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CASE STUDY

Socio-ecological transformation and biodiversity dynamics under agromaritime development

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ABSTRACT

BACKGROUND AND OBJECTIVES: Agromaritime development transformation in tropical regions reflects the complex relationship between development pressure, biodiversity degradation, and socio-ecological vulnerability. Central Sulawesi has experienced significant ecological changes across upland landscapes, coastal zones, and small islands due to agricultural expansion, infrastructure development, aquaculture growth, and marine resource exploitation. However, biodiversity management and spatial planning frameworks remain heavily fragmented by sectoral approaches that artificially decouple terrestrial, coastal, and marine ecosystems, thereby obscuring critical ecological connectivity and its associated socio-economic ramifications. The study objectives were to analyze biodiversity dynamics and socio-ecological transformation across four major ecoregions of Central Sulawesi using a cross-ecoregional socio-ecological framework.

METHODS: This study employed a socio-ecological qualitative approach by adapting the Drivers–Pressures–State–Impact–Response framework and integrating perspectives from socio-ecological systems, ecological justice, feminist political ecology, and relational planning. The methodological framework relied on an integrated approach, utilizing spatial analysis, an extensive literature review, ecological field observations, stakeholder interviews, and an evaluation of environmental governance documentation. The research covered four interconnected ecoregions, including the Lore Lindu Highlands, Eastern Tomini Bay, Tolo Bay Coast, and Banggai Islands.

FINDINGS: The analysis revealed that biodiversity changes across Central Sulawesi occurred through interconnected terrestrial, coastal, and marine processes. The Lore Lindu Highlands lost approximately 28,495 hectares of primary forest between 2001 and 2021. Eastern Tomini Bay experienced around a 24 percent decline in seagrass cover, while mangrove conversion along the Tolo Bay Coast exceeded 1,600 hectares. In the Banggai Islands, the endemic Banggai Cardinalfish population decreased by approximately 60 percent due to overexploitation and habitat degradation. These ecological pressures manifested as asymmetrical socio-economic impacts, disproportionately affecting small-scale fishers, women, indigenous populations, and vulnerable coastal communities. The findings also indicate that existing governance responses remain fragmented and have not sufficiently integrated upstream-downstream and land-sea management systems.

CONCLUSION: Biodiversity transformation in Central Sulawesi represents a socio-ecological process shaped by ecological connectivity, development pressure, and unequal environmental impacts. Ultimately, the cross-ecoregional socio-ecological framework formulated herein elucidates the systemic linkages between ecological dynamics, institutional governance, and local community vectors, establishing a robust baseline for adaptive biodiversity conservation across tropical agromaritime interfaces.

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INTRODUCTION

The global biodiversity crisis shows that ecological degradation and economic growth often occur simultaneously, particularly in the tropical regions of the Global South. Anthropogenic drivers, namely land-use change, infrastructure expansion, and natural resource exploitation—compounded by the accelerating pressures of climate change, have severely exacerbated biodiversity loss and compromised the critical ecosystem services that sustain human well-being. The report by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Brondizio *et al*., 2019) indicates that nearly one million species are at risk of extinction due to human activities. Within this framework, biodiversity is no longer conceptualized merely as an isolated conservation metric, but rather as a foundational pillar of socio-ecological resilience and regional sustainability (Newell *et al*., 2022; Washington *et al*., 2024). However, ecological degradation does not affect everyone equally. Communities that are highly dependent on natural resources are often the most affected, particularly because they have limited involvement in decision-making on development. The overexploitation of marine resources, forest conversion, and coastal reclamation can reduce access to food, water, and traditional livelihoods. For indigenous communities, these environmental transformations risk severing the socio-ecological attachments that have historically anchored their cultural identity and subsistence practices (Bacon *et al*., 2022; Schlosberg and Collins, 2014). Thus, the biodiversity crisis is fundamentally also a crisis of ecological justice. For several decades, modern regional development has been built on the assumption that economic growth, infrastructure expansion, and spatial optimization are the key indicators of regional progress, although this approach often overlooks the complexity of socio-ecological relationships and the spatial inequalities that arise in the development process (Porter *et al*., 2020; Uitermark, 2012). Within this paradigm, biodiversity is frequently conceptualized as a residual concern, remaining external to the core operational logic of regional development. Space is understood primarily as an economic and administrative object that can be regulated to enhance regional productivity and capital accumulation (Schragger, 2023). Consequently, numerous regions characterized by high ecological richness are concurrently subjected to the most intensive development pressures, this paradox is especially pronounced within the tropical territories of the Global South, where local economies remain heavily reliant on primary resource extraction (Martinez-Alier, 2021; Sultana, 2023). In fact, various studies show that biodiversity loss not only affects species and habitats, but also impacts regional resilience, socio-ecological stability, and the long-term sustainability of development (Newell *et al*., 2022; Nishi *et al*., 2026). Deforestation, coastal degradation, and the decline in the quality of marine ecosystems represent a spatial crisis that impacts food systems, water availability, coastal protection, and the sustainability of local communities' livelihoods (Langemeyer and Connolly, 2020). Therefore, biodiversity loss should be understood as part of broader socio-ecological transformation involving ecological processes, development trajectories, and changing relationships between humans and nature. In response to these concerns, the landscape approach has emerged as a compelling paradigm that conceptualizes landscapes as integrated socio-ecological systems (SES) effectively coupling upstream catchment areas, river basins, coastal zones, marine ecosystems with both production and conservation matrices. Recent findings by Nishi *et al*. (2026) establish a direct causal link between upstream land-use changes and the degradation of downstream coastal and marine ecosystems driven by sedimentation, altered water chemistry, and habitat fragmentation. Consequently, regions

cannot be understood solely through administrative boundaries, but through the ecological and social interconnections that form a landscape continuum. In the Indonesian context, these challenges are becoming more complex as rapid development transforms areas of high biodiversity. Gunawan *et al*., (2022) shows that natural resource management in Indonesia is still largely focused on sectoral interests and economic growth, while biodiversity conservation often receives less attention in regional development policies. In agromaritime zones, such pressures manifest through diverse developments, including plantations, mining, coastal urbanization, and port construction, as well as the intensification of aquaculture and the depletion of marine resources. Therefore, agromaritime transformation reshapes both regional economy and human-nature relationships, while also creating new forms of socio-ecological vulnerability. Until now, regional development has often been based on a separation between social and ecological systems. Developmental discourse consistently privileges economic expansion as the core objective, conversely relegating environmental governance to a subordinate sector addressed primarily through technocratic and regulatory interventions. The *coupled human-natural systems* approach subsequently emerged to explain the reciprocal relationship between human activities and environmental dynamics (Liu *et al*., 2007). This perspective emphasizes that ecological pressures are not only generated by economic activities but are also influenced by development policies, power relations, technological change, and social transformation. In this context, agromaritime development should not be conceptualized solely through the lens of regional economic growth, but rather as a structural socio-ecological transformation that redefines human-nature relations. The perspective of *ecological justice* has emerged as a critique of development models that result in an unequal distribution of environmental benefits and burdens. (Washington *et al*., 2024) assert that biodiversity conservation cannot be separated from social justice and communities' ecological rights. Contemporary environmental governance frameworks frequently remain tethered to exclusionary, technocratic conservation paradigms that conceptualize indigenous and local populations as external threats to biodiversity, rather than as intrinsic components of the socio-ecological matrix. This perspective is further reinforced by Schlosberg and Collins (2014), who demonstrate that the ecological crisis is fundamentally also a crisis of distribution, recognition, and participation in development processes. These socio-ecological challenges are clearly reflected in Central Sulawesi Province, an important biodiversity region within Wallacea characterized by high endemism and strong ecological connectivity among terrestrial, coastal, and marine ecosystems. The region connects the Lore Lindu Mountain landscape, river basin systems, Tomini and Tolo coastal areas, and the small island ecosystems of the Banggai Archipelago (Mujio *et al*., 2026). Over the past two decades, agricultural expansion, infrastructure development, mining activities, coastal transformation, aquaculture growth, and marine resource exploitation have increased pressures on these interconnected ecosystems (CSPEA, 2022). This perspective aligns with the SES framework, which conceptualizes human communities and the biophysical environment as a unified, complex adaptive system characterized by reciprocal interdependencies and continuous, dynamic change (Folke *et al*., 2005; Reyers and Selig, 2020). In this approach, biodiversity does not merely represent the physical presence of a species and its habitat, but also reflects regional resilience, ecological connectivity, and the adaptive capacity of local communities to respond to environmental pressures and developmental changes (Biggs *et al*., 2021; Norström *et al*., 2020). Consequently, ecological change defies isolated, sectoral analysis; rather, it demands an analytical framework grounded in cross-scale feedback loops that dynamically integrate anthropogenic

activities, spatial planning, and regional ecological systems (Bennett *et al*., 2021; Preiser *et al*., 2017). This perspective is increasingly relevant in tropical agromaritime regions experiencing rapid development pressures, where connectivity between land–sea systems, land-use changes, and socio-ecological inequalities shape complex and mutually influencing biodiversity dynamics. This situation has given rise to criticism of conventional spatial planning approaches, which are regarded as overly sectoral and technocratic (Mattila *et al*., 2024). Schragger (2023) refers to this as a 'conflict of rationalities'—a clash between the logic of modern, state- and market-oriented development and ecological rationality, as well as the way of life of local communities. The decoupling of biodiversity conservation from spatial planning frameworks frequently exacerbates ecological fragmentation, intensifies spatial inequities, and compounds socio-environmental vulnerabilities during developmental processes (Figueroa *et al*., 2024). This criticism subsequently gave rise to the ecological regional planning approach, which places ecological structure and biodiversity at the heart of regional development. In this approach, a region is understood as an ecological system interconnected through water flows, habitat corridors, ecological processes, and human-environment interactions (Newell *et al*., 2022). This approach has evolved into biodiversity-sensitive planning, which considers ecological sensitivity in every spatial development decision, including protecting habitat connectivity, ensuring environmental carrying capacity, and safeguarding the sustainability of ecosystem services. Analogous conceptual limitations characterize the Drivers-Pressures-State-Impact-Response (DPSIR) framework, despite its historical ubiquity within environmental analysis. Although the DPSIR framework has been widely applied to analyze environmental change, conventional applications often emphasize linear cause–effect relationships and provide limited explanation of cross-scale ecological connectivity, governance complexity, and differentiated socio-ecological impacts (Patrício *et al*., 2016). Notwithstanding the growing scholarly emphasis on biodiversity conservation and socio-ecological frameworks, three salient research gaps persist. First, many studies still examine terrestrial, coastal, and marine ecosystems separately, limiting understanding of biodiversity dynamics across interconnected landscapes and seascapes. Second, biodiversity assessments frequently emphasize ecological changes while giving less attention to unequal impacts experienced by different social groups. Third, conventional applications of the DPSIR framework seldom synthesize ecological connectivity, governance mechanisms, and environmental justice considerations within a comprehensive cross-ecoregional analytical matrix. This limitation is particularly relevant in agromaritime regions, where biodiversity dynamics are shaped by complex interactions among mountainous landscapes, river systems, coastal zones, marine ecosystems, and the livelihoods of local communities. Within these regions, environmental pressures frequently propagate across the land–sea interface, generating asymmetrical socio-ecological consequences across heterogeneous communities. To fill this gap, the study introduces a cross-ecoregional socio-ecological DPSIR framework that integrates several perspectives, including SES, ecological connectivity, ecological justice, and relational regional planning, to better understand environmental change across interconnected regions. Departing from traditional DPSIR methodologies, the framework introduced herein conceptualizes biodiversity transformation as a highly dynamic phenomenon operating across interconnected ecosystems and trans-regional boundaries. It is shaped by the interactions among development pressures, environmental changes, governance systems, and the varying vulnerabilities of different social groups. The framework is designed to identify the factors driving biodiversity change, explore ecological interactions across regions, assess the socio-

ecological consequences of biodiversity loss, and evaluate governance responses through a relational planning approach. By synthesizing socio-ecological and social dimensions, this study elucidates the complex mechanisms through which agromaritime development reconfigures human–nature relationships across contiguous land–sea interfaces. This study aims to analyze biodiversity transformation and socio-ecological dynamics across interconnected agromaritime ecoregions in Central Sulawesi. This study was conducted across four major agromaritime ecoregions of Central Sulawesi Province, Indonesia, namely the Lore Lindu Highlands, Eastern Tomini Bay, the Tolo Bay Coast, and the Banggai Islands, in 2025.

MATERIALS AND METHODS

The study area

The study focuses on four major ecoregions in Central Sulawesi: The Lore Lindu Highlands, Eastern Tomini Bay, the Tolo Bay Coast, and the Banggai Islands. These four ecoregions were selected as study sites because they encompass a diverse range of SES and different agromaritime development pressures, while simultaneously exhibiting robust land–sea ecological connectivity. The Lore Lindu Highlands are an upstream location with a tropical montane forest habitat that acts as the primary buffer for the regional river basin. Eastern Tomini Bay is a transitional zone between the river basin and the coast, heavily influenced by sedimentation and coastal urbanization. The littoral zone of Tolo Bay is subject to profound anthropogenic pressures, characterized primarily by mangrove conversion, accelerated aquaculture intensification, and the concomitant degradation of marine ecosystems. Meanwhile, the Banggai Islands contain a system of small tropical islands with high marine endemism but significant ecological vulnerability due to ornamental fish trading and the exploitation of marine resources. Geographical location of the study area in the four major agromaritime ecoregions of Central Sulawesi Province, Indonesia shows in Fig. 1.

Epistemological positioning and research design

Based on the relational socio-ecological planning paradigm, this research adopts an approach that views biodiversity, regional development, and the social life of communities as processes that mutually shape one another ecologically, spatially, and politically. With this paradigm, environmental change is conceptualized not as an isolated biophysical reality, but rather as an emergent property of the interconnections among development dynamics, power relations, spatial governance, and the lived experiences of local communities. This epistemological stance is important because most studies of biodiversity and regional development are still dominated by positivist and sectoral approaches that separate social systems from ecological systems. In much conventional research, biodiversity is treated as an environmental indicator that can be measured technically, while the development process is understood primarily as an economic and administrative spatial planning issue. Such an approach obscures the mechanisms through which ecological transformations propagate across adjacent ecosystems, generate asymmetrical impacts among diverse social groups, and institutionalize forms of environmental injustice within regional development paradigms. To address these limitations, this study develops the cross-ecoregional socio-ecological DPSIR Framework, an expanded version of the DPSIR framework that combines the perspective of SES, ecological justice, feminist political ecology (FPE), and cross-ecoregional analysis. This approach was developed because the conventional DPSIR framework is often criticized for being linear, technocratic, and state-centric, and thus unable to adequately capture power relations, communities' ecological experiences, and cross-ecosystem interconnections in regional transformation (Bennett *et al*., 2021; Mattila *et al*., 2024; Patrício *et al*., 2016). In the conventional DPSIR framework, the interplay among drivers,

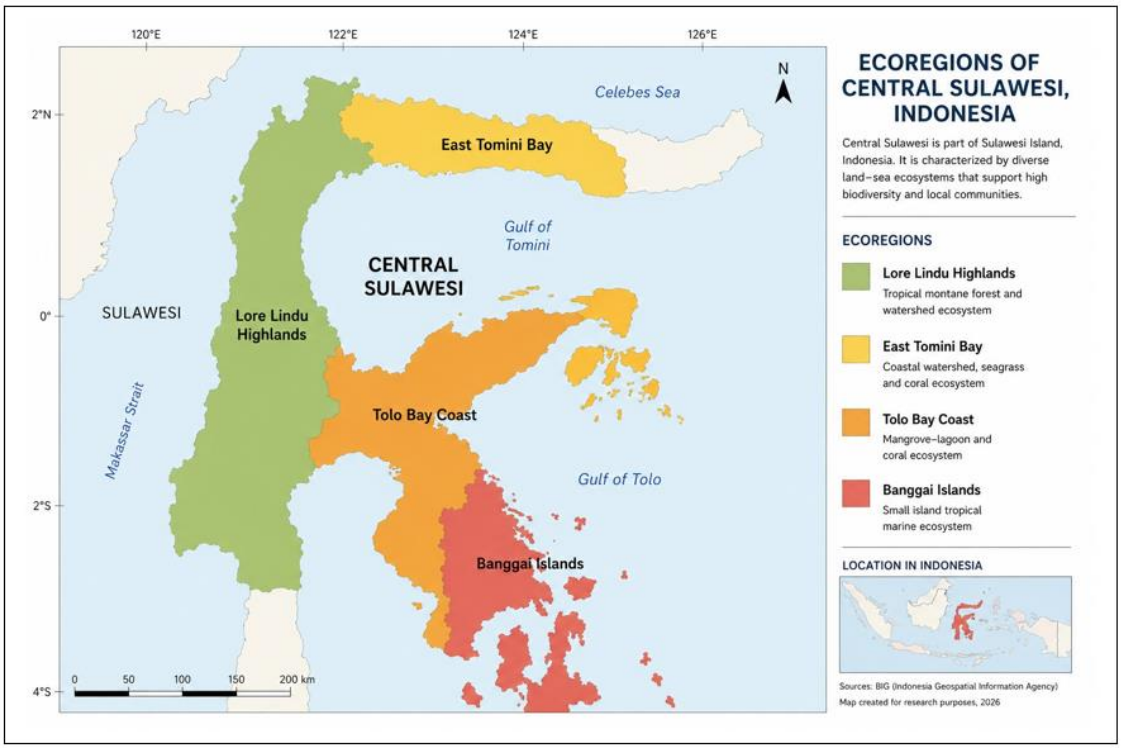


Fig. 1: Geographical location of the study area in the four major agromaritime ecoregions of Central Sulawesi Province, Indonesia

pressures, state, impact, and response are typically conceptualized as a simplistic, linear causal chain. In reality, however, socio-ecological change operates through relational dynamics and multi-scalar processes rather than isolated events. Policy responses can in turn influence development drivers; changes in ecological conditions (state) can intensify pressures, while ecological impacts are not experienced equally by all community groups. Consequently, this study views the DPSIR framework not as a linear environmental model, but as a relational framework for analyzing socio-ecological transformations at the regional level. Through this approach, the region is conceptualized not analyzed as an isolated administrative unit, but rather as a network of socio-ecological flows that structurally link upstream, coastal, and marine environments within a singular, interdependent ecological system. This perspective is consistent with the coupled human-natural systems approach, which views humans and the environment as parts of a system that dynamically influence one another (Liu *et al.*, 2007). Furthermore, this study also adopts a relational planning approach that views space not merely as a technical object of planning, but as a dynamic construct co-constituted by evolving social, ecological, and political interactions. (Porter *et al.*, 2020; Schragger, 2023). In practical terms, this study employs a cross-ecoregional approach to understand how agromaritime development pressures move across terrestrial and marine systems. This approach was chosen because the region's transformation in Central Sulawesi portrays strong ecological connectivity among upstream areas, river basins, coastal zones, and small islands. Consequently, biodiversity decline cannot be adequately explained through the lens of isolated administrative boundaries or discrete environmental typologies alone across interconnected socioecological landscapes.

Cross-ecoregional socio-ecological framework

This study employs the cross-ecoregional socio-ecological framework as its primary analytical framework to understand the relationship between agromaritime development transformations and changes in biodiversity in Central Sulawesi. This framework extends the conventional DPSIR model by integrating the SES approach, ecological justice, FPE, and cross-ecoregional spatial analysis. The development of this framework originates from a critical appraisal of the conventional DPSIR model, which has historically functioned primarily as a tool for environmental monitoring and the technical evaluation of environmental policy (Langemeyer and Connolly, 2020). In rapidly transforming agromaritime regions such as Central Sulawesi, biodiversity dynamics cannot be comprehensively assessed through isolated sectoral or administrative lenses. Rather, ecological alterations must be conceptualized as features of interconnected SES that bridge diverse ecoregions, developmental trajectories, and human–environment interactions. This perspective is consistent with the SES approach, which views human communities and ecological systems as interdependent components that continuously influence one another adaptively (Folke *et al*., 2005; Liu *et al*., 2007). In this approach, the environment is treated as an object that can be measured through biophysical indicators, while social dimensions, power relations, and people's ecological experiences are often overlooked in the analysis. To address these limitations, this study reconfigures the traditional DPSIR model into a more relational, multi-scalar, and spatially explicit socio-ecological framework. In this framework, regional transformation is driven by several structural factors, including agricultural expansion, coastal urbanization, mining, port development, and global trade in marine resources. These factors lead to pressures such as deforestation, sedimentation, mangrove conversion, overfishing, habitat deterioration, and coastal pollution. These anthropogenic and environmental pressures profoundly alter the region's socio-ecological state, driving systemic changes in forest cover, the degradation of critical marine habitats—such as seagrass beds and coral reefs and a concomitant decline in both water quality and endemic species populations. However, in this study, 'state' is understood not only as the biophysical condition of the environment, but also as changes in the socio-ecological capacity of communities to sustain their livelihoods and the region's sustainability. Furthermore, impacts are understood as uneven ecological and social impacts. The effects of environmental change are not experienced equally by all social groups. Small-scale fishers, coastal women, indigenous peoples, and small island communities typically constitute the demographics most susceptible to biodiversity degradation and the destabilization of their critical living spaces. This perspective is integrated from the approaches of ecological justice and FPE, which emphasize the importance of interpreting communities' ecological experiences in a more contextual and differential manner (Bacon *et al*., 2022; Schlosberg and Collins, 2014). Meanwhile, 'response' is understood not merely as formal government policy, but also includes community adaptation practices, community-based conservation, local ecological knowledge, and forms of social resistance to development pressures. Within this framework, 'response' is conceptualized not as a terminal, linear output, but as a dynamic component that exerts reciprocal feedback on drivers, pressures, and socio-ecological states. Thus, the relationships among the DPSIR framework components are understood as dynamic, relational processes rather than linear cause-and-effect. This approach enables the study to analyze agromaritime transformation more integratively, accounting for complex land–sea interconnections, power dynamics, diverse local communities' ecological experiences and cross scale upstream–downstream relationships. The conceptual framework developed in this study is presented in Fig. 2.

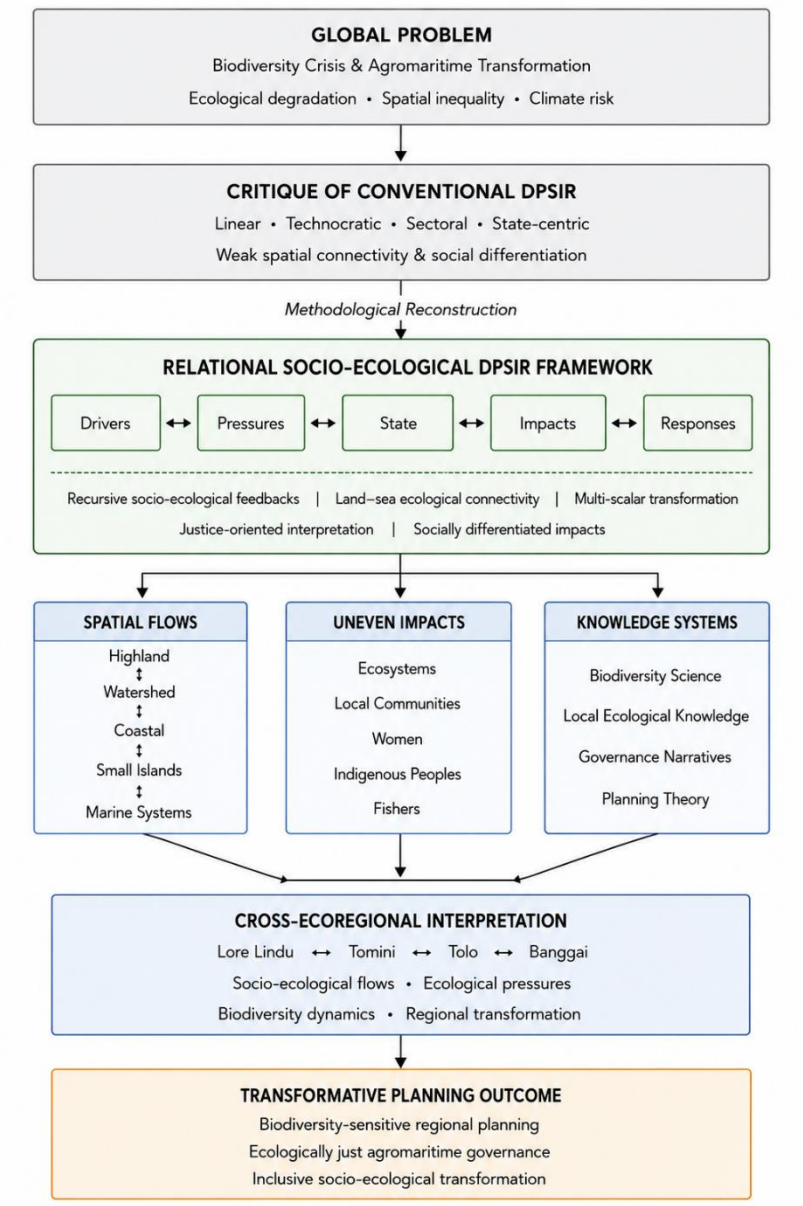


Fig. 2: Relational socio-ecological DPSIR framework for understanding biodiversity transformation in Central Sulawesi

Multi-source evidence and relational data collection

This study employs a multi-source evidence approach to capture the complexity of socio-ecological transformations in the region through the integration of various types of data and knowledge sources. This approach was chosen because changes in biodiversity and development pressures defy comprehensive analysis when restricted to a singular data type or a strictly positivist paradigm. Data collection was carried out through the triangulation of five main sources, namely spatial analysis; literature review; field ecological observations; stakeholder interviews; and biodiversity data and environmental governance documents. This synthesis serves to

minimize uncertainty in the interpretation of complex socio-ecological transformations. By integrating primary field observations and stakeholder perspectives with secondary spatial and institutional datasets, a robust analytical framework is established to cross-validate findings across terrestrial, coastal, and marine systems. Spatial analysis was conducted to identify patterns of land-use change, ecosystem degradation, and ecological connectivity between regions. Building on this, the study evaluated longitudinal land cover transitions by leveraging multi-temporal datasets spanning the 2001–2021 period. Coastal ecosystem alterations, namely mangrove conversion and seagrass degradation—were then assessed by synthesizing satellite-based spatial data with regional monitoring reports and existing ecological studies. This integrated approach enabled a systematic tracing of both the trajectory and magnitude of socio-ecological shifts spanning the upstream-coastal-marine continuum. This approach was used to understand the distribution of development pressures and ecological relationships across ecoregions within upstream–downstream and land–sea systems. To ground this study, a comprehensive literature review was executed, spanning international journals, policy documents, government reports, and scientific publications at the intersection of biodiversity, regional development, SES, ecological justice, and FPE. The literature was used not only as a source of secondary data but also as a theoretical interpretative tool for analyzing regional transformations. The data source, analytical procedures, and validation methods of this study are summarized in Table 1. Following the methodological framework presented in Table 1, this study combined ecological field observations with information obtained from stakeholders to develop a more comprehensive understanding of socio-ecological changes occurring across the study areas. To evaluate existing ecological baselines and isolate the developmental drivers affecting regional biodiversity, targeted field surveys were executed across a diverse range of ecosystems, spanning montane, mangrove, seagrass, coral reef, and coastal environment. Observation sites were selected purposively to represent four major SES in Central Sulawesi, namely the Lore Lindu highland ecosystem, Eastern Tomini Bay coastal system, Tolo Bay coastal landscape, and Banggai Islands marine ecosystem. To complement ecological information, stakeholder perspectives were collected through semi-structured interviews and regional consultations involving approximately 487 participants from 13 districts and provincial-level institutions in Central Sulawesi. A purposive sampling strategy was employed to select participants based on their specialized knowledge, practical experience, institutional mandates, and direct involvement in natural resource management, biodiversity conservation, and regional development initiatives. The participants represented government institutions, conservation practitioners, local communities, farmers, small-scale fishers, indigenous groups, coastal communities, and women representatives. To extract meaningful insights, the stakeholder-derived data were subjected to systematic thematic coding to identify key patterns related to environmental changes, livelihood vulnerability, community adaptation, and governance challenges. These findings were then compared and integrated with spatial data, ecological information, field observations, and policy documents to strengthen the interpretation and reliability of the socio-ecological analysis.

Interpretive socio-ecological analysis

Data analysis was conducted using an interpretive socio-ecological approach to examine the relationships among development transformation, biodiversity change, and socio-ecological dynamics across different ecoregions. This approach was deployed not merely to track ecological alterations, but to critically examine the ways in which environmental pressures intersect with localized livelihoods, resource access, and socio-ecological conditions within regional

Table 1: Data sources, analytical procedures, and validation methods

Data category	Data type	Source and period	Analytical procedure	Validation
Forest cover change	Secondary data	Satellite-based land cover data and environmental reports (2001–2021)	Temporal comparison of forest cover change	Cross-checking with published studies and field observations
Mangrove, seagrass, and marine biodiversity indicators	Secondary data	Government monitoring reports and scientific publications (2007–2022)	Synthesis of ecological trends and reported biodiversity changes	Comparison among multiple independent data sources
Field ecological observations	Primary data	Selected observation sites in four ecoregions	Direct observation of ecosystem conditions and development pressures	Comparison with spatial and secondary ecological data
Stakeholder perspectives	Primary data	Semi-structured interviews with government, community, fishers, and local actors	Thematic analysis of socio-ecological impacts and governance responses	Triangulation across stakeholder groups and document analysis
Policy and governance documents	Secondary data	Spatial plans, biodiversity reports, and environmental policies (2010–2025)	Document review using DPSIR categories	Cross-validation with interview findings

development trajectories**.** The first stage involved interpreting the DPSIR framework to identify the relationships between drivers, pressures, state, impacts, and responses in each ecoregion. The analysis was conducted in a relational manner, accounting for the interconnections between terrestrial and marine systems. The second stage used socio-ecological interpretation to understand how biodiversity decline affects different community groups. This analytical approach successfully captured the identification of differentiated socio-ecological impacts experienced by women, small-scale fishers, indigenous communities, and broader coastal communities. The third stage consisted of conducting a cross-ecoregional comparison analysis to examine patterns of development pressures and socio-ecological transitions between ecoregions. This analytical approach was deployed to discern recurrent patterns, heterogeneities in ecological pressures, and cross-ecosystem linkages inherent within the agromaritime development system of Central Sulawesi. To improve analytical validity, methodological triangulation was applied by comparing spatial evidence, ecological indicators, stakeholder information, and policy documents. To ensure analytical validity, a triangulation process was deployed to discern convergent patterns and systemic relationships across diverse data streams, thereby mitigating the limitations of relying on a singular dataset. Therefore, the interpretation of biodiversity transformation was developed based on the convergence of multiple data sources across ecological, social, and institutional dimensions.

RESULTS AND DISCUSSION

Cross-ecoregional patterns of biodiversity transformation

The analysis across the four ecoregions shows that biodiversity changes in Central Sulawesi occurred in different ways, influenced by local ecological conditions, development pressures, and patterns of natural resource use. The ecological shifts documented in terrestrial forests, coastal zones, and small island settings do not represent decoupled processes; instead, they are functionally unified by catchment-level hydrology and bidirectional land–sea ecological interactions. By integrating spatial analysis, ecological indicators, and biodiversity records, this study identified three main patterns of change: forest fragmentation in the Lore Lindu Highlands, degradation of coastal ecosystems in Tomini and Tolo Bays, and increasing vulnerability of endemic marine species in the Banggai Islands. The evidence base of biodiversity transformation across coregions is presented in Table 2. In the Lore Lindu Highlands, biodiversity changes were closely related to the conversion of forest areas and increasing fragmentation of the montane

Table 2: Evidence base of biodiversity transformation across ecoregions

Ecoregion	Indicator	Assessment period	Observed change	Main pressure	Evidence source
Lore Lindu Highlands	Primary forest cover	2001–2021	Loss of 28,495 ha	Agricultural expansion, infrastructure development, forest fragmentation	Satellite-based land cover analysis; environmental reports
Eastern Tomini Bay	Seagrass ecosystem condition	2007–2022*	Decline approximately 24 percent (%)	Sedimentation, coastal development, watershed pressures	Marine ecosystem monitoring; published ecological studies
Tolo Bay Coast	Mangrove ecosystem extent	2007–2022*	Conversion exceeding 1,600 ha	Aquaculture expansion and coastal land conversion	Spatial analysis; coastal ecosystem assessment
Banggai Islands	Banggai Cardinalfish population	2007–2022*	Decline approximately 60%	Ornamental fish trade and habitat degradation	Species assessment; biodiversity records

* Assessment periods for coastal and marine indicators were determined based on the availability of validated ecological monitoring data and published studies for each ecosystem

landscape. Between 2001 and 2021, approximately 28,495 hectares (ha) of primary forest was lost, reflecting continuous pressure on forest habitats and the ecological role of this area in maintaining upstream watershed functions (CSPEA, 2022). This reduction in forest cover extends beyond a mere biophysical alteration of the montane landscape; it represents a critical spatial transformation that fractures ecological connectivity between upstream-downstream continuum. From the perspective of coupled human and natural systems, ecological changes in Lore Lindu demonstrate that development pressures in the upstream region have cross-ecosystem impacts on coastal and marine systems, including increased erosion, sedimentation in the catchment, and changes in downstream water quality (Liu *et al*., 2007). These findings demonstrate that biodiversity degradation in the upstream catchment extends far beyond a localized forest conservation issue; rather, it reflects macro-level regional transformations that reverberate across the entire SES of Central Sulawesi. These conditions highlight the importance of the relational socio-ecological DPSIR Framework, which views ecological pressures as processes that move between places and ecoregions. These conditions demonstrate that ecological degradation is never entirely socially neutral; rather, it manifests as highly uneven socio-ecological pressures that disproportionately burden marginalized community groups reliant on localized natural resources (Schlosberg and Collins, 2014). In the Eastern Tomini Bay, ecological pressures are primarily driven by coastal urbanization, port infrastructure development, and chronic sedimentation from the upstream catchment area. The decline in coastal environmental quality is reflected in the reduction of seagrass cover to around 24% over the last two decades, which has been followed by a decline in coral reef quality and coastal fisheries productivity (CSPEA, 2022). In this context, coastal degradation cannot be treated as an isolated marine environmental issue; rather, it represents the structural manifestation of regional spatial transformation that links mountain systems, river catchments, coastlines, and marine environments into a singular, continuous ecological landscape. This perspective reinforces the landscape connectivity approach, which places ecological connectivity at the heart of efforts to safeguard regional sustainability (Newell *et al*., 2022). The degradation of tropical fish breeding habitats has contributed to lower catch yields for small-scale fishers. Concurrently, coastal women have experienced escalating economic vulnerability, driven by the progressive depletion of localized food sources and marine resources. A similar situation is also evident along the coast of Tolo Bay. The growing popularity of aquaculture and the expansion of coastal development have put enormous human strain on mangrove and coral reef ecosystems. Data show that over 1,600 hectares (ha) of mangroves have been converted into fish ponds and coastal

aquaculture areas over the past two decades (CSPEA, 2022). Within the framework of regional development, the coastal transformation occurring across Tolo Bay exemplifies a highly extractive paradigm, wherein littoral zones are strategically reconfigured as specialized frontiers for economic production and commodity expansion. Consequently, the ecological functions of mangroves as natural coastal defenses, habitats for marine life, and blue carbon sinks have declined significantly (Friess *et al*., 2019). From the perspective of ecological regional planning, this situation indicates that development that fails to consider socio-ecological connectivity risks increasing the vulnerability of coastal areas to erosion, tidal flooding, and declining fisheries productivity. In the Banggai Islands, localized environmental stressors elucidate a highly nuanced intersection between site-specific ecological vulnerability and macro-level global economic pressures. International market demand for tropical ornamental fish has led to the intensive exploitation of the Banggai cardinalfish, an endemic species with limited adaptive capacity (Jawad, 2012). Concurrently, anthropogenic coral reef degradation—driven by destructive fishing modalities—compounds the inherent ecological vulnerability of small island systems, characterized by restricted carrying capacities. According to relational SES, ecological pressures in Banggai are caused not only by local activities, but also by global economic and political interactions that influence patterns of marine resource exploitation in small island locations. These conditions illustrate that localized biodiversity remains highly susceptible to global economic forces that operate independently of regional ecological thresholds and socio-economic sustainability. Small-scale fishers, coastal women, and communities living on small islands are among the most vulnerable to these changes because their livelihoods depend heavily on marine resources. Overall, the biodiversity changes across the four ecoregions are closely linked to broader agromaritime development transformations in Central Sulawesi. These transformations are driven by interacting factors, including land-use change, economic pressures, ecological fragmentation, and socio-ecological inequality. These findings underscore that biodiversity should not be conceptualized as an isolated environmental component distinct from regional development; rather, it constitutes the foundational bedrock of the regional socio-ecological system. Consequently, biodiversity management requires a regional planning approach that is not only oriented toward economic growth, but is also capable of maintaining ecological connectivity, strengthening social resilience, and reducing ecological inequalities in a more inclusive and adaptive manner (Bennett *et al*., 2021; Porter *et al*., 2020).

Drivers and mechanisms of biodiversity degradation under agromaritime development

The results of the analysis using the cross-ecoregional socio-ecological DPSIR framework indicate that biodiversity degradation in Central Sulawesi does not occur in a linear and isolated manner, but is shaped by interconnected socio-ecological relationships between terrestrial, coastal and marine areas. Unlike the conventional DPSIR framework, which tends to be sectoral and state-centric, this study establishes that the linkages among drivers, pressures, changes in ecological conditions, social impacts, and governance responses are inherently relational, multi-scalar, and mediated by cross-ecoregional connectivity (Fan *et al*., 2024; Patrício *et al*., 2016). This perspective aligns with the SES approach, which views humans and the environment as systems that dynamically influence one another through constantly evolving ecological, social, and spatial relationships (Folke *et al*., 2021; Reyers and Selig, 2020). In the context of Central Sulawesi, the compounding pressures of agromaritime development transcend administrative boundaries, propagating through river basin networks, driving coastal sedimentation, and accelerating marine habitat degradation to generate acute socio-ecological vulnerabilities for coastal and small island communities (Mujio *et al*., 2026). The comparative relational DPSIR

characteristics of the four ecoregions are presented in Table 3. In the Lore Lindu Highlands, agricultural expansion, road construction and the growth of upstream settlements are driving deforestation and watershed degradation, which are weakening the ecological connectivity between the mainland and coastal areas. Primary forest cover in this area is recorded to have decreased by approximately 28,495 ha during the period 2001–2021 (Mujio *et al*., 2026). From a relational DPSIR perspective, upstream land-use changes transcend localized forestry concerns; instead, they propagate downstream as accelerated sedimentation and a decline in water quality degradation that ultimately impact coastal and marine ecosystems. This situation illustrates how cross-ecoregional ecological pressures are formed through interdependent upstream–downstream and land–sea relationships, as described in the landscape connectivity and regional ecological planning approaches (Langemeyer and Connolly, 2020; Mujio *et al*., 2026; Newell *et al*., 2022). The interconnected socio-ecological DPSIR dynamics and cross-ecoregional land–sea connectivity mapping established throughout this research are visually conceptualized in Fig. 3. This relationship is most evident in the Eastern Tomini Bay, a coastal–marine transition zone. Seagrass beds and coral reefs are increasingly threatened by coastal urban growth, port development, and sediment runoff from nearby river basins. The area covered by seagrass has declined by around 24%, and fewer than 30% of coral reefs are considered healthy (Mujio *et al*., 2026). Rather than viewing coastal degradation merely as a standalone marine environmental problem, this analysis frames it as a consequence of broader regional spatial restructuring—one that functionally binds highlands, river basins, and the coastline within a unified, interconnected socio-ecological system. This perspective reinforces the argument that ecological pressures in agromaritime regions move across administrative boundaries through ecological connectivity and regional socio-economic flows (Folke *et al*., 2021; Mujio *et al*., 2026; Reyers and Selig, 2020). A similar pattern is found along the Tolo Bay coastline. Fish pond expansion, coastal development, and the exploitation of marine resources have resulted in the loss of almost 1,600 ha of mangrove forest and an increasing strain on coastal habitats (Mujio *et al*., 2026). In the DPSIR relational diagram, this area represents the intersection between land-based development pressures and the exploitation of marine ecosystems. Consequently, there has been a critical erosion of key coastal ecosystem services, severely compromising the shoreline's capacity to provide natural defense, sustain marine habitats, and serve as a socio-ecological buffer for local communities. This situation indicates that regional development still tends to treat coastal areas as spaces for economic production, rather than as part of an interconnected regional ecological system (Bennett *et al*., 2021; Langemeyer and Connolly, 2020). In the Banggai Islands, ecological pressures reveal a complex relationship between the global economy and local vulnerability. Driven by international market demands for tropical ornamental fish, the heavy exploitation of the endemic Banggai Cardinalfish (*Pterapogon kauderni*) has triggered a severe population decline of approximately 60%, a crisis exacerbated by its restricted ecological range and ongoinghabitat loss. (Mujio *et al*., 2026). From a relational DPSIR perspective, this situation demonstrates that the ecological vulnerability of small islands is produced not only by local activities but also by global economic relations that shape patterns of marine resource extraction in peripheral regions. This situation demonstrates how biodiversity transformation in coastal areas and small islands forms part of an uneven socio-ecological transformation process. The diagram ‘relational socio-ecological DPSIR dynamics and cross-ecoregional land–sea connectivity’ also shows that ecological impacts are not experienced equally by all social groups. Degrading coastal environmental quality intensifies the livelihood precarity of small-scale artisanal fishers, compounds the gendered ecological burdens on

Table. 3: Comparative relational DPSIR across ecoregions

Ecoregion	Main drivers	Ecological pressures	Socio-ecological impacts	Governance responses
Lore Lindu Highlands	Agricultural expansion, road development	Deforestation, watershed degradation	Sedimentation, declining downstream water quality	Forest rehabilitation programmes
Eastern Tomini Bay	Coastal urbanization, port development	Coastal conversion, sedimentation	Coral decline, vulnerability of fisheries	Fragmented coastal governance
Tolo Bay Coast	Aquaculture expansion, growth in coastal settlements	Mangrove conversion, overfishing	Declining coastal resilience	Local mangrove restoration
Banggai Islands	Global ornamental fish trade	Overexploitation, coral degradation	Vulnerability of marine biodiversity	Weak species protection

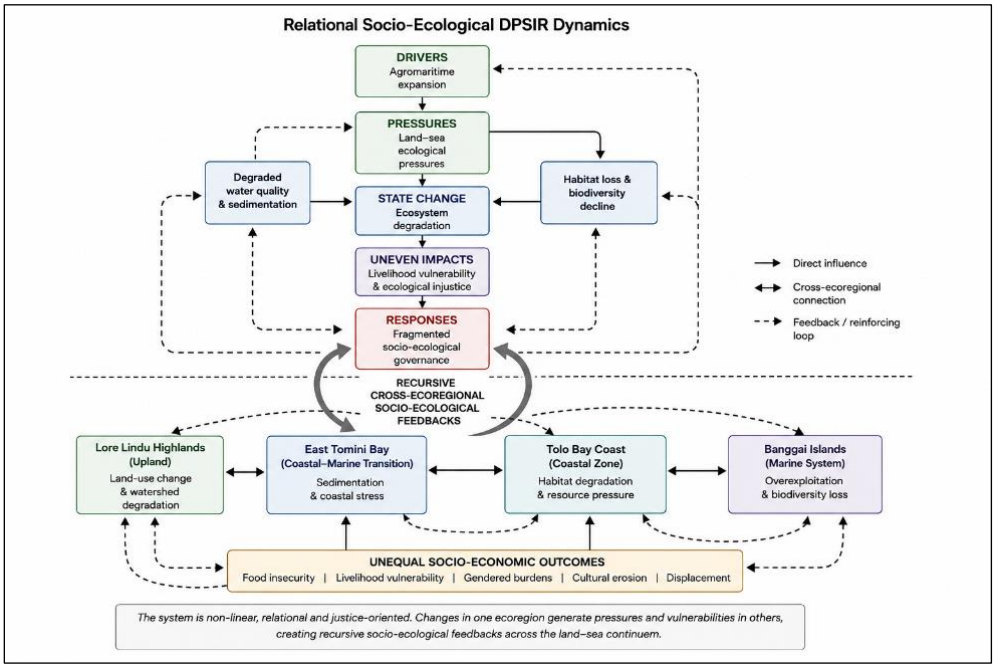


Fig. 3: Relational socio-ecological DPSIR dynamics and cross-ecoregional land–sea connectivity

women in securing domestic water and food supplies, and encroaches upon the critical living space of resource-dependent indigenous and local communities. In this context, biodiversity degradation not only represents the loss of species and habitats, but also reveals a form of ecological injustice resulting from the unequal distribution of environmental impacts (Schlosberg and Collins, 2014). This perspective emphasizes that ecological change is always linked to power relations, access to resources, and communities' ability to defend their living spaces. This situation highlights the limitations of regional development and governance approaches, which remain dominated by sectoral and technocratic approaches, and are thus unable to adequately integrate the complexity of socio-ecological relationships into the regional planning process (Bennett *et al*., 2021; Porter *et al*., 2020). As illustrated by the DPSIR framework, the absence of integrated governance precipitates recurrent socio-ecological feedback loops that transcend ecoregional boundaries, progressively amplifying ecological pressures across diverse territories. Therefore, this study demonstrates that biodiversity transformation in Central Sulawesi cannot be understood solely as an environmental issue, but rather as a consequence of a regional development model that still fails to integrate ecological connectivity, socio-ecological justice,

and spatial sustainability. At the same time, existing governance responses remain largely piecemeal and fragmented. Terrestrial forest rehabilitation, mangrove restoration, and species conservation initiatives continue to be executed on a fragmented, sectoral basis, lacking substantive structural integration across the upstream-to-marine continuum (Mujio *et al*., 2026).

Cross-ecoregional connectivity and socio-ecological feedback mechanisms

The comparison of the four ecoregions shows that biodiversity change in Central Sulawesi cannot be explained by examining each ecosystem separately. Although each ecoregion experienced different pressures, changes in the Lore Lindu Highlands, Eastern Tomini Bay, Tolo Bay Coast, and Banggai Islands were linked through ecological processes connecting upland, coastal, and marine environments. In upland areas, forest conversion and land-use change have degraded watershed integrity, generating cascading ecological effects beyond forest boundaries. Increased sediment movement, declining water quality, and reduced habitat connectivity have intensified pressures on coastal and marine ecosystems, including seagrass beds, coral reefs, and fisheries habitats (Sakti *et al.,* 2026). These findings demonstrate that biodiversity change in Central Sulawesi is driven by interactions among ecosystems rather than a single environmental pressure, underscoring the need for integrated ecosystem management and biodiversity governance (Almunawwaroh et al., 2026). This interpretation aligns with the SES perspective, which conceptualizes human activities and biophysical systems as inherently coupled and continuously co-evolving through dynamic feedback loops (Folke *et al*., 2005; Liu *et al*., 2007). From this perspective, biodiversity represents not only species and ecosystem conditions, but also the ability of landscapes to maintain ecological functions, support community resilience, and sustain local livelihoods. Understanding these relationships is important for regional ecological planning, particularly in areas where upstream, downstream, and marine systems are strongly connected (Cumming, 2011; Newell *et al*., 2022). Fig. 4 illustrates the movement of ecological pressures across the upland–coastal–marine continuum. Changes occurring in terrestrial landscapes influence downstream ecosystems through hydrological processes, sediment flows, and changes in habitat conditions. Simultaneously, escalating anthropogenic and environmental pressures on coastal and marine ecosystems directly undermine the resilience of local communities whose livelihoods are inextricably linked to natural resources. Within the relational socio-ecological DPSIR framework, these findings suggest that biodiversity transformation should be understood as part of broader interactions among development processes, ecosystem change, and human–environment relationships. Therefore, biodiversity governance within agromaritime regions necessitates frameworks that transcend rigid administrative jurisdictions, account for cross-scale ecological connectivity and integrate reciprocal landscape–seascape feedback dynamics.

Toward adaptive and just agromaritime governance

The socio-ecological changes observed across the four ecoregions indicate that biodiversity degradation extends beyond ecological impacts and influences the relationship between communities and their surrounding environments. Consequently, the impacts of these environmental shifts diverge among demographics, varying as a function of each group's reliance on natural capital, livelihood strategies, and adaptive capacity in the face of changing ecosystem conditions. In the Lore Lindu Highlands, forest degradation and watershed changes have affected communities whose livelihoods are closely connected to forest landscapes, water resources, and traditional production systems. Similarly,

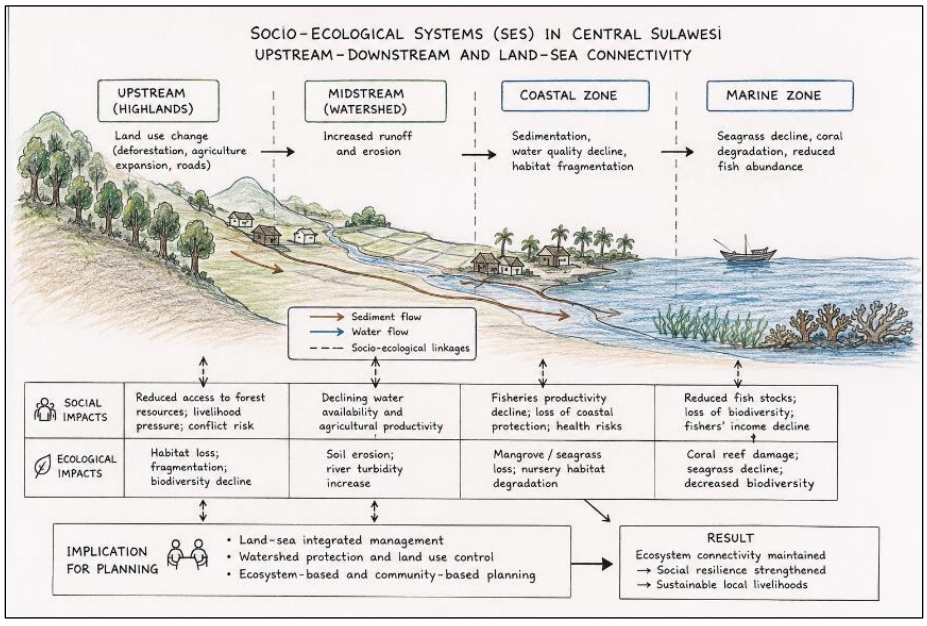


Fig. 4: Socio-ecological connectivity across upstream, watershed, coastal, and marine systems in Central Sulawesi

declining ecosystem conditions in Tomini Bay, Tolo Bay, and the Banggai Islands have created additional pressures for coastal and small island communities that depend on fisheries resources, mangroves, coral reefs, and marine biodiversity (Fadilah *et al.,* 2026). These transformations have progressively compromised community access to the ecological spaces and customary resources that have historically supported local livelihoods. These findings suggest that biodiversity transformation is closely related to broader questions of access, participation, and environmental justice (Almunawwaroh et al., 2026). Shifting environmental conditions can restructure local social systems, creating differentiated vulnerabilities among communities, particularly those that depend heavily on ecosystem services (Langemeyer and Connolly, 2020). From the perspective of ecological justice and FPE, environmental pressures should therefore be understood not only through ecological indicators but also through how benefits, risks, and decision-making opportunities are distributed among different social groups, including indigenous communities, small-scale fishers, coastal women, and small island communities (Bacon *et al*., 2022; Schlosberg and Collins, 2014). Notwithstanding these interconnected socio-ecological challenges, biodiversity governance in Central Sulawesi continues to be dominated by fragmented, sector-specific frameworks that fail to account for systemic cross-scale dynamics. Forest rehabilitation, mangrove restoration, coastal management, and species conservation programs have contributed to ecosystem protection, but they are often implemented separately and have not fully incorporated ecological connectivity across upland, watershed, coastal, and marine systems (Mujio *et al*., 2026). Consequently, future agromaritime governance necessitates an institutional transition toward a more adaptive and integrated paradigm—one that seamlessly couples biodiversity conservation, spatial planning, and localized community participation across distinct ecoregional scales. Such an approach recognizes conservation not only as an effort to protect species and habitats but also as a process of maintaining socio-ecological resilience, ecological connectivity, and sustainable relationships between communities and nature (Bennett *et al*., 2021; Porter *et al*., 2020).

CONCLUSION

This study demonstrates that biodiversity transformation in Central Sulawesi is not merely an ecological phenomenon, but a socio-ecological process shaped by the continuous interaction between development dynamics, ecosystem changes, and community dependence on natural resources. The analysis of four ecoregions shows that the Lore Lindu Highlands, Eastern Tomini Bay, Tolo Bay Coast, and Banggai Islands are connected through ecological processes that cross administrative boundaries. Environmental changes propagating across terrestrial landscapes fundamentally alter watershed functions, thereby driving cascading impacts through coastal ecosystems and marine habitats that ultimately threaten the livelihoods of resource-dependent communities. Applying the Cross-Ecoregional Socio-Ecological DPSIR Framework provides a broader understanding of how agromaritime development pressures move across land and sea systems. The findings indicate that agricultural expansion, infrastructure development, coastal transformation, and marine resource exploitation act as major development drivers that generate land conversion, habitat fragmentation, sedimentation, and coastal degradation. Rather than presenting as isolated environmental phenomena, these stressors operate as cumulative processes that fundamentally restructure regional resilience and transboundary ecological connectivity. Therefore, biodiversity management requires an integrated perspective that considers the relationships among ecosystems, human activities, and governance systems. This study also highlights the limitations of conventional approaches that view biodiversity primarily through ecological indicators or sectoral management. By synthesizing social-ecological systems thinking, ecological connectivity, and socio-ecological justice dimensions, the adapted DPSIR framework presented in this study offers a deeply relational ontology for understanding of biodiversity transformation. It emphasizes that environmental degradation affects communities differently, particularly small-scale fishers, women, indigenous groups, and coastal communities whose livelihoods are closely linked to ecosystem services. The empirical results suggest a necessary paradigm shift for future agromaritime strategies, moving away from merely trade-off compromises between ecological protection and economic expansion toward cultivating systemic adaptability and environmental justice at the society–nature interface. Strengthening land-seascape connectivity, protecting critical ecosystems, incorporating local knowledge, and transforming fragmented sectoral governance into integrated cross-ecoregional management are essential elements for maintaining biodiversity resilience. In this context, spatial planning must transcend its traditional regulatory role over terrestrial land and marine resources; instead, it should be operationalized as a strategic mechanism to orchestrate sustainable socio-ecological transformation. Overall, the experience of Central Sulawesi provides important lessons for tropical regions facing similar challenges between development and biodiversity conservation. The Cross-Ecoregional Socio-Ecological DPSIR Framework proposed in this study offers an integrated approach to support more sustainable, inclusive, and resilient agromaritime management in interconnected land-sea systems.

AUTHOR CONTRIBUTIONS

Mujio conceptualized the study, developed the socio-ecological framework, conducted data interpretation, and prepared the original manuscript draft. M. Natsir conducted ecological observations, biodiversity assessment, and environmental data validation. M. Ermyanyla carried out stakeholder interviews, socio-ecological analysis, and data curation. A. Yanuadi contributed to theoretical integration, relational planning analysis, manuscript review and editing, visualization, and final manuscript preparation. All authors read and approved the final version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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During the preparation of this work, the authors used Artificial Intelligence (AI), specifically ChatGPT (OpenAI), as an AI-assisted tool to support language refinement, grammar checking, readability improvement, and editorial enhancement of selected sections of the manuscript. The AI tool was not used to generate research data, perform data analysis, develop scientific findings, or formulate conclusions. After using this tool, the authors carefully reviewed, verified, and edited all AI-assisted outputs to ensure scientific accuracy, originality, and consistency with the research objectives. The authors take full responsibility for the content and integrity of the final publication.

ABBREVIATIONS

%	Percent
CBD	Convention on Biological Diversity
DAS	River Basin (Daerah Aliran Sungai)
DLH	Environmental Agency (Dinas Lingkungan Hidup)
DPSIR	Drivers–pressures–state–impact–response
FAO	Food and Agriculture Organization
FPE	Feminist political ecology
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GmbH	Gesellschaft mit beschränkter Haftung
ha	Hectare
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IUCN	International Union for Conservation of Nature
km	Kilometer
km²	Square kilometer
NGO	Non-governmental organization
SDGs	Sustainable Development Goals

SEPLS	Socio-ecological production landscapes and seascapes
SES	Socio-ecological systems
SOLUSI	Solutions for Integrated Land and Seascapes Management in Indonesia
UN	United Nations
UNEP	United Nations Environment Programme

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