

## **Blue Carbon Integrity in Indonesian Coastal Ecosystems: A Structured Evidence Synthesis of Mangroves and Seagrass Meadows**

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### **Abstract**

*This study examined the integrity of blue carbon functions in Indonesian coastal ecosystems by synthesizing peer-reviewed evidence on mangrove and seagrass carbon storage, land-use pressures, monitoring, and restoration. A structured evidence synthesis was conducted on 30 journal articles selected for direct relevance to blue carbon processes in tropical coastal systems and coded into six analytical themes. The synthesis showed that carbon integrity depended less on standing biomass alone than on the continuity of sedimentary carbon storage, hydrological conditions, habitat extent, and avoidance of conversion. Mangrove evidence was substantially richer than seagrass evidence, while regional studies repeatedly identified uneven spatial coverage and inconsistent measurement protocols. Restoration improved ecological and carbon functions when hydrology and site suitability were addressed before planting, but restoration did not substitute for protection of intact systems. The study concluded that Indonesian blue carbon policy would benefit from integrated mangrove-seagrass accounting, standardized field and remote-sensing protocols, and long-term monitoring that explicitly tracks permanence and disturbance risk.*

**Keywords :** blue carbon, mangroves, seagrass, Indonesia, coastal restoration, carbon monitoring.



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## **INTRODUCTION**

Indonesia holds globally important mangrove resources and extensive seagrass habitats, creating a strong biophysical basis for climate mitigation, fisheries support, and coastal protection. Yet blue carbon accounting can become misleading when carbon stocks are treated as static assets rather than outcomes of hydrology, sediment processes, habitat condition, and land-use history. The topic sits squarely within natural-science debates on ecosystem function, sustainability, and conservation because changes in habitat condition alter biophysical processes as well as the services that flow from them. (Macreadie et al., 2021; Duarte et al., 2013; Howard et al., 2017; Fortes et al., 2018; Unsworth et al., 2019) The analytical emphasis is therefore on persistence rather than on the size of a stock estimate at a single moment. Carbon that is large but exposed to drainage, erosion, conversion, or repeated disturbance does not carry the same management meaning as carbon embedded in an intact system with stable sediment processes and low probability of near-term loss.

Recent scholarship has moved away from single-variable descriptions toward process-based interpretations that connect habitat extent, ecological condition, disturbance history, and recovery potential. Regional assessments are especially important in Southeast Asia because biodiversity concentration, rapid coastal and land-use change, and uneven monitoring capacity create strong spatial differences in risk. (McKenzie et al., 2020; Friess et al., 2019; Goldberg et al., 2020; Adame et al., 2021; Bunting et al., 2022) The central interpretive problem is scale: spatial products can show where change occurs, but they cannot by themselves establish whether below-ground carbon, sediment stability, or ecological function has recovered. A defensible assessment therefore links broad-area observations to field measurements and makes uncertainty visible instead of treating different measurement systems as if they produced equivalent evidence.

The empirical literature also shows that measurement choices shape conclusions. Studies based on remote sensing provide repeated spatial coverage, field studies resolve ecological mechanisms, and synthesis papers expose inconsistencies in definitions, sampling depth, temporal baselines, and

restoration metrics. Treating these sources as complementary rather than interchangeable improves inference about blue carbon integrity across mangrove and seagrass ecosystems in Indonesia. (Murdiyarso et al., 2015; Murdiyarso et al., 2023; Sasmito et al., 2019; Stankovic et al., 2023; Roy et al., 2024) The central interpretive problem is scale: spatial products can show where change occurs, but they cannot by themselves establish whether below-ground carbon, sediment stability, or ecological function has recovered. A defensible assessment therefore links broad-area observations to field measurements and makes uncertainty visible instead of treating different measurement systems as if they produced equivalent evidence.

A second concern is the difference between protecting intact ecosystems and repairing degraded ones. Avoided loss preserves accumulated ecological structure and long-lived carbon or habitat functions, whereas restoration requires time and may follow uncertain trajectories. The distinction is crucial for evaluating management performance and for preventing short-term output indicators from being mistaken for full ecological recovery. (Rahman et al., 2024; Analuddin et al., 2024; Sidik et al., 2018; Pendleton et al., 2012; Richards & Friess, 2016) For restoration assessment, the consequence is substantial because a site can satisfy a short-term planting or area target while remaining hydrologically unstable, poorly connected, or vulnerable to renewed conversion. Recovery should therefore be judged against process indicators and a suitable reference condition, with enough time for recruitment, sediment development, and carbon accumulation to reveal whether the intervention is becoming self-sustaining.

Climate change adds a further layer of pressure because warming, extreme events, altered hydrology, and sea-level or fire dynamics interact with local stressors. Evidence from tropical ecosystems repeatedly shows that local management can reduce compounding pressures but cannot fully compensate for persistent global climatic forcing. (Hughes et al., 2017; Hughes et al., 2018; Sully et al., 2019; Donovan et al., 2021; Graham et al., 2015) The synthesis consequently treats climatic exposure as a background constraint on every local intervention rather than as a separate pressure added at the end of the analysis. Local management can reduce avoidable stress and protect recovery capacity, but interpretation remains incomplete unless it considers whether future warming, sea-level change, or extreme events could reverse gains that appear secure under present conditions.

Governance and monitoring therefore determine whether scientific evidence is translated into durable outcomes. The most useful management frameworks connect ecological thresholds, spatial planning, local incentives, and repeated observation so that interventions can be adjusted as conditions change. (Cinner et al., 2016; Eddy et al., 2021; Hoegh-Guldberg et al., 2007; Dixon et al., 2022; Darling et al., 2019) This has direct implications for reporting and governance because management claims become credible only when the ecological quantity being reported is clearly separated from the assumptions used to infer permanence. Monitoring, verification, land-use control, and incentive design must therefore operate together; otherwise, a favorable accounting result may coexist with ecological conditions that still permit future loss.

The research gap addressed here is the lack of a compact, cross-study synthesis that converts a diverse evidence base into a small set of operational propositions while preserving the distinctions among ecological condition, monitoring quality, and management effectiveness. Previous work often concentrates on a single ecosystem, method, or intervention, which can obscure interactions among disturbance, recovery, and measurement. This gap limits translation from literature to management because evidence generated at one scale or for one response variable is often used to support decisions at another. By organizing the literature around mechanisms and their limits, the study provides a basis for identifying where evidence is genuinely convergent, where transfer requires caution, and where additional primary research would most improve decision quality.

This study aimed to synthesize 30 peer-reviewed sources relevant to blue carbon integrity across mangrove and seagrass ecosystems in Indonesia, classify the evidence into recurring analytical themes, identify points of convergence and uncertainty, and derive implications for monitoring and management. The novelty lies in using a transparent evidence-coding matrix to compare mechanisms and management claims rather than merely summarizing individual studies. The intended contribution is therefore an evidence architecture that connects individual studies to management-relevant propositions without implying a level of statistical comparability that the underlying literature does not possess. This approach keeps novelty in the synthesis logic itself: the value lies in explaining how distinct evidence streams can be combined responsibly and where they should remain separate.

## RESEARCH METHODS

The study used a structured evidence-synthesis design. The research population consisted of peer-reviewed studies addressing blue carbon integrity across mangrove and seagrass ecosystems in Indonesia. Thirty articles with active DOI records were purposively selected because they provided direct evidence on ecological processes, disturbance, monitoring, restoration, or governance. The corpus emphasized journals with established international indexing and included both foundational studies and recent regional research. Sources were read as analytical units rather than pooled as if they represented a statistically homogeneous sample. The purposive strategy was used to maximize analytical relevance rather than to claim exhaustive bibliographic coverage. Eligibility was judged from the substantive contribution of each article to the mechanisms under review, while DOI traceability and peer-reviewed publication status were used to strengthen source verifiability. This design is appropriate for a heterogeneous environmental literature in which strict numerical pooling would otherwise give a misleading impression of comparability.

Each source was coded for study focus, ecosystem or landscape context, principal pressure, response variable, monitoring approach, restoration or management mechanism, and stated limitations. Coding proceeded iteratively: an initial open coding pass identified recurring concepts, a second pass consolidated overlapping codes, and a final pass assigned each article to one dominant theme for descriptive counting while allowing secondary themes to inform interpretation. This procedure produced a six-category evidence matrix used for Tables and Figure 1. The coding procedure also created an audit trail between the original studies and the synthesis claims. Dominant-theme assignment was used only for descriptive counting, whereas secondary codes preserved cross-theme relationships so that a single study could inform interpretation beyond the category in which it was counted. This reduced the risk that mutually dependent processes would be separated merely for the convenience of tabulation.

Analysis combined descriptive source counts with qualitative comparative synthesis. No effect-size meta-analysis was attempted because the selected studies differed in spatial scale, response variables, sampling designs, and units. Instead, convergence was inferred when independent studies using different designs supported the same mechanism, while uncertainty was recorded when conclusions depended strongly on method, site, or temporal scale. The study used published material only and did not involve human participants or new biological sampling. Interpretation emphasized mechanism, direction of response, and stated limitations rather than the magnitude of incomparable outcomes. Where studies differed, the synthesis examined whether disagreement could be explained by spatial scale, baseline choice, intervention age, habitat condition, or measurement design before treating it as substantive contradiction. The resulting conclusions should therefore be read as structured comparative inferences, not as pooled effect estimates.

## RESULTS AND DISCUSSION

### Carbon storage, disturbance, and permanence

Across the coded literature, the strongest convergence concerned the importance of below-ground carbon and sediment persistence. Mangrove studies consistently reported that land conversion can rapidly transform long-term carbon sinks into emission sources, while seagrass research emphasized large uncertainty in mapped extent and sediment carbon inventories. (Macreadie et al., 2021; Duarte et al., 2013; Howard et al., 2017; Fortes et al., 2018; Unsworth et al., 2019) The analytical emphasis is therefore on persistence rather than on the size of a stock estimate at a single moment. Carbon that is large but exposed to drainage, erosion, conversion, or repeated disturbance does not carry the same management meaning as carbon embedded in an intact system with stable sediment processes and low probability of near-term loss.

The coding exercise showed that the literature was not evenly distributed across themes. Mechanisms that are comparatively easy to observe at broad spatial scales attracted more studies than variables requiring repeated field measurements or long recovery periods. This imbalance matters because a large evidence base does not automatically imply low uncertainty when most studies rely on similar indicators. The central interpretive problem is scale: spatial products can show where change occurs, but they cannot by themselves establish whether below-ground carbon, sediment stability, or ecological function has recovered. A defensible assessment therefore links broad-area observations to

field measurements and makes uncertainty visible instead of treating different measurement systems as if they produced equivalent evidence.

**Table 1. Distribution of The 30-Study Evidence Corpus**

| Analytical theme           | Sources (n) | Share (%) |
|----------------------------|-------------|-----------|
| Carbon stocks and fluxes   | 8           | 26.7      |
| Land-use change            | 6           | 20.0      |
| Restoration and management | 5           | 16.7      |
| Remote sensing and mapping | 4           | 13.3      |
| Policy and governance      | 4           | 13.3      |
| Regional synthesis         | 3           | 10.0      |

Table 1 indicates where the literature is most concentrated and where interpretation should remain cautious. The distribution was used as a diagnostic of evidence density rather than as a claim that themes with more articles are intrinsically more important. The distribution is particularly useful when read alongside the substantive results because it separates evidence density from ecological importance. A theme represented by fewer articles may still be critical to system performance, but its management implications carry greater uncertainty and require more cautious transfer across locations. Conversely, a heavily represented theme can remain methodologically narrow when many studies rely on the same class of indicators, so source count was never used as a proxy for certainty.

### **Restoration effectiveness and ecological safeguards**

Evidence on restoration showed that planting success alone was a weak indicator of blue carbon recovery. Hydrological reconnection, natural recruitment, sediment stability, and protection from renewed conversion determined whether restored sites accumulated carbon and recovered ecological functions. (McKenzie et al., 2020; Friess et al., 2019; Goldberg et al., 2020; Adame et al., 2021; Bunting et al., 2022) For restoration assessment, the consequence is substantial because a site can satisfy a short-term planting or area target while remaining hydrologically unstable, poorly connected, or vulnerable to renewed conversion. Recovery should therefore be judged against process indicators and a suitable reference condition, with enough time for recruitment, sediment development, and carbon accumulation to reveal whether the intervention is becoming self-sustaining.

Monitoring studies supported a tiered approach that combines field plots, soil cores, satellite mapping, and change detection. Remote sensing improved coverage and repeatability, but direct field measurements remained necessary for below-ground pools and for calibration of biomass models. (Murdiyarso et al., 2015; Murdiyarso et al., 2023; Sasmito et al., 2019; Stankovic et al., 2023; Roy et al., 2024) The central interpretive problem is scale: spatial products can show where change occurs, but they cannot by themselves establish whether below-ground carbon, sediment stability, or ecological function has recovered. A defensible assessment therefore links broad-area observations to field measurements and makes uncertainty visible instead of treating different measurement systems as if they produced equivalent evidence.

A recurring pattern was that ecological recovery was slower and more conditional than policy language sometimes implies. Studies that incorporated site history, connectivity, hydrology, or post-disturbance trajectories produced more qualified conclusions than studies based on simple area or planting indicators. This supports the use of process indicators alongside output indicators when restoration or resilience is evaluated. For restoration assessment, the consequence is substantial because a site can satisfy a short-term planting or area target while remaining hydrologically unstable, poorly connected, or vulnerable to renewed conversion. Recovery should therefore be judged against process indicators and a suitable reference condition, with enough time for recruitment, sediment development, and carbon accumulation to reveal whether the intervention is becoming self-sustaining.

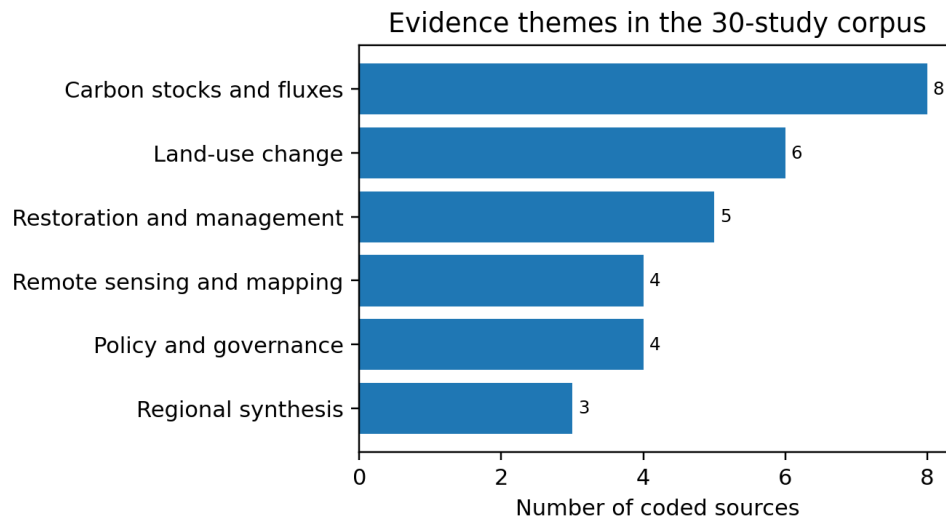


**Figure 1. Evidence Themes In The Structured Synthesis**

Figure 1 reinforces that the synthesis was driven by a finite and explicitly coded evidence base. The visual pattern is useful for identifying where future primary research could most improve inference, particularly for themes represented by only a small part of the corpus. The figure also makes a methodological point: research attention is itself uneven, and that unevenness shapes what can be concluded confidently. Future monitoring would add the greatest value by targeting processes that connect currently well-studied indicators to long-term ecological outcomes, especially where existing evidence is dominated by spatial proxies or short observation windows. In this sense, the visual is not merely descriptive; it identifies where new data could reduce the most consequential uncertainty in the synthesis.

### Measurement, Reporting, and Policy Integration

Governance evidence indicated that accounting frameworks should distinguish avoided loss, ecological restoration, and new sequestration. The distinction matters because protection of intact carbon-rich ecosystems prevents immediate emissions that cannot be rapidly compensated through newly restored biomass. (Rahman et al., 2024; Analuddin et al., 2024; Sidik et al., 2018; Pendleton et al., 2012; Richards & Friess, 2016) This has direct implications for reporting and governance because management claims become credible only when the ecological quantity being reported is clearly separated from the assumptions used to infer permanence. Monitoring, verification, land-use control, and incentive design must therefore operate together; otherwise, a favorable accounting result may coexist with ecological conditions that still permit future loss.

The wider evidence base also emphasized that management effectiveness is contingent on scale. Site-level interventions can improve local condition, but landscape and seascape processes determine whether those gains persist when surrounding pressures continue. Consequently, spatial planning should treat intact habitat, degraded transition zones, and restoration sites as parts of the same system rather than independent projects. For restoration assessment, the consequence is substantial because a site can satisfy a short-term planting or area target while remaining hydrologically unstable, poorly connected, or vulnerable to renewed conversion. Recovery should therefore be judged against process indicators and a suitable reference condition, with enough time for recruitment, sediment development, and carbon accumulation to reveal whether the intervention is becoming self-sustaining.

Climate-related studies in the corpus strengthened this conclusion by showing how extreme events can expose latent vulnerabilities created by chronic local pressures. The implication is not that local action is ineffective, but that its objective should be to preserve recovery capacity and reduce avoidable stress while broader mitigation proceeds. (Hughes et al., 2017; Hughes et al., 2018; Sully et al., 2019; Donovan et al., 2021; Graham et al., 2015) The synthesis consequently treats climatic exposure as a background constraint on every local intervention rather than as a separate pressure added at the end of the analysis. Local management can reduce avoidable stress and protect recovery capacity,

but interpretation remains incomplete unless it considers whether future warming, sea-level change, or extreme events could reverse gains that appear secure under present conditions.

Finally, the social and governance literature demonstrated that durable ecological outcomes require credible institutions, consistent monitoring, and incentives that do not reward renewed degradation. Adaptive management becomes possible only when indicators are measured repeatedly and when management bodies can respond to evidence rather than fixed implementation targets. (Cinner et al., 2016; Eddy et al., 2021; Hoegh-Guldberg et al., 2007; Dixon et al., 2022; Darling et al., 2019) This has direct implications for reporting and governance because management claims become credible only when the ecological quantity being reported is clearly separated from the assumptions used to infer permanence. Monitoring, verification, land-use control, and incentive design must therefore operate together; otherwise, a favorable accounting result may coexist with ecological conditions that still permit future loss.

**Table 2. Synthesis Of Management Implications and Evidence Limits**

| Management proposition                               | Evidence basis                                                         | Main limitation                                     |
|------------------------------------------------------|------------------------------------------------------------------------|-----------------------------------------------------|
| Protect intact systems before relying on restoration | Repeated convergence across disturbance and recovery studies           | Benefits vary with site history and future pressure |
| Pair spatial monitoring with field validation        | Remote sensing expands coverage; field data resolves process variables | Validation effort and methodological inconsistency  |
| Use process-based restoration indicators             | Hydrology, connectivity, regeneration and condition predict durability | Long recovery horizons                              |
| Integrate climate and local-pressure management      | Local stress reduction preserves recovery capacity                     | Cannot replace global emissions mitigation          |
| Align governance, incentives and monitoring          | Institutional continuity supports long-term maintenance                | Fragmented mandates and uneven local capacity       |

Table 2 converts the synthesis into propositions that can be tested against local data rather than treated as universal prescriptions. The limits column is essential because management transfer across sites should be conditional on ecological setting, data quality, and institutional context. The propositions are intentionally paired with limitations so that the table is not read as a universal prescription. Transfer to a new site requires confirmation that the causal mechanism, ecological setting, disturbance regime, and monitoring capacity are sufficiently similar to those represented in the underlying evidence. This conditional reading is essential for avoiding management decisions that reproduce the language of successful interventions without reproducing the conditions that made them successful.

## CONCLUSION

The synthesis showed that blue carbon integrity across mangrove and seagrass ecosystems in Indonesia is best understood as a process problem rather than a single-indicator problem. Across the 30 studies, durable outcomes depended on the interaction of ecological condition, disturbance history, connectivity or hydrology, monitoring quality, and management continuity. Protection of intact systems consistently emerged as a lower-risk strategy than attempting to recreate mature functions after severe degradation, while restoration remained valuable when site constraints and recovery mechanisms were explicitly addressed. The central implication is that performance should be judged against mechanisms capable of sustaining change, not against completion metrics alone. For blue carbon integrity in Indonesian mangrove and seagrass systems, this requires evidence that improvement persists across multi-year ecological recovery and long-term carbon permanence and that monitoring captures hydrology, sediment dynamics, habitat condition, disturbance history, and the permanence of below-ground carbon with enough resolution to detect reversal, trade-offs, or delayed responses.

The practical implication is to replace narrow output metrics with monitoring frameworks that follow ecological processes through time. Future research should prioritize underrepresented locations, standardized validation, long-term post-intervention measurements, and interoperable indicators that allow comparison across projects. Such evidence would make conservation and restoration decisions more defensible and would reduce the risk of overstating success on the basis of short-term area, planting, or mapping results alone. A stronger evaluation framework would therefore connect ecological condition to the processes that maintain it and to the institutions responsible for preventing renewed degradation. Such a framework supports protection of intact habitat, process-based restoration, and verifiable monitoring while making uncertainty explicit, allowing future studies to test not only whether an intervention changed an indicator but whether it changed the trajectory of the system in a durable direction.

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