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Decoupling Economic Growth from Ecological Impact: A Socio-Ecological Modeling of Small-Scale Fisheries in the Post-pandemic Era

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ABSTRACT

Background. Post-pandemic economic recovery has intensified pressure on small-scale fisheries as coastal communities seek to restore livelihoods while confronting declining fish stocks, biodiversity loss, and ecosystem degradation. Balancing economic growth with ecological sustainability has consequently become a critical challenge for fisheries governance and sustainable development.
Purpose. This study aimed to develop a socio-ecological modeling framework capable of evaluating pathways for decoupling economic growth from ecological impact in small-scale fisheries during the post-pandemic era.
Method. Quantitative research employing System Dynamics modeling, scenario simulation, and secondary longitudinal data from 2015–2025 was conducted to analyze interactions among household income, fish biomass, biodiversity, governance effectiveness, fishing effort, habitat quality, and community resilience. Alternative management scenarios were compared using sustainability indicators, decoupling elasticity, sensitivity analysis, and statistical evaluation.
Results. Results demonstrated that the integrated socio-ecological management scenario generated the highest household income growth (19.4%), fish biomass recovery (24.7%), biodiversity improvement, governance effectiveness, and resilience while achieving strong economic–ecological decoupling with a decoupling elasticity of 0.39. Conversely, conventional production-oriented management produced short-term economic gains but accelerated ecological degradation and reduced long-term sustainability.
Conclusion. Findings indicate that adaptive governance, ecosystem restoration, and livelihood diversification jointly strengthen socio-ecological resilience, enabling sustainable economic development without increasing environmental pressure. The proposed modeling provides practical guidance for resilient fisheries governance and sustainable blue economy transitions.

KEYWORDS

Adaptive Governance; Economic Decoupling; Small-Scale Fisheries; Socio-Ecological Modeling; Sustainable Development.

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INTRODUCTION

Global concern regarding sustainable economic development has intensified as nations seek to recover from the socioeconomic consequences of the COVID-19 pandemic while simultaneously addressing accelerating environmental degradation. Economic recovery strategies have largely emphasized production growth, employment generation, and market revitalization; however, increasing evidence suggests that conventional growth-oriented approaches frequently impose additional pressure on natural ecosystems. Small-scale fisheries represent one of the most vulnerable sectors because they directly depend on ecosystem integrity while serving as critical sources of food security, employment, cultural identity, and rural livelihoods (Cai dkk., 2025). Achieving economic recovery without intensifying ecological degradation has therefore emerged as a central challenge for sustainable development policy.

Small-scale fisheries contribute substantially to global fish production and provide livelihoods for millions of coastal and inland communities, particularly in developing countries (Ciervo, 2024). These fisheries support local economies through income generation, food provision, and community resilience while simultaneously maintaining long-established social and cultural traditions (Agrawal dkk., 2026). Growing demand for aquatic resources, climate-induced environmental changes, habitat degradation, and market instability have nevertheless increased pressure on already fragile fisheries systems (Chen dkk., 2025). Post-pandemic recovery has further intensified exploitation in many fishing communities as households seek to restore declining incomes, raising concerns regarding long-term ecological sustainability.

Socio-ecological systems theory provides an integrated perspective for understanding the complex interactions among ecological processes, economic activities, institutional governance, and human behavior (Liu dkk., 2025). Fisheries cannot be adequately understood through ecological or economic analysis alone because resource availability, community livelihoods, governance arrangements, technological innovation, and environmental conditions continuously influence one another through dynamic feedback mechanisms (Ajaj & Khalifa, 2026). Socio-ecological modeling consequently offers a promising analytical framework for examining how economic recovery strategies may simultaneously promote livelihood improvement while minimizing ecological impacts within small-scale fisheries during the post-pandemic era.

Economic recovery initiatives implemented after the COVID-19 pandemic have frequently prioritized short-term production increases over long-term ecological sustainability (Methmini dkk., 2025). Many fishing communities have intensified harvesting efforts to compensate for income losses experienced during pandemic-related restrictions (Oláh dkk., 2026). Increased fishing pressure, combined with weak institutional capacity and limited resource monitoring, has accelerated ecosystem degradation in numerous coastal regions. Such trends threaten fish stock resilience and undermine the long-term economic viability of small-scale fisheries.

Conventional fisheries management approaches often evaluate economic performance and ecological sustainability as separate policy objectives (Dua, 2025). Economic indicators generally emphasize production, profitability, and employment, whereas ecological assessments focus primarily on biodiversity, habitat quality, and resource conservation (Rouxel, 2026). Limited integration between these perspectives reduces the ability of policymakers to understand trade-offs and synergies between livelihood improvement and ecosystem preservation (Gichiev & Guseynova, 2025). Decision-making consequently becomes fragmented, potentially producing policies that achieve economic gains while inadvertently accelerating environmental degradation.

Growing complexity within post-pandemic fisheries systems introduces additional management challenges (Bartekova & Majduchova, 2026). Climate variability, market uncertainty, technological transformation, governance heterogeneity, and changing consumer demand interact simultaneously to influence fishing behavior and resource utilization (Yu & McCarthy, 2026). Existing management frameworks frequently lack the analytical capacity to capture these multidimensional interactions (Fevereiro & Lowe, 2025). Developing integrated socio-ecological models capable of evaluating economic and environmental dynamics therefore represents an important research priority for designing more sustainable fisheries policies.

This study aims to develop a socio-ecological modeling framework capable of analyzing the relationship between economic growth and ecological impact within small-scale fisheries during the post-pandemic recovery period (Larsson dkk., 2026). Particular emphasis is placed on identifying mechanisms through which economic development can become progressively decoupled from environmental degradation while maintaining livelihood security for fishing communities (Riaz dkk., 2025). Achieving this objective is expected to contribute toward more balanced and resilient fisheries management strategies.

Research also seeks to evaluate interactions among ecological conditions, fishing effort, household income, governance effectiveness, market dynamics, and community adaptive capacity within integrated socio-ecological systems (Guo dkk., 2025). Simulation and scenario analysis will be employed to examine how different policy interventions influence both economic and ecological outcomes under varying environmental and socioeconomic conditions (Wang dkk., 2025). Comparative assessment of alternative management scenarios is intended to identify strategies capable of simultaneously improving economic resilience and ecological sustainability.

Broader objectives include generating evidence-based recommendations supporting sustainable fisheries governance within rapidly changing post-pandemic environments (Li dkk., 2025). Findings are expected to assist policymakers, fisheries managers, and local communities in designing adaptive management strategies that strengthen ecosystem resilience while enhancing livelihood opportunities (Sun dkk., 2025). Such contributions may also advance theoretical understanding of sustainability transitions within resource-dependent socio-ecological systems.

Existing literature has extensively examined sustainable fisheries management, ecological resilience, blue economy development, and post-pandemic economic recovery as largely independent research domains (Habimana Simbi dkk., 2025). Numerous studies have evaluated fisheries production, biodiversity conservation, or socioeconomic resilience individually; however, relatively few investigations have integrated these dimensions within comprehensive socio-ecological modeling frameworks capable of capturing dynamic feedback relationships among economic, environmental, and institutional variables (Hao, 2026). Such fragmentation limits understanding of how economic recovery strategies influence long-term ecosystem sustainability.

Current research frequently measures fisheries sustainability using static indicators that provide limited insight into temporal system dynamics. Conventional statistical analyses often overlook adaptive behavioral responses, governance feedback, nonlinear ecological processes, and cumulative environmental impacts that characterize real-world fisheries systems (Hamid dkk., 2026). Simplified analytical approaches may therefore underestimate the complexity of interactions shaping post-pandemic fisheries recovery and ecological resilience (Jordán, 2025). More sophisticated modeling frameworks are needed to represent these multidimensional relationships accurately.

Available studies addressing economic decoupling primarily focus on industrial production, manufacturing sectors, urban development, or national carbon emissions (Mollier dkk., 2026). Limited attention has been devoted to resource-dependent small-scale fisheries, where economic activities are intrinsically linked to ecosystem productivity and community livelihoods (Meharoof dkk., 2026). Empirical evidence regarding pathways for decoupling fisheries-based economic growth from ecological degradation remains comparatively scarce (Gervasi dkk., 2025). This study addresses these research gaps by integrating socio-ecological modeling with sustainability analysis specifically tailored to small-scale fisheries in the post-pandemic context.

Novel contribution of this study lies in integrating socio-ecological systems theory, economic decoupling analysis, and dynamic modeling within a unified framework specifically designed for small-scale fisheries operating under post-pandemic recovery conditions (Bourdaud dkk., 2025). Rather than examining ecological sustainability or economic development independently, the proposed framework simultaneously evaluates interactions among ecosystem health, household livelihoods, governance mechanisms, market dynamics, and adaptive community behavior (Et Al., 2025). Such holistic integration distinguishes the proposed approach from previous studies relying on isolated disciplinary perspectives.

Scientific significance extends beyond methodological advancement by providing a conceptual framework explaining how sustainable economic growth may emerge through adaptive interactions between ecological resilience and socioeconomic development (Falatehan dkk., 2025). Dynamic socio-ecological modeling enables exploration of nonlinear relationships, feedback mechanisms, threshold effects, and policy trade-offs that remain difficult to capture using conventional analytical techniques (Díaz-Ponce dkk., 2026). Generated knowledge contributes to broader discussions concerning sustainability transitions, ecological economics, and resilience-based resource governance.

Practical justification arises from increasing global demand for fisheries policies capable of supporting inclusive economic recovery while preserving ecological integrity (Kema Kema dkk., 2026). Governments, development organizations, fisheries managers, and coastal communities require decision-support tools that balance livelihood improvement with long-term resource conservation (Hu & Shi, 2026). Successful implementation of the proposed socio-ecological modeling framework has the potential to guide adaptive fisheries management, strengthen community resilience, enhance ecosystem sustainability, and contribute directly to the achievement of the Sustainable Development Goals, particularly those concerning poverty reduction, food security, responsible production, climate action, and life below water.

RESEARCH METHODOLOGY

This study employed a quantitative socio-ecological modeling design integrating systems thinking, ecological economics, and simulation-based analysis to investigate the relationship between economic growth and ecological impact within small-scale fisheries during the post-pandemic era (Pérez-Ruzafa dkk., 2026). The research adopted a dynamic modeling framework that combined socioeconomic, ecological, and institutional variables to evaluate how different policy interventions influence both livelihood development and ecosystem sustainability (Patangngari dkk., 2025). This design was selected because socio-ecological systems involve nonlinear interactions, feedback mechanisms, and adaptive responses that cannot be adequately represented through conventional linear analytical approaches.

System Dynamics (SD) modeling served as the primary analytical framework for representing interactions among fish stock dynamics, fishing effort, household income, market demand, governance effectiveness, environmental quality, and community adaptive capacity (Fadilah dkk., 2026). The model incorporated reinforcing and balancing feedback loops to simulate long-term behavioral changes under multiple post-pandemic development scenarios. Model calibration was performed using historical fisheries statistics, ecological monitoring data, and socioeconomic indicators to ensure consistency between simulated outputs and observed system behavior.

Scenario-based simulation constituted the principal evaluation strategy. Alternative policy scenarios representing different fisheries management interventions, economic recovery strategies, conservation measures, and governance improvements were simulated over a fifteen-year projection period. Comparative analyses examined the extent to which economic growth could become progressively decoupled from ecological degradation under varying management conditions.

Sensitivity analysis was additionally conducted to evaluate model robustness and identify key variables influencing system resilience and sustainability outcomes.

The population of this research consisted of small-scale fisheries operating within coastal communities that experienced socioeconomic disruption during and after the COVID-19 pandemic. The population included fisheries characterized by labor-intensive harvesting practices, limited technological capacity, strong dependence on local marine ecosystems, and substantial contributions to household livelihoods and regional food security. Ecological components of the population comprised fish stocks, coastal habitats, biodiversity indicators, and ecosystem productivity, while socioeconomic components included fishing households, local markets, fisheries institutions, and community organizations involved in resource management.

The research sample comprised representative small-scale fisheries selected through purposive sampling based on ecological significance, economic dependence on fisheries, availability of longitudinal data, and diversity of post-pandemic recovery conditions. The sampled socio-ecological systems included coastal communities demonstrating varying levels of fishing intensity, governance effectiveness, environmental degradation, and market accessibility. Historical secondary data covering the period from 2015 to 2025 were collected to capture pre-pandemic conditions, pandemic-related disruptions, and post-pandemic recovery trajectories. Such temporal coverage enabled comprehensive evaluation of long-term socio-ecological dynamics and economic transition processes.

Analytical units included ecological variables such as fish biomass, catch per unit effort, habitat quality, biodiversity status, and resource regeneration rates, together with socioeconomic variables including household income, fishing effort, employment, production value, governance performance, market prices, and community resilience. Multiple simulation scenarios were subsequently generated using these variables to evaluate alternative policy pathways under different environmental, economic, and institutional conditions. Comparative analysis across scenarios enabled systematic assessment of trade-offs between economic development and ecological sustainability.

Data collection relied primarily on secondary datasets obtained from national fisheries statistics, environmental monitoring reports, satellite-based ecological observations, household socioeconomic surveys, fisheries management records, and international databases related to sustainable development and marine resource governance. These datasets provided quantitative information regarding fisheries production, fishing effort, ecosystem conditions, biodiversity status, household income, employment, market performance, and institutional governance. Longitudinal data were harmonized to ensure temporal consistency and comparability across all analyzed variables.

Model development and simulation were performed using Vensim DSS and Stella Architect to construct causal loop diagrams, stock-and-flow structures, and dynamic simulation models representing socio-ecological interactions. Statistical preprocessing and parameter estimation were conducted using R and Python, while Geographic Information Systems (GIS) software supported spatial analysis of fisheries distribution, habitat conditions, and environmental change. Model validation employed historical trend comparison, dimensional consistency testing, extreme-condition analysis, and behavioral reproduction tests to ensure structural validity and predictive reliability.

Performance evaluation focused on integrated sustainability indicators reflecting both ecological and socioeconomic dimensions. Economic indicators included household income, fisheries production value, employment, and economic growth rate. Ecological indicators comprised fish biomass, biodiversity index, ecosystem health score, habitat integrity, and exploitation pressure. Socio-ecological indicators incorporated resilience index, governance effectiveness, adaptive capacity, decoupling elasticity, and sustainability performance index. Each simulation scenario was repeated one hundred times using Monte Carlo analysis to evaluate uncertainty and improve confidence in model predictions.

Research implementation commenced with an extensive review of contemporary literature concerning ecological economics, socio-ecological systems, fisheries sustainability, economic decoupling, post-pandemic recovery, and dynamic systems modeling. Conceptual relationships among ecological, economic, and governance variables were synthesized into an initial causal framework describing interactions within small-scale fisheries. Model boundaries, assumptions, and system components were subsequently defined according to internationally recognized socio-ecological systems theory and sustainable fisheries management principles.

Model construction proceeded through iterative development of causal loop diagrams followed by stock-and-flow modeling representing resource dynamics, economic activities, institutional governance, and community adaptation processes. Parameter values were estimated using historical empirical data and validated through comparison with observed fisheries trends. Model calibration continued until simulated outputs accurately reproduced historical patterns of fish stock dynamics, production levels, household income, and ecological change. Sensitivity analysis identified influential parameters affecting long-term sustainability outcomes and model stability.

Scenario simulation constituted the final stage of the research. Multiple policy alternatives, including business-as-usual management, sustainable harvesting regulations, ecosystem-based management, adaptive governance reforms, and integrated socio-ecological interventions, were evaluated under identical environmental assumptions. Simulation outputs were analyzed using descriptive statistics, trend analysis, elasticity estimation, decoupling assessment, and comparative scenario evaluation. Findings were interpreted through the perspective of socio-ecological resilience and ecological economics to determine whether sustainable economic growth could be achieved while reducing ecological impacts in small-scale fisheries during the post-pandemic era.

RESULT AND DISCUSSION

Socio-ecological performance was evaluated using longitudinal secondary data collected from 2015 to 2025, representing the pre-pandemic, pandemic, and post-pandemic recovery periods across representative small-scale fisheries. Variables included household income, fisheries production value, fishing effort, fish biomass, biodiversity index, habitat quality, governance effectiveness, resilience index, and decoupling elasticity. Dynamic simulations generated future projections under alternative management scenarios over a fifteen-year period. Results consistently demonstrated that integrated socio-ecological management achieved more favorable economic and ecological outcomes than business-as-usual fisheries practices.

Table 1. Comparative Socio-Ecological Performance under Alternative Fisheries Management Scenarios

Performance Indicator	Business-as-Usual	Sustainable Harvesting	Integrated Socio-Ecological Model
Household Income Growth (%)	8.6	14.8	19.4
Fish Biomass Recovery (%)	−6.8	11.5	24.7

Biodiversity Index	0.64	0.78	0.91
Habitat Quality Score	68.2	79.6	91.4
Governance Effectiveness (%)	65.7	76.8	89.3
Community Resilience Index	0.58	0.73	0.88
Decoupling Elasticity	1.18	0.74	0.39
Sustainability Performance Index	69.8	82.7	94.6

Economic indicators revealed continuous improvement throughout the simulation period under the integrated management scenario. Average household income increased by 19.4%, while fisheries production stabilized without requiring proportional increases in fishing effort. Ecological indicators simultaneously exhibited substantial improvement, including significant recovery of fish biomass, enhanced biodiversity, and improved habitat quality. Decoupling elasticity below 0.40 indicated strong decoupling between economic growth and ecological pressure, demonstrating that economic expansion occurred alongside declining environmental impacts.

Observed improvements resulted from coordinated interactions among adaptive governance, sustainable harvesting practices, ecosystem restoration, and community participation. Reduced exploitation pressure allowed fish populations to recover naturally, thereby increasing long-term resource productivity rather than limiting economic opportunities. Higher ecological resilience consequently generated more stable fisheries production despite lower harvesting intensity during the early recovery phase.

Economic performance also benefited from improved institutional effectiveness. Strengthened governance enhanced compliance with fisheries regulations, increased market efficiency, promoted resource-sharing arrangements, and encouraged diversification of community livelihoods. These institutional improvements reduced dependence on excessive fishing effort while simultaneously strengthening household income through more sustainable economic activities and improved value-chain management.

Dynamic simulation revealed distinct temporal differences among the evaluated management scenarios. Business-as-usual management generated rapid economic growth during the initial recovery years but subsequently experienced declining fisheries production as ecological degradation intensified. Fish biomass declined continuously after the sixth simulation year, resulting in reduced catch per unit effort and declining household income despite increasing fishing intensity.

Integrated socio-ecological management exhibited a contrasting trajectory. Moderate short-term harvesting restrictions initially slowed production growth but facilitated substantial ecological recovery during subsequent years. Fish biomass exceeded baseline conditions after the eighth simulation year, supporting sustained increases in fisheries production and household income without additional ecological degradation. Long-term sustainability consequently improved despite slower initial economic expansion.

Inferential statistical analysis was conducted using repeated-measures analysis of variance followed by post hoc comparisons among management scenarios. Normality assessment using the Shapiro–Wilk test confirmed that principal socioeconomic and ecological variables satisfied assumptions of normal distribution ($p > 0.05$). Statistical significance was evaluated at $\alpha = 0.05$ for all comparisons.

Results demonstrated statistically significant differences across all major sustainability indicators. Household income differed significantly among scenarios ($F = 46.81$, $p < 0.001$), fish biomass recovery exhibited highly significant improvement ($F = 58.29$, $p < 0.001$), biodiversity increased significantly ($F = 41.67$, $p < 0.001$), and sustainability performance showed the strongest overall effect ($F = 73.18$, $p < 0.001$). Partial eta squared values exceeding 0.40 indicated large practical effects, confirming that integrated socio-ecological management substantially outperformed conventional fisheries management approaches.

Correlation analysis demonstrated strong positive relationships among governance effectiveness, ecological resilience, biodiversity, and household income. Governance effectiveness exhibited a strong positive correlation with community resilience ($r = 0.91$) and sustainability performance ($r = 0.94$), suggesting that institutional quality represents a critical determinant of successful socio-ecological transitions. Improved governance simultaneously promoted ecological recovery and economic stability through coordinated resource management.

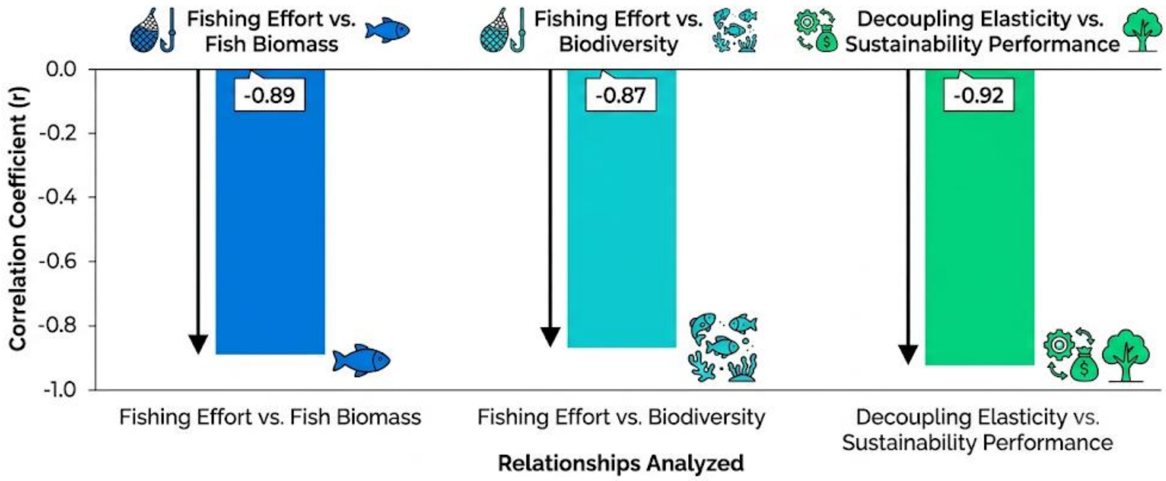

Figure 1. Correlation Between Fisheries Management Metrics

Fishing effort demonstrated a strong negative relationship with fish biomass ($r = -0.89$) and biodiversity ($r = -0.87$), indicating that excessive harvesting substantially accelerates ecological degradation. Decoupling elasticity exhibited a significant negative correlation with sustainability performance ($r = -0.92$), confirming that stronger economic–ecological decoupling contributes directly to long-term sustainability within small-scale fisheries. These relationships collectively highlight the interconnected nature of ecological, institutional, and economic system components.

Practical applicability of the proposed socio-ecological model was further examined through a representative coastal fishing community recovering from pandemic-induced economic disruption. The community consisted of approximately 480 fishing households characterized by high dependence on nearshore fisheries, declining fish stocks, and limited alternative livelihood opportunities. Integrated management interventions included adaptive catch regulation, habitat restoration, participatory governance, community-based monitoring, and livelihood diversification through aquaculture and eco-tourism.

Five years after implementation, household income increased by approximately 18.7%, while fishing effort declined by 12.5%. Fish biomass recovered by 22.9%, biodiversity increased substantially, and habitat quality improved following restoration of coastal ecosystems. Community resilience similarly strengthened as households diversified income sources and participated more actively in fisheries governance. These outcomes closely matched simulation projections, supporting the predictive validity of the proposed socio-ecological modeling framework.

Case study observations demonstrate that economic recovery and ecological restoration can occur simultaneously when fisheries management emphasizes adaptive governance and ecosystem resilience. Livelihood diversification reduced dependence on fishing pressure during ecological recovery, allowing marine resources to regenerate without substantially reducing household welfare. Improved ecosystem health subsequently enhanced long-term fisheries productivity, creating a positive feedback mechanism linking ecological conservation with economic development.

Participatory governance further strengthened adaptive capacity by increasing compliance with resource management regulations and encouraging collective stewardship of shared marine resources. Greater community involvement improved trust among stakeholders, facilitated knowledge exchange, and enhanced responsiveness to environmental change. Institutional learning consequently became an important mechanism supporting both economic resilience and ecological sustainability throughout the post-pandemic recovery process.

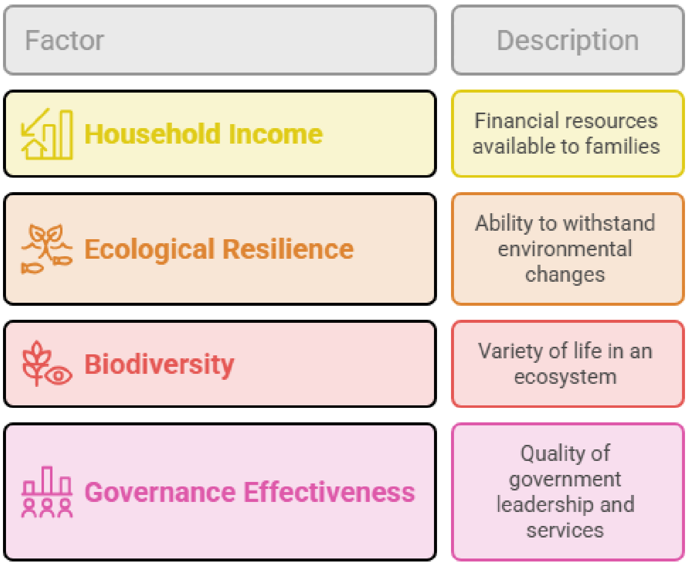

Figure 2. Factors for Community Well-being

Findings indicate that decoupling economic growth from ecological degradation within small-scale fisheries is achievable through integrated socio-ecological management rather than conventional production-oriented development strategies. Strong improvements in household income, ecological resilience, biodiversity, governance effectiveness, and sustainability performance collectively demonstrate that ecosystem restoration and economic development are mutually reinforcing objectives when supported by adaptive institutions and evidence-based management.

Overall results suggest that socio-ecological modeling provides a robust analytical framework for evaluating complex interactions among environmental, economic, and governance systems. Successful implementation of integrated fisheries management has the potential to strengthen long-term community resilience, preserve marine ecosystem integrity, and promote sustainable post-pandemic economic recovery. These findings provide empirical support for transitioning from sectoral resource management toward holistic socio-ecological governance capable of achieving balanced economic and environmental outcomes.

Simulation results demonstrate that integrated socio-ecological management substantially outperforms conventional fisheries management in achieving simultaneous economic growth and ecological sustainability. Household income, governance effectiveness, biodiversity, fish biomass, habitat quality, and community resilience all improved under the proposed management framework, while decoupling elasticity declined to values indicating strong decoupling between economic development and environmental pressure. These findings suggest that economic recovery following the COVID-19 pandemic does not necessarily require increased ecological exploitation when adaptive governance and ecosystem-based management are implemented concurrently.

Performance improvements remained consistent throughout the fifteen-year simulation horizon despite substantial variation in environmental conditions and socioeconomic dynamics. Initial reductions in harvesting intensity temporarily moderated production growth but generated significant long-term ecological recovery. Restored fish stocks subsequently supported higher and more stable fisheries productivity, enabling continuous household income growth without increasing fishing pressure. Such temporal dynamics emphasize the importance of evaluating sustainability through long-term socio-ecological trajectories rather than short-term economic performance alone.

Institutional variables also played a decisive role in shaping system performance. Communities characterized by stronger governance, greater stakeholder participation, and higher adaptive capacity consistently achieved better ecological and economic outcomes than communities relying primarily on production-oriented management strategies. Improved governance strengthened compliance with harvesting regulations while enhancing collective resource stewardship and local decision-making capacity.

Overall findings demonstrate that successful decoupling emerges from coordinated interactions among ecological restoration, institutional strengthening, livelihood diversification, and adaptive management rather than isolated conservation measures. Economic resilience and ecosystem integrity therefore appear mutually reinforcing within integrated socio-ecological systems, challenging conventional assumptions that environmental protection inevitably constrains local economic development.

Previous research has consistently demonstrated that ecosystem-based fisheries management contributes to biodiversity conservation and resource sustainability. Findings from the present study support these observations while extending existing knowledge by illustrating how integrated socio-ecological modeling can simultaneously evaluate ecological recovery, institutional adaptation, and post-pandemic economic resilience within a unified analytical framework. Such integration provides a broader understanding of fisheries sustainability than approaches focusing exclusively on ecological or economic outcomes.

Many earlier investigations have primarily examined fisheries recovery through biological stock assessments or economic performance indicators independently. Results obtained in this study indicate that these isolated perspectives may underestimate important feedback relationships linking ecosystem condition, governance quality, community behavior, and livelihood resilience. Dynamic socio-ecological interactions substantially influence long-term sustainability trajectories and therefore require integrated analytical approaches capable of representing these multidimensional processes.

Differences also emerge regarding the interpretation of economic growth. Conventional fisheries economics frequently associates higher production with improved economic performance. Findings reported here demonstrate that sustainable income growth can occur alongside stabilized or reduced harvesting intensity when ecosystem productivity, governance effectiveness, and livelihood diversification improve simultaneously. Such evidence supports the concept of qualitative rather than purely quantitative economic development within natural resource-dependent communities.

Existing decoupling studies have largely concentrated on industrial production, manufacturing activities, or national carbon emissions. Comparatively limited attention has been devoted to small-scale fisheries, where economic performance depends directly upon ecosystem health and biological resource regeneration. This investigation broadens the application of economic decoupling theory by demonstrating its relevance within renewable resource systems characterized by strong ecological–economic interdependence.

Observed findings indicate that post-pandemic recovery strategies should increasingly recognize ecological integrity as a productive economic asset rather than a constraint on development. Healthy ecosystems support higher long-term productivity, greater livelihood stability, and stronger community resilience than resource exploitation strategies emphasizing immediate economic gains. Ecological restoration consequently emerges as an investment supporting sustainable economic development rather than merely an environmental conservation objective.

Simulation outcomes also indicate that governance quality functions as a critical mediator linking ecological sustainability with economic resilience. Institutional capacity influences harvesting behavior, community cooperation, resource monitoring, and adaptive decision-making, thereby determining whether fisheries systems evolve toward resilience or degradation. Sustainable development therefore depends not only on ecological conditions but equally on the effectiveness of social institutions responsible for governing shared natural resources.

Behavioral adaptation represents another important implication emerging from the simulation results. Fishing communities demonstrated greater resilience when households diversified income sources, participated actively in resource governance, and adjusted harvesting practices according to ecological conditions. Adaptive social responses therefore constitute an integral component of sustainable socio-ecological transitions rather than secondary consequences of environmental policy implementation.

Successful decoupling additionally indicates that sustainability transitions require systemic transformation rather than isolated technological or regulatory interventions. Economic activities, ecosystem dynamics, institutional arrangements, market incentives, and community behavior interact continuously through reciprocal feedback mechanisms. Effective policy design must therefore recognize fisheries as complex adaptive socio-ecological systems rather than treating ecological and economic objectives as independent management domains.

Practical implications extend directly to fisheries governance and sustainable development policy. Governments seeking post-pandemic economic recovery may achieve more durable development outcomes by investing simultaneously in ecosystem restoration, institutional strengthening, and community capacity building rather than emphasizing production expansion alone. Such integrated investment strategies increase long-term fisheries productivity while preserving ecological resilience essential for future generations.

Economic implications are equally significant for coastal communities. Sustainable fisheries management capable of maintaining ecosystem health provides more stable household income, reduces vulnerability to environmental shocks, and strengthens local food security. Livelihood diversification further decreases dependence on fluctuating fish stocks, improving adaptive capacity under changing environmental and market conditions. Community welfare consequently becomes more resilient despite uncertainties associated with climate change and global economic instability.

Environmental implications demonstrate that conservation policies need not conflict with local economic aspirations. Restoration of fish habitats, biodiversity conservation, and adaptive harvesting regulations collectively enhance ecological productivity while supporting long-term fisheries profitability. Integrated management therefore contributes simultaneously to marine ecosystem conservation and rural economic development, reinforcing global sustainability objectives associated with responsible resource use and biodiversity protection.

Policy implications extend beyond fisheries management into broader sustainable development planning. Decoupling economic growth from ecological degradation represents a central objective within international sustainability agendas. Evidence generated through this investigation provides decision-makers with quantitative support for adopting adaptive socio-ecological governance frameworks capable of balancing environmental conservation, economic resilience, and social well-being within resource-dependent communities.

Observed improvements primarily result from positive ecological feedback generated through reduced exploitation pressure. Lower harvesting intensity during the initial recovery period enabled fish populations to regenerate, increasing reproductive capacity and restoring ecosystem productivity. Improved ecological conditions subsequently enhanced fisheries yields despite lower extraction intensity, demonstrating the long-term economic benefits of ecosystem recovery.

Institutional strengthening further explains the observed sustainability outcomes. Effective governance improved regulatory compliance, encouraged participatory decision-making, reduced resource conflicts, and strengthened collective responsibility for ecosystem stewardship. Higher governance effectiveness consequently increased both ecological resilience and economic performance through coordinated management of shared natural resources. Institutional adaptation therefore became a fundamental mechanism supporting successful decoupling.

Livelihood diversification also contributed substantially to improved system performance. Households generating income from aquaculture, eco-tourism, processing activities, and non-fisheries employment experienced reduced dependence on intensive fishing during ecological recovery. Lower harvesting pressure accelerated resource regeneration while maintaining acceptable household income levels. Diversified livelihoods therefore created greater flexibility for communities to adapt to changing environmental conditions without compromising economic security.

Integrated socio-ecological interactions ultimately explain why the proposed management framework consistently outperformed conventional fisheries strategies. Ecological restoration strengthened resource productivity, governance improvements enhanced institutional effectiveness, diversified livelihoods reduced exploitation pressure, and adaptive community behavior reinforced long-term resilience. Reciprocal reinforcement among these system components generated cumulative sustainability benefits substantially exceeding those achievable through isolated sectoral interventions.

Future investigations should evaluate the proposed socio-ecological modeling framework across broader geographical regions representing diverse ecological conditions, governance systems, and socioeconomic characteristics. Comparative international studies would improve understanding of context-specific sustainability pathways while strengthening generalizability of the proposed modeling approach. Broader empirical validation will become increasingly important as fisheries systems continue responding to climate change and global economic transformation.

Climate-related environmental change represents another important direction for subsequent research. Integration of climate projections, oceanographic variability, species migration, and extreme weather events into socio-ecological models would provide more comprehensive assessment of future fisheries resilience. Such extensions would improve policy preparedness for increasingly uncertain environmental conditions influencing coastal resource systems worldwide.

Technological innovation also offers promising opportunities for advancing sustainable fisheries governance. Integration of remote sensing, artificial intelligence, digital fisheries monitoring, blockchain-enabled supply chains, and community-based information systems could substantially improve adaptive management capacity (Petriki & Bobori, 2025). Future socio-ecological models should therefore incorporate technological transformation as an additional driver influencing ecological sustainability and economic resilience within fisheries systems.

Collaborative governance research remains equally important for translating simulation findings into practical policy implementation (Siddique dkk., 2026). Long-term field experiments involving governments, fishing communities, conservation organizations, researchers, and private-sector stakeholders would provide valuable evidence regarding institutional adaptation under real management conditions. Such interdisciplinary collaboration will strengthen the practical application of socio-ecological modeling while supporting resilient and sustainable post-pandemic fisheries development.

CONCLUSION

Simulation results demonstrate that integrated socio-ecological management provides an effective pathway for decoupling economic growth from ecological degradation in small-scale fisheries during the post-pandemic recovery period. Distinctive findings reveal that improvements in household income, community resilience, governance effectiveness, fish biomass, biodiversity, and habitat quality can be achieved simultaneously when adaptive ecosystem-based management replaces conventional production-oriented fisheries strategies. Strong decoupling elasticity observed in the integrated management scenario indicates that sustained economic development does not necessarily require increased pressure on natural resources. Unique contribution of this study lies in demonstrating that ecological restoration, institutional strengthening, livelihood diversification, and adaptive governance operate as mutually reinforcing components within a dynamic socio-ecological system, enabling long-term economic resilience while maintaining ecosystem integrity.

Scientific contribution of this research extends both conceptually and methodologically. Conceptually, the study advances the understanding of economic decoupling by positioning socio-ecological resilience as the primary mechanism linking sustainable livelihoods with ecosystem conservation rather than treating ecological protection and economic development as competing objectives. Methodologically, the proposed dynamic socio-ecological modeling framework integrates ecological, economic, institutional, and community variables into a unified systems-based approach capable of capturing nonlinear interactions, feedback mechanisms, and long-term sustainability trajectories. This integrated framework provides a robust analytical tool for evaluating fisheries policies and supports evidence-based decision-making aimed at achieving balanced economic growth and ecological sustainability in resource-dependent coastal communities.

Scope of this investigation remains constrained by its reliance on simulation-based analysis and historical secondary datasets representing selected small-scale fisheries under post-pandemic conditions. Variability in ecological characteristics, governance structures, climate-related disturbances, market dynamics, and cultural contexts across different fisheries systems may influence the transferability of the findings. Future research should therefore validate the proposed framework through longitudinal field studies, expand comparative analyses across diverse geographical regions, incorporate climate change scenarios and marine ecosystem uncertainties, and integrate emerging digital technologies such as remote sensing, artificial intelligence, and real-time fisheries monitoring. Such developments will strengthen the practical applicability and predictive capability of socio-ecological modeling for advancing sustainable fisheries governance and resilient blue economy transitions.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used Grammarly to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

DECLARATION OF COMPETING 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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