic Value but also provides empirical evidence on the relationship between ecological sustainability and economic efficiency in mangrove-pond systems.

Based on this background, this study aims to estimate the Total Economic Value of mangrove ecosystems in Pasangkayu Regency, analyze the influence of pond intensity on the quality of mangrove vegetation, identify ecological thresholds that are the limits of sustainable use of coastal space, and evaluate coastal management scenarios that can provide a balance between economic benefits and environmental sustainability. The results of the research are expected to make a scientific contribution to the development of environmental economics and natural resource economics, as well as provide a basis for the formulation of evidence-based coastal area management policies that support the achievement of sustainable coastal development.

METHOD

Research Design

This study uses the exploratory sequential mixed method (QUAN–QUAL). The quantitative stage analyzes Total Economic Value (TEV), OLS regression, and Cost-Benefit Analysis (CBA) and Net Present Value (NPV) simulations. The qualitative stage is carried out through in-depth interviews and Focus Group Discussions (FGD) to explain and strengthen the results of the quantitative analysis.

Population, Sample, and Sampling Technique

The research population consists of 450 shrimp farming households in Pasangkayu Regency and a mangrove area of 52.40 ha. A quantitative sample of 212 respondents was determined using the Slovin formula with an error rate of 5%. Respondents were selected by stratified random sampling based on business scale, namely traditional (85 respondents), semi-intensive (78 respondents), and intensive (49 respondents). The qualitative informants amounted to 15 people, consisting of the heads of farmer groups, community leaders, officials of the Marine and Fisheries Service, academics, and NGO representatives. Data collection will be carried out in July-December 2025.

Operational Definition of Variables

The operational definition of a variable is used to describe the concepts, indicators, measurement methods, and data sources used in the research.

Mangrove Health (Y)

Mangrove health is a bound variable that describes the condition of the mangrove ecosystem. This variable was measured based on the area of cover and density of mangrove vegetation using Landsat 8/9 and Sentinel-2 satellite imagery verified through field observations (Boyd et al., 2022; Syed Zafar et al., 2018).

Pond Intensity (X_1)

Pond intensity is an independent variable that indicates the level of shrimp pond utilization. This variable is measured through the conversion area of mangroves into ponds (ha) and fry stocking density (heads/m^2). Data were obtained through surveys of farmers and mapping using Geographic Information Systems (GIS) (Boyd et al., 2022).

Application of Silvofishery (X_2)

The application of silvofishery is an independent variable that shows the integration of shrimp farming with mangrove conservation. This variable is measured using a dummy variable, which is a value of 1 if the pond implements a silvofishery system and 0 if it uses a monoculture system. Data were obtained through field observation and interviews (Ahmed et al., 2018).

Distance from Coastline (X_3)

Distance from the coastline is a control variable that shows the position of the pond to the coastline. This variable was measured based on Euclidean distance (km) using GIS analysis (Ahmed et al., 2018).

Total Economic Value (TEV)

Total Economic Value (TEV) is the total economic value produced by the mangrove ecosystem. This value consists of Direct Use Value (DUV), Indirect Use Value (IUV), Option Value (OV), and Existence Value (EV). TEV is calculated in rupiah per hectare per year (Rp/ha/year) using the Market Price, Replacement Cost, and Contingent Valuation Method (CVM) methods (Costanza et al., 1998; Ahmed et al., 2018).

Research Model Specifications

1. Model Total Economic Value (TEV)

The total economic value of mangrove ecosystems is calculated using the Total Economic Value (TEV) approach as follows:

$$TEV = DUV + IUV + OV + EV$$

Description:

DUV (Direct Use Value): direct use value derived from capture fisheries and pond cultivation.

IUV (Indirect Use Value): an indirect use value that includes the functions of beach protection, water filtration, and blue carbon storage.

OV (Option Value): the value of the option based on the benefits of biodiversity.

EV (Existence Value): the value of existence measured using the Contingent Valuation Method (CVM) through the Willingness to Pay (WTP) of the community (Barbier et al., 2011; Kumar, 2018; Sathirathai & Barbier, 2001).

2. Multiple Linear Regression Model

The effect of pond intensity on mangrove health was analyzed using multiple linear regression with Robust Ordinary Least Squares (OLS) as follows:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} + \beta_3 X_{3i} + \varepsilon_i$$

Description:
Y = Mangrove health
X_1 = Pond intensity
X_2 = Application of silvofishery
X_3 = Distance from the coastline
ε = Error
The Robust OLS model is used to produce more reliable estimates in the event of heteroscedasticity in cross-sectional data (Dhrymes, 2017; Cameron & Trivedi, 2021).

3. Economic Feasibility Analysis

Economic feasibility is analyzed using Cost-Benefit Analysis (CBA) with the Net Present Value (NPV) indicator.

$$NPV = \sum_{t=1}^{n} \frac{B_t - C_t}{(1+r)^t}$$

Description:
Bt = benefits obtained;
Ct = costs incurred;
r = discount rate (8%);
t = analysis period (20 years).

4. Validity and Robustness Test

To ensure that the results of the analysis are valid, several tests are carried out, namely:

1. classical assumption tests (normality, multicollinearity, and heteroscedasticity);
2. validation of the Willingness to Pay (WTP) value in the CVM method;
3. validation of spatial data using satellite imagery and field surveys; and
4. Controlling the endogeneity potential is carried out by including the distance from the coastline variable as the control variable.

RESULTS AND DISCUSSION

Research Results

1. Spatial Dynamics of Mangrove Area and NDVI Index (2020–2024)

The results of remote sensing spatial analysis utilizing Landsat 8/9 and Sentinel-2 satellite imagery in the coastal region of Pasangkayu over the past five years are presented in Table 2.

Table 1. Dynamics of Mangrove Cover Area and NDVI Index in Pasangkayu Regency (2020–2024)

Observation Year	Mangrove Area (ha)	Area Change (ha)	Percentage Change (%)	Mean NDVI Index	Vegetation Density Category
2020	52.40	-	-	0.71	Very Dense / Healthy
2021	49.10	-3.30	-6.30%	0.66	Dense
2022	47.20	-1.90	-3.87%	0.61	Moderate
2023	45.80	-1.40	-2.97%	0.57	Moderate
2024	44.60	-1.20	-2.62%	0.53	Moderate / Degraded
Cumulative Total	**44.60**	**-7.80**	**-14.88%**	**-0.18**	**Significant Degradation**

Based on Table 2, the mangrove cover area in Pasangkayu Regency has decreased gradually during the 2020–2024 period, from 52.40 ha in 2020 to 44.60 ha in 2024. Cumulatively, there was a reduction in mangrove cover by 7.80 ha or 14.88% from the initial condition. The largest decline occurred in the 2020–2021 period with a loss of mangrove cover of 3.30 ha (6.30%), while in the following years the rate of decline was relatively lower.

The change in mangrove cover area was followed by a decrease in vegetation quality as indicated by the average value of the Normalized Difference Vegetation Index (NDVI). The NDVI value decreased from 0.71 in 2020 to 0.53 in 2024, or a decrease of 0.18 points. The decline showed a change in vegetation conditions from the very dense/healthy to moderate/degraded category during the observation period. Details of mangrove area change and NDVI value are presented in Table 2, while the spatial distribution of mangrove cover change is shown in Figure 1, and the trend of area change and NDVI are presented in Figure 1.

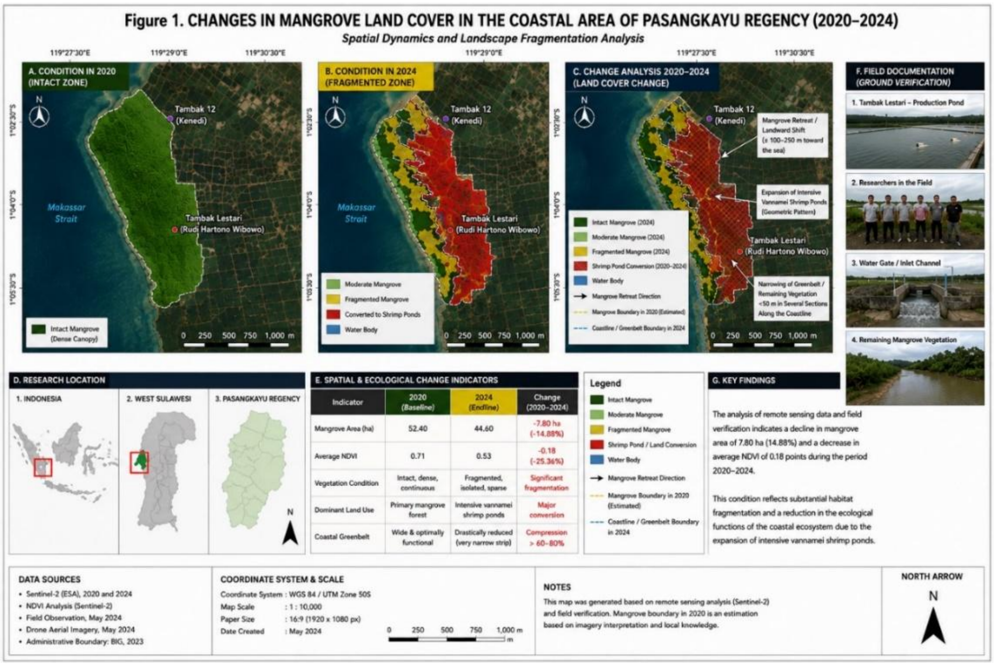

Figure 1. Map of Mangrove Cover Change Locations in Pasangkayu Regency (2020–2024)

Figure 1 shows the spatial changes in mangrove cover in Pasangkayu Regency during the 2020–2024 period. The map shows the shrinkage of mangrove areas, which is characterized by the reduction of dark green zones and the increase in yellow and red areas, which indicate land conversion. The most noticeable changes occurred in coastal areas, where the previously fused mangrove cover turned into fragmented patches of vegetation.

The results of field observations showed that most of the converted areas were used as intensive vannamei shrimp (Litopenaeus vannamei) ponds. The area is characterized by using geomembranes (HDPE), embankments, water inlets and outlets, as well as waterwheels as aquaculture infrastructure. The change in land use causes the remaining mangrove vegetation to be only on a narrow path along the coastline. The visualization of spatial change is presented in Figure 1, while the summary of land use change is shown in Table 2.

Table 2. Spatial Changes

Spatial & Ecological Indicators	2020 Condition (Intact Zone)	2024 Condition (Fragmented Zone)
Map Visualization	Dark Green	Yellow / Red
Vegetation Condition	Dense, continuous, and intact	Fragmented (patches), thin, isolated
Dominant Land Use	Primary mangrove forest	Intensive monoculture *vannamei* shrimp ponds

Greenbelt	Wide and fully functional	Compressed into a narrow coastal strip

As summarized in Table 2, spatial and ecological indicators demonstrate a significant landscape transformation in Pasangkayu Regency between 2020 and 2024. Dense and continuous primary mangrove forests—which originally formed a wide and fully functional coastal greenbelt (dark green zone) have been heavily converted into intensive monoculture vannamei shrimp ponds (yellow/red zones). Consequently, the remaining vegetation structure shifted from an intact ecological matrix into thin, isolated vegetation patches compressed along the shoreline, reflecting severe landscape fragmentation and an overall decline in ecosystem function. The decline in the NDVI index and mangrove cover area is presented in the following figure 2

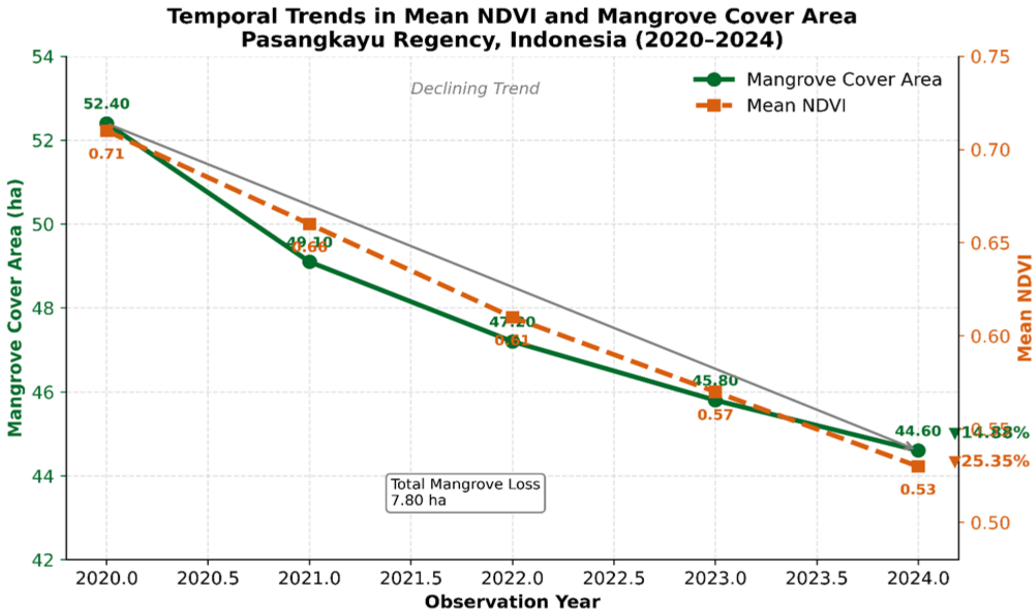

Figure 2. Decline in NDVI Index and Mangrove Cover Area in Pasangkayu Regency, 2020–2024

Over the five years, mangrove cover contracted by 7,80 ha (14,88%), accompanied by a reduction in mean NDVI of 0,18 points (from 0,71 to 0,53). The most severe physical deforestation occurred during the 2020–2021 period (-6,30%). Although the rate of land clearing slowed down by 2024 (-2,62%), the decline in NDVI values persisted. This simultaneous reduction in both vegetation quantity and quality confirms the occurrence of dual degradation and hidden degradation, wherein the accumulated initial shock of land conversion undermines the resilience and canopy density of the remaining vegetation.

Economic Valuation of Mangrove Ecosystem (Total Economic Value -TEV)

The assessment of the total economic benefits of the mangrove ecosystem was calculated using the Total Economic Value (TEV) decomposition approach. Based on the economic valuation decomposition results at the research site, the economic value per hectare per year is presented in Table 3.

Table 3. Summary of Total Economic Value (TEV) Valuation of the Pasangkayu Mangrove Ecosystem

TEV Valuation Component	Economic Value (IDR/ha/year)	Proportion / Contribution (%)	Valuation Method Applied	Ecosystem Service Description
Direct Use Value (DUV)	IDR 68,200,000	22.23%	Market Price Approach	Capture fisheries, crabs, and shrimp

Indirect Use Value (IUV)	IDR 218,450,000	71.20%	Replacement Cost & Carbon Pricing	Coastal erosion protection, waste biofiltration, carbon sequestration
Option Value (OV)	IDR 5,100,000	1.66%	Benefit Transfer Method	Biodiversity potential & future medicinal resources
Existence Value (EV)	IDR 15,050,000	4.91%	Contingent Valuation Method (CVM)	Willingness to Pay (WTP) for existence conservation
Total Economic Value (TEV)	**IDR 306,800,000**	**100.00%**	**Integrated Decomposition**	**Total Ecosystem Economic Value per Hectare/Year**

Table 3 shows that Indirect Use Value (IUV) is the largest component in Total Economic Value (TEV), which is 71.20% or Rp218,450,000/ha/year, while Direct Use Value (DUV) is only 22.23% or Rp68,200,000/ha/year. These findings show that the ecological benefits of mangroves, such as coastal protection, sewage filtering, and carbon storage, have much greater economic value than the benefits of direct utilization. These results are in line with Barbier et al. (2011), who affirm that ecosystem services are the main component of the economic value of coastal ecosystems.

Econometric Estimation: Robust OLS Regression Statistical Output

The effect of pond intensity on mangrove health (NDVI) was analyzed using Ordinary Least Squares (OLS) regression with Huber-White Robust Standard Errors. The estimation results showed that the model had a good ability to explain the variation in data ($R^2 = 0.842$; Adjusted $R^2 = 0.838$; $F = 206.45$; $p < 0.001$). The full results of the estimates are presented in Table 4

Table 4. Robust OLS Regression Statistical Output (Dependent Variable: NDVI Index (Y))

Independent Variable	Coefficient (β)	Robust Std. Error	t-Statistic	p-Value	95% Confidence Interval
Constant (β_0)	0.742	0.025	29.68	< 0.001***	[0.692, 0.791]
Aquaculture Intensity (X_1)	-0.710	0.042	-16.90	< 0.001***	[-0.793, -0.627]
Silvofishery (X_2)	0.185	0.031	5.97	< 0.001***	[0.124, 0.246]
Distance from Shoreline (X_3)	0.048	0.018	2.67	0.008**	[0.013, 0.083]

Note on Significance: *** Significant at $\alpha = 1\%$; ** Significant at $\alpha = 5\%$.

The results of the Robust OLS regression estimate showed that mangrove health (NDVI) was significantly influenced by pond intensity, silvofishery application, and distance from shoreline ($p < 0.01$). Pond intensity (X_1) had a negative effect ($\beta = -0.710$; $p < 0.001$), which suggests that increasing pond land conversion reduces mangrove quality (Bunting et al., 2022). On the other hand, the application of silvofishery (X_2) had a positive effect ($\beta = 0.185$; $p < 0.001$), so that it was able to support the sustainability of mangroves (Ahmed et al., 2018). Distance from the coastline (X_3) also had a positive effect ($\beta = 0.048$; $p = 0.008$), which suggests that mangroves farther away from the coastline have better vegetation conditions (Barbier et al., 2011).

Economic-Ecological Feasibility Evaluation of Counterfactual Scenarios (CBA & NPV)

The long-term financial-ecological evaluation was calculated using the Cost-Benefit Analysis (CBA) and Net Present Value (NPV) approaches over a time horizon of $T = 20$ years with a social discount rate of $r = 8\%$. To establish the ecological threshold, a simulation of three long-term coastal management counterfactual scenarios (20-year horizon, discount rate $r = 8\%$) was conducted, as presented in Table 5.

Table 5. Results of CBA and NPV Economic-Ecological Evaluation of Counterfactual Scenarios (20-Year Horizon, r = 8%)

Financial & Ecological Evaluation Parameter	Scenario 1: Intensive Monoculture (Full Conversion)	Scenario 2: Total Mangrove Conservation	Scenario 3: Silvofishery Integration (60:40 Ratio)
Initial Investment & Reforestation (IDR/ha)	IDR 150,000,000	IDR 15,000,000	IDR 45,000,000
Financial Net Present Value (NPV)	IDR 42,500,000	IDR 18,200,000	IDR 89,700,000 (Highest)
Benefit-Cost Ratio (BCR)	1.12	1.45	2.38 (Highly Feasible)
Internal Rate of Return (IRR)	10.2%	12.8%	24.6%
Vulnerability Impact & TEV	TEV Collapse (-IDR 128.4M/ha)	Maximum Ecological Sustainability	Optimal Balance (+IDR 184.2M/ha)
Ecological Threshold Status	Exceeds Threshold (<20% Mangrove)	No Ecological Stress	Safe Zone (60% Mangrove)

Based on Table 5, the evaluation of three management scenarios shows that Scenario 3 (Silvofishery 60:40) provides the best performance with an NPV of IDR 89.7 million/ha, BCR of 2.38, and IRR of 24.6%. This scenario also results in a surplus of Total Economic Value (TEV) of Rp184.2 million/ha and is in the ecologically safe zone. In contrast, Scenario 1 (Intensive Monoculture) requires the highest investment (Rp150 million/ha), but only produces a BCR of 1.12 and a decrease in TEV of Rp128.4 million/ha due to mangrove cover being below the ecological threshold (<20%). Meanwhile, Scenario 2 (Full Conservation) provides the best ecological protection, but produces lower economic benefits with an NPV of Rp18.2 million/ha.

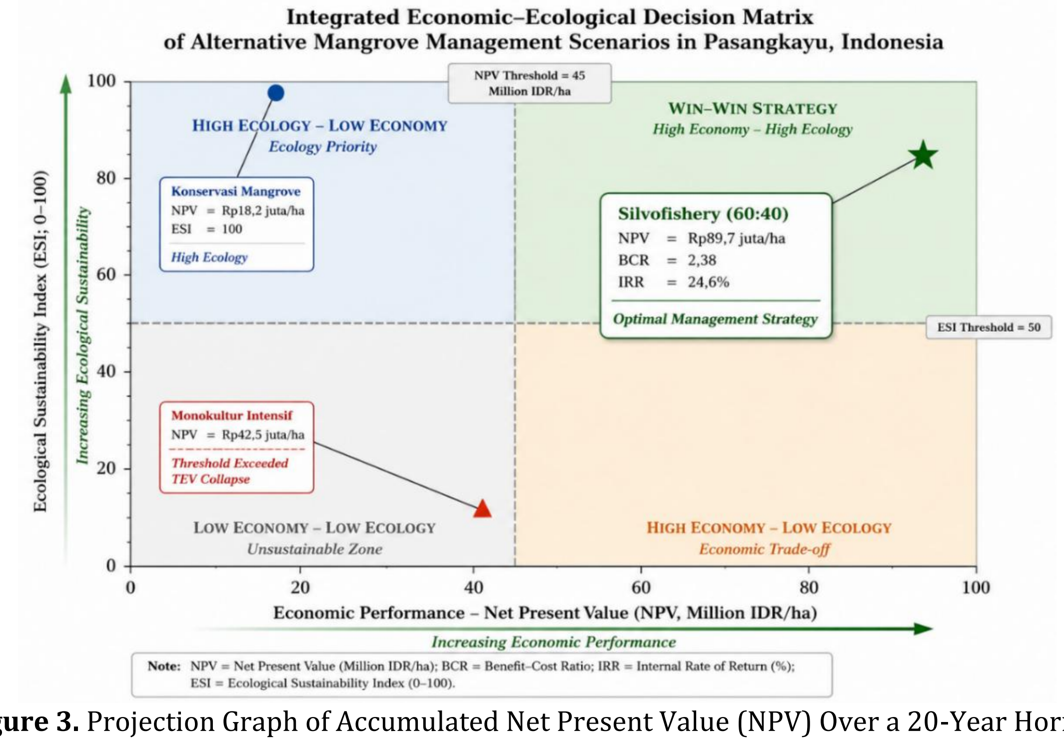

Figure 3. Projection Graph of Accumulated Net Present Value (NPV) Over a 20-Year Horizon

Counterfactual analysis shows that Scenario 3 (silvofishery ratio 60:40) is the most optimal option. This scenario provides the best financial performance (NPV of IDR 89.7 million/ha, BCR of 2.38, and IRR of 24.6%) and results in a surplus of Total Economic Value (TEV) of IDR 184.2 million/ha without exceeding the ecological limit. In contrast, Scenario 1 (intensive monoculture) requires the highest investment costs, but only provides low financial benefits and causes a decrease in TEV of Rp128.4 million/ha due to excessive mangrove conversion. These results show that silvofishery systems are more sustainable than intensive monocultures (Sathirathai & Barbier, 2001; Ahmed et al., 2018).

Discussion

The scenario modeling results in this study reveal contrasting economic trajectories between Scenario 1 (Intensive Monoculture) and Scenario 3 (60:40 Silvofishery). The economic collapse in the monoculture scenario and the sustained high profitability in the silvofishery scenario do not occur randomly; rather, they are driven by ecological-economic transmission mechanisms operating through explicit cause-and-effect causality chains.

1) Causality of TEV Collapse in the Intensive Monoculture Scenario

The high financial Net Present Value (NPV) observed in Scenario 1 during the first two years represents a form of phantom profit. This phenomenon emerges because farmers convert all mangrove vegetation (100%) into culture ponds to maximize short-term production capacity without bearing environmental maintenance costs. This condition aligns with Total Economic Value (TEV) theory, which emphasizes that short-term capital accumulation frequently ignores natural capital depreciation (Costanza et al., 2014).

The inter-variable mechanism in this scenario begins with total land clearing (clear-cutting), which eliminates biofiltration and physical coastal protection functions. Without mangrove vegetation, unconsumed feed, shrimp feces, and cumulative chemicals do not undergo natural assimilation. This finding confirms the study by Primavera (2006), which established that restricting or removing mangrove vegetation in intensive shrimp culture triggers organic waste concentration, raw water quality deterioration (eutrophication), and ideal conditions for disease outbreaks such as White Spot Syndrome Virus (WSSV) and Acute Hepatopancreatic Necrosis Disease (AHPND).

Concurrently, the loss of the coastal greenbelt accelerates erosion that compromises the structural integrity of pond dikes. Deteriorating raw water quality and physical infrastructure damage force operators to incur ballooning operation and maintenance (O&M) expenses for therapeutics, external water treatment, and dike reconstruction. When these remediation costs exceed revenues due to recurring crop failures from Year 3 onward, net cash flow turns negative. Accumulated financial losses, compounded by the loss of ecosystem services (carbon sequestration, erosion control, and nursery grounds), ultimately precipitate a TEV collapse down to -IDR 128.4 million/ha over the long-term horizon. (Das & Vincent 2009; Barbier et al. 2011).

2) Causality of the Efficiency Frontier and Safe Operating Space in the Silvofishery Scenario (60:40)

Scenario 3 exhibits exponential financial NPV growth, reaching a peak value of IDR 89.7 million/ha (BCR = 2,38; IRR = 24,6%). This phenomenon occurs because retaining a 60% mangrove cover proportion functions as a safe operating space, a carrying capacity threshold concept popularized by Rockström et al. (2009). At a 60:40 ratio, a dynamic equilibrium is established between economic utilization and ecosystem assimilation capacity. Rockström et al. (2009). At a 60:40 ratio, a dynamic equilibrium is established between economic utilization and ecosystem assimilation capacity, with 60% mangrove vegetation to act as a natural biofilter that processes organic waste loads from the 40% pond area. As demonstrated by Alongi (2008) and Primavera (2006), mangrove root systems (*Rhizophora* spp.) possess high remediation capacity for nitrates and phosphorus through vegetative uptake and sediment accumulation. Consistently high raw water quality suppresses stress levels in shrimp, eliminates mass crop failure risks, and significantly lowers production costs (Engle, 2010 Furthermore, decomposed mangrove leaf litter supplies detritus as a natural supplementary feed source that naturally enhances shrimp growth rates (Binh et al., 1997). This synergy creates a cost-efficiency pattern that enables farmers to sustain high productivity over time. The combination of stable culture income, operational cost efficiency, and potential ecosystem service compensation (blue carbon) establishes this scenario as the best efficiency frontier in coastal management.

3) Empirical Implications and Study Novelty

These empirical findings provide key contributions that update and refine several foundational assumptions in coastal environmental economics literature:

a) Departure from the Linearity Paradigm: Previous studies, such as Ahmed et al., (2018) and Boyd, Davis, et al., (2022) generally employed linear modeling approaches assuming that each unit of mangrove clearing yields a constant economic decline. The empirical evidence from this study breaks this assumption and supports the non-linear ecosystem service function theory formulated by Barbier et al., (2011) and Koch et al., (2009). The relationship between mangrove degradation and economic value exhibits a clear ecological threshold. When mangrove clearing crosses a critical tipping point (specifically dropping below 60% cover), economic value does not decline gradually; rather, it suffers a steep plunge that culminates in complete aquaculture economic collapse.

b) Internalization of Environmental Damage into Financial Risk: This study empirically demonstrates that coastal ecosystem damage is not merely a passive externality borne by the public or future generations (Barbier et al. 2011), but operates as a direct internal financial feedback loop for operators. Farmers who neglect the ecological functions of mangroves ultimately bear those losses through production failures and medium-to-long-term business bankruptcy.

c) Identification of the Economic Value Crossover Point: It is empirically proven that although monoculture systems generate higher revenues during initial years, the silvofishery scenario overtakes monoculture's accumulated earnings between Years 7 and 8. Identifying this crossover point provides a solid academic foundation confirming green investment theory: environmentally sustainable investments require an initial incubation period but deliver far more stable, secure, and low-risk returns over the long term (Eyraud, et al., 2011).

4) Evidence-Based Policy Implications

Based on the causal mechanisms, theoretical foundations, and empirical implications above, three strategic policy recommendations are formulated for coastal governance in Pasangkayu Regency toward a Blue Economy:

a) Mandating a 60% Threshold in Coastal Zoning Plans (RZWP3K): The Regional Government of Pasangkayu Regency should revise its Coastal Zone and Small Islands Spatial Plan (RZWP3K) by establishing a legally binding 60% mangrove cover threshold. This ratio must serve as a mandatory prerequisite for issuing Marine Spatial Utilization Suitability (KKPRL) permits for all coastal aquaculture activities, aligned with ecosystem tolerance limit principles (Rockström et al., 2009).

b) Restructuring Program for Degraded Monoculture Ponds: Given the substantial number of monoculture ponds experiencing declining productivity in Pasangkayu, local government should facilitate a structured transition from monoculture to a 60:40 silvofishery system. Under this scheme, 60% of the land area must be reforested with mangrove vegetation to function as ecological corridors and natural biofilters, while 40% is optimized for measured-intensity aquaculture.

Implementation of Payment for Ecosystem Services (PES) Schemes: To overcome initial capital constraints during pond restructuring, PES-based economic incentive schemes should be developed (Bast & Shamshak, 2017). Under this framework, large-scale intensive aquaculture industries or carbon market stakeholders provide financial compensation to local communities and smallholders who consistently maintain 60% mangrove cover within their coastal zones.

CONCLUSIONS

The conclusion section contains the research findings and the essence of the results of the discussion. Write concisely the substantial findings of the research conducted. Conclusions must be supported by data and not speculative. Conclusions are consistent with the objectives/problems studied. Provide recommendations for follow-up research results and further research needed. Suggestions that are common sense do not need to be written. If suggestions are needed, write them down specifically. Conclusions are presented in paragraph form. The length of the conclusion is between 5-10% of the total length of the manuscript.

Based on the analytical results and research objectives, the study concludes that:

1. The coastal land cover dynamics of Pasangkayu Regency during the 2020–2024 period reveal the conversion of 830 ha of primary mangrove vegetation into intensive monoculture aquaculture ponds, resulting in spatial fragmentation and the narrowing of the coastal greenbelt.
2. The Total Economic Value (TEV) assessment demonstrates that the mangrove ecosystem contributes a dominant economic value through indirect service functions (carbon sequestration and coastal erosion protection), which significantly exceed short-term financial direct use values.
3. NPV projection modeling over a 20-year horizon confirms that Scenario 3 (60:40 Silvofishery) represents the optimal management scenario (efficiency frontier), generating the highest NPV of IDR 89.7 million/ha, BCR = 2,38; IRR = 24,6%). This scenario is proven to overtake the accumulated economic value of monoculture by Year 7.6 while maintaining the sustainability of coastal environmental carrying capacity

IMPLICATIONS AND LIMITATIONS OF THE STUDY

The primary limitation of this study lies in the use of spatial data spanning a five-year timeframe (2020–2024), which does not fully capture long-term climate change dynamics. Future research is encouraged to expand dynamic spatial econometric modeling, integrate laboratory-based blue carbon valuation, and simulate the impacts of sea-level rise on coastal ecological thresholds.

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