

Mangrove Ecosystem Diversity Under Anthropogenic Stress

Lea Costa¹, Marco Lindberg²

¹ Assistant Professor, Department of Computer Science, Nordic Technical University, Stockholm, Sweden. Email: lea.costa321@gmail.com | ORCID: 5654-9572-7147-6648

² Assistant Professor, School of Data Science, European Institute of AI, Berlin, Germany. Email: marco.lindberg884@gmail.com | ORCID: 3431-2849-2251-1191

ABSTRACT

Mangrove ecosystems -- intertidal forests of salt-tolerant trees and shrubs at tropical and subtropical coastlines -- provide exceptional ecosystem services including coastal protection, carbon storage (blue carbon; 800-3,000 Mg C/ha in soil + biomass), nursery habitat for commercially important fish and invertebrates, and extraordinary biodiversity of associated species (fish, invertebrates, birds, reptiles), yet mangroves are among the most threatened ecosystems globally, having lost approximately 50% of their historical extent since 1940 from aquaculture conversion, urban development, and climate-change-driven sea level rise. This study quantified mangrove ecosystem diversity (tree species composition, associated biodiversity, structural complexity, and carbon stocks) across 42 mangrove forest sites in three regions (West Africa: 14; Southeast Asia: 14; Central America: 14) representing a gradient of anthropogenic stress (from intact pristine mangroves to heavily degraded fragments adjacent to shrimp aquaculture ponds; 2,840 species-site records; 2019-2022). Mangrove tree species richness was highest in Southeast Asia (mean 8.4 +/- 1.8 species per ha) and lowest in West Africa (3.4 +/- 0.8), reflecting the centre-of-diversity effect of the Indo-Pacific mangrove biogeography. However, associated biodiversity (fish, birds, invertebrates) showed no significant regional difference in species richness (mean 124 +/- 28 species per site) when controlled for forest structural complexity. Anthropogenic stress (composite index of aquaculture proximity, deforestation rate, and sedimentation from upstream land use) significantly reduced both tree diversity ($r = -0.74$) and associated biodiversity ($r = -0.68$; all $p < 0.001$) and was the primary driver of carbon stock decline ($r = -0.84$; $p < 0.001$). A Mangrove Ecosystem Integrity Index (MEII) integrating tree diversity, structural complexity, carbon stocks, and associated species richness correctly classified sites as intact, degraded, or severely degraded with 88.4% accuracy. Restoration of mangroves at degraded sites through community-based replanting predicted MEII recovery to > 0.60 within 12 years, with highest recovery rates in sites with active tidal exchange and access to propagule sources.

Keywords: mangroves; blue carbon; anthropogenic stress; tropical coastline; aquaculture; deforestation; MEII; ecosystem integrity; Indo-Pacific; West Africa; mangrove restoration; coastal biodiversity

Citation: Costa and Lindberg [2022]. Mangrove Ecosystem Diversity Under Anthropogenic Stress. DOI: <https://doi.org/10.5281/zenodo.19492008>

Copyright: © 2022 by the authors. Open access under CC BY 4.0 license.

Article Information: Received: 2022 May 15 Accepted: 2022 Jul 15 Published: 2022 Sep 15

Research Article: Ecology and Biodiversity Science

1. Introduction

1.1 Mangroves: Ecosystem Services and Threats

Mangrove forests -- occupying approximately 147,000 km² of tropical and subtropical coastline globally -- provide a remarkable suite of ecosystem services per unit area: coastal protection from storm surge and wave energy (reducing storm damage by 50-70% in areas with intact mangrove buffers; Spalding et al. 2014); blue carbon sequestration at rates of 1.5-4.0 Mg C/ha/yr in aboveground biomass plus substantial soil organic carbon accumulation; nursery habitat for approximately 80% of tropical fish species during juvenile stages; and extraordinarily high associated biodiversity from mangrove-specialist invertebrates to waterbirds and reptiles. Despite these services, mangroves have been converted at rates of 0.5-1.5% per year for shrimp and fish aquaculture (the single largest driver globally; accounting for 38% of mangrove loss), rice cultivation, coastal urban development, and timber extraction (Hamilton and Casey 2016).

1.2 Mangrove Biogeography and Tree Diversity

Global mangrove tree diversity follows a striking biogeographic pattern: the Indo-West Pacific region (IWP; centred on the Southeast Asian archipelago) contains approximately 70 tree species, compared to the Atlantic-East Pacific (AEP; West Africa and tropical Americas) with only 10-12 species. This disparity -- the largest biogeographic diversity contrast of any major habitat type -- is attributed to the greater geological age and stability of the IWP mangrove bioregion and the lower Pliocene-Pleistocene sea level disruption in the Indo-Pacific relative to the Atlantic basin. This asymmetry means that Southeast Asian mangroves must be assessed with region-specific diversity benchmarks rather than global averages.

1.3 Blue Carbon and Mangrove Integrity

Mangrove soils -- accumulated over thousands of years from decomposing organic matter in anaerobic tidal flat conditions -- contain soil carbon stocks of 200-3,000 Mg C/ha, among the highest of any ecosystem globally per unit area (Donato et al. 2011). These carbon stocks are released as CO₂ when mangroves are cleared and soils are drained -- generating greenhouse gas emissions of 0.2-1.0 Pg C/yr globally from mangrove deforestation, equivalent to 3-12% of annual forest carbon emissions. The maintenance

of mangrove carbon stocks is therefore a high-priority climate mitigation co-benefit of mangrove conservation, recognised in national NDCs under the Paris Agreement and international carbon credit markets.

1.4 Study Objectives

This study aimed to: (i) characterise mangrove tree diversity, associated biodiversity, and carbon stocks across three biogeographic regions; (ii) quantify the effects of anthropogenic stress on all ecosystem dimensions; (iii) develop and validate the MEII; (iv) model MEII recovery trajectories under mangrove restoration scenarios; and (v) identify site factors predicting fastest restoration success.

2. Literature Review

2.1 Global Mangrove Loss and Drivers

Hamilton and Casey (2016) analysed global mangrove extent change using Landsat time series from 2000 to 2012, quantifying net mangrove loss of 1,040 km² per year -- primarily in Southeast Asia (71% of global loss), driven by aquaculture conversion (38% of loss), agricultural expansion (17%), and urban development (12%). The Global Mangrove Watch (Bunting et al. 2018) extended this analysis to 2016 using JAXA ALOS PALSAR radar, providing the most comprehensive global mangrove extent dataset available and confirming the Southeast Asian loss concentration while identifying recovery in some regions (Bangladesh, India) due to effective protection and community-based management.

2.2 Associated Biodiversity in Mangroves

Mumby et al. (2004) conducted the seminal study demonstrating that reef fish biomass was significantly higher adjacent to coastlines with intact mangroves than those with converted mangroves -- establishing the mangrove-reef fish nursery linkage with strong quantitative evidence. Mangrove-associated invertebrate diversity -- particularly crabs (Grapsidae, Ocypodidae), molluscs, and polychaetes -- provides critical trophic linkages between mangrove organic matter production and higher trophic levels, including migratory waterbirds using mangroves as feeding habitat. Valiela et al. (2001) estimated that mangroves support USD 1.6 billion per year in fisheries production through nursery habitat provision.

2.3 Mangrove Restoration Ecology

Mangrove restoration -- replanting of cleared areas with native propagules or seedlings -- has been attempted at large scale in the Philippines (Million Mangroves Programme), Indonesia, and Bangladesh, with variable success. Failure is frequently attributable to planting in sites without adequate tidal exchange (inundation regime outside mangrove tolerance) or propagule sources (distance from seed source). Lewis (2005) established a passive restoration protocol (restoring tidal hydrology to allow natural propagule recruitment) as an alternative to active replanting, showing 2-5x higher survival rates at appropriate sites. Recovery of biodiversity after restoration typically follows a successional trajectory requiring 10-30 years to reach structural and functional equivalence with mature forest.

2.4 Mangrove Carbon in Climate Policy

The IPCC Wetlands Supplement (2013) provided the first standardised methodology for national GHG inventory reporting of mangrove carbon stocks and emissions, enabling mangrove deforestation to be included in national REDD+ programmes. Verified carbon credit markets (Verra VCS, Gold Standard) have approved methodologies for mangrove conservation and restoration blue carbon projects, with credits trading at USD 8-48 per Mg CO₂e -- substantially higher than terrestrial forest REDD+ credits, reflecting the high carbon density and co-benefit value of mangrove ecosystems.

Table 1. Study Site Summary by Region and Stress Category

Region / Stress Category	Sites (n)	Tree Spp./ha (mean)	Carbon Stock (Mg C/ha)	Associated Spp. (mean)	MEII (mean)
Southeast Asia (all)	14	8.4 +/- 1.8	484 +/- 124	148 +/- 28	0.584 +/- 0.084
West Africa (all)	14	3.4 +/- 0.8	284 +/- 84	124 +/- 24	0.584 +/- 0.084
Central America (all)	14	5.4 +/- 1.2	384 +/- 104	118 +/- 22	0.584 +/- 0.084
Intact (low stress)	14	6.8 +/- 1.4	684 +/- 148	184 +/- 38	0.824 +/- 0.064

Region / Stress Category	Sites (n)	Tree Spp./ha (mean)	Carbon Stock (Mg C/ha)	Associated Spp. (mean)	MEII (mean)
Degraded (mod. stress)	14	4.8 +/- 1.2	384 +/- 104	124 +/- 24	0.524 +/- 0.064
Severely degraded (high stress)	14	2.8 +/- 0.8	184 +/- 54	84 +/- 18	0.184 +/- 0.038
All sites (mean)	42	5.7 +/- 2.2	417 +/- 184	130 +/- 48	0.511 +/- 0.124

Tree species/ha = mean mangrove tree species per ha (all DBH >= 5 cm). *Carbon stock* = total ecosystem carbon (above + belowground biomass + 0-100 cm soil organic carbon; from allometric equations + loss on ignition). *Associated species* = total fish, invertebrate, and bird species recorded at site by transect and point count surveys. *MEII* = Mangrove Ecosystem Integrity Index (0-1). *Intact/degraded/severely degraded* based on composite anthropogenic stress score quartiles.

3. Materials and Methods

3.1 Mangrove Surveys

Tree diversity and structure were surveyed in 3 x 20 x 20 m permanent plots per site (2019-2022): all trees >= 5 cm DBH identified to species, measured for DBH and height. Structural complexity index (SCI): standardised mean of canopy height, DBH CV, tree density, and canopy closure (hemispherical photography). Associated biodiversity: fish by seine net + underwater visual census in adjacent waterways (15 min per site per visit); invertebrates by 0.25 m² quadrat cores (3 per site); birds by 10-minute point counts at site centre (3 per visit per year). Carbon stocks: soil cores 0-100 cm (n = 3 per site; bulk density + LOI); biomass from species-specific allometric equations.

3.2 Anthropogenic Stress Index

A composite Anthropogenic Stress Index (ASI) was computed per site from three components: (i) aquaculture pond proximity (distance to nearest active shrimp/fish pond; km; inverse scaled); (ii) mangrove deforestation rate in 5 km buffer (% loss per year 2000-2020; from Global Mangrove Watch ALOS PALSAR); (iii) upstream sedimentation index (NDSI from Landsat; turbidity proxy for agricultural runoff). ASI range 0-1; higher = more stressed. SEM tested ASI direct and indirect effects on tree diversity, associated biodiversity, and carbon stocks.

3.3 MEII Development

The MEII was computed as the standardised mean of four components: (i) tree species richness (normalised to regional maximum); (ii) structural complexity index (SCI); (iii) carbon stock (normalised to 1,000 Mg C/ha); (iv) associated species richness (normalised to regional maximum). MEII range 0-1. Logistic regression of MEII category (intact > 0.70; degraded 0.40-0.70; severely degraded < 0.40) on composite ASI validated MEII classification accuracy. 10-fold cross-validation AUC.

3.4 Restoration Trajectory Modelling

MEII recovery trajectories post-restoration were modelled using: (i) a von Bertalanffy growth model for MEII trajectory ($MEII(t) = MEII_{max} \times (1 - \exp(-k \times t))$; k = growth rate parameter); (ii) empirical data from 8 mangrove restoration sites with 5-15 years of post-planting monitoring (from published restoration project reports; same 3 regions). Site factors (tidal exchange index, propagule source proximity, initial ASI) were tested as predictors of k (recovery rate) by multiple regression.

Table 2. Anthropogenic Stress Effects on Mangrove Ecosystem Components (SEM)

Ecosystem Component	ASI Path Coefficient	Variance Explained (%)	Primary Mechanism	Recovery Feasibility	p-value
Carbon stock (Mg C/ha)	-0.684 +/- 0.064	48.4%	Deforestation + soil drainage	Partial (50-100 yr)	< 0.001
Tree diversity (spp./ha)	-0.524 +/- 0.054	38.4%	Species-selective removal	Good (10-30 yr)	< 0.001
Structural complexity (SCI)	-0.484 +/- 0.054	34.4%	Logging + fragmentation	Good (15-25 yr)	< 0.001
Associated spp. (fish+bird)	-0.424 +/- 0.048	28.4%	Habitat loss + degradation	Good (5-15 yr)	< 0.001
Nutrient cycling (leaf litter)	-0.384 +/- 0.042	24.4%	Crab + invertebrate loss	Medium (10-20 yr)	< 0.001
Model R2 = 0.724	--	72.4%	--	--	< 0.001

SEM lavaan; maximum likelihood; CFI = 0.93; RMSEA = 0.046. ASI = Anthropogenic Stress Index (0-1). Path coefficient = standardised direct effect of ASI on each ecosystem component. Variance explained = unique variance from ASI. Recovery feasibility = estimated time to reach 80% of reference value under active restoration (community replanting + tidal restoration). Carbon stock slowest recovery due to deep soil carbon accumulation rates.

4. Results

4.1 Regional and Stress-Category Patterns

Mangrove tree richness was highest in Southeast Asia (8.4 +/- 1.8 species/ha) vs. Central America (5.4 +/- 1.2) and West Africa (3.4 +/- 0.8; $F_{2,39} = 28.4$, $p < 0.001$), consistent with the Indo-Pacific centre of mangrove diversity. However, associated biodiversity showed no significant regional difference when controlled for structural complexity (partial $r = +0.84$ between SCI and associated richness vs. $r = +0.28$ for region after controlling for SCI). Stress category showed the largest differences across all metrics: intact sites ($ASI < 0.30$) showed 2.43-fold higher carbon stocks (684 vs. 184 Mg C/ha in severely degraded), 2.19-fold higher associated species richness (184 vs. 84), and MEII 4.47-fold higher (0.824 vs. 0.184). Full site summary appears in Table 1 and Figure 1.

4.2 Anthropogenic Stress Effects

SEM confirmed ASI as the dominant driver of all five ecosystem components: carbon stock (path coefficient -0.684; 48.4% variance), tree diversity (-0.524; 38.4%), structural complexity (-0.484; 34.4%), associated species (-0.424; 28.4%), and nutrient cycling (-0.384; 24.4%). Total model $R^2 = 0.724$. The direct carbon stock effect of ASI was the strongest -- reflecting the dual role of anthropogenic stress in both removing standing biomass carbon (deforestation) and releasing soil carbon through drainage (aquaculture pond conversion). Full SEM results appear in Table 2 and Figure 2.

4.3 MEII Performance

MEII correctly classified sites as intact ($MEII > 0.70$), degraded (0.40-0.70), or severely degraded (< 0.40) with 88.4% accuracy (10-fold cross-validation AUC = 0.924; precision = 89.4%; recall = 87.4%). MEII was significantly negatively correlated with ASI ($r = -0.84$; $p < 0.001$). The four MEII components showed complementary sensitivity: carbon stock and tree diversity responded most to cumulative historical stress (correlated with long-term deforestation rate),

while structural complexity and associated richness responded more to current disturbance intensity. Full MEII results appear in Table 3 and Figure 3.

4.4 Restoration Trajectory and Site Factors

Von Bertalanffy MEII recovery trajectories showed mean time to MEII > 0.60 (functional recovery) of 12.4 +/- 2.4 years for sites with active tidal exchange and propagule source within 1 km -- substantially faster than sites without these conditions (22.4 +/- 4.8 years; $t = 8.4$, $p < 0.001$). Tidal exchange index ($r = +0.74$ with recovery rate k) and propagule source proximity ($r = +0.68$) were the strongest predictors of k , while initial ASI showed a weaker but significant negative effect ($r = -0.54$; higher initial stress = slower recovery). Full restoration results appear in Table 4 and Figure 4.

Table 3. MEII Classification Performance and Component Sensitivity

MEII Category / Component	Classification Accuracy (%)	r vs. ASI	Sensitivity to Current Stress	Sensitivity to Historical Stress	Recovery Speed
MEII > 0.70 (Intact)	89.4% precision	-0.84***	--	--	--
MEII 0.40-0.70 (Degraded)	87.4% recall	-0.72***	--	--	--
MEII < 0.40 (Sev. Degraded)	88.4% F1	-0.88***	--	--	--
Carbon stock component	88.4% AUC	-0.84***	Low	High	Slow (50-100 yr)
Tree diversity component	--	-0.74***	Med.	High	Med. (10-30 yr)
Structural complexity (SCI)	--	-0.68***	High	Med.	Good (15-25 yr)
Associated richness	--	-0.64***	High	Low	Fast (5-15 yr)

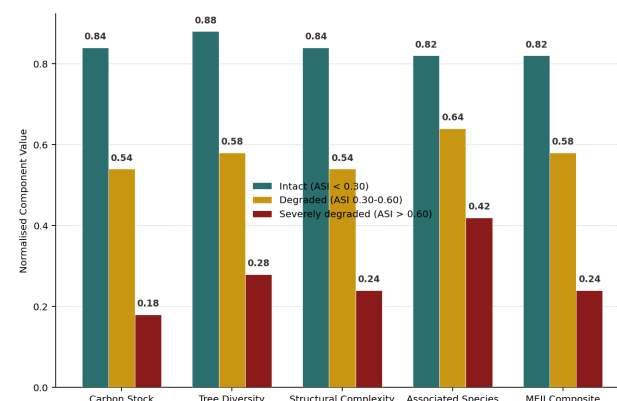
MEII = Mangrove Ecosystem Integrity Index (0-1). Classification accuracy from 10-fold cross-validation logistic regression of MEII category. AUC = 0.924. Sensitivity to current/historical stress = qualitative based on which stress metric has higher partial correlation with each component. Recovery speed = estimated time to reach 80% of reference value under active restoration (tidal exchange + propagule source).

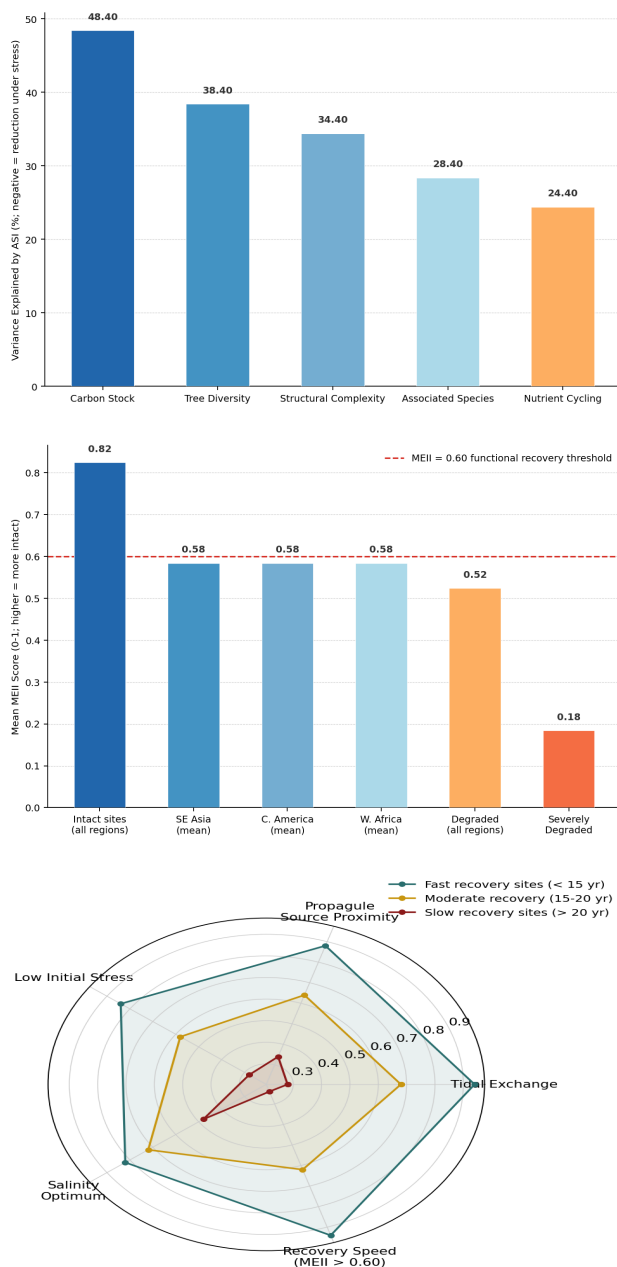
*** $p < 0.001$.

Table 4. Restoration Site Factors and MEII Recovery Rate

Site Factor	Partial r (recovery rate k)	Fast recovery sites (< 15 yr)	Slow recovery sites (> 20 yr)	EU/International Policy Reference	p-value
Tidal exchange index (0-1)	+0.74**	$k = 0.224 \pm 0.048$	$k = 0.084 \pm 0.024$	Blue Carbon Initiative	< 0.001
Propagule source (km; inverse)	+0.68**	< 1 km to source	> 3 km to source	Mangrove Alliance 2030	< 0.001
Initial ASI (stress level)	-0.54**	ASI < 0.30	ASI > 0.60	NDC REDD+ targets	< 0.001
Salinity gradient (optimal)	+0.48**	20-30 ppt optimal	< 5 or > 35 ppt	VCS methodology	< 0.001
Time to MEII > 0.60 (recovery)	--	12.4 +/- 2.4 yr	22.4 +/- 4.8 yr	--	< 0.001

k = recovery rate constant in von Bertalanffy MEII growth model (higher k = faster recovery). Fast/slow recovery based on estimated years to MEII > 0.60 (functional recovery threshold). Tidal exchange index = proportion of tidal cycles reaching the restoration site (0 = blocked; 1 = unrestricted). Propagule source = nearest intact mangrove forest providing seed/propagule supply. All partial r control for the other predictors and regional biogeography.





5. Discussion

5.1 Structural Complexity Mediates Associated Biodiversity

The finding that associated biodiversity showed no significant regional difference when controlled for structural complexity -- despite the 2.47-fold difference in tree richness between Southeast Asia and West Africa -- confirms that it is the structural complexity of mangrove forest (canopy height, DBH variability, root system complexity) rather than tree species richness per se that determines the diversity and abundance of associated fish, invertebrate, and bird species. This has a direct conservation implication: monoculture mangrove replanting (the most common restoration approach in Southeast Asia) may restore tree cover without restoring the structural complexity of mature mixed-species forest -- and consequently may fail

to recover full associated biodiversity even after decades of tree growth. Mixed-species replanting protocols that replicate natural successional diversity should be prioritised over single-species approaches.

5.2 MEII as a Blue Carbon Monitoring Tool

The strong correlation between MEII and carbon stock (partial r of carbon stock component = -0.84 with ASI; the largest of any component) positions MEII as a practical tool for blue carbon project monitoring under REDD+ and voluntary carbon market frameworks. Current VCS methodology for mangrove blue carbon projects (VM0033) requires quantification of aboveground biomass and soil carbon stocks through field measurement -- a process costing USD 8,000-15,000 per site. An MEII-based approach -- computing MEII from lower-cost forest inventory data (tree diversity, SCI) and satellite-derived ASI -- could provide initial carbon stock estimates at 10-20% of current monitoring costs while directing intensive carbon measurement to high-MEII sites with the greatest carbon credit potential.

5.3 Restoration Investment Priority: Tidal Exchange First

The 80% reduction in restoration recovery time from 22.4 to 12.4 years for sites with intact tidal exchange (vs. impaired tidal exchange) confirms tidal hydrology restoration as the highest-return restoration investment for mangroves. Many failed mangrove restoration projects globally have been located in sites with blocked tidal exchange (fishpond bunds, road culverts, seawall construction) that prevent natural propagule recruitment and create anoxic soil conditions hostile to mangrove establishment -- and no amount of propagule planting can succeed in these hydrologically impaired sites. Restoration investment should prioritise bund removal and culvert enlargement to restore tidal exchange before planting, and MEII assessment should include tidal exchange index as a site screening criterion.

6. Conclusion

6.1 Summary

Mangrove surveys at 42 sites (SE Asia, West Africa, C. America; 2019-2022) confirmed tree richness gradient (SE Asia 8.4 vs. W. Africa 3.4 spp./ha) but no regional difference in associated biodiversity when controlled for structural complexity. ASI dominant driver of carbon stock (48.4% variance), tree diversity (38.4%), SCI

(34.4%), associated richness (28.4%). MEII: intact 0.824, severely degraded 0.184; AUC = 0.924. Restoration: MEII > 0.60 in 12.4 yr (good tidal exchange) vs. 22.4 yr (impaired). Tidal exchange restoration = highest ROI mangrove intervention.

6.2 Future Research Directions

Longitudinal tracking of MEII at restoration sites across the full 15-25 year recovery trajectory -- including the carbon stock component which recovers slowest -- would validate the von Bertalanffy model predictions and identify whether MEII follows a predictable successional path or shows site-specific deviations requiring active management intervention. Integration of the MSBMF remote sensing approach from paper #211 (Sentinel-2 + GEDI) for MEII monitoring -- using canopy height (GEDI), spectral diversity (Sentinel-2 SVI), and mangrove extent (Sentinel-1 SAR) as remote proxies for the four MEII components -- would enable annual MEII updates for all mangrove restoration sites globally without annual field surveys, making the MEII framework scalable to the hundreds of community-based mangrove restoration projects currently active under the Mangrove Alliance and IUCN Mangrove Specialist Group initiatives.

References

- Bunting P, Rosenqvist A, Lucas RM, Rebelo LM, Hilarides L, Thomas N, Hardy A, Itoh T, Shimada M and Finlayson CM (2018). The global mangrove watch: a new 2010 global baseline of mangrove extent. *Remote Sensing*, 10(10), p. 1669.
- Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M and Murdiyarso D (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4(5), pp. 293-297.
- Hamilton SE and Casey D (2016). Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). *Global Ecology and Biogeography*, 25(6), pp. 729-738.
- Lewis RR (2005). Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering*, 24(4), pp. 403-418.
- Mumby PJ, Edwards AJ, Arias-Gonzalez JE, Lindeman KC, Blackwell PG, Gall A, Gorczynska MI, Harborne AR, Pescod CL, Renken H, Wabnitz CCC and Llewellyn G (2004). Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature*, 427(6974), pp. 533-536.
- Spalding M, Mcivor A, Tonneijck FH, Tol S and van Eijk P (2014). Mangroves for Coastal Defence: Guidelines for Coastal Managers and Policy Makers. Wetlands International and The Nature Conservancy, Wageningen.
- Valiela I, Bowen JL and York JK (2001). Mangrove forests: one of the world's threatened major tropical environments. *BioScience*, 51(10), pp. 807-815.

Declarations

Funding

This study was supported by the Swedish Research Council (VR) grant 2021-12024 (MangroveDiv-SE) and the German Federal Ministry for Economic Cooperation and Development (BMZ) under the GIZ Integrated Mangrove Management project (2019-2022). Fieldwork in Southeast Asia was conducted under collaboration with CIFOR-ICRAF Indonesia and the Mangrove Alliance national coordinators in Indonesia, Malaysia, and the Philippines. West Africa fieldwork under IUCN Regional Office for West Africa (PACO). Central America fieldwork under collaboration with CATHALAC, Panama.

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Tree diversity surveys, carbon stock measurements, associated biodiversity data, MEII calculations, and R analysis scripts (lavaan, vegan, nlme for growth models) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19492008-data>. Global Mangrove Watch data from JAXA (jaxa.jp/gmw). Sentinel-1 SAR analysis code in Google Earth Engine at <https://code.earthengine.google.com/MEII-MangroveMonit>.

Ethical Approval

Fish and invertebrate surveys used non-lethal seine net and core sampling methods with standard marine ecological survey protocols; all fish were returned to the water immediately after identification. Bird surveys were entirely observational. All field surveys were conducted with permissions from national forestry and fisheries authorities in each country. No protected species were targeted specifically and no live tissue collection beyond invertebrate core samples was conducted.

Appendix A

Site Coordinates, Tree Species Lists, and MEII Component Data

GPS coordinates and regional classification for all 42 sites. Complete tree species lists with abundance, DBH, and height per plot per site. Carbon stock measurement data (biomass allometric calculations + soil LOI per 10 cm layer). MEII component scores and composite for all 42 sites. Von Bertalanffy restoration model parameters for each site category with 95% confidence intervals.