JPPIPA 11(12) (2025)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

Biodiversity and Carbon Storage in Mangroves with Varying Protection in North Sulawesi

Wawan Nurmawan[1*], Martina A. Langi[1]

[1] Study Program of Forestry, Faculty of Agriculture, Universitas Sam Ratulangi, Manado, Indonesia.

Received: October 09, 2025
Revised: November 06, 2025
Accepted: December 29, 2025
Published: December 31, 2025

Corresponding Author:
Name Wawan Nurmawan
wawan2828@unsrat.ac.id

DOI: 10.29303/jppipa.v11i12.13082

Abstract: Mangrove ecosystems contribute to biodiversity conservation and climate-change mitigation through carbon storage. This study assessed the association between biodiversity (flora and fauna) and carbon stocks in mangroves of North Sulawesi across three management contexts: a conservation zone (Bunaken), a protected forest (Sondaken), and an unprotected area (Bitung). Field surveys were conducted to compile species inventories, and carbon stocks were estimated from biomass measurements. Protected sites showed higher species richness and larger carbon stocks than the unprotected site. Species richness was positively and significantly correlated with carbon storage, indicating that sites with greater biodiversity also tended to store more carbon. These results support the role of effective protection in maintaining both ecological integrity and carbon sequestration capacity. In conclusion, strengthening mangrove protection in North Sulawesi is likely to deliver co-benefits for biodiversity conservation and climate mitigation.

Keywords: Biodiversity; Carbon; Mangrove; Species richness

Introduction

Mangrove forests are globally important coastal ecosystems that sustain high biodiversity and provide essential services for people, including shoreline stabilization, water-quality regulation, and support for fisheries. A key function with direct relevance to climate policy is their capacity to sequester and store blue carbon in biomass and, especially, organic-rich sediments (Duarte et al., 2013; Hamilton & Friess, 2018; Alongi, 2014). Carbon storage in mangroves is influenced by forest structure, species composition, and below-ground processes that regulate productivity, root biomass, and sediment accretion. Biodiversity can therefore be mechanistically linked to carbon accumulation through complementary resource use and increased ecosystem functioning, which may enhance long-term carbon retention (Tilman et al., 2014; Seddon et al., 2020; Alongi, 2014). As the country with the largest mangrove extent globally, Indonesia is a major contributor to blue-carbon dynamics and national mitigation efforts (Friess et al., 2020).

In North Sulawesi, mangrove ecosystems occur under markedly different protection regimes (BKSDA Sulut 2021; BTNB 2022; Donato et al., 2011; Murdiyarso et al., 2015; Pemkot Bitung 2021; Sutran et al., 2024; Saputra et al., 2024). Bunaken is managed within a national park framework with comparatively strong legal and institutional safeguards, Sondaken is designated as protected forest with more variable enforcement, and Bitung represents largely unprotected urban mangroves exposed to rapid land-use change, pollution, and aquaculture expansion. This governance gradient provides a natural "management experiment" to test how protection status translates into measurable ecological outcomes, particularly biodiversity and carbon storage (Langi et al., 2023; Hikmawan et al. 2024; Langi et al. 2025).

The novelty of this study is an integrated, field-based assessment of biodiversity–carbon relationships across contrasting protection levels within the same

How to Cite:
Nurmawan, W., & Langi, M. A. (2025). Biodiversity and Carbon Storage in Mangroves with Varying Protection in North Sulawesi. *Jurnal Penelitian Pendidikan IPA*, *11*(12), 442–449. https://doi.org/10.29303/jppipa.v11i12.13082

biogeographic region. Despite the recognized importance of mangroves, integrated studies that jointly quantify biodiversity (flora and fauna) and carbon stocks across varying protection categories remain limited in eastern Indonesia (Langi et al., 2023; Hikmawan et al. 2024; Langi et al. 2025). Many existing studies address biodiversity (e.g., species inventories) or carbon/biomass estimates separately, or focus on settings with relatively uniform land-use contexts, which constrains inference about governance-driven differences (Arifanti et al., 2019; Beselly et al., 2025; BKSDA Sulut 2021; BTNB 2022; Friess et al., 2020; Pemkot Bitung 2021). By applying consistent field surveys, species inventories, and biomass-based carbon measurements across three sites, this research explicitly evaluates whether protection status is associated with (i) higher biodiversity, (ii) higher carbon storage, and (iii) a stronger coupling between biodiversity and carbon dynamics (BTNB 2022; Duarte et al., 2013; Langi et al., 2023; Hikmawan et al. 2024; Langi et al. 2025; Seddon et al., 2020).

Method

Study Sites

Three mangrove areas in North Sulawesi were selected based on their protection status: Bunaken National Park (strictly protected), Sondaken (designated protected forest), and Bitung (unprotected). Each site was surveyed during the dry season (March–May 2025).

Data Collection

Biodiversity Assessment

Biodiversity data were collected during March to April 2025 where variability due to tidal or seasonal changes was considered relatively low. Vegetation surveys were conducted using 10 m x 10 m quadrats placed systematically along transects perpendicular to the coastline (Arifanti et al. 2019). In each quadrat, all tree species with diameter at breast height (DBH) ≥ 5 cm were identified and counted. Species identification in the field was assisted by digital plant identification tools, notably Flora Incognita (Boho et al. 2020) and Naturalist (Van Horn et al. 2018), which enabled rapid recognition and photographic documentation of tree and shrub species. These tools were especially useful for distinguishing morphologically similar mangrove taxa in remote areas with limited internet access. Tree height was measured using a clinometer, and canopy cover was visually estimated. Faunal surveys included bird point counts (at dawn), crab and mollusk collection using hand capture and pitfall traps, and fish sampling using hand nets during high tide in tidal creeks (Hikmawan et al. 2024; Langi & Nurmawan 2023). Species were identified in the field or photographed for later verification.

Carbon Stock Assessment

Carbon stock data were collected following the CIFOR guidelines (Arifanti et al. 2019). Aboveground Biomass (AGB) was assessed through tree biomass estimated using allometric equations specific to tropical mangrove species based on DBH and tree height; whereas wood density values were obtained from literature or local species databases. Belowground Biomass (BGB) was estimated using root-to-shoot ratios according to published models, adjusted for mangrove species composition and site conditions. Soil cores were collected at three depths (0–15 cm, 15–30 cm, and 30–50 cm) using a stainless-steel corer. Samples were weighed, dried, and analyzed for organic carbon content using the Walkley-Black method in the laboratory (Komiyama et al., 2008; Alongi, 2012). Where applied, in selected plots litter traps (0.5 m^2) were used to collect leaf and woody debris over a 30-day period. Samples were dried and weighed to estimate litter production as a proxy for carbon input.

Data Analysis

Biodiversity metrics—including species richness, abundance, and diversity—were calculated using the Shannon-Wiener Diversity Index (H′), with evenness assessed to evaluate species distribution across sites. Carbon stock per site (Mg C/ha) was estimated by summing aboveground biomass, belowground biomass, and soil organic carbon. To examine the relationship between biodiversity and carbon storage, Pearson correlation analysis was conducted. One-way ANOVA was applied to test for significant differences in biodiversity indices and carbon stocks among the three mangrove sites. Prior to analysis, assumptions of normality and homogeneity were verified using Shapiro-Wilk and Levene's tests, respectively. All statistical analyses were performed in R software (version 4.3.1), with significance determined at $p < 0.05$.

Result and Discussion

Biodiversity

Table 1 and Table 2 present respectively the flora and fauna species observed at each of the three study sites: Bunaken (Site A), Sondaken (Site B), and Bitung (Site C). At each site there are key mangrove species in terms of dominance. At Bunaken site (conservation zone) the key species are *Rhizophora mucronata*, *Bruguiera gymnorrhiza*, *Sonneratia alba*, *Avicennia marina*, and *Xylocarpus granatum*. At Sondaken (protected forest) the key species are *Avicennia marina*, *Bruguiera gymnorrhiza*, *Rhizophora apiculata*, *Excoecaria agallocha*, and *Lumnitzera* *racemosa*. At Bitung (unprotected area) the key species are *Avicennia marina*, *Rhizophora stylosa*, *Ceriops tagal*, *Sonneratia alba*, and *Lumnitzera racemosa*. These key species indicate the resilience and successional stage of the mangrove ecosystems across the three sites.

Table 1. The Plant Species Identified in Each Study Site

Bunaken	Sondaken	Bitung
Acrostichum aureum	Acrostichum aureum	Aegiceras corniculatum
Aegiceras corniculatum	Aegiceras corniculatum	Avicennia marina
Avicennia marina	Avicennia marina	Barringtonia asiatica
A. officinalis	Barringtonia asiatica	Bruguiera gymnorrhiza
Barringtonia asiatica	Bruguiera gymnorrhiza	Ceriops tagal
Bruguiera gymnorrhiza	Cassytha filiformis	Dolichandrone spathacea
B. sexangula	Ceriops tagal	Excoecaria agallocha
Calophyllum inophyllum	Clerodendrum inerme	Heritiera littoralis
Cassytha filiformis	Dolichandrone spathacea	Lumnitzera racemosa
Ceriops tagal	Excoecaria agallocha	Rhizophora apiculata
Clerodendrum inerme	Heritiera littoralis	R. mucronata
Dolichandrone spathacea	Hibiscus tiliaceus	R. stylosa
Excoecaria agallocha	Lumnitzera racemosa	Sonneratia alba
Ficus septica	Pemphis acidula	Xylocarpus granatum
Heritiera littoralis	Rhizophora apiculata	
Hibiscus tiliaceus	R. mucronata	
Lumnitzera racemosa	R. stylosa	
Nypa fruticans	Scyphiphora hydrophylacea	
Pemphis acidula	Sonneratia alba	
Rhizophora apiculata	Terminalia catappa	
R. mucronata	Thespesia populnea	
R. stylosa	Xylocarpus granatum	
Scyphiphora hydrophylacea		
Sonneratia alba		
Terminalia catappa		
Thespesia populnea		
Vitex trifolia		
Xylocarpus granatum		

Table 2. Fauna Species Identified in Each Study Site

Bunaken	Sondaken	Bitung
Anadara granosa	Ardea sumatrana	Ardea sumatrana
Ardea sumatrana	Arius maculatus	Arius maculatus
Arius maculatus	Astropecten polyacanthus	Centropus sinensis
Astropecten polyacanthus	Centropus sinensis	Cerithidea obtusa
Babylonia spirata	Cerithidea obtusa	Chanos chanos
Brachidontes variabilis	Chanos chanos	Chelonodon patoca
Centropus sinensis	Chelonodon patoca	Egretta sacra
Cerithidea obtusa	Egretta sacra	Gerres oyena
Chanos chanos	Gerres oyena	Halcyon chloris
Chelonodon patoca	Grapsus albolineatus	Liza vaigiensis
Egretta sacra	Halcyon chloris	Lutjanus argentimaculatus
Gerres oyena	Holothuria atra	Periophthalmus argentilineatus
Grapsus albolineatus	Liza vaigiensis	Scylla serrata
Halcyon chloris	Lutjanus argentimaculatus	Siganus canaliculatus
Holothuria atra	Metapenaeus ensis	Stenella longirostris
Liza vaigiensis	Octopus cyanea	Terebralia palustris
Lutjanus argentimaculatus	Ocypode ceratophthalmus	Turdus poliocephalus
L. fulviflamma	Periophthalmus argentilineatus	Uca vocans
Metapenaeus ensis	Portunus pelagicus	
Nemipterus japonicus	Scylla serrata	
Octopus cyanea	Siganus canaliculatus	
Ocypode ceratophthalmus	Stenella longirostris	
Panulirus versicolor	Terebralia palustris	

Bunaken	Sondaken	Bitung
Penaeus monodon	Tridacna crocea	
Periophthalmus argentilineatus	T. maxima	
Portunus pelagicus	Turdus poliocephalus	
Scylla serrata	Uca vocans	
Sepioteuthis lessoniana		
Siganus canaliculatus		
Stenella longirostris		
Terebralia palustris		
Tridacna crocea		
T. maxima		
Turdus poliocephalus		
Uca vocans		

The key fauna species at Bunaken mangrove site are *Egretta sacra* (specialist bird indicating undisturbed tidal zones), *Lutjanus argentimaculatus* (commercial fish), *Scylla serrata* (mud crab), *Tridacna crocea*, *T. maxima* (giant clams), *Periophthalmus argentilineatus* (mudskipper in intertidal flats), *Octopus cyanea* (benthos-mangrove linkages), and *Stenella longirostris* (spinner dolphin between mangrove and offshore waters). At Sondaken site the key species are *Arius maculatus* (euryhaline catfish at brackish creeks), *Centropus sinensis* (bird sensitive to disturbance), *Chanos chanos* (milkfish feed on mangrove detritus), *Metapenaeus ensis* (estuarine shrimp), and *Ocypode ceratophthalmus* (crabs on intertidal flats). At Bitung site the key species are Periophthalmus argentilineatus,* Scylla serrata*, *Terebralia palustris*, *Uca vocans*, and *Halcyon chloris* – all adaptable to urbanized mangrove fragments.

Table **3** summarizes the biodiversity metrics measured across the three mangrove study sites. These include species richness (plant and animal), total species abundance, Shannon-Wiener diversity index (H'), and evenness (E), which reflects the distribution of individuals among species. The conservation zone (Bunaken) recorded the highest biodiversity index (H′ = 3.2), reflecting high species richness and ecological stability. In contrast, the unprotected area (Bitung) had a much lower index (H′ = 1.8), indicating degraded conditions and anthropogenic stress (BTNB 2022; Pemkot Bitung 2021). These findings support the role of formal protection in sustaining ecological integrity. Higher values of H' and E are generally associated with more stable and resilient ecosystems.

Table 3. The Biodiversity Metrics Measured

Site	PSR	ASR	TSR	TSA	SWI	E
Bunaken	28	35	63	750	3.2	0.91
Sondaken	22	27	49	540	2.6	0.84
Bitung	14	18	32	310	1.8	0.72

PSR: Plant Species Richness
ASR: Animal Species Richness
TSR: Total Species Richness
TSA: Total Species Abundance
SWI: Shannon-Wiener Index (H')
E: Evenness

Biodiversity varied significantly among the three study sites, with a clear gradient corresponding to protection status. Bunaken (Site A) exhibited the highest biodiversity across all metrics (Figure **1**). The Shannon-Wiener index (H') was 3.2, indicating a well-balanced and rich community, with 28 plant species and 35 animal species identified. In contrast, Sondaken (Site B) recorded a moderate H' index of 2.6, with 22 plant species and 27 animal species, reflecting its intermediate level of protection and moderate anthropogenic pressure. Bitung (Site C), the unprotected site, had the lowest biodiversity (H' = 1.8), with only 14 plant species and 18 animal species, consistent with its more fragmented and degraded habitat.

Carbon Stocks

Carbon stock estimates followed a similar pattern to biodiversity. The highest total carbon stock was found in Bunaken, averaging 235 Mg C/ha, followed by Sondaken with 162 Mg C/ha, and the lowest in Bitung at 98 Mg C/ha (Figure 1). These figures account for both above- and below-ground carbon pools. Environmental factors such as tidal inundation, soil type, and salinity likely contributed to the observed differences in carbon storage. The relatively undisturbed structure of Bunaken's mangroves, with mature tree stands and dense vegetation cover, supports greater carbon sequestration. Conversely, the fragmented and disturbed mangrove patches in Bitung store significantly less carbon (BTNB 2022; Pemkot Bitung 2021). These findings are consistent with those of Langi et al. (2023), who found that litterfall production—and thus carbon input—was significantly influenced by environmental variability in mangroves of Teling Tombariri (within Bunaken National Park). Conversely, the fragmented and disturbed mangrove patches in Bitung store significantly less carbon (Donato et al., 2011; Murdiyarso et al., 2015; Sutran et al., 2024; Saputra et al., 2024). These findings are consistent with those of Langi et al. (2023), who found that litterfall production—and thus carbon input—was significantly influenced by environmental variability in mangroves of Teling Tombariri (within Bunaken National Park).

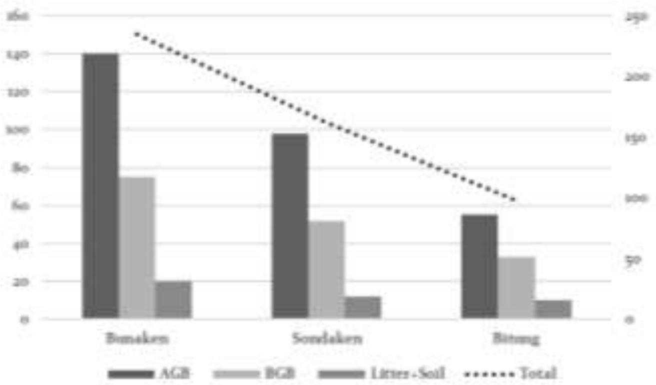

Figure 1. Estimated carbon stock components by site (in Mg C/ha)

Biodiversity and Carbon Correlation

A strong positive correlation was observed between total species richness and carbon stock across the three study sites ($r = 0.82$, $p < 0.01$), indicating that mangrove areas with higher biodiversity tend to store more carbon. This relationship reinforces existing global and local research suggesting that biodiversity enhances multiple ecosystem functions, including productivity, resilience, and carbon sequestration (Alongi 2014; Seddon et al. 2020; Tilman et al. 2014). At Bunaken (Site A)—a legally protected conservation zone within the Bunaken National Park—the highest values of both biodiversity (H' = 3.2) and total carbon stock (235 Mg C/ha) were recorded. The forest structure here is intact, with dominant mangrove species such as *Rhizophora mucronata*, *Sonneratia alba*, and *Bruguiera gymnorrhiza*, supporting diverse faunal groups and maintaining high ecological function. These findings align with periodic ecological monitoring conducted by Balai Taman Nasional Bunaken (BTNB), which has consistently reported high biological productivity and low levels of degradation in the park's core zones (BTNB 2022; Donato et al., 2011; Murdiyarso et al., 2015).

In contrast, Bitung (Site C)—an unprotected, urban-fringe mangrove site—exhibited the lowest biodiversity (H' = 1.8) and lowest carbon stock (98 Mg C/ha). This reflects the impact of unregulated development, waste discharge, and mangrove clearance, issues frequently highlighted in environmental assessments by the Pemerintah Daerah Kota Bitung (Pemkot Bitung 2021; van Zanten et al., 2021; Pendleton et al., 2012). Meanwhile, Sondaken (Site B)—a protected forest under the oversight of Balai Konservasi Sumber Daya Alam (BKSDA) Sulawesi Utara—showed moderate ecological values, representing transitional conditions between full protection and open access. The species composition and carbon stock (162 Mg C/ha) reflect both conservation potential and existing anthropogenic pressures (BKSDA Sulut 2021; Saputra et al., 2024; Sutran et al., 2024).

This study affirms that mangrove biodiversity contributes directly to ecosystem functionality, particularly in terms of carbon storage (Kusumaningtyas et al. 2024). High species diversity enhances vertical forest structure, root biomass, and sediment trapping—all contributing to carbon accumulation in both biomass and soils (Langi et al. 2025; Langi & Nurmawan 2023). Furthermore, faunal diversity, including burrowing crabs, mollusks, and fish, plays a role in nutrient cycling and organic matter breakdown, processes that reinforce long-term carbon retention (Alongi 2014). From a policy standpoint, the data underscore the importance of legally protected areas such as Bunaken in delivering nature-based solutions (NbS) for both biodiversity conservation and climate mitigation. This aligns with the Rencana Pengelolaan Hutan Mangrove Nasional dan Daerah (RPHMN), which prioritizes ecosystem-based carbon strategies, particularly in eastern Indonesia (van Zanten et al. 2021).

Conclusion

Across three mangrove sites representing a clear protection gradient in North Sulawesi, both biodiversity and carbon storage were consistently higher in better-managed areas. Bunaken (conservation zone) showed the highest diversity (H′ = 3.2) with 28 plant species and 35 animal species, and the largest total carbon stock (235 Mg C/ha). Sondaken (protected forest) was intermediate (H′ = 2.6; 22 plant species; 27 animal species; 162 Mg C/ha), while Bitung (unprotected) had the lowest biodiversity (H′ = 1.8; 14 plant species; 18 animal species) and the smallest carbon stock (98 Mg C/ha). A strong positive relationship between total species richness and carbon stock ($r = 0.82$, $p < 0.01$) indicates that mangrove systems with richer biotic communities also tend to retain higher carbon stocks. Generalizing from these results, differential governance and disturbance pressure are likely to influence mangrove "co-benefits": where protection maintains stand structure, habitat continuity, and diverse communities, carbon storage potential is also higher; where mangroves are fragmented and degraded, both biodiversity and carbon storage decline. Practically, these findings support (1) prioritizing enforcement and sustained protection in high-performing sites (e.g., Bunaken) to safeguard established biodiversity–carbon co-benefits; (2) targeting unprotected urban mangroves (e.g., Bitung) for zoning controls, pollution reduction, and rehabilitation to recover biodiversity and carbon function; and (3) integrating biodiversity indicators alongside carbon metrics in local monitoring and management decisions so that conservation and climate-mitigation outcomes can be pursued simultaneously.

Acknowledgments
This research was funded by the DIPA Universitas Sam Ratulangi Tahun Anggaran 2025. The authors thank Bunaken National Park Authority, BKSDA Sulut, and the local governments of Bitung and Minahasa for supporting field access. Special thanks to the local community members and assistants involved in data collection and species identification.

Author Contributions
Data collection, analysis, and drafting the manuscript, WN; conceptualization, supervision, and final manuscript review, MAL.

Funding
This study was supported by the 2025 DIPA Grant of Sam Ratulangi University. The funding agency had no role in the design, data collection, interpretation, or publication of this manuscript.

Conflicts of Interest
The authors declare no conflict of interest.

References

Alongi, D. M. (2012). Carbon sequestration in mangrove forests. *Carbon Management*, *3*(3), 313–322. https://doi.org/10.4155/cmt.12.20

Alongi, D. M. (2014). Carbon cycling and storage in mangrove forests. *Annual Review of Marine Science*, *6*, 195–219. https://doi.org/10.1146/annurev-marine-010213-135020

Alongi, D. M. (2018). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Forests*, *9*(10), 596. https://doi.org/10.3390/f9100596

Arifanti, V. B., Kauffman, J. B., Hadriyanto, D., Murdiyarso, D., & Diana, R. (2019). Carbon dynamics and land use carbon footprints in mangrove-converted aquaculture: The case of the Mahakam Delta, Indonesia. *Forest Ecology and Management*, *432*, 17–29. https://doi.org/10.1016/j.foreco.2018.08.047

Ati, R. N., Rustam, A., & Kepel, T. L. (2016). Stok karbon dan struktur komunitas mangrove sebagai blue carbon di Tanjung Api-api, Sumatera Selatan. *Omni-Akuatika*, *12*(3), 19–26. https://doi.org/10.20884/1.oa.2016.12.3.126

Beselly, S. M., van der Wegen, M., Reyns, J., Grueters, U., Dijkstra, J. T., & Roelvink, D. (2025). Strategic mangrove restoration increases carbon stock capacity. *Communications Earth & Environment*, *6*(1), 422. https://doi.org/10.1038/s43247-025-02401-2

Boho, D., Rzanny, M., Wäldchen, J., & Nitsche, F. (2020). Flora Incognita – Towards automatic plant identification in natural habitats. *Computers and Electronics in Agriculture*, *176*, 105628. https://doi.org/10.1016/j.compag.2020.105628

Budiarti, E. P., Prakoso, J., & Suwondo, E. (2023). Utilization of mangrove plants by coastal communities in Mandah District, Indragiri Hilir Regency, Riau Province. *Jurnal Penelitian Pendidikan IPA*, *9*(12), 12082–12097. https://doi.org/10.29303/jppipa.v9i12.6311

Caella, L. A., & Yulianto, S. (2024). The effectiveness of animation video media to increase interest and learning outcomes in science subjects. *Jurnal Penelitian Pendidikan IPA*, *10*(9), 6621–6630. https://doi.org/10.29303/jppipa.v10i9.8445

Chmura, G. L., Anisfeld, S. C., Cahoon, D. R., & Lynch, J. C. (2003). Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles*, *17*(4), 1111. https://doi.org/10.1029/2002GB001917

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, *4*, 293–297. https://doi.org/10.1038/ngeo1123

Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., & Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*, *3*, 961–968. https://doi.org/10.1038/nclimate1970

Easteria, G. S., Sanjaya, A., & Badruzsaufari, B. (2022). Estimasi stok karbon di kawasan hutan mangrove Mempawah Mangrove Park dan Desa Pasir, Kabupaten Mempawah, Kalimantan Barat. *Jurnal Ilmu dan Teknologi Kelautan Tropis*, *14*(2), 463–478. https://doi.org/10.29244/jitkt.v14i2.39861

Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., Apostolaki, E. T., Kendrick, G. A., Krause-Jensen, D., McGlathery, K. J., & Serrano, O. (2012). Seagrass ecosystems as a globally significant carbon stock. *Nature Geoscience*, *5*, 505–509. https://doi.org/10.1038/ngeo1477

Friess, D. A., Richards, D. R., & Phang, J. M. (2020). Deriving emission factors for mangrove blue carbon ecosystems in Indonesia. *Ecological Indicators*, 108, 105714. https://doi.org/10.1016/j.ecolind.2019.105714

Hadiprayitno, G., Wazim, A., Syukur, A., Nursan, M., & Saputra, H. H. (2023). Public perceptions and preferences for mangrove ecotourism development in East Ekas, West Nusa Tenggara, Indonesia. *Jurnal Penelitian Pendidikan IPA*, *9*(9), 7553–7562. https://doi.org/10.29303/jppipa.v9i9.5221

Handayani, S., Zulkarnaini, Z., & Komala, P. S. (2024). Composition of environmental parameters in aquatic sediments in West Sumatra. *Jurnal Penelitian Pendidikan IPA*, *10*(8), 6170–6180. https://doi.org/10.29303/jppipa.v10i8.7579

Jelibseda, D. H., Kamal, F. R., Razak, A., & Diliarosta, S. (2025). Analysis of vegetation structure and sustainable management of mangrove forests. *Jurnal Penelitian Pendidikan IPA*, *10*(12), 11239–11248. https://doi.org/10.29303/jppipa.v10i12.9683

Kenedi, A. K., Febriandhika, I., & Alamsyah, Y. (2024). Beach quality evaluation through coastal environment monitoring: Study in Pariaman City Beach, West Sumatera. *Jurnal Penelitian Pendidikan IPA*, *10*(10), 7397–7408. https://doi.org/10.29303/jppipa.v10i10.8792

Komiyama, A., Ong, J. E., & Poungparn, S. (2008). Allometry, biomass, and productivity of mangrove forests: A review. *Aquatic Botany*, *89*(2), 128–137. https://doi.org/10.1016/j.aquabot.2007.12.006

Kristianingrum, S. (2024). Analyzing the value of Nusantara food and local wisdom in meeting the daily nutritional needs of society. *Jurnal Penelitian Pendidikan IPA*, *10*(3), 1629–1636. https://doi.org/10.29303/jppipa.v10i3.5638

Kusumaningtyas, M. A., Kepel, T. L., Solihuddin, T., Lubis, A. A., Putra, A. D. P., Sugiharto, U., & Rustam, A. (2022). Carbon sequestration potential in the rehabilitated mangroves in Indonesia. *Ecological Research*, *37*(1), 80–91. https://doi.org/10.1111/1440-1703.12279

Kusumaningtyas, M. (2024). Carbon sequestration potential in rehabilitated Indonesian mangroves (Banten Province). *Journal of Environmental Management*, *310*, 114768. https://doi.org/10.1016/j.jenvman.2022.114768

Laliberté, E., & Tylianakis, J. M. (2012). Cascading effects of long-term land-use changes on plant traits and ecosystem functioning. *Ecology*, *93*(1), 145–155. https://doi.org/10.1890/11-0338.1

Langi, M., Nurmawan, W., Saroinsong, F., & Walangitan, H. (2025). Comparative economic valuation of mangrove ecosystems in conservation and non-conservation zones in North Sulawesi. *Jurnal Agroekoteknologi Terapan*, *6*(1), 161–167. https://doi.org/10.35791/jat.v6i1.62743

Langi, M. A., & Nurmawan, W. (2023). Hubungan faktor lingkungan terhadap produksi serasah mangrove Teling Tombariri, Taman Nasional Bunaken. *Risalah Kebijakan Pertanian dan Lingkungan*, *10*(3), 125–132. https://doi.org/10.29244/jkebijakan.v10i3.48394

Latifa, R., Nurrohman, E., & Hadi, S. (2024). Characteristic exploration of family Fabaceae leaf trichomes. *Jurnal Penelitian Pendidikan IPA*, *10*(8), 4589–4598. https://doi.org/10.29303/jppipa.v10i8.6721

Murdiyarso, D., Purbopuspito, J., Kauffman, J. B., Warren, M. W., Sasmito, S. D., Donato, D. C., Manuri, S., Krisnawati, H., Taberima, S., & Kurnianto, S. (2015). The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change*, *5*, 1089–1092. https://doi.org/10.1038/nclimate2734

Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., Sifleet, S., Craft, C., Fourqurean, J. W., Kauffman, J. B., Marbà, N., Megonigal, P., Pidgeon, E., Herr, D., Gordon, D., & Baldera, A. (2012). Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLoS ONE*, *7*(9), e43542. https://doi.org/10.1371/journal.pone.0043542

Prananta, A. W., Rohman, A., Agustin, R., & Pranoto, N. W. (2024). Augmented reality for interactive, innovative and fun science learning: Systematic literature review. *Jurnal Penelitian Pendidikan IPA*, *10*(SpecialIssue), 45–51. https://doi.org/10.29303/jppipa.v10iSpecialIssue.7519

Rahmania, R., Suryono, S., & Efendy, M. (2023). Carbon stock assessments in mangrove forests: A bibliometric analysis. *Frontiers in Marine Science*, *10*, 1239904. https://doi.org/10.3389/fmars.2023.1239904

Ramli, A. R., Rea, I. C., Sarango, A. R., & Zakaria, A. (2025). Potensi karbon biomassa dan kandungan nutrien daun Avicennia alba di Tahura Ngurah Rai, Bali. *Jurnal Manajemen Hutan Tropika*, *31*(1), 25–34. https://doi.org/10.7226/jtfm.31.1.25

Safitri, I. N., Indarto, Sunarminto, B. H., & Shrestha, R. P. (2023). Inventory and carbon stock assessment of mangrove forest in Dibamba, Cameroon using Sentinel-2 and ALOS-2. *Jurnal Ilmu Lingkungan*, *22*(1), 109–124. https://doi.org/10.14710/jil.22.1.109-124

Salahuddin, S., Hairunnisa, H., & Alfiansyah, F. (2024). Analysis of mangrove forest management in Teluk Lembar, West Lombok, West Nusa Tenggara. *Jurnal Penelitian Pendidikan IPA*, *10*(10), 7712–7725. https://doi.org/10.29303/jppipa.v10i10.9485

Saputra, K. A., Nasution, S., & Nurzainah, N. (2024). Coastal vulnerability index for mangrove conservation to sea level rise and coastal hazards. *Aquacoastmarine: Journal of Aquatic and Fisheries Sciences*, *3*(1). https://doi.org/10.32734/jafs.v3i1.15545

Seddon, N., Chausson, A., Berry, P., Girardin, C. A. J., Smith, A., & Turner, B. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philosophical Transactions of the Royal Society. *Biological Sciences*, *375*(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Septinar, L. R., Arfa, M., & Ade, R. (2023). Pendidikan dan pelatihan pengelolaan mangrove sebagai habitat nursery ground di Desa Tanjung Kuras, Kabupaten Karimun. *E-Sosial Journal, 1*(2), 129–134. https://doi.org/10.31851/esjo.v1i2.11920

Sutran, R., Sulistiono, S., & Sutejo, N. (2024). Impact of anthropogenic activities on mangrove vegetation based on the anthropogenic pressure index in Youtefa Bay, Jayapura City, Papua. *Akuatiklestari*, *7*(1), 58–66. https://doi.org/10.31629/akuatiklestari.v7i1.6236

Tambunan, A. A., Adi, T. B., & Tukijan, T. (2024). The role of creative economics in Sei Nagalawan mangrove ecotourism sector. *Jurnal Penelitian Pendidikan IPA*, *10*(SpecialIssue), 505–513. https://doi.org/10.29303/jppipa.v10iSpecialIssue.6146

Tilman, D., Isbell, F., & Cowles, J. M. (2014). Biodiversity and ecosystem functioning. *Annual Review of Ecology, Evolution, and Systematics*, *45*, 471–493. https://doi.org/10.1146/annurev-ecolsys-120213-091917

van Zanten, B. T., Brander, L. M., & Torres, D. G. (2021). *The economics of large-scale mangrove conservation and restoration in Indonesia*. World Bank Group. https://doi.org/10.1596/37605