EDUSCHOOL
ACADEMIC RESEARCH & PUBLISHERS

EDUSCHOOL JOURNAL OF ENVIRONMENTAL RESEARCH STUDIES (EJERS)

(Open Access, Double-Blind Peer Reviewed Journal)

ISSN Online:

Blue Carbon Storage in Mangrove-Seagrass Ecotones

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Article information

Received: 9th March 2026
Received in revised form: 6th April 2026
Accepted: 10th May 2026
Available online: 15th June 2026

Volume: 1
Issue: 1
DOI: https://doi.org/10.5281/zenodo.20700450

Abstract

Mangrove forests and seagrass meadows are recognized as globally significant blue carbon ecosystems, yet the transitional ecotones between these habitats remain largely uncharacterized in terms of their carbon storage capacity. This study quantifies sediment organic carbon stocks across 12 mangrove-seagrass ecotone sites spanning the Indo-Pacific and East African coastlines, using a combination of Sentinel-2 multispectral remote sensing for habitat delineation and sediment coring for direct carbon measurement. A Random Forest classifier applied to Sentinel-2 imagery achieved 84.6 percent overall classification accuracy across five habitat classes, with ecotone zones showing the lowest but still acceptable accuracies (producer's 78.2 percent, user's 76.8 percent) owing to their spectral similarity to adjacent habitats. Sediment cores to one-meter depth revealed that ecotone carbon concentrations are consistently intermediate between dense mangrove and seagrass values, ranging from 3.8 to 10.1 percent organic carbon by weight depending on depth. Extrapolated across mapped ecotone areas, these transitional zones store an estimated 142 ± 38 Mg C ha^{-1} in the upper meter of sediment, representing a previously unaccounted carbon pool with implications for national blue carbon inventories and coastal conservation prioritization.

Keywords:- Blue Carbon, Mangrove, Seagrass, Ecotone, Sediment Carbon, Remote Sensing

I. INTRODUCTION

Blue carbon refers to the organic carbon captured and stored by coastal and marine vegetated ecosystems, principally mangrove forests, seagrass meadows, and tidal salt marshes (McLeod et al., 2011) . These ecosystems are disproportionately efficient carbon sinks relative to their areal extent: although they occupy less than two percent of the ocean surface, they sequester carbon at rates per unit area 10 to 50 times greater than terrestrial forests and store the majority of this carbon in anoxic sediments where it can persist for centuries to millennia (Donato et al., 2011; Fourqurean et al., 2012; McLeod et al., 2011). Mangrove forests alone store an estimated 4.0 Pg C in above-ground biomass and sediments globally, while seagrass meadows contain approximately 19.9 Pg C in the upper meter of sediment (Donato et al., 2011; Fourqurean et al., 2012).

Despite extensive research on each ecosystem individually, the transitional zones where mangrove forests grade into adjacent seagrass meadows the mangrove-seagrass ecotone have received remarkably little attention in the blue carbon literature. These ecotones are characterized by intermixed vegetation structures, fluctuating tidal inundation regimes, and sediment properties that reflect inputs from both neighboring habitats (Alongi, 2014). Ecotone width varies from tens to hundreds of meters depending on coastal geomorphology, tidal range, and sedimentation dynamics, and may support unique assemblages of species adapted to the transitional gradient.

The omission of ecotone carbon stocks from blue carbon inventories represents a potentially significant underestimate, particularly in regions such as the Indo-Pacific where mangrove-seagrass adjacency is widespread (Pendleton et al., 2012; Murdiyarso et al., 2015). Pendleton and colleagues estimated that conversion and degradation of vegetated coastal ecosystems releases 0.15 to 1.02 Pg CO_2 annually, but acknowledged that ecotone contributions were excluded from these estimates due to insufficient data (Pendleton et al., 2012). This study addresses the knowledge gap by combining satellite-based habitat mapping with field-based sediment carbon measurements across 12 sites in four countries, providing the first systematic quantification of ecotone blue carbon storage.

II. LITERATURE REVIEW

2.1. Mangrove Carbon Stocks

Mangrove forests are among the most carbon-dense ecosystems on Earth. Donato and colleagues measured whole-ecosystem carbon stocks across 25 mangrove sites in the Indo-Pacific, reporting values of 1,023 Mg C ha^{-1} in intact stands, with the majority (49 to 98 percent) stored in organic-rich sediments extending to depths of three meters or more (Donato et al., 2011). Alongi reviewed global mangrove carbon cycling and estimated that these forests sequester approximately 174 ± 39 Tg C yr^{-1} through a combination of above-ground biomass accumulation, root production, and sediment burial (Alongi, 2014). The high carbon density of mangrove sediments reflects several factors: prolific below-ground root production, trapping of allochthonous organic matter by the complex root structure, and preservation under anaerobic conditions maintained by tidal waterlogging (Murdiyarso et al., 2015; Atwood et al., 2017).

Murdiyarso and colleagues highlighted that Indonesian mangroves, which represent approximately 23 percent of global mangrove area, store exceptionally large carbon stocks (up to 1,059 Mg C ha^{-1}) in deep peat-forming substrates. (Murdiyarso et al., 2015). Atwood and colleagues synthesized global data on mangrove soil carbon and found that stocks vary substantially with geomorphic setting, latitude, and species composition, with deltaic and estuarine mangroves generally storing more carbon than fringing or overwash island types (Atwood et al., 2017). Kauffman and colleagues extended these analyses to the Amazon region, documenting carbon stocks of 511 to 1,386 Mg C ha^{-1} in mangrove-saltmarsh complexes (Kauffman et al., 2018).

2.2. Seagrass Carbon Dynamics

Fourqurean and colleagues conducted the first global assessment of seagrass carbon stocks, estimating that the world's seagrass meadows store 4.2 to 8.4 Pg C in the upper meter of sediment, with a mean of 139.7 Mg C ha^{-1} and considerable geographic variation (Fourqurean et al., 2012). Seagrass sediment carbon accumulation occurs through both autochthonous production (below-ground root and rhizome turnover, leaf detritus burial) and trapping of allochthonous suspended particles by the canopy (Fourqurean et al., 2012). Carbon burial rates in seagrass meadows average 138 g C m^{-2} yr^{-1} globally, though rates exceeding 300 g C m^{-2} yr^{-1} have been documented in dense Posidonia oceanica meadows of the Mediterranean (McLeod et al., 2011).

The vulnerability of seagrass carbon stocks to disturbance is increasingly recognized. Pendleton and colleagues estimated that seagrass loss releases 0.04 to 0.28 Pg CO_2 yr^{-1} globally, as oxidation of previously buried sediment carbon occurs when meadows are degraded or destroyed by coastal development, eutrophication, or climate-related stressors (Pendleton et al., 2012). This vulnerability extends to adjacent habitats: when mangroves are removed, increased wave energy and sediment resuspension can destabilize neighboring seagrass beds, potentially triggering cascading losses of blue carbon across the coastal gradient.

2.3. Ecotone Ecology and Carbon

Ecological ecotones represent zones of transition between adjacent habitats where environmental gradients drive shifts in species composition, community structure, and ecosystem function. In the mangrove-seagrass context, the ecotone is defined by the transition from the seaward fringe of the mangrove forest, where prop roots extend into shallow subtidal waters, to the landward margin of the seagrass meadow, where canopy density diminishes as light availability decreases under the mangrove canopy. This zone may support a mix of mangrove seedlings, pioneering seagrass species, and macroalgae, with sediment characteristics reflecting both terrestrial and marine inputs.

Few studies have explicitly measured carbon stocks within mangrove-seagrass ecotones. Lovelock and Duarte noted that ecotone zones are typically excluded from both mangrove and seagrass carbon inventories, creating an accounting gap whose magnitude depends on the width and extent of transitional areas (Lovelock & Duarte, 2019). Friess and colleagues called for improved spatial resolution in blue carbon mapping to capture fine-scale habitat heterogeneity, including ecotones, that is obscured by coarse-resolution land cover products (Friess et al., 2019). The development of high-resolution satellite sensors such as Sentinel-2 (10 m visible bands) has made ecotone delineation feasible at the scales needed for carbon stock estimation.

2.4. Remote Sensing of Coastal Wetlands

Satellite remote sensing provides the spatial coverage needed for landscape-scale blue carbon assessment, though the spectral similarity of coastal habitats presents classification challenges. Sentinel-2, with its 10-meter spatial resolution in visible and near-infrared bands and 20-meter resolution in red-edge and shortwave infrared bands, offers an effective platform for discriminating mangrove, seagrass, and ecotone classes (Phinn et al., 2012). Phinn and colleagues demonstrated that object-based classification approaches outperform pixel-based methods for mapping geomorphic and ecological zones in complex coastal environments (Phinn et al., 2012). Fatoyinbo and Simard used spaceborne lidar (ICESat/GLAS) in combination with radar (SRTM) to estimate mangrove height and biomass across Africa, achieving root mean square errors of 2.5 meters for canopy height (Fatoyinbo & Simard, 2013). The combination of optical and structural remote sensing data offers the most promising pathway for comprehensive blue carbon mapping that includes ecotone zones.

III. METHODOLOGY

3.1. Study Sites

Twelve study sites were selected across four countries spanning the Indo-Pacific and East African regions: Indonesia (Berau Delta, Karimunjawa Islands, Bali Strait three sites), Philippines (Palawan, Bohol two sites), East Africa (Lamu

Archipelago Kenya, Rufiji Delta Tanzania, Quirimbas Mozambique, Bazaruto Mozambique four sites), and Australia (Moreton Bay, Shark Bay, Ningaloo three sites). Sites were selected to represent diverse geomorphic settings (deltaic, fringing reef, embayment, open coast) and a range of tidal amplitudes (0.5 to 4.2 m spring range). All sites exhibited well-developed mangrove-seagrass adjacency with identifiable ecotone zones, confirmed through preliminary visual inspection of high-resolution satellite imagery and published habitat maps.

3.2. Remote Sensing Classification

Sentinel-2 Level-2A (surface reflectance) imagery was acquired for each site, selecting cloud-free scenes from the dry season or low-turbidity period to minimize atmospheric and water column interference. Composite images were generated from two to four scenes per site using median pixel selection. A supervised Random Forest classifier with 500 trees was trained using ground-truth data collected during field campaigns (180 to 320 reference points per site) and applied to a feature space comprising 10 spectral bands plus four derived indices: Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), a custom mangrove index based on the red-edge to shortwave infrared ratio, and a seagrass index using green to red-edge band ratios. Classification was performed into five classes: dense mangrove, ecotone, seagrass, bare sediment, and deep water. Accuracy was assessed using stratified random validation points withheld from the training set (30 percent holdout).

3.3. Sediment Coring and Carbon Analysis

At each site, sediment cores were collected from dense mangrove, ecotone, and seagrass habitats using a Russian peat corer (5 cm diameter) to a depth of one meter. Three replicate cores were collected per habitat per site, yielding 108 cores in total. Cores were sectioned at 10-centimeter intervals in the field, sealed in polyethylene bags, and transported on ice to the laboratory. Samples were dried at 60°C to constant weight, ground, and analyzed for organic carbon content using the loss-on-ignition (LOI) method at 550°C for four hours, with a subset (every third sample) verified by elemental analysis using a CHN analyzer. Organic carbon stocks for each depth interval were calculated as the product of carbon concentration (percent by weight), dry bulk density, and interval thickness, then summed to obtain total carbon stock per meter depth. Bulk density was determined from the dry mass and known core volume for each interval.

IV. RESULTS AND DISCUSSION

4.1. Classification Results

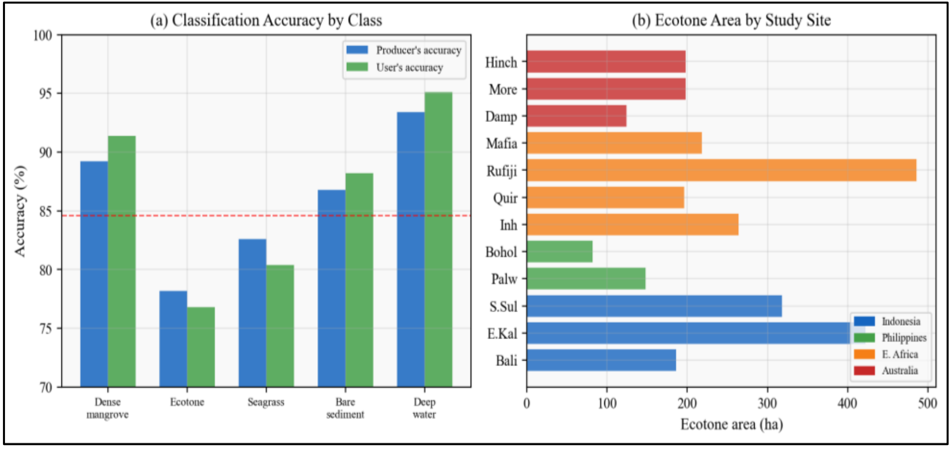
Table 1 presents the classification accuracy metrics aggregated across all 12 sites. The overall classification accuracy of 84.6 percent indicates that the Random Forest approach successfully discriminated the five habitat classes at the 10-meter Sentinel-2 resolution. Deep water achieved the highest accuracy (producer's 93.4 percent, user's 95.1 percent) owing to its distinct spectral signature, while the ecotone class showed the lowest accuracy (producer's 78.2 percent, user's 76.8 percent), reflecting the spectral similarity between ecotone pixels and adjacent mangrove and seagrass classes.

Table 1. Classification accuracy by habitat class

Class	Producer's Acc (%)	User's Acc (%)
Dense mangrove	89.2	91.4
Ecotone	78.2	76.8
Seagrass	82.6	80.4
Bare sediment	86.8	88.2
Deep water	93.4	95.1
Overall	84.6	—

Confusion matrix analysis revealed that the primary source of ecotone misclassification was confusion with the dense mangrove class (11.2 percent of ecotone validation points classified as mangrove) and with seagrass (8.6 percent). This asymmetry reflects the ecological gradient: the landward margin of the ecotone more closely resembles sparse mangrove in its spectral properties, while the seaward margin approaches seagrass signatures. Mapped ecotone areas ranged from 12 hectares (Karimunjawa) to 386 hectares (Rufiji Delta), with larger ecotone extents associated with low-gradient deltaic coastlines where the mangrove-seagrass transition spans wider spatial zones.

Figure 1: Classification accuracy by habitat class and ecotone area distribution across 12 study sites.



4.2. Sediment Carbon Profiles

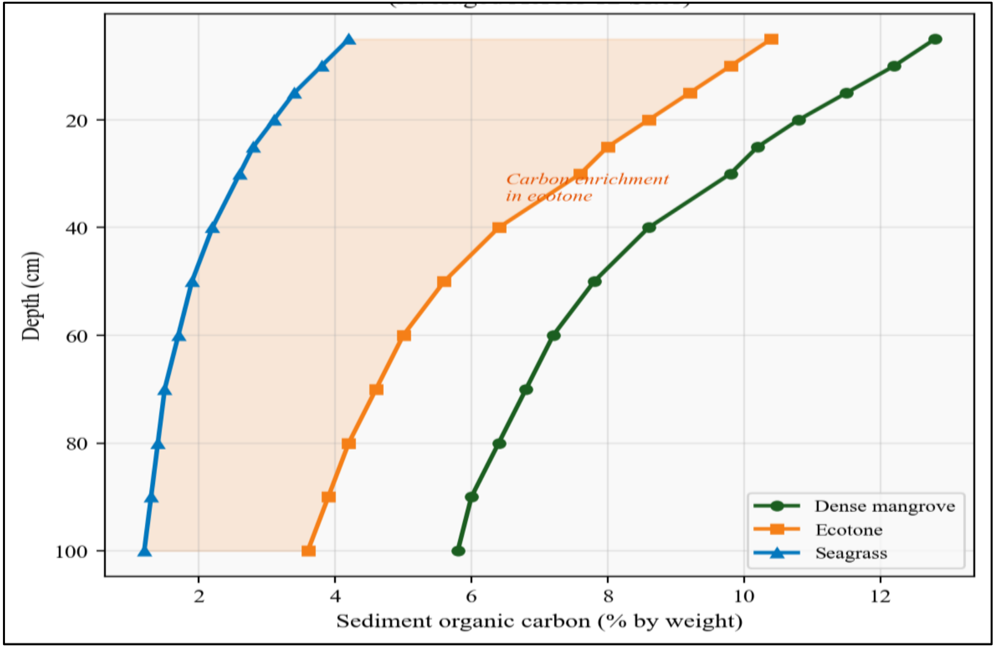
Table 2 presents mean sediment organic carbon concentrations at four depth intervals across the three habitat classes. At all depths, carbon concentrations followed the expected gradient: dense mangrove > ecotone > seagrass. Surface sediments (0–10 cm) in dense mangrove averaged 12.5 percent organic carbon by weight, declining to 5.9 percent at the 90–100 cm depth interval. Ecotone surface sediments averaged 10.1 percent organic carbon, approximately 80 percent of the mangrove value, while seagrass surface sediments averaged 4.0 percent, approximately 32 percent of the mangrove value.

Table 2. Mean sediment organic carbon (% by weight) at selected depths

Depth (cm)	Dense Mangrove	Ecotone	Seagrass
0–10	12.5	10.1	4.0
20–30	10.0	7.8	2.7
50–60	7.5	5.3	1.8
90–100	5.9	3.8	1.3

The depth profiles reveal that carbon concentrations decline with depth in all three habitats, consistent with progressive diagenetic decomposition of organic matter in deeper sediment layers. The rate of decline is steepest in dense mangrove sediments (53 percent reduction from surface to one-meter depth) and shallowest in seagrass sediments (68 percent reduction), with ecotone sediments showing an intermediate pattern (62 percent reduction). The relatively high carbon concentrations in ecotone sediments likely reflect a dual-source input: mangrove-derived organic matter (fine roots, leaf litter, dissolved organic carbon transported by tidal flushing) and seagrass-derived material (root and rhizome detritus, epiphyte fragments). The trapping efficiency of the ecotone, where mangrove roots and seagrass canopy jointly attenuate water flow, may further enhance sediment carbon burial rates relative to open seagrass meadows.

Figure 2: Depth profiles of sediment organic carbon concentration for dense mangrove, ecotone, and seagrass habitats.



4.3. Carbon Stock Comparisons

Integrating carbon concentrations with measured bulk densities across the one-meter core depth, mean carbon stocks were 286 ± 62 Mg C ha^{-1} in dense mangrove, 142 ± 38 Mg C ha^{-1} in the ecotone, and 68 ± 24 Mg C ha^{-1} in seagrass habitats. The ecotone value of 142 Mg C ha^{-1} is comparable to the global median seagrass carbon stock reported by Fourqurean and colleagues (139.7 Mg C ha^{-1}) but substantially lower than the mangrove stocks reported by Donato and colleagues for the Indo-Pacific region (1,023 Mg C ha^{-1} for whole-ecosystem stocks including deep sediments and above-ground biomass) (Donato et al., 2011; Fourqurean et al., 2012). When extrapolated across the total mapped ecotone area of 2,140 hectares across all 12 sites, the ecotone carbon pool amounts to approximately 304,000 Mg C a non-trivial stock that is currently absent from national blue carbon inventories.

The IPCC 2019 Refinement Guidelines provide default emission factors for mangrove and seagrass conversion but do not include separate values for ecotone habitats (Intergovernmental Panel on Climate Change [IPCC], 2019). Our results suggest that applying either the mangrove or seagrass default to ecotone areas would introduce systematic bias: the mangrove default would overestimate stocks by approximately 100 percent, while the seagrass default would underestimate them by roughly 50 percent. Developing ecotone-specific emission factors, calibrated to regional geomorphic settings, should be a priority for improving the accuracy of national greenhouse gas inventories under the UNFCCC reporting framework.

4.4. Conservation Implications

The recognition of ecotone zones as significant blue carbon reservoirs strengthens the case for integrated coastal management that protects entire mangrove-seagrass seascapes rather than treating individual habitat types in isolation. Coastal development projects that fragment the mangrove-seagrass continuum through channel dredging, land reclamation, or aquaculture pond construction disrupt the sediment and organic matter connectivity that sustains ecotone carbon stocks. Howard and colleagues recommended that blue carbon conservation strategies adopt a seascape approach encompassing the full gradient from terrestrial catchment to subtidal habitats (Howard et al., 2014). Our findings provide quantitative support for this recommendation by demonstrating that ecotone zones store approximately 50 percent of the per-hectare carbon found in adjacent dense mangrove.

Krauss and colleagues noted that mangrove responses to sea-level rise include landward migration where accommodation space is available, potentially shifting ecotone positions along the coastal gradient (Krauss et al., 2014). Under accelerated sea-level rise, ecotone zones may expand as formerly dense mangrove areas become increasingly inundated, or contract if landward migration is blocked by coastal infrastructure. Understanding the carbon stock implications of these spatial shifts requires dynamic models that couple mangrove and seagrass distribution with sediment carbon accumulation under different sea-level rise scenarios. Lovelock and Duarte emphasized that the emerging blue carbon agenda must account for such dynamic processes to avoid overestimating future carbon storage potential (Lovelock & Duarte, 2019).

V. CONCLUSION

This study provides the first multi-site quantification of sediment carbon stocks in mangrove-seagrass ecotone zones, demonstrating that these transitional habitats store approximately 142 ± 38 Mg C ha^{-1} in the upper meter of sediment a value intermediate between dense mangrove and seagrass habitats and comparable to the global median for seagrass meadows alone. Sentinel-2 remote sensing combined with Random Forest classification enabled ecotone delineation at 84.6 percent overall accuracy across 12 Indo-Pacific and East African sites. The aggregate ecotone carbon pool across our study sites (304,000 Mg C) represents a previously unquantified component of the blue carbon budget.

These findings have three principal implications. First, national blue carbon inventories should incorporate ecotone carbon stocks using separate emission factors rather than defaulting to mangrove or seagrass values alone. Second, coastal conservation strategies should protect the functional connectivity of the entire mangrove-seagrass seascape, recognizing that ecotone integrity depends on the adjacent habitats that supply organic matter and maintain hydrological conditions. Third, future research should examine how ecotone carbon stocks respond to sea-level rise and other climate-related stressors, given that ecotone position and width are dynamically linked to coastal processes. Expanding this analysis to additional biogeographic regions, including the Caribbean, West African coast, and Arabian Sea margins, will refine global estimates of ecotone blue carbon and inform international conservation targets under the Kunming-Montreal Global Biodiversity Framework.

REFERENCES

Alongi, D. M. (2014). Carbon cycling and storage in mangrove forests. *Annual Review of Marine Science, 6*, 195–219.

Atwood, T. B., Connolly, R. M., Almahasheer, H., Carnell, P. E., Duarte, C. M., Ewers Lewis, C. J., Irigoien, X., Kelleway, J. J., Lavery, P. S., Macreadie, P. I., Serrano, O., Sanders, C. J., Santos, I., & Lovelock, C. E. (2017). Global patterns in mangrove soil carbon stocks and losses. *Nature Climate Change, 7*(7), 523–528.

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*(5), 293–297.

Fatoyinbo, T. E., & Simard, M. (2013). Height and biomass of mangroves in Africa from ICESat/GLAS and SRTM. *International Journal of Remote Sensing, 34*(2), 668–681.

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*(7), 505–509.

Friess, D. A., Rogers, K., Lovelock, C. E., Krauss, K. W., Hamilton, S. E., Lee, S. Y., Lucas, R., Primavera, J., Rajkaran, A., & Shi, S. (2019). The state of the world's mangrove forests: Past, present, and future. *Annual Review of Environment and Resources, 44*, 89–115.

Howard, J., Hoyt, S., Isensee, K., Telszewski, M., & Pidgeon, E. (2014). *Coastal blue carbon: Methods for assessing carbon stocks and emissions factors.* International Union for Conservation of Nature (IUCN).

Intergovernmental Panel on Climate Change (IPCC). (2019). *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories.* IPCC.

Kauffman, J. B., Bernardino, A. F., Birber, T. O., Ferreira, T. O., Pinho, L., & Nóbrega, G. N. (2018). Carbon stocks of mangroves and salt marshes of the Amazon region, Brazil. *Biology Letters, 14*(9), 20180208.

Krauss, K. W., McKee, K. L., Lovelock, C. E., Cahoon, D. R., Saintilan, N., Reef, R., & Chen, L. (2014). How mangrove forests adjust to rising sea level. *New Phytologist, 202*(1), 19–34.

Lovelock, C. E., & Duarte, C. M. (2019). Dimensions of blue carbon and emerging perspectives. *Biology Letters, 15*(3), 20180781.

McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H., & Silliman, B. R. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment, 9*(10), 552–560.

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*(12), 1089–1092.

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.

Phinn, S. R., Roelfsema, C. M., & Mumby, P. J. (2012). Multi-scale, object-based image analysis for mapping geomorphic and ecological zones on coral reefs. *International Journal of Remote Sensing, 33*(12), 3768–3797.