

# Ethics, Governance, and Adaptive Management of Mangrove Social-Ecological Systems: An Updated Integrative Review of Conservation, Restoration, Monitoring, and Coastal Livelihoods

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## ABSTRACT

Mangrove scholarship has shifted from documenting ecosystem loss to analyzing how conservation, restoration, law, livelihoods, and climate policy interact within social-ecological systems. Drawing only on the extracted studies supplied in the attached files, this review updates the prior literature base by synthesizing recent advances in governance, ethics, blue carbon, restoration ecology, and monitoring innovation. Across the reviewed evidence, mangroves are consistently shown to provide biodiversity support, fisheries habitat, coastal protection, carbon storage, and livelihood opportunities, yet outcomes remain uneven because ecological interventions are often separated from tenure security, local participation, hydrological diagnosis, and policy coordination [1, 2, 5, 7, 8, 9]. Recent studies further show that the effectiveness of legal protection and protected areas depends on implementation quality, cross-sectoral alignment, and fair engagement with local communities rather than on formal designation alone [5, 6, 11, 12, 51]. Restoration evidence indicates that success depends less on planting numbers than on matching species, hydrology, geomorphology, and social incentives to site

conditions [15, 16, 22, 27, 35, 36, 37]. At the same time, remote sensing, UAV photogrammetry, machine learning, phenocams, and spatial prioritization frameworks are strengthening the evidence base for condition assessment and restoration targeting [27, 29, 30, 31, 32, 33, 42]. This review argues that future mangrove management must be ethically grounded, ecologically site-specific, and institutionally accountable. Durable mangrove futures will depend on integrating restoration quality, livelihood justice, blue carbon policy, and transparent monitoring within a single adaptive governance framework.

**Keywords:** mangrove ethics; mangrove governance; blue carbon; restoration; remote sensing; community-based management; coastal resilience

## INTRODUCTION

Mangroves now occupy a central position in global debates on biodiversity conservation, climate mitigation, coastal resilience, and equitable development. Their value is no longer understood only in terms of habitat area or timber resources, but as a bundle of ecological functions and social benefits that are deeply entangled with institutions, rights, and coastal change [1, 2, 3, 4, 7, 8]. The

reviewed literature shows a decisive shift from sectoral management toward a social-ecological framing in which mangrove condition is influenced simultaneously by land use conversion, hydrological disruption, legal arrangements, restoration design, protected area performance, local livelihoods, and climate stressors [5, 6, 8, 9, 10, 11, 12].

This shift has important consequences for review writing. A conventional review can summarize threats, restoration techniques, or ecosystem services. Yet the newer literature contained in the attached files suggests that the most important frontier is integrative: how to manage mangroves as ethical, political, and ecological systems at once. Recent studies on national legal frameworks, biodiversity targets, governance after disturbance, stakeholder perceptions, and blue carbon policy make clear that technical measures succeed only when they are embedded in fair and workable institutions [5, 6, 7, 11, 12, 51]. Conversely, community-oriented restoration or ecotourism can fail when tenure is uncertain, when land stability is poor, when hydrological constraints are ignored, or when benefits are distributed unevenly [15, 16, 19, 20, 21, 22, 23].

The attached literature also expands the geographical and thematic range of mangrove scholarship. Indonesia remains especially prominent, with work on biodiversity, ecosystem services, blue carbon, ecotourism, urban rehabilitation, policy design, land suitability, charcoal production, carbon loss from illegal logging, and production forest dynamics [1, 2, 7, 17, 18, 19, 20, 21, 22, 24, 26, 31, 34]. However, the evidence base also spans India, Sri Lanka, Bangladesh, Brazil, Mexico, Mauritius, Hong Kong, the Philippines, Ecuador, South China, Egypt, and northern Australia, making it possible to compare governance regimes, restoration logics, monitoring methods, and social outcomes across settings [10, 11, 12, 13, 14, 15, 25, 28, 30, 32, 33, 38, 39, 43, 44, 45, 46, 47, 48, 49, 50, 51, 53]. These studies do not point to a

single universal model. Instead, they indicate a recurring principle: mangrove management is most robust when ecological diagnosis, institutional legitimacy, and livelihood compatibility reinforce one another.

The present article therefore has four aims. First, it updates the attached review base by integrating the newer studies included in the supplemental file, especially those from 2023–2026 on legal protection, policy targets, geospatial monitoring, governance, protected area outcomes, and restoration prioritization [5, 6, 11, 12, 29, 31, 32, 33, 35, 41, 51]. Second, it reframes mangrove management through an ethics lens, foregrounding distributive justice, participation, recognition of local knowledge, and accountability in conservation and restoration. Third, it synthesizes evidence into extensive summary tables that organize the discussion around governance, ecological processes, and monitoring innovations. Fourth, it develops a conceptual argument for top-tier scholarship: the future of mangrove management lies not in maximizing any single objective such as carbon, tourism, planting counts, or protection coverage, but in negotiating trade-offs explicitly and transparently across multiple values [3, 5, 6, 7, 8, 9, 11, 13, 40, 51].

A central contribution of the recent literature is the recognition that ethics is not an external add-on to mangrove science. It is embedded in site selection, species choice, restoration financing, enclosure, compensation, risk distribution, and the interpretation of “success.” For example, legal protection can be globally extensive and still locally inadequate if enforcement is weak or if communities are excluded from decision-making [5, 11, 12, 51, 52]. Blue carbon can provide a powerful new policy narrative, but if carbon valuation overrides subsistence uses or obscures local vulnerability, it risks creating distributive tensions rather than resilience [7, 38, 39, 40, 41]. Ecotourism can align income and conservation, yet may also intensify pressures if carrying capacity,

infrastructure impacts, and benefit-sharing arrangements are not governed carefully [19, 20, 21, 22, 23, 49, 50, 53]. These themes justify an explicitly ethics-containing title and analytical frame.

**REVIEW BASIS AND SYNTHESIS APPROACH**

This review is based exclusively on the extracted literature supplied in the attached files. No external references were added, and all substantive claims are anchored to the information available in those extracted records and abstracts. The resulting evidence base comprises review papers, case studies, methodological articles, governance analyses, restoration studies, and remote sensing applications published between 2017 and 2026, with strong representation from Asia and growing contributions from Latin America, Africa, and global-scale policy assessments [1, 2, 3, 4, 5, 6].

The supplied corpus supports an integrative review rather than a statistical meta-analysis. Most records are heterogeneous in aims, methods, units of analysis, and reporting style. Some analyze national legal frameworks or biodiversity targets [5, 6]; others assess local stakeholder perceptions and management arrangements [11, 12, 13, 14, 17, 18, 23]; others examine rehabilitation, restoration, afforestation, and post-harvest or post-disturbance ecological trajectories [15, 16, 22, 27, 34, 35, 36, 37]; still others focus on monitoring innovations such as satellite time series, UAV-based classification, deep learning, phenocams, and suitability modeling [4, 27, 28, 29, 30, 31, 32, 33, 42]. The review therefore uses thematic synthesis

to identify consistent patterns, recurrent tensions, and emerging fronts.

Three interpretive principles guide the synthesis. First, ecological and social findings are treated as co-constitutive, not parallel. This reflects the social-ecological framing made explicit in multiple studies, especially those on ecosystem-based management, community participation, vulnerability, and stakeholder discourse [8, 9, 11, 12, 18, 40]. Second, recency is emphasized where the corpus provides new evidence, especially for legal protection, GBF alignment, protected areas, geospatial restoration targeting, and microbial succession in restored stands [5, 6, 29, 31, 32, 33, 35, 51]. Third, ethical analysis is inferred cautiously from the studies’ reported findings on participation, rights, trade-offs, and distributional outcomes, without imposing unsupported external theory. In this sense, “ethics” in the present review refers to fairness in decision-making, recognition of affected communities, proportionality in burden-sharing, transparency of management goals, and the duty to avoid ecologically inappropriate interventions.

The synthesis is organized around six interlocking themes: (1) the changing status and condition of mangrove systems; (2) ethics, governance, and policy coherence; (3) restoration and adaptive management; (4) monitoring and analytical innovation; (5) livelihoods, ecotourism, and blue carbon economies; and (6) a forward research and policy agenda. The tables included below summarize representative literature in each area and function as an evidentiary backbone for the discussion.

**Table 1. Representative literature on governance, ethics, and management transitions in mangrove systems**

Focus area	Geographic scope	Main contribution	Ethical/governance implication	Management lesson	Ref.
Ecosystem-services review	Indonesia	Consolidates ecosystem services as a management basis	Welfare gains must be linked to ecological safeguards	Integrate valuation, social analysis, and future strategy	[1]
National biodiversity	Indonesia	Synthesizes biodiversity,	Conservation without implementation	National ambition requires	[2]

and management review		conservation, and current management challenges	capacity remains fragile	local delivery mechanisms	
National legal frameworks	Global	Shows extensive but uneven explicit legal protection	Law coverage is not equivalent to equitable governance	Match legal architecture with implementation and coordination	[5]
GBF target alignment	Global	Evaluates whether national targets address key loss drivers	High-value loss may continue outside protected areas	Complement area protection with driver-specific reforms	[6]
Coastal wetland policy review	Global	Identifies recurring failures in governance and planning	Participation and decentralization are normative as well as practical needs	Reflect ecological dynamics and local decision-making	[9]
Research-policy dichotomy	Mesoamerican Reef	Reveals mismatch between management concerns and research emphases	Knowledge asymmetry can distort legitimacy	Managers and researchers must be institutionally connected	[10]
Post-tsunami governance	Andaman Islands	Maps multi-stakeholder governance challenges	Exclusion and ambiguity undermine fairness	Clear guidelines, monitoring, and communication are essential	[11]
Stakeholder perceptions	Jaffna Peninsula	Identifies divergent discourses and post-conflict barriers	Recognition of community experience is central to legitimacy	Overlapping jurisdictions and weak data hinder collaboration	[12]
Community spaces, conservation, tourism	Mexico	Develops socioenvironmental stages linking policy and productive change	Conservation can create conflict if social context is neglected	Adapt policy to scenario-specific community conditions	[13]
Bio-rights incentive scheme	Indonesia	Links micro-credit to conservation services	Incentives can be fairer when benefits and obligations are transparent	Align livelihood security and stewardship	[16]
Eco-DRR governance	Indonesia	Examines mistrust in community-engaged coastal restoration	Participation without confidence-building can be extractive	Democratic environmental management is a prerequisite for durable DRR	[18]
Protected area outcomes	Brazil	Finds PAs stabilize mangroves but governance tools alone were insufficient	Formal instruments without active engagement may be ethically hollow	Enforcement and stakeholder activation matter more than paperwork	[51]

### **CHANGING STATUS, CONDITION, AND PRESSURES IN MANGROVE SYSTEMS**

The reviewed literature offers a more nuanced picture than a simple narrative of universal decline. At the global scale, mangrove condition appears mixed: some indicators improve, yet stressors remain spatially concentrated and socially consequential. Global NDVI analysis

indicates a slow overall increase from 2000 to 2018, with significantly increasing mangrove condition occurring in a much larger area than significantly decreasing condition [4]. Likewise, global coastal wetland typologies show that impacts vary systematically, with some regions functioning as relative refuges and others subject to high land-based, marine-based, or climate-related pressures [3]. These findings

are encouraging, but they do not justify complacency. They also reveal that area-based recovery and functional integrity are not the same thing. Positive vegetation trends can coexist with salinity stress, altered species composition, fisheries vulnerability, carbon loss, or governance deficits [3, 4, 38, 40].

Recent case studies sharpen this point. In the Indian Sundarbans, repeated cyclonic disturbance and rising salinity were associated with reduced soil organic blue carbon, nutrient decline, local loss of salinity-sensitive taxa, and a shift toward more homogeneous, salinity-tolerant assemblages dominated by species such as *Avicennia marina* [38]. This is not simply a story of damage, but of compositional and functional reorganization under climate stress. The ethical implication is significant: management that reports area maintained or expanded may still mask deteriorating ecological quality and reduced livelihood security. Similarly, in the Mai Po Nature Reserve, substantial mangrove expansion under protection appears to have occurred partly at the expense of mudflat habitat, creating an internal conservation trade-off rather than a straightforward win [33]. The lesson is that successful mangrove conservation cannot be judged exclusively by mangrove area increase; managers must also assess habitat mosaics, biodiversity complementarities, and downstream user effects.

At local and regional scales, land use change remains a major driver. The Muthupet Lagoon analysis documented dense mangrove degradation associated with salinity, coastal erosion, salt pans, aquaculture, and other human activities, even while sparse mangrove area increased due to restoration effort [28]. In Bali, time-series monitoring of abandoned aquaculture landscapes showed mangrove expansion inside and outside ponds, but also demonstrated that replanted *Rhizophora* stands had far lower regeneration than natural mangrove assemblages dominated by

*Avicennia* and *Sonneratia* [27]. These paired studies reveal a recurring theme across the corpus: restoration can produce visible vegetation gains while still locking systems into simplified structure, low regeneration, or hydrologically constrained trajectories [27, 28, 36, 37]. In practical terms, restoration quality matters more than planting counts.

Spatial heterogeneity also appears strongly in national and subnational assessments. Langsa City in Aceh showed increased mangrove area over time but also extensive damaged and severely damaged zones, underscoring the coexistence of recovery and critical degradation within the same landscape [43]. Panguil Bay in the Philippines likewise displayed substantial historical reduction followed by partial recovery through rehabilitation programs, yet remaining fragmentation and uneven regeneration across municipalities [44]. In Southeast Mauritius, a 2026 geospatial framework identified both expansion zones and areas of severe decline, while also detecting recent decreases in vegetation health despite some gains in area [32]. Such findings suggest that management must differentiate among contraction zones, expansion zones, and latent stress zones rather than treating all mangroves as equally threatened or equally resilient.

The literature also broadens the spectrum of pressures beyond deforestation alone. Illegal logging can dramatically reduce carbon stocks, as shown in North Sumatra where UAV photogrammetry and field surveys captured a steep one-year decline in aboveground biomass and carbon following renewed extraction [31]. Invasive species are another underappreciated threat, with UAV-based deep learning developed specifically to identify *Derris trifoliata* in South China's mangrove systems [30]. Sedimentation, although explored more broadly in coral reef contexts than directly in mangroves in the supplied literature, reminds us that adjacent coastal ecosystem processes can reshape mangrove function and management priorities [55]. Even where mangrove cover

is stable, pressures on associated fauna, microbial communities, fisheries, and sediment dynamics may alter system resilience [35, 42, 45, 48].

A major insight from the newer literature is that mangrove trajectories should be read as social-ecological signals rather than merely vegetation signals. For example, the Brazilian protected area study found that protected areas can reduce fragmentation and loss, yet governance tools such as management plans and councils did not on their own produce significantly stronger conservation outcomes [51]. Similarly, global policy assessments found that many high-value loss areas remain insufficiently addressed under current target formulations [6]. These findings reframe “status” as partly a governance diagnostic. Where ecological gains occur, analysts must still ask whether they are institutionally durable, socially legitimate, and robust to future coastal change.

### **ETHICS, GOVERNANCE, AND POLICY COHERENCE**

Ethics enters mangrove management through questions that are often disguised as technical design: who decides, who benefits, who loses access, who carries risk, and what counts as success. The attached literature is especially rich on this front. Global assessments show that a large proportion of mangroves are now under some form of explicit national legal protection, and that countries differ in how they combine environmental impact assessment, coastal planning, community management, and cross-sectoral coordination [5]. Yet the same evidence also implies that legal existence does not guarantee practical protection, procedural fairness, or ecological effectiveness. This distinction is essential for a rigorous review article. Law can designate value; governance determines whether value is enacted.

The GBF-related analysis deepens this concern by showing that high-value mangrove losses frequently occur outside protected zones and that many national

targets remain too weak or incomplete to halt loss within the 2030 horizon [6]. From an ethics perspective, this is a problem of both omission and misalignment. Protection is often allocated where it is politically or administratively feasible rather than where ecological function, livelihood dependence, or exposure to risk is highest. In other words, the geography of policy can diverge from the geography of need. The reviewed studies suggest that ethical governance in mangrove systems requires at least three forms of fit: ecological fit between intervention and site conditions; institutional fit between regulations and implementation capacity; and social fit between management rules and local livelihood realities [5, 6, 8, 9, 11, 12]. Several case studies illuminate how lack of fit manifests on the ground. In the Andaman Islands, mangrove governance after the 2004 earthquake and tsunami was constrained by top-down management, poorly regulated fisheries, limited community participation, conflicts over resources and ownership, and restoration efforts that did not always adapt to new elevation conditions [11]. In the Jaffna Peninsula, post-conflict management was hindered by land permit issues, overlapping jurisdictions, weak interaction among stakeholders, failed replantation attempts, and a scarcity of scientific data [12]. In both cases, governance challenges are not secondary to ecological management; they are the main mechanism through which ecological goals are enabled or blocked. These studies show that ethics in mangrove management is inseparable from recognition of local history, institutional pluralism, and the need for transparent rule-making.

The review literature also indicates that governance tensions are recurrent across regions. Coastal wetland policy scholarship identifies uncontrolled development, mismatched territorial planning, weak adaptation, and insufficient integration of local populations in decision-making as pervasive challenges [9]. The Mesoamerican Reef review similarly highlights a disconnect between the threats emphasized by managers

and those emphasized by researchers, alongside governance opacity and geopolitical differences that reduce management efficacy [10]. Such evidence suggests a knowledge ethics issue: whose evidence is prioritized, and how are management agendas constructed? When scientific emphasis diverges from operational experience, governance can become technocratic without being useful, or locally pragmatic without being evidence-based. A top-tier review should therefore not treat “more science” as an automatic solution. The key is better institutional coupling between knowledge production and decision processes.

Community participation emerges across the corpus as both a normative and instrumental necessity. Bio-rights schemes in Indonesia linked micro-credit to conservation services and increased active participation in mangrove restoration and protection [16]. Community-based restoration in the Indian Sundarbans showed that grassroots participation can support both ecology and livelihoods [15]. Studies from South Sulawesi and Jakarta’s coastal fringe emphasized that communities want involvement in planning, implementation, and monitoring, and that counseling, working groups, land certainty, and seed availability all influence outcomes [17, 22]. These cases do not imply that all participation is automatically fair or effective. Participation can be symbolic, burdensome, or captured by elites. But across the reviewed evidence, exclusion consistently appears as a risk factor for restoration failure, mistrust, and weak stewardship [11, 12, 16, 17, 18, 22].

An ethics lens also changes how one interprets blue carbon policy. The Indonesian blue carbon review positions mangroves as central to climate mitigation and calls for integrated policy, coordination, and funding

frameworks [7]. This is strategically important: carbon can elevate mangroves from a marginal conservation concern to a national climate priority. Yet blue carbon agendas also raise classic justice questions. If carbon becomes the dominant rationale, will local users be compensated for restrictions? Will restoration prioritize carbon-dense species or sites over culturally and economically important uses? Will financing mechanisms reward communities that already conserve, or mainly actors able to document carbon gains? Although the supplied studies do not answer all these questions directly, the vulnerability lens applied in Palawan and the adaptation work in Bangladesh show why they matter: mangrove-related ecosystem services are deeply tied to food security, adaptive capacity, and uneven social exposure [39, 40]. Ethical blue carbon policy must therefore move beyond aggregate mitigation potential and explicitly address social vulnerability and benefit distribution.

Protected areas illustrate another ethical paradox. They remain indispensable, and recent evidence from Brazil indicates they can stabilize mangroves by reducing fragmentation and cover loss [51]. Yet the same study found that governance tools such as plans and councils did not significantly improve outcomes, implying that formal participation structures can exist without meaningful practice. The Mexico literature likewise shows that conservation and tourism policies can reshape communal spaces in ways that create new socioenvironmental tensions [13]. Protected areas, then, should not be idealized as ethically self-justifying. Their legitimacy depends on whether they protect ecosystems while respecting local rights, providing fair alternatives, and engaging affected communities in durable ways.

**Table 2. Mangrove ecological change, restoration pathways, and site-specific management evidence**

System/process	Study context	Core finding	Key risk or constraint	Strategic implication	Ref.
Cyclone-driven salinity change	Indian Sundarbans	Salinity increase reduced blue carbon and shifted species composition	Climate shocks can erode both carbon and biodiversity	Adaptation must address salinity, nutrients, and species turnover	[38]
Mangrove expansion under protection	Mai Po, Hong Kong	Strong expansion occurred, but mudflat loss emerged as a trade-off	Area gain may reduce habitat diversity	Evaluate habitat mosaics, not mangroves alone	[33]
Post-aquaculture revegetation	Bali, Indonesia	Mangroves expanded, but planted <i>Rhizophora</i> regenerated poorly	Monoculture-style restoration can limit resilience	Favor natural recruitment and species-hydrology fit	[27]
Dense mangrove degradation and sparse recovery	Muthupet Lagoon, India	Human pressures degraded dense stands while restoration increased sparse cover	Apparent recovery can mask structural decline	Monitor condition classes, not only net area change	[28]
Secondary forest dynamics after harvest	Bintuni Bay, Indonesia	Thirty-year secondary forests retained substantial standing stock and biomass	Production systems require regeneration evidence	Managed use needs long-rotation ecological monitoring	[34]
Restored stand age and sediment microbes	Malaysia	Older restored stands had more stable, diverse bacterial networks	Younger restored stands may remain functionally fragile	Include belowground recovery in success metrics	[35]
Hydrological manipulation	Semiarid Mexico	Underground pipes reduced hypersalinity and improved recruitment conditions	Poor hydroperiod can block recovery even with planting	Restore hydrology before or alongside planting	[36]
Constructed platforms and nonlinear modeling	Semiarid Mexico	Modeled platform placement enabled long-term afforestation	Inappropriate siting reduces survival	Ecological engineering should be site-modeled, not generic	[37]
Urban rehabilitation	Kali Adem, Jakarta	Success depended on land stability, tenure, seeds, and stakeholder support	Urban mangroves are highly contingent on enabling conditions	Rehabilitation requires infrastructure-governance alignment	[22]
Land suitability and carrying capacity	East Kalimantan	Suitability constrained by density, pH, and salinity	Development pressure can exceed site limits	Assess carrying capacity before zoning decisions	[26]
Illegal logging and carbon loss	North Sumatra	Carbon stock fell sharply after renewed logging	Restoration gains can be rapidly reversed	Monitoring must detect enforcement failures early	[31]
Restoration prioritization	Southeast Mauritius	Spatial MCDA identified highly suitable restoration zones	Area expansion alone does not define priority	Prioritize by connectivity and stress profiles	[32]

## **RESTORATION, REHABILITATION, AND ADAPTIVE MANAGEMENT**

The literature strongly rejects a simplistic “plant more mangroves” paradigm. Restoration success depends on hydrology, geomorphology, tenure, species selection, community buy-in, and follow-up monitoring. This conclusion appears across diverse settings and methods. The semiarid Mexico studies are especially instructive: enhancing hydroperiod with underground pipes markedly reduced hypersaline conditions, while combining hydrodynamic modeling with constructed platforms created favorable recruitment sites that remained functional after many years [36, 37]. The implication is foundational: in many degraded systems, hydrological dysfunction is the limiting factor, so planting without restoring tidal connectivity is ecologically inefficient and ethically questionable because it consumes funds and labor while providing weak long-term returns.

This insight resonates with work in Indonesia and India. Urban rehabilitation in Kali Adem succeeded not because seedlings were planted in large numbers alone, but because land stability, land tenure certainty, seed availability, and stakeholder collaboration were addressed together [22]. Community-based restoration in the Sundarbans is similarly presented as effective when local participation is substantive and intertwined with livelihood support [15]. Bio-rights schemes extend this logic by institutionalizing reciprocal obligations between livelihood incentives and conservation actions [16]. These studies move restoration from a biophysical event to a governance arrangement. Planting becomes only one component of a broader adaptive management cycle involving incentives, rights, maintenance, and local monitoring.

Recent ecological studies broaden what counts as recovery. The Bintuni Bay analysis demonstrates that secondary mangrove forests can accumulate substantial standing volume and extractable biomass over a 30-year rotation, contributing evidence relevant

to managed-use systems [34]. Meanwhile, the study of restored *Rhizophora apiculata* stands in Malaysia shows that bacterial communities and sediment properties continue to change with stand age, with older stands exhibiting more stable, diverse, and better-connected microbial networks [35]. Together, these findings suggest that restoration success should not be judged only by early survival or canopy closure. Functional recovery includes stand structure, regeneration capacity, belowground microbial organization, nutrient status, and resilience to salinity. A review that ignores these dimensions would be technically incomplete.

The Bali time-series study provides a cautionary example of why such broader criteria matter. It documented mangrove expansion within abandoned aquaculture landscapes, yet also found that dense *Rhizophora* plantations had low regeneration compared with natural mangroves [27]. This indicates that visually successful restoration can still produce simplified ecosystems with weaker self-renewal. Similar caution emerges from studies on suitability and ecological sustainability. In East Kalimantan, land suitability for conservation depended on density, pH, salinity, and substrate conditions, showing that site constraints should shape management zoning [26]. In Jeneponto, ecological sustainability assessment for mangrove ecotourism identified a generally sustainable status but also pinpointed low-value dimensions requiring improvement, especially tree thickness [20]. These findings support a shift from project-oriented restoration to adaptive landscape management grounded in site diagnostics and multi-criteria evaluation.

Adaptive management also requires clear thinking about production and use. The literature does not present mangrove management as synonymous with strict exclusion. In Bintuni Bay, sustained timber production is analyzed through a regeneration and standing-stock lens [34]. In

Madura, mangrove ecosystems are linked to sustainable coastal economies through non-fish fisheries that contribute significantly to household income [41]. In Batu Ampar, policy debates around mangroves as charcoal raw material reveal the difficulty of reconciling local dependence with conservation goals [24]. These studies show that utilization is not intrinsically unethical or unsustainable; the critical question is whether use regimes remain within ecological limits, are based on transparent rules, and distribute benefits in ways that do not incentivize degradation. Restoration planning that ignores resource dependence may be politically brittle, while utilization planning that ignores regeneration dynamics may be ecologically irresponsible.

A major lesson from the recent corpus is that restoration should be evaluated against counterfactuals. What would have happened without intervention? Would natural recruitment have outperformed planting? Would hydrological repair have been more cost-effective than seedling campaigns? The evidence from post-aquaculture recovery, hydrological manipulation, and geospatial prioritization suggests that intervention intensity should be calibrated to the actual limiting factor [27, 32, 36, 37]. In some sites, passive or assisted natural regeneration may be preferable; in others, engineered or species-specific interventions are justified. Ethically, this matters because mis-specified restoration can waste public resources, volunteer labor, and community trust. It can also create an illusion of action that delays more fundamental reforms such as tenure clarification, aquaculture regulation, or enforcement against logging [22, 24, 31].

The restoration literature therefore points toward a mature doctrine of adaptive management with five elements. First, diagnose the site ecologically, including hydrology, salinity, substrate, elevation, and disturbance history [26, 36, 37, 38]. Second, diagnose the governance context, including tenure, access, stakeholders, and sources of conflict [11, 12, 22, 24]. Third, design

interventions that match both diagnoses, rather than deploying standardized planting templates [15, 16, 27, 32]. Fourth, monitor multiple dimensions of recovery, from canopy and condition to carbon, regeneration, and microbial dynamics [29, 31, 34, 35]. Fifth, adapt rules and incentives over time. This framework is implicit across the literature and should become explicit in future mangrove restoration guidelines.

## **MONITORING, MAPPING, AND ANALYTICAL INNOVATION**

One of the most visible developments in the supplied literature is the rapid diversification of monitoring methods. Mangrove assessment has expanded from field vegetation surveys and interviews to encompass multi-temporal satellite analyses, UAV photogrammetry, deep learning classification, phenocams, and decision-support tools for restoration targeting [27, 28, 29, 30, 31, 32, 33, 42]. This methodological turn matters because ethics and governance require evidence that is timely, spatially explicit, and interpretable across agencies and communities.

At broad scales, remote sensing now supports both status assessment and trend diagnosis. Global NDVI analysis detected an overall growing trend and spatially differentiated the roles of precipitation, temperature, and salinity in mangrove condition [4]. Global typologies of coastal wetland status further show how multiple indicators can be synthesized into interpretable management clusters [3]. These approaches are valuable because they move beyond isolated case reporting and help identify where certain combinations of pressures recur. However, the literature also cautions against reducing management to single indicators. As the typology study notes, areas categorized through one dimension of risk may not align neatly with others [3]. In practice, this means that area change, NDVI, or protection status should not be treated as complete proxies for ecosystem integrity.

Mid-scale and local studies show how newer tools can sharpen management decisions. In Surabaya, Sentinel-2 imagery and spectral analysis were used to map species distribution and density, producing information directly relevant to conservation planning [29]. In Southeast Mauritius, geospatial multi-criteria analysis integrated change detection, health assessment, terrain, hydrology, and freshwater access to identify highly suitable restoration zones [32]. These studies exemplify an increasingly action-oriented remote sensing tradition: monitoring is no longer just descriptive but prescriptive, supporting prioritization, zoning, and site selection. The ethical value of such tools lies in their potential transparency. If openly communicated, they can help justify why some sites are prioritized and others are not.

UAV-based approaches are particularly promising for detecting threats that conventional satellite products may miss. Deep learning on UAV imagery improved identification of invasive *Derris trifoliata* in South China [30], while UAV photogrammetry combined with field surveys quantified sharp carbon loss following illegal logging in North Sumatra [31]. These methods address two longstanding management problems: fine-grained detection of ecological disturbance and rapid verification of enforcement failures. In governance terms, they can reduce ambiguity about whether degradation is occurring and where. Yet they also raise ethical and practical questions about data access, technical capacity, and surveillance. If high-resolution monitoring is available only to external actors or remains uninterpretable to local stakeholders, it could reinforce rather than reduce power asymmetries. The literature implies, though does not fully develop, the need for participatory data governance alongside technical innovation.

Phenocams and repeated photography add another useful dimension: temporal ecological process. In Thailand, digital

repeat photography revealed diurnal and seasonal interactions between canopy signals, tidal water levels, and water color, including lunar periodicity in seasonal vegetation metrics [42]. This is important because it shows how easy it is to misread mangrove “greenness” without accounting for water background effects. For a top-tier review, the deeper implication is methodological humility. Mangrove systems are intertidal and optically complex; monitoring methods must reflect that complexity rather than import terrestrial assumptions uncritically. The same point is supported by the Mai Po study, where sediment supply, shoreline progradation, and management intervention shaped long-term expansion [33]. Change detection is thus strongest when remote sensing is interpreted through geomorphological and management context.

Field-based ecological inventories remain indispensable. The Langsa biophysical study, Panguil Bay status assessment, and Bintuni production-forest inventory all demonstrate the value of direct measurement for species composition, density, regeneration, and biomass estimation [34, 43, 44]. These data provide the calibration and ecological detail that remote sensing alone cannot supply. Likewise, microbial and biochemical studies—whether on restored sediment bacterial communities, actinobacterial diversity, amylase-producing *Streptomyces*, sex-related responses in *Excoecaria agallocha*, or snail growth rates—show that mangrove monitoring must include functional and organismal dimensions if it is to support biodiversity-conscious management [35, 45, 46, 47, 48]. While some of these studies are not immediately managerial, they widen the concept of what mangrove integrity includes.

A useful synthesis across the monitoring literature is the idea of layered observability. Satellite time series are strong for regional trends and broad prioritization [4, 27, 28, 29, 32, 33]. UAVs are strong for local threat detection and high-resolution carbon or

invasive-species assessment [30, 31]. Field measurements are strong for species, regeneration, biomass, sediment, and community-level condition [34, 43, 44]. Participatory and interview methods are strong for perceived drivers, governance

failures, and adaptive capacity [11, 12, 18, 23, 39, 40]. Top-tier mangrove management research will increasingly depend on combining these layers rather than choosing among them.

**Table 3. Monitoring and decision-support tools in the reviewed mangrove literature**

Method/tool	Spatial scale	Management question addressed	Main strength	Key limitation or caution	Ref.
Global NDVI time series	Global	Are condition trends improving or deteriorating?	Consistent long-term trend assessment	Vegetation increase does not capture all functional change	[4]
Coastal wetland typologies	Global	Which regions share similar wetland pressure/status profiles?	Integrates multiple indicators for prioritization	Single clusters can obscure local complexity	[3]
Legal and policy analysis	Global/national	Do jurisdictions explicitly protect mangroves?	Reveals governance architecture	Legal presence does not equal implementation	[5]
Policy-target analysis under GBF	Global/national	Can national targets address loss drivers?	Connects spatial loss with policy ambition	Protected-area focus may miss broader drivers	[6]
VHSR image time series	Estuary/landscape	How do mangroves recover after aquaculture abandonment?	Fine-grained trajectory analysis	Needs ground truth for ecological interpretation	[27]
Landsat change detection	Regional/local	Where is degradation or sparse recovery occurring?	Multi-decadal accessible monitoring	Class mapping can hide structural simplification	[28]
Sentinel-2 spectral analysis/LSU	Conservation area	Which species and density classes dominate?	Actionable species-density mapping	Spectral separability varies by site and season	[29]
UAV + deep learning	Local	Where are invasive plants spreading?	High accuracy with fine detail	Training data and transferability remain constraints	[30]
UAV photogrammetry + field survey	Local	How much carbon has been lost after logging?	Rapid high-resolution carbon accounting	Requires technical capacity and validation	[31]
MCDA restoration prioritization	Regional/local	Where should restoration resources be targeted first?	Transparent prioritization logic	Output depends on weighting and input quality	[32]
Reserve spatiotemporal machine-learning analysis	Protected area	What are long-term growth patterns and trade-offs?	Links ecological trend with drivers and management	Expansion can conceal cross-habitat trade-offs	[33]
Phenocams/repeat photography	Stand/canopy	How do canopy signals vary with water and tides?	Captures high-frequency dynamics	Optical signals are influenced by water background	[42]

## **LIVELIHOODS, ECOTOURISM, BLUE CARBON, AND COASTAL ECONOMIES**

A major strength of the supplied literature is its refusal to treat mangroves only as conservation objects. Many studies foreground their role in sustaining livelihoods, adaptive capacity, and local economies. This is particularly clear in work on community participation, ecotourism, blue carbon, fisheries, and non-fish coastal resources [15, 16, 19, 20, 39, 40, 41]. For a publication-oriented review, the key analytical move is to connect these livelihood dimensions to governance quality and ecological condition rather than discussing them as separate topics.

Ecotourism is frequently presented as a mechanism for aligning income with conservation. In Karangsong, positive local perceptions were linked to economic benefits and strengthened motivation for mangrove conservation, while effective management depended on local involvement and active driver groups [19]. In Jenepono, ecological indicators suggested that mangrove ecotourism could be sustained if lower-scoring dimensions were improved [20]. Urban rehabilitation at Kali Adem was even linked to the creation of an eco-marine tourism area [22]. However, the broader tourism literature in the corpus introduces needed caution. Work from Ecuador and the Galapagos emphasizes the importance of integrated coastal zone management, policy coherence, and citizen participation for tourism sustainability [49, 50], while the West Bengal tourism perception study documents strong local concern about environmental impacts such as habitat fragmentation, waste disposal, and forest clearance [53]. Taken together, these studies suggest that ecotourism is ethically attractive only when carrying capacity, infrastructure impacts, and local benefit distribution are governed deliberately. Otherwise, “eco” branding can legitimize new pressures on already vulnerable coasts.

Blue carbon has become a particularly powerful organizing idea in recent mangrove policy. The Indonesian review argues that recognition of mangroves’ climate value has elevated their political salience and created opportunities for integrated national strategy, while also exposing regulatory gaps and coordination challenges between forestry and marine sectors [7]. This policy shift is reinforced by social-vulnerability research in the Philippines, which shows that mangrove-related ecosystem services contribute materially to fisheries, livelihoods, and adaptive capacity, with vulnerability differing across communities according to livelihood diversity, ecosystem condition, and organizational support [40]. The ethical implication is that blue carbon should not be treated only as a carbon-accounting exercise. Its legitimacy depends on whether climate policy supports or displaces the people whose wellbeing is already tied to blue carbon ecosystems.

The literature on local adaptation in coastal Bangladesh supports this argument. Adaptation there involved rainwater harvesting, crop diversification, local filtering, cyclone shelters, and coastal afforestation, illustrating how ecosystem-based measures and social infrastructure coexist in real resilience strategies [39]. This complements the Eco-DRR study in Indonesia, which warns that local communities can feel left behind even within ostensibly participatory environmental programs [18]. Together, these studies indicate that ecosystem-based adaptation is not ethically neutral. It can either deepen trust and capacity or reproduce exclusion depending on who controls space, whose anxieties are acknowledged, and whether livelihoods are stabilized.

Resource use studies further complicate the conservation-development binary. In Madura, non-fish fisheries associated with mangrove ecosystems contributed substantially to household income, and stronger conservation practices were associated with higher economic returns and

ecological stability [41]. This finding is analytically important because it broadens the concept of mangrove economy beyond timber or tourism. It also aligns with the vulnerability study showing that mangrove fisheries can matter significantly to social resilience, even where catch sensitivity remains high [40]. By contrast, the Batu Ampar charcoal case illustrates the opposite dynamic: heavy dependence on mangroves as raw material can drive degradation and force difficult policy choices around forest status, funding, and user capacity [24]. These examples suggest that ethical mangrove management should not ask whether local use exists, but what forms of use are ecologically regenerative, socially fair, and governable over time.

The ecosystem-services literature provides a useful conceptual bridge. Early review work in Indonesia already argued that ecosystem services should serve as an organizing framework for management, connecting ecological function to human wellbeing and policy strategy [1]. More recent blue carbon and vulnerability studies operationalize this bridge by linking mangrove condition to mitigation, fisheries, and adaptive capacity [7, 40]. Yet services language can also become reductive if it counts only what is easily monetized. The stakeholder and governance studies remind us that goods and services are embedded in community identity, historical access, and local institutional memory [11, 12, 13, 14]. Ethical review writing should therefore treat ecosystem services as necessary but insufficient. Recognition, justice, and participation are not secondary “social add-ons” to service provision; they shape whether ecosystem services are sustained and by whom they are enjoyed.

### **EMERGING ECOLOGICAL FRONTIERS AND UNDERUSED DIMENSIONS**

Although governance, restoration, and monitoring dominate much of the corpus, several studies point to underdeveloped

ecological dimensions that deserve more attention in future syntheses. One such frontier is belowground and microbial recovery. The restored-stand chronosequence in Malaysia demonstrates that bacterial community structure, stability, and network connectivity vary strongly with stand age and sediment properties, especially salinity and carbon content [35]. This suggests that restoration success metrics based only on aboveground vegetation are incomplete. Older restored stands may look successful from the surface but still differ functionally from intact systems, while younger stands may remain fragile despite visible canopy establishment.

A second frontier involves biotic interactions and species-specific responses. The review of mangrove actinobacteria identifies limited but growing knowledge of microbial diversity and novel *Streptomyces* from mangrove systems [45], while the Egyptian sediment study highlights the industrial and biotechnological promise of mangrove-derived actinomycetes [46]. The study on sex-related differences in *Excoecaria agallocha* further shows that even within a single mangrove species, ecological function and biochemical investment can vary substantially [47]. Snail growth studies from northern Australia remind us that faunal metrics can be useful indicators of community condition and environmental gradients [48]. These studies are peripheral to mainstream policy debate, but they signal a broader point: mangrove integrity includes evolutionary, microbial, biochemical, and faunal dimensions that are often omitted from management discourse.

A third frontier concerns inter-ecosystem linkages. The global wetland typology work and the broader coastal wetland policy review already encourage cross-ecosystem thinking [3, 9]. The coral sedimentation review, although not mangrove-specific, reinforces the importance of catchment-to-coast processes and sediment pathways in shaping coastal ecosystem health [55]. This matters because mangrove management

often interacts with mudflats, estuaries, fisheries grounds, coral systems, and built coastal infrastructure. The Mai Po study explicitly shows that even apparently successful mangrove expansion can generate habitat trade-offs with mudflats [33]. Future mangrove scholarship should therefore avoid ecosystem isolation and instead embed mangroves within wider coastal mosaics.

## **RESEARCH AND POLICY AGENDA FOR TOP-TIER MANGROVE SCHOLARSHIP**

The reviewed literature allows several priorities to be stated with confidence. First, future mangrove research should move from counting area and planting effort toward evaluating functional, social, and institutional outcomes together. This means integrating indicators of hydrology, salinity, regeneration, carbon, microbial recovery, habitat trade-offs, and stakeholder legitimacy into one evaluative framework [3, 4, 11, 12, 27, 35, 38]. Second, legal and policy analysis should focus more directly on implementation pathways. Global studies have already shown where law exists and where national targets remain inadequate [5, 6]; the next step is to explain why some jurisdictions translate law into protection and others do not.

Third, participatory governance needs sharper analytical treatment. Many studies recommend community involvement, but fewer specify what meaningful participation looks like, how conflict is mediated, how burdens are shared, or how local knowledge enters technical decisions [11, 12, 15, 16, 17, 18]. A stronger ethics-oriented research agenda would compare participatory forms not just by presence or absence, but by depth, accountability, and distributive outcome. Fourth, restoration science should continue to move beyond generic planting campaigns. Hydrological rehabilitation, species-habitat matching, post-project monitoring, and restoration prioritization frameworks already provide a strong basis for this shift [27, 32, 36, 37]. Fifth, monitoring systems should be

designed for governance use, not merely scientific publication. This implies interoperable methods, public-facing dashboards, and mechanisms through which local stakeholders can interpret and contest monitoring outputs.

Sixth, blue carbon scholarship should integrate justice explicitly. The current literature establishes strong policy momentum and social relevance [7, 40], but future work should better track who receives benefits, how restrictions are negotiated, and whether carbon programs strengthen or weaken local adaptive capacity. Seventh, livelihood research should expand beyond ecotourism and timber to include fisheries, non-fish resources, and hybrid coastal economies [19, 20, 24, 41]. Finally, comparative work should become more historically attentive. The post-conflict, post-tsunami, and post-aquaculture cases in the corpus show that mangrove governance is path dependent [11, 12, 27]. Interventions succeed or fail partly because of legacies of damage, ownership, and institutional trust.

For publication in a top-tier journal, the broader message is straightforward but demanding: the next phase of mangrove scholarship must be integrative without becoming vague, normative without becoming ungrounded, and policy-relevant without losing ecological specificity. The evidence in the attached literature already points in this direction. What remains is to translate that evidence into management frameworks that are empirically disciplined and ethically explicit.

## **CONCLUSION**

The supplied literature shows that mangrove management has entered a new phase. The field no longer revolves solely around documenting decline or promoting restoration in generic terms. It increasingly addresses how biodiversity, carbon, hydrology, fisheries, tourism, law, and community life are organized across dynamic coastal landscapes [1, 2, 5, 7, 8]. This review argues that ethics should be

placed at the center of that conversation. Ethical mangrove management does not simply protect trees; it aligns ecological intervention with fair procedures, realistic livelihoods, transparent trade-offs, and accountable institutions [9, 11, 12, 13, 16, 18, 51, 52].

Three conclusions follow from the synthesis. First, ecological recovery is highly contingent. Area gains or planting outputs are insufficient indicators of success unless they are supported by hydrological fit, regeneration, functional recovery, and protection from renewed degradation [27, 31, 32, 35, 36, 37]. Second, governance is decisive. National legal protection, biodiversity targets, protected areas, and local participation all matter, but none are effective in isolation [5, 6, 10, 11, 12, 51]. Third, social legitimacy is not optional. Mangrove futures will be durable only where local communities are not merely consulted but recognized as rights-bearing actors whose livelihoods, knowledge, and vulnerabilities shape what sustainable management can mean in practice [15, 16, 17, 18, 39, 40, 41].

Recent advances in remote sensing, UAV analysis, machine learning, phenological observation, and geospatial prioritization provide unprecedented opportunities for evidence-based intervention [29, 30, 31, 32, 33, 42]. Yet the literature also warns that better tools do not automatically resolve ethical and political questions. The core challenge is therefore integrative governance: to combine ecological intelligence, legal coherence, participatory legitimacy, and adaptive finance into management systems capable of withstanding coastal change. On the basis of the attached evidence base alone, that is the strongest conclusion available—and the most compelling agenda for future mangrove scholarship and practice.

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