


Mangrove Blue Carbon in Weda Bay: Remote Sensing and Indonesia's NDC Legal Framework

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ABSTRACT

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This study employs multi-temporal remote sensing integrated with Google Earth Engine (GEE) to assess mangrove blue carbon dynamics and carbon offset potential at Indonesia Weda Bay Industrial Park (IWIP), Halmahera, North Maluku, from 2013 to 2024. Sentinel-2 Surface Reflectance Harmonized composites and Landsat NDVI time series were applied across four concentric analytical zones (CORE, BUF_5 km, BUF_10 km, BUF_20 km) and four monitoring sites (WEDABAY, SAGEA, SOSOWO, WOSTULO). Results document consistent blue carbon stock decline across all zones from 2019 to 2024, with cumulative losses of -0.53 MtCO_{2e} in the CORE zone and -2.23 MtCO_{2e} in BUF_20km, while paradoxically increasing per-hectare carbon density revealed a survivor bias driven by progressive loss of low-density peripheral pixels. Three of four monitoring sites exhibited mangrove area expansion of 64 to 76 ha at the 500 m buffer scale, while SAGEA remained persistently stagnant, reflecting site-specific ecological regimes within the same industrial landscape. The carbon stock indicators generated in this study provide preliminary spatial evidence that may support future measurement, reporting and verification (MRV) baseline development for Indonesia's Agriculture, Forestry and Other Land Use (AFOLU)-related Nationally Determined Contributions (NDC) reporting and blue carbon conservation planning. A regulatory gap analysis further evaluates the carbon economic value (Nilai Ekonomi Karbon/NEK) legal framework under Presidential Regulation No. 110 of 2025 and its derivative ministerial regulations, indicating that no clearly identifiable, dedicated provincial-level NEK, Gas Rumah Kaca (GRK), or blue carbon implementation rules for North Maluku were found within the scope of this study. These findings underscore that translating Weda Bay's modeled mangrove carbon indicators into formal MRV, registry, or carbon market mechanisms requires field validation, clearer subnational regulatory pathways, and stronger alignment with Indonesia's national NEK framework.

1. INTRODUCTION

Mangrove ecosystems are recognized as globally significant blue carbon sinks, storing disproportionately large amounts of carbon in both biomass and sediment compared to most terrestrial forest systems, and thus serve as critical natural assets for climate change mitigation. The formalization of blue carbon within international climate governance has been shaped by science-policy co-production and standardization, enabling coastal carbon sequestration to be integrated into national greenhouse gas inventories and market-based accounting mechanisms [1]. At the site level, mangrove soil organic carbon, which constitutes the dominant carbon pool in these ecosystems, has been shown to be highly vulnerable to anthropogenic disturbance, with degradation capable of releasing substantial portions of accumulated carbon stocks [2]. This governance trajectory underscores that the legitimacy of blue carbon in climate frameworks is contingent upon the establishment of robust measurement, reporting, and verification systems that can credibly track carbon

permanence across temporal and spatial scales. The demonstrated sensitivity of mangrove soil carbon to human pressures further reinforces the scientific rationale for spatially explicit monitoring approaches that can detect degradation trajectories before irreversible loss thresholds are crossed. Together, these governance and biophysical foundations establish the imperative for rigorous multi-temporal assessments of mangrove blue carbon to support evidence-based climate policy and conservation planning in tropical archipelagic nations.

Indonesia, as the custodian of the largest mangrove estate in the world, faces accelerating mangrove degradation driven by coastal urbanization, aquaculture expansion, and land-use conversion, creating an urgent need for systematic monitoring to quantify carbon stock changes and support national climate commitments. Remote sensing evidence from Indonesian coastlines has confirmed that built-up development and associated thermal changes are strongly linked to progressive mangrove decline, indicating that conversion pressures continue to intensify across the archipelago [3]. Concurrently,

Indonesia's pathway toward its net-zero pledge remains constrained by structural barriers in the energy sector, including financing gaps and persistent fossil fuel dependence, which necessitate the diversification of mitigation strategies to encompass nature-based carbon solutions [4]. The ongoing trajectory of mangrove loss implies that without timely satellite-based monitoring, substantial emissions from mangrove conversion risk remaining unaccounted in national greenhouse gas inventories, thereby undermining the integrity of Indonesia's climate reporting. The structural impediments to energy-sector decarbonization further position mangrove blue carbon as a complementary and cost-effective mitigation pathway capable of contributing meaningfully to closing the gap between current emissions trajectories and stated Nationally Determined Contributions (NDC) targets. This convergence of ecological degradation pressures and policy implementation constraints demands immediate scientific attention to mangrove blue carbon assessment in strategically important and ecologically vulnerable sites such as Weda Bay, Halmahera.

This study aims to assess the multi-temporal dynamics of mangrove blue carbon offset potential in Weda Bay, Halmahera, using remote sensing approaches to generate spatially explicit carbon estimates that support Indonesia's Low Carbon Development Initiative (LCDI) and Nationally Determined Contribution commitments. Cloud-based geospatial platforms, particularly Google Earth Engine (GEE), have enabled the development of scalable and reproducible annual mangrove mapping frameworks that can be applied across diverse coastal landscapes with high classification accuracy [5]. At the policy level, cross-country analyses of net-zero compatible development pathways have emphasized the necessity of country-driven policy packages that operationalize long-term decarbonization targets through sector-specific short-term interventions, including land-use sector contributions [6]. The availability of such cloud-computing methodologies provides a transferable analytical framework that this study adapts for the Weda Bay context, enabling consistent multi-temporal mangrove extent mapping as the foundational spatial input for carbon stock change estimation. The policy imperative for translating NDC commitments into measurable, site-specific carbon accounting further contextualizes this study within the broader need for spatially disaggregated blue carbon data that can inform both national reporting and sub-national conservation prioritization. By integrating multi-temporal remote sensing analysis with carbon offset estimation, this study bridges the persistent gap between spatial monitoring capabilities and policy-relevant carbon accounting for Indonesia's blue carbon agenda.

This study contributes to the theoretical advancement of blue carbon science by integrating multi-temporal remote sensing with carbon offset quantification in an understudied eastern Indonesian mangrove landscape, addressing a persistent gap between spatial monitoring and carbon accounting in the existing literature. Recent developments in remote sensing-based mangrove health assessment have demonstrated that landscape-scale diagnostic tools can effectively identify degradation zones where carbon permanence is most at risk, yet these diagnostics remain largely disconnected from carbon stock quantification frameworks [7]. Similarly, studies combining multitemporal satellite monitoring with socio-institutional analysis have shown that remotely sensed mangrove cover change alone is

insufficient for meaningful blue carbon assessment without contextual interpretation of the underlying drivers and recovery conditions [8]. The existence of sophisticated spatial diagnostic tools that are not systematically coupled with carbon accounting exposes a clear theoretical gap, which this study directly addresses by proposing an integrated analytical approach linking mangrove extent dynamics to estimated carbon offset values. The recognition that area-based change detection requires deeper contextual framing reinforces this study's contribution of embedding spatial dynamics within a policy-relevant carbon offset framework rather than treating cover change as a self-sufficient metric. This study therefore advances the theoretical integration of geospatial analysis and blue carbon economics within the specific and underrepresented context of eastern Indonesian mangrove systems.

The practical implications of this study extend to informing Indonesia's national climate policy instruments, emerging carbon market mechanisms, and site-specific conservation prioritization for the Weda Bay mangrove ecosystem. Economy-wide analyses of carbon pricing in Indonesia have demonstrated that the design and scope of carbon tax instruments must be accompanied by distributional safeguards, underscoring the critical need for sector-specific emissions data, including from land-based sources, to ensure equitable and effective policy formulation [9]. Global cost-effectiveness assessments have further established that integrating mangrove-based green infrastructure with engineered coastal protection yields substantially higher benefit-cost ratios than structural measures alone, strengthening the economic justification for mangrove conservation as a multi-benefit investment [10]. The need for spatially disaggregated emissions baselines in carbon pricing design implies that credible blue carbon data from priority sites such as Weda Bay can directly contribute to the operationalization of Indonesia's emerging carbon trading system and associated fiscal policy frameworks. The demonstrated economic advantages of combined mangrove-engineered protection further illustrate that blue carbon offset quantification carries practical value beyond mitigation accounting, simultaneously supporting investment cases for coastal adaptation, resilience planning, and disaster risk reduction. These practical dimensions position this study as a decision-support contribution for policymakers, carbon market participants, and coastal zone managers operating within Indonesia's LCDI and NDC implementation framework.

This study acknowledges several limitations inherent in remote sensing-based blue carbon assessment, including the reliance on satellite-derived spatial proxies and the absence of direct field-based carbon stock measurements at the Weda Bay study site. Integrated field-satellite approaches for biomass estimation have confirmed that spectral vegetation indices, while capable of producing acceptable predictive models, function as proxies that require ground-truth calibration specific to local vegetation conditions and structural characteristics [11]. At the policy level, assessments of national climate strategies have cautioned that carbon dioxide removal accounting frequently contains ambiguities, recommending that offset claims be supported by transparent and verifiable measurement systems rather than assumed carbon permanence [12]. This methodological dependency on published carbon density emission factors rather than site-specific field measurements represents a key constraint, as the

carbon offset estimates necessarily carry uncertainty that can only be reduced through dedicated ground-truth campaigns in Weda Bay. The broader international concern regarding accountability in carbon removal accounting further contextualizes this limitation, acknowledging that the offset potential reported herein represents a modeled estimate requiring field verification before formal integration into NDC reporting mechanisms. Future research should therefore prioritize field-calibrated carbon stock inventories and soil carbon sampling campaigns in Weda Bay to validate, refine, and strengthen the remote sensing-based estimates presented in this study.

This study is therefore guided by two integrated questions. First, why does apparent carbon density per unit area increase in several IWIP-adjacent mangrove zones while total carbon stock continues to decline at the landscape scale? Second, why do remotely sensed mangrove carbon losses in Weda Bay remain difficult to translate into operational subnational measurement, reporting and verification (MRV), registry, and compliance mechanisms despite the existence of Indonesia's national carbon economic value (NEK) framework? By addressing these questions, this study does not treat remote sensing outputs as direct proof of creditable carbon offsets. Instead, it positions them as preliminary spatial evidence for identifying carbon-stock dynamics, measurement uncertainty, and governance gaps that must be resolved before Weda Bay's mangrove carbon assets can be credibly incorporated into NDC reporting or carbon market instruments.

2. STUDY AREA

The study area is situated in Weda Bay, Central Halmahera Regency, North Maluku Province, Indonesia, encompassing the industrial and coastal landscape surrounding the Indonesia Weda Bay Industrial Park (IWIP). This region borders an extensive mangrove belt along the western coast of Halmahera Island, which functions as a critical blue carbon reservoir within the Wallacea biodiversity hotspot [13]. The IWIP site represents one of the largest nickel-processing industrial complexes in eastern Indonesia, where rapid industrial development directly intersects with sensitive coastal ecosystems [14]. The ecological significance of this location is further amplified by its position within a globally recognized center of marine biodiversity, where mangrove carbon dynamics carry both local conservation and international climate policy relevance. Previous studies have identified the North Maluku coastline as a zone of accelerating mangrove pressure, driven by industrial expansion, coastal land conversion, and inadequate spatial governance. These combined factors establish Weda Bay as a scientifically compelling and policy-relevant priority site for multi-temporal blue carbon stock monitoring and assessment.

Figure 1 illustrates pronounced spatial heterogeneity in total carbon density across the IWIP landscape, with the highest carbon density concentrated in the northern interior forested zones and visible degradation signatures in the coastal and peri-industrial areas. Green-toned pixels, representing higher carbon density values, are predominantly distributed in areas with intact forest cover distant from the industrial center, while red-toned pixels indicate reduced carbon stock capacity in zones most proximate to IWIP operations. The inset trend chart further confirms that BUF_5 km consistently maintains elevated mean carbon density values throughout the

observation period, while the CORE zone records the lowest trajectory across all years. This spatial gradient is consistent with the directional influence of industrial disturbance on surrounding mangrove biomass, where land clearing, hydrological modification, and sediment disruption progressively reduce carbon storage capacity with proximity to the industrial epicenter. The pattern observed across the 2019 to 2024 period also reveals a sustained rather than episodic decline in carbon density, suggesting structural rather than temporary ecosystem stress. Collectively, Figure 1 underscores the analytical utility of spatially explicit carbon mapping in detecting fine-scale degradation dynamics that aggregate-level estimates would otherwise obscure.

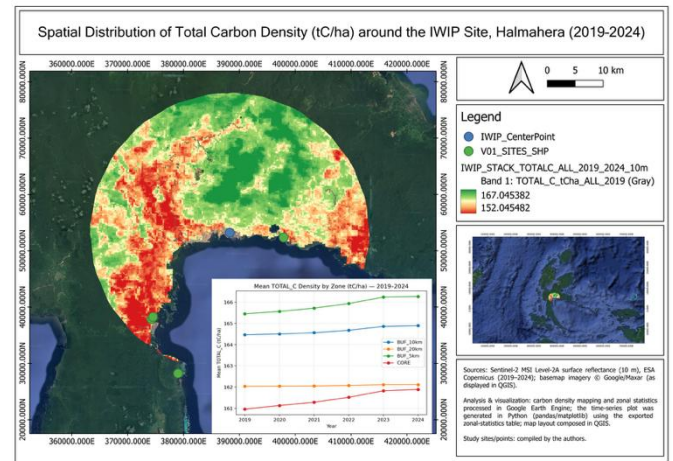


Figure 1. Spatial distribution of total carbon density (tC/ha) around the IWIP site, Halmahera (2019–2024)

Source: Sentinel-2 Multi-Spectral Instrument Level-2A surface reflectance (10 m), ESA Copernicus (2019–2024); basemap imagery Google/Maxar (as displayed in QGIS); carbon density mapping and zonal statistics processed in Google Earth Engine (GEE); time-series plot generated in Python (pandas/matplotlib) using the exported zonal-statistics table; map layout composed in QGIS; study sites/points compiled by the authors.

The spatial analysis was structured using a concentric buffer zonation scheme derived from the IWIP center point, delineating four analytical zones: CORE (inner boundary), BUF_5 km (5 km buffer), BUF_10 km (10 km buffer), and BUF_20 km (20 km buffer). This multi-zone framework follows established remote sensing protocols for zonal carbon stock quantification, enabling the detection of spatial gradients in ecosystem condition from the industrial epicenter outward. The total land area encompassed by each zone was consistently recorded across all observation years, covering approximately 4,515.72 ha (CORE), 17,579.73 ha (BUF_5 km), 42,190.68 ha (BUF_10 km), and 126,343.74 ha (BUF_20 km). The proportional increase in area from the innermost to the outermost zone reflects the geometric expansion inherent in concentric buffer analysis, providing progressively larger spatial samples for ecosystem-level carbon accounting. Stable zone boundaries across all six observation years further validate the reproducibility of the spatial delineation framework, ensuring that observed changes in carbon stock or vegetation condition are attributable to genuine ecosystem dynamics rather than methodological inconsistencies. This zonation design therefore provides a robust spatial scaffold for interpreting directional and distance-dependent patterns of mangrove carbon change throughout the 2019 to 2024 study period.

Figure 2 presents the spatial extent of the four concentric

analytical zones overlaid on the total carbon density map, with the inset bar chart illustrating the valid analyzed area per zone across all observation years from 2019 to 2024. The spatial overlay confirms that the CORE zone is concentrated in the immediate coastal and peri-industrial area adjacent to the IWIP center point, while the BUF_5 km, BUF_10 km, and BUF_20 km zones progressively extend into the interior forested landscape and surrounding coastal mosaic. It is important to note that marine and coastal water bodies falling within the concentric buffer zones were systematically excluded from the analysis through the application of NDVI-based vegetation masking and ESA WorldCover v200 land classification, ensuring that carbon stock estimations were derived exclusively from terrestrial and mangrove vegetation pixels. This exclusion accounts for a portion of the difference between total zone area and valid analyzed area, particularly in the BUF_10 km and BUF_20 km zones where the Weda Bay coastal waters intersect the buffer boundaries. The bar chart inset further reveals a consistent decline in valid pixel coverage across all zones throughout the observation period, with the most pronounced reductions occurring in the CORE and BUF_5 km zones, reflecting the compounding effects of cloud contamination and land surface disturbance in the innermost areas. Collectively, Figure 2 establishes both the spatial configuration and the data quality framework that underpins all subsequent carbon stock analyses presented in this study.

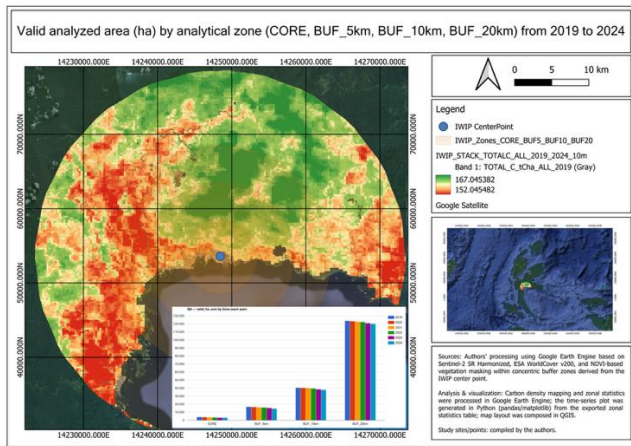


Figure 2. Valid analyzed area (ha) by analytical zone (CORE, BUF_5 km, BUF_10 km, BUF_20 km) from 2019 to 2024

Source: Authors' processing using Google Earth Engine (GEE) based on Sentinel-2 Surface Reflectance Harmonized, ESA WorldCover v200, and NDVI-based vegetation masking within concentric buffer zones derived from the Indonesia Weda Bay Industrial Park (IWIP) center point; carbon density mapping and zonal statistics processed in Google Earth Engine (GEE); time-series plot generated in Python (pandas/matplotlib) from the exported zonal statistics table; map layout composed in QGIS; study sites/points compiled by the authors.

To contextualize the spatial carbon dynamics at IWIP Weda Bay within a broader regional perspective, three comparative mangrove monitoring sites were incorporated: SAGEA, SOSOWO, and WOSTULO, all located within the Halmahera coastal zone alongside the primary WEDABAY site. The geographic positioning of the four sites confirms that WEDABAY (lon = 127.87, lat = 0.34) and WOSTULO (lon = 127.87, lat = 0.35) are situated in close spatial proximity along the western Halmahera coast, while SOSOWO (lon = 127.91, lat = 0.26) is located approximately 4 km to the southeast.

SAGEA (lon = 128.08, lat = 0.47) occupies the most northeastern position, approximately 21 km from WEDABAY, providing the greatest spatial separation among the four monitoring sites. This inter-site spatial configuration ensures that the comparative analysis captures genuine ecological variation across distinct coastal landscape units rather than spatially autocorrelated signals from overlapping buffer zones. The mangrove area change recorded between 2018 and 2024 further underscores the ecological differentiation among sites, with WOSTULO recording the largest net expansion of 76.48 ha, followed by WEDABAY (68.76 ha) and SOSOWO (64.67 ha), while SAGEA recorded near-zero area change of only 0.09 ha over the same period. These contrasting area change trajectories, combined with the spatial carbon change patterns derived from Sentinel-2 Surface Reflectance Harmonized composites, establish the multi-site framework as an essential ecological reference baseline for interpreting blue carbon dynamics in the IWIP coastal zone.

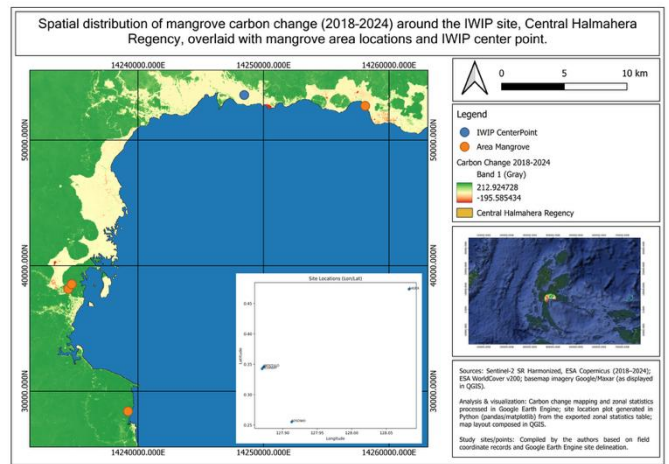


Figure 3. Mangrove carbon change (2018–2024) around the Indonesia Weda Bay Industrial Park (IWIP) site, Halmahera, and comparative monitoring site locations

Source: Sentinel-2 Surface Reflectance Harmonized, ESA Copernicus (2018–2024); ESA WorldCover v200; basemap imagery Google/Maxar (as displayed in QGIS); carbon change mapping and zonal statistics processed in Google Earth Engine (GEE); site location scatter plot generated in Python (pandas/matplotlib) from the exported zonal statistics table; map layout composed in QGIS; study sites/points compiled by the authors based on field coordinate records and Google Earth Engine (GEE) site delineation.

Figure 3 presents the spatial distribution of mangrove carbon change across the IWIP landscape from 2018 to 2024, simultaneously providing the geographic context for the four comparative monitoring sites through the inset scatter plot. The main map reveals a predominantly green-toned landscape in the inland areas of Central Halmahera Regency, indicating net carbon gain up to a maximum of 212.92 tC/ha, while localized red-toned patches along the immediate coastal fringe proximate to the IWIP center point indicate carbon loss reaching as low as -195.59 tC/ha. The inset scatter plot confirms the relative geographic positioning of the four monitoring sites, with WEDABAY and WOSTULO clustered at approximately 127.87 longitude and 0.34 to 0.35 latitude, SOSOWO positioned at approximately 127.91 longitude and 0.26 latitude, and SAGEA at approximately 128.08 longitude and 0.47 latitude. The spatial coincidence of red-toned carbon loss signatures with the orange-point mangrove area locations along the coastal fringe confirms that the documented carbon stock decline is concentrated within the vegetated coastal

buffer zones most directly exposed to industrial and hydrological disturbance from the IWIP operations. The administrative boundary of Central Halmahera Regency visible in the map further contextualizes the jurisdictional framework within which the IWIP industrial activities and associated mangrove monitoring are situated, reinforcing the relevance of this study for regional conservation governance. Collectively, Figure 3 establishes both the spatial foundation and the comparative site framework for interpreting the carbon change dynamics and vegetation health trajectories discussed in the subsequent analytical sections of this study.

Long-term Landsat Normalized Difference Vegetation Index (NDVI) analysis from 2013 to 2024 across the four monitoring sites reveals distinct and persistently differentiated vegetation health trajectories within the Halmahera coastal zone. SOSOWO consistently records the highest mean NDVI values throughout the entire observation period, ranging from 0.855 in 2013 to a peak of 0.877 in 2021, while SAGEA exhibits the lowest and most volatile trajectory, with values fluctuating between 0.691 and 0.751 across the same period. WEDABAY and WOSTULO occupy intermediate positions, with WEDABAY ranging from 0.803 to 0.848 and WOSTULO from 0.827 to 0.856, though WEDABAY displays a more pronounced declining trend from 2021 onward compared to the relative stability of WOSTULO over the same period. The three lowest annual NDVI values at SAGEA were recorded in 2015 (0.701), 2018 (0.712), and 2021 (0.691), suggesting recurring episodic canopy disruption events rather than a gradual linear degradation trajectory. These inter-site differentials reflect the heterogeneous distribution of anthropogenic disturbance, hydrological modification, and natural vegetation succession across the Halmahera coastline, with SOSOWO's sustained elevation indicative of a relatively undisturbed mangrove stand and SAGEA's persistent low

values consistent with greater exposure to localized disturbance pressures. The comparative NDVI framework thus provides an essential long-term ecological baseline for contextualizing the carbon stock dynamics observed at the WEDABAY site in relation to broader regional mangrove health conditions.

Figure 4 presents clearly differentiated NDVI trajectories across the four Halmahera monitoring sites, with SOSOWO and SAGEA occupying consistently distinct upper and lower bounds throughout the entire 12-year observation window. SOSOWO maintains a stable and elevated NDVI ranging from 0.855 to 0.877, while SAGEA fluctuates markedly between 0.691 and 0.751, with the lowest values recorded in 2021 (0.691), 2015 (0.701), and 2018 (0.712), representing episodic canopy disruption events that periodically reduce vegetation density at that site. WEDABAY and WOSTULO exhibit broadly convergent trajectories in the intermediate range, though WEDABAY displays a more pronounced declining trend from 2021 onward, declining from 0.848 in 2020 to a minimum of 0.803 in 2023, before a marginal recovery to 0.818 in 2024. The post-2021 divergence between WEDABAY and WOSTULO is particularly significant, as WOSTULO maintains relatively stable values between 0.827 and 0.855 over the same period, suggesting that the decline at WEDABAY reflects site-specific anthropogenic influence rather than regional climatic variability. The oscillatory pattern at SAGEA, characterized by recurring troughs at roughly three-year intervals, may correspond to a combination of episodic drought stress, localized land use change, and hydrological fluctuation specific to that northeastern coastal location. Taken together, Figure 4 establishes the multi-site NDVI comparative framework as an essential interpretive reference for contextualizing the blue carbon dynamics detected at the IWIP-adjacent WEDABAY monitoring site.

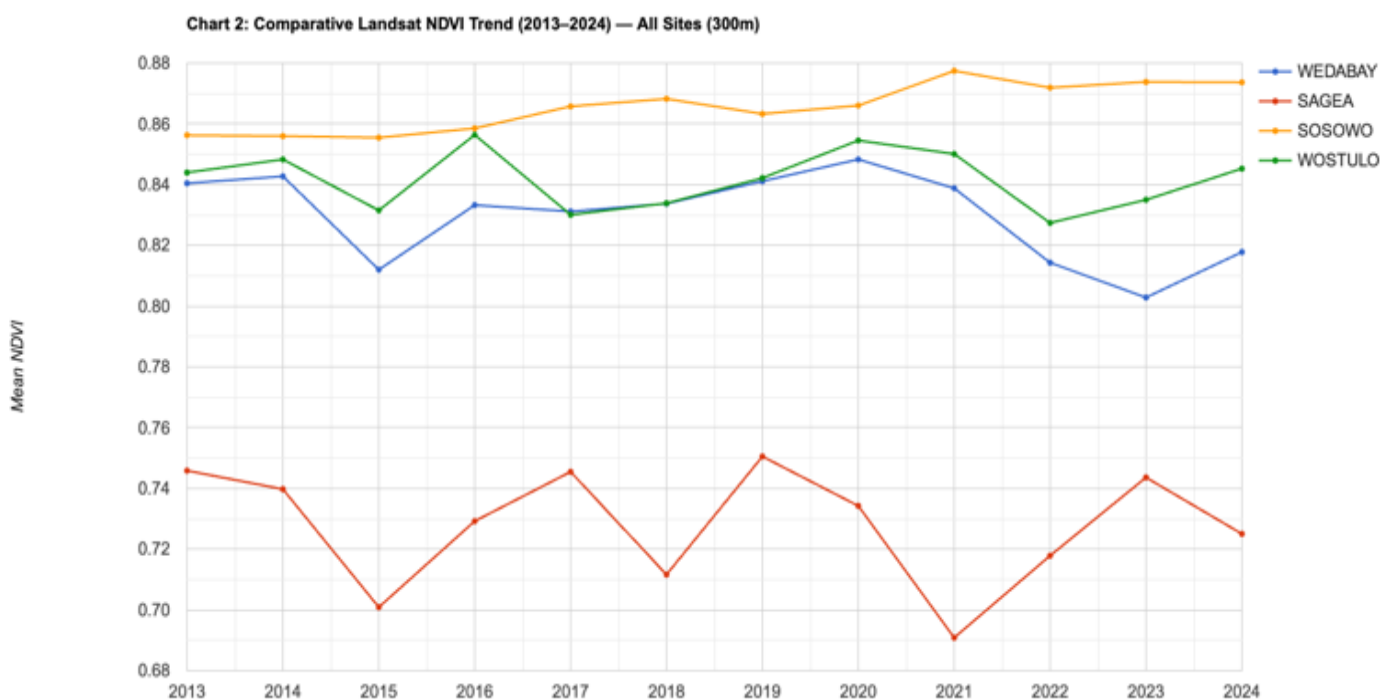


Figure 4. Comparative Landsat Normalized Difference Vegetation Index (NDVI) trend (2013–2024) across four mangrove monitoring sites in the Halmahera coastal zone: WEDABAY, SAGEA, SOSOWO, and WOSTULO, at 300 m buffer resolution. Source: Authors' processing using Google Earth Engine (GEE) based on Landsat surface reflectance time-series composites; annual mean Normalized Difference Vegetation Index (NDVI) derived from 300 m buffer zones at each monitoring site; chart generated in Python (pandas/matplotlib) from the exported zonal statistics table; compiled by the authors.

The spatial, temporal, and ecological evidence collectively presented across this study area characterization underscores the critical scientific and policy relevance of conducting rigorous multi-temporal blue carbon assessment in the Weda Bay context. The convergence of accelerating industrial development, documented mangrove carbon loss, declining vegetation indices at WEDABAY, and heterogeneous ecological conditions across four comparative monitoring sites within a single coastal regency establishes a uniquely compelling case for spatially explicit carbon stock quantification. The Weda Bay mangrove system occupies a strategic position at the intersection of Indonesia's industrial expansion agenda and its international climate commitments under the Paris Agreement and NDC, rendering spatially disaggregated carbon monitoring not merely academically valuable but operationally necessary. The contrast between SOSOWO's sustained high NDVI and stable mangrove extent and WEDABAY's post-2021 decline and documented carbon loss further demonstrates that mangrove ecosystem responses to industrial pressure are highly site-specific, reinforcing the need for site-level rather than regional-level carbon accounting frameworks. Remote sensing-based multi-temporal assessment, as applied in this study across four concentric buffer zones and four comparative monitoring sites, provides the spatial resolution and temporal depth required to detect fine-scale ecosystem dynamics and translate them into policy-actionable blue carbon offset estimates. This study therefore addresses a critical evidence gap in Indonesia's blue carbon knowledge base, contributing spatially disaggregated carbon data from an ecologically significant and industrially pressured eastern Indonesian mangrove landscape that has remained largely underrepresented in the existing scientific literature.

3. MATERIAL AND METHOD

This study employed a multi-scale spatial analytical framework implemented in GEE, initiating with the standardization of site coordinates for four mangrove monitoring sites across the Halmahera coastal zone: WEDABAY, SAGEA, SOSOWO, and WOSTULO. Site coordinates recorded in latitude/longitude format were normalized to longitude/latitude order as required by GEE's geometry input convention, ensuring spatial accuracy across all subsequent buffer delineation and zonal extraction operations. Four concentric circular buffer zones were generated around each site at radii of 50 m, 100 m, 300 m, and

500 m, producing a total of 16 site-level feature collections that served as the primary spatial units for mangrove vegetation and carbon stock analysis. In parallel, a second spatial delineation framework was applied at the IWIP landscape scale, defining four concentric analytical zones centered on the IWIP center point: CORE, BUF_5 km, BUF_10 km, and BUF_20 km, spanning a total coverage of approximately 126,343.74 ha at the outermost boundary. The dual-scale buffer design enabled simultaneous analysis at the fine site level, capturing localized vegetation dynamics within 50 m to 500 m of each monitoring point, and at the landscape level, quantifying carbon stock gradients across the broader IWIP industrial zone (Table 1). This spatial delineation framework establishes the foundational analytical scaffold upon which all subsequent image processing, spectral analysis, and carbon stock quantification steps were constructed.

Satellite image data were acquired from two primary sources: Sentinel-2 Multi-Spectral Instrument Level-2A surface reflectance composites at 10 m spatial resolution from ESA Copernicus, covering the observation period from 2019 to 2024, and Landsat surface reflectance time-series composites for long-term vegetation trend analysis from 2013 to 2024. Sentinel-2 Surface Reflectance Harmonized imagery was filtered for the study area extent, and cloud and shadow contamination were systematically removed using the Scene Classification Layer (SCL) masking procedure available through the GEE Sentinel-2 Surface Reflectance Harmonized collection, retaining only clear-sky observations for composite generation. Annual median composites were subsequently generated from the cloud-masked image stack for each observation year, providing spatially continuous surface reflectance layers that minimized residual atmospheric and seasonal variability across the multi-year study period. The SCL-based masking approach specifically excluded cloud shadow (SCL class 3), cloud medium probability (class 8), cloud high probability (class 9), and cirrus (class 10) pixels, ensuring that the resulting annual composites contained only high-quality surface reflectance observations over the study area. ESA WorldCover v200 land classification was additionally applied as a supplementary mask to exclude marine and coastal water body pixels falling within the buffer zone boundaries, preventing non-vegetated water surface reflectance values from contaminating the mangrove carbon stock estimates. This dual masking approach, combining SCL cloud filtering with WorldCover land classification, ensured the analytical integrity of all spectral and carbon estimation outputs derived from the satellite image composites.

Table 1. Spatial analytical framework: buffer zone design and total area coverage for site-level monitoring and Indonesia Weda Bay Industrial Park (IWIP) landscape analysis

| Analytical Framework | Zone / Buffer | Radius / Scale | Total Area (ha) | Observation Period |
|---|---------------|----------------|-----------------|--------------------|
| Site-Level Monitoring (4 Sites: WEDABAY, SAGEA, SOSOWO, WOSTULO) | Buffer 50 m | 50 m radius | 0.77 (avg.) | 2018–2024 |
| | Buffer 100 m | 100 m radius | 3.02 (avg.) | |
| | Buffer 300 m | 300 m radius | 24.31 (avg.) | |
| | Buffer 500 m | 500 m radius | 63.52 (avg.) | |
| IWIP Landscape Zones (Centered on IWIP Center Point) | CORE | Inner boundary | 4,515.72 | 2019–2024 |
| | BUF_5 km | 5 km buffer | 17,579.73 | |
| | BUF_10 km | 10 km buffer | 42,190.68 | |
| | BUF_20 km | 20 km buffer | 126,343.74 | |

Note: Site-level buffer area values represent mean area (ha) across all four monitoring sites (WEDABAY, SAGEA, SOSOWO, WOSTULO). Indonesia Weda Bay Industrial Park (IWIP) landscape zone areas are constant across the 2019–2024 observation period. Source: Authors' processing using Google Earth Engine (GEE)

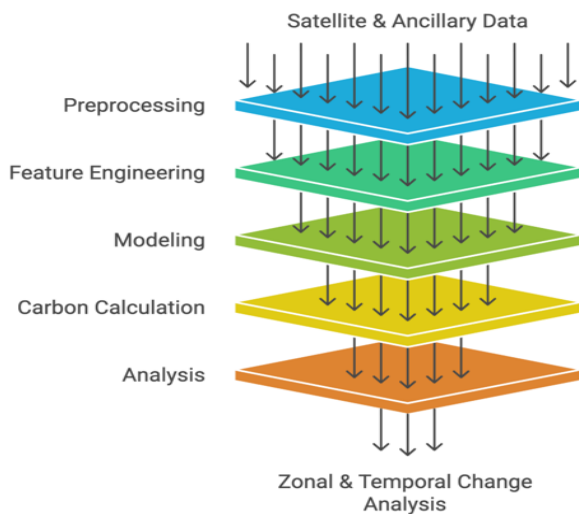


Figure 5. Mangrove blue carbon change analysis workflow
 Source: Authors' illustration using Napkin; workflow design based on analytical procedures implemented in Google Earth Engine (GEE) by the authors.

Figure 5 shows the complete mangrove change analysis workflow, illustrating the sequential analytical steps from site coordinate standardization and buffer delineation through spectral index computation, mangrove identification, carbon stock estimation, zonal statistics summarization, and final map visualization and export. The workflow confirms that spectral indices constitute the central computational layer, with four primary indices calculated from the annual median composites: the NDVI, the Canopy Mangrove Red Index (CMRI), the Normalized Difference Moisture Index (NDMI), and the Enhanced Vegetation Index (EVI). NDVI served as the primary indicator of photosynthetically active vegetation density derived from the near-infrared and red band ratio, while CMRI provided a mangrove-specific spectral discrimination signal exploiting the characteristic reflectance properties of mangrove canopy structure in the red-edge and shortwave infrared domains. NDMI and EVI were incorporated as supplementary indices to capture canopy moisture content and reduce soil and atmospheric noise respectively, improving the discriminative capacity of the mangrove classification mask in heterogeneous coastal landscapes. A rule-based mangrove mask was subsequently constructed by applying threshold criteria across the combined spectral index stack, identifying pixels exhibiting spectral signatures consistent with mangrove vegetation and excluding non-mangrove land cover classes including bare soil, water, and non-mangrove forest, before the resulting binary mask was applied consistently across all observation years to delineate valid mangrove extent within each buffer zone. This spectrally-grounded identification procedure, as visualized in Figure 5, provides the methodological foundation for the subsequent carbon stock estimation step, ensuring spatial correspondence between mapped mangrove extent and the carbon density values extracted for each analytical zone.

Above-ground carbon (AGC), CO₂ equivalent (CO₂e), and total carbon density (TOTC) were estimated for each analytical zone by applying empirically-derived allometric model constants to the NDVI-derived vegetation index values extracted from the annual Sentinel-2 composites, producing spatially explicit carbon stock layers for each observation year. The carbon stock model integrated NDVI as the primary input variable with species-specific and ecosystem-level scaling

constants calibrated for tropical mangrove systems, generating mean carbon density estimates in units of tC/ha for AGC and TOTC, and tCO₂e/ha for the CO₂ equivalent layer, enabling direct comparability with international carbon offset reporting standards. At the 500 m site-level buffer, mean AGC values in 2024 ranged from 178.91 tC/ha at SAGEA to 198.71 tC/ha at SOSOWO, with corresponding CO₂e values of 1,998.99 tCO₂e/ha and 2,100.01 tCO₂e/ha respectively, while WEDABAY and WOSTULO recorded intermediate values of 188.88 tC/ha and 195.42 tC/ha. Zonal statistics encompassing area (ha), mean carbon density, and standard deviation were extracted for all buffer zones across all observation years using GEE's reduceRegions function, with results exported as tabular data for subsequent analysis in Python using the pandas and matplotlib libraries. Map visualization layers including spatial carbon change maps, site location scatter plots, and time-series trend charts were generated by combining GEE-exported raster outputs with QGIS cartographic layout tools, producing the composite figures presented in this study. The complete analytical workflow, from coordinate standardization and image preprocessing through spectral index computation, mangrove identification, carbon estimation, and statistical summarization, was implemented programmatically in GEE to ensure full reproducibility and temporal scalability of the multi-year assessment framework.

It should be emphasized that the carbon estimates in this study are derived from remote sensing proxies and published model assumptions rather than from direct field-based biomass or soil carbon measurements. Therefore, the term “blue carbon” is used in this study to refer to modeled mangrove carbon indicators associated with mapped vegetation condition and estimated carbon density, not to a fully validated accounting of all mangrove carbon pools. The analysis does not directly measure below-ground biomass or sediment organic carbon, which are major components of mangrove blue carbon systems. Consequently, the resulting CO₂e values should be interpreted as indicative carbon-stock estimates for ecological monitoring and policy discussion, rather than as certified carbon credits or final values for formal offset issuance. Field calibration, soil carbon sampling, independent validation, and locally specific allometric equations would be required before these estimates could be used for compliance-grade carbon accounting.

4. RESULTS AND DISCUSSION

4.1 Spatiotemporal dynamics of mangrove cover and blue carbon stock in Weda Bay (2013–2024)

Multi-temporal analysis of the IWIP landscape reveals a consistent and progressive decline in total blue carbon stock across all four concentric analytical zones from 2019 to 2024, as presented in Figure 6. At the landscape scale, total stock in the CORE zone decreased from 2.35 MtCO₂e in 2019 to 1.82 MtCO₂e in 2024, while the outermost BUF_20 km zone recorded a net reduction from 73.54 MtCO₂e to 71.31 MtCO₂e over the same period, consistent with documented patterns of mangrove carbon loss associated with industrial coastal development along Indonesian coastlines. The cumulative net stock change over the five-year period amounted to -0.53 MtCO₂e in CORE, -1.29 MtCO₂e in BUF_5 km, -1.69 MtCO₂e in BUF_10 km, and -2.23 MtCO₂e in BUF_20 km, confirming that cumulative carbon loss magnitude increases

with spatial extent across the zonal gradient in a pattern attributable to the progressive spatial propagation of industrial disturbance outward from the IWIP center point. The distance-dependent pattern of cumulative carbon loss is consistent with the spatial propagation of industrial disturbance outward from the IWIP center point, where hydrological modification, land clearing, and sediment disruption progressively reduce the carbon sequestration capacity of surrounding mangrove systems. The greater absolute stock losses recorded in the outer buffer zones relative to the CORE reflect the substantially larger vegetated areas captured at greater distances from the industrial epicenter, rather than proportionally higher rates of per-hectare carbon loss. These landscape-level stock dynamics establish the broad spatial and temporal context for the more granular carbon density and site-level analyses presented in the subsequent sub-sections.

Figure 6 illustrates a consistent downward trajectory in total blue carbon stock across all four analytical zones throughout the 2019 to 2024 observation period, with the steepest proportional decline concentrated in the CORE zone and a progressive increase in cumulative loss magnitude toward the outer buffer zones. The annualized carbon stock loss rates derived from the 2019–2024 zonal exchange analysis quantify the scale and spatial distribution of blue carbon depletion at operationally relevant temporal resolution for carbon offset accounting purposes. CORE zone records the lowest absolute annualized loss at $-0.107 \text{ MtCO}_2\text{e/year}$, while BUF_5 km, BUF_10 km, and BUF_20 km record progressively higher losses of -0.257 , -0.338 , and $-0.446 \text{ MtCO}_2\text{e/year}$ respectively, establishing a spatial gradient in annual carbon flux consistent with findings from multi-temporal remote sensing studies of industrially disturbed coastal mangrove systems. The cumulative stock trajectory further reveals that BUF_5 km declined from $9.18 \text{ MtCO}_2\text{e}$ in 2023 to $8.83 \text{ MtCO}_2\text{e}$ in 2024, a single-year loss of $0.35 \text{ MtCO}_2\text{e}$ representing the steepest annual reduction recorded across all years, suggesting a potential acceleration of degradation dynamics in the most recent observation period.

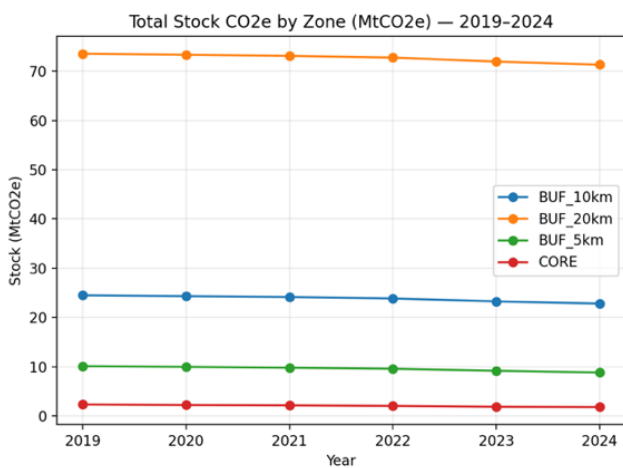


Figure 6. Total blue carbon stock (MtCO_2e) by analytical zone (CORE, BUF_5 km, BUF_10 km, BUF_20 km) from 2019 to 2024 at the Indonesia Weda Bay Industrial Park (IWIP) landscape scale, Weda Bay, Halmahera

Source: Authors' processing using Google Earth Engine (GEE) based on Sentinel-2 Surface Reflectance Harmonized annual median composites; total carbon stock (tCO_2e) aggregated per zone using reduceRegions zonal statistics and converted to MtCO_2e ; time-series chart generated in Python (pandas/matplotlib); compiled by the authors.

This acceleration signal in BUF_5 km is particularly significant as this zone encompasses the immediate coastal mangrove belt most directly subject to IWIP-related hydrological modification and land reclamation, where shoreline accretion driven by industrial activities has been documented at rates exceeding 36 m/year in recent years. The non-linear nature of the stock decline trajectory implies that point-in-time assessments at any single year would systematically underestimate the full trajectory of carbon loss, reinforcing the scientific necessity of multi-temporal monitoring frameworks for credible blue carbon accounting in industrial coastal contexts. These annualized loss rates collectively quantify the scale of ongoing carbon depletion at Weda Bay and establish the empirical foundation for evaluating the offset potential of conservation interventions discussed in Section 4.2.

Figure 7 shows that annualized carbon stock loss rates increase systematically from the innermost to the outermost analytical zone, with CORE recording the lowest absolute loss at $-0.107 \text{ MtCO}_2\text{e/year}$ and BUF_20 km recording the highest at $-0.446 \text{ MtCO}_2\text{e/year}$, confirming a clear distance-dependent gradient in blue carbon depletion intensity across the IWIP industrial landscape. A critical paradox emerges from the comparison of total carbon stock trajectories and mean carbon density per hectare across the IWIP analytical zones, wherein carbon density per unit area exhibits a persistent upward trend while total carbon stock simultaneously declines throughout the 2019 to 2024 observation period. Mean total carbon density in the CORE zone increased from 161.0 tC/ha in 2019 to 161.9 tC/ha in 2024, while BUF_5 km recorded a rise from 165.5 to 166.3 tC/ha and BUF_10 km increased from 164.5 to 164.9 tC/ha over the same period, a pattern broadly consistent with documented observations of biomass densification in residual mangrove patches persisting under disturbance pressure.

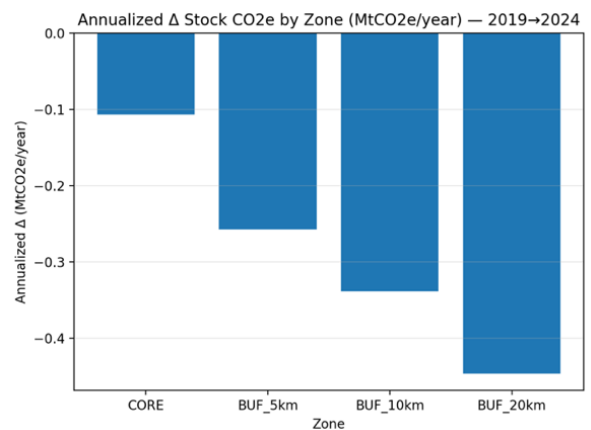


Figure 7. Annualized carbon stock loss rate ($\text{MtCO}_2\text{e/year}$) by analytical zone (CORE, BUF_5 km, BUF_10 km, BUF_20 km) over the 2019–2024 observation period at the Indonesia Weda Bay Industrial Park (IWIP) landscape scale, Weda Bay, Halmahera

Source: Authors' processing using Google Earth Engine (GEE) based on Sentinel-2 Surface Reflectance Harmonized annual median composites; annualized delta stock computed as total net stock change divided by the five-year observation period; bar chart generated in Python (pandas/matplotlib); compiled by the authors.

This apparent contradiction between increasing per-hectare carbon density and decreasing total stock may be explained by a density-area trade-off, in which the reduction of valid

vegetated area occurs alongside modest increases in estimated carbon density among remaining pixels. The densification signal in remaining mangrove stands likely reflects a combination of canopy structural maturation in relatively undisturbed remnant patches and a methodological survivor bias effect, whereby low-density pixels at the degradation frontier are progressively excluded from valid pixel coverage as vegetation loss expands from the industrial core outward. This density-area trade-off carries direct implications for carbon offset accounting, as area-normalized carbon density metrics alone would suggest improving ecosystem carbon condition, while aggregate stock-based metrics reveal the true direction of net carbon loss at the landscape scale. The simultaneous increase in per-hectare density and decrease in total stock therefore constitutes a critical diagnostic finding, demonstrating that carbon density metrics and total stock metrics are not interchangeable for landscape-level blue carbon assessment and that both must be evaluated concurrently to accurately characterize net offset potential.

Figure 8 reveals a counterintuitive upward trajectory in mean total carbon density across all analytical zones from 2019 to 2024, with BUF_5 km consistently recording the highest density values and CORE showing the steepest rate of increase, a pattern that stands in direct contrast to the declining total stock trend documented in Figure 6 and constitutes the central paradox addressed in this section. The decline in valid carbon-analyzed area should be interpreted cautiously because this metric combines several possible influences, including cloud contamination, masking thresholds, classification rules, vegetation loss, land surface alteration, and mixed coastal pixels. Therefore, the valid-area ratio is not treated here as direct evidence of ecological degradation by itself. Rather, it is used as a diagnostic indicator that helps identify where data coverage and possible land-cover disturbance require closer scrutiny. In the CORE zone, the decline in valid-area ratio may partly reflect ecological change associated with industrial land transformation, but this interpretation remains plausible rather than causally confirmed. Additional evidence from field surveys, high-resolution imagery, tidal records, and land-development data would be needed to separate actual mangrove degradation from methodological filtering effects.

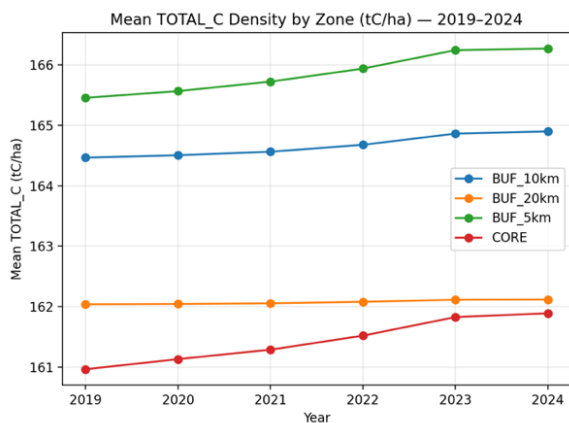


Figure 8. Mean total carbon density (tC/ha) by analytical zone (CORE, BUF_5 km, BUF_10 km, BUF_20 km) from 2019 to 2024

Source: Authors' processing using Google Earth Engine (GEE) based on Sentinel-2 Surface Reflectance Harmonized annual median composites; mean total carbon density (TOTC, tC/ha) extracted per zone using reduceRegions zonal statistics; time-series chart generated in Python (pandas/matplotlib); compiled by the authors.

The observed increase in mean carbon density per hectare should therefore not be interpreted as an overall improvement in mangrove carbon condition. A more cautious interpretation is that this pattern may reflect a density-area trade-off, in which remaining vegetated pixels retain or slightly increase their estimated carbon density while low-density or disturbed peripheral pixels are progressively excluded from the valid mangrove mask. This possible survivor-bias effect provides a useful explanatory hypothesis, but it should not be treated as a confirmed causal mechanism without field validation and independent classification accuracy assessment. The key analytical implication is that per-hectare carbon density and total landscape carbon stock must be interpreted together, because density-based indicators alone may obscure net carbon-stock decline caused by contraction of valid vegetated area.

Figure 9 illustrates that the valid carbon-analyzed area ratio declines most severely in the CORE zone, falling from 0.89 in 2019 to 0.68 in 2024, while the outer buffer zones maintain comparatively stable ratios throughout the observation period, establishing a spatially graduated pattern of data coverage reduction that closely mirrors the disturbance gradient documented across the IWIP industrial landscape. At the site level, mangrove area dynamics from 2018 to 2024 across the four comparative monitoring sites reveal a pronounced spatial bifurcation between three actively expanding sites and one stagnant site, with area change patterns exhibiting a strong buffer-radius-dependent scaling relationship at all three expanding locations. WOSTULO recorded the largest net mangrove area expansion of 76.48 ha at the 500 m buffer, followed by WEDABAY with 68.76 ha and SOSOWO with 64.67 ha, while SAGEA registered near-zero net change of only 0.09 ha over the same period, a contrast consistent with site-level heterogeneity in hydrological connectivity, anthropogenic disturbance intensity, and natural recovery potential documented in the Weda Bay mangrove system.

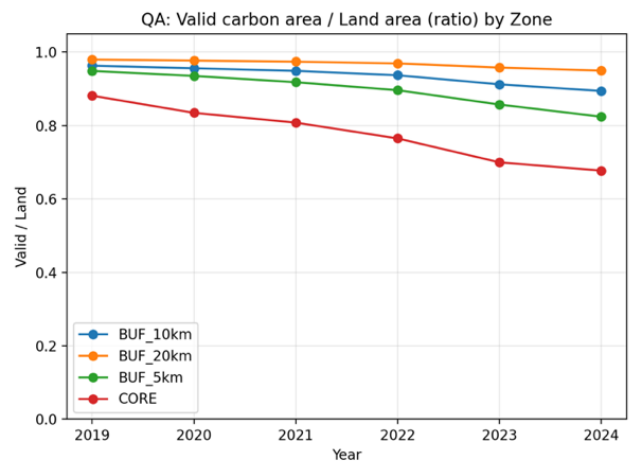


Figure 9. Valid carbon-analyzed area ratio (valid area / total land area) by analytical zone (CORE, BUF_5 km, BUF_10 km, BUF_20 km) from 2019 to 2024

Source: Authors' processing using Google Earth Engine (GEE) based on Sentinel-2 Surface Reflectance Harmonized annual median composites with SCL cloud masking and ESA WorldCover v200 land classification; valid pixel area and total land area extracted per zone using reduceRegions; ratio computed as valid_ha divided by land_ha; time-series chart generated in Python (pandas/matplotlib); compiled by the authors.

The area change versus buffer radius relationship, as presented in Figure 10, reveals that WEDABAY, SOSOWO,

and WOSTULO all exhibit strongly non-linear increases in net mangrove area with expanding buffer radius, with values accelerating from near-zero at the 50 m scale to 64–76 ha at the 500 m scale, whereas SAGEA remains consistently flat across all buffer radii, indicating that near-zero change at SAGEA reflects a genuine landscape-level stagnation rather than a scale-dependent sampling artifact. The exponential area growth pattern at WEDABAY, SOSOWO, and WOSTULO from the 50 m through 500 m buffer radii suggests that mangrove expansion at these sites is predominantly occurring at greater distances from the site center points, consistent with natural recruitment and colonization of peripheral intertidal zones rather than densification of existing core stands. In contrast, the persistently flat area change trajectory at SAGEA across all buffer radii confirms that this northeastern site operates under a fundamentally different ecological regime, characterized by constrained recovery capacity that limits

Figure 10 shows a pronounced ecological bifurcation among the four monitoring sites, wherein WEDABAY, SOSOWO, and WOSTULO exhibit strongly non-linear mangrove area expansion with increasing buffer radius while SAGEA remains persistently flat across all radii, demonstrating that near-zero area change at SAGEA reflects a genuine landscape-level constraint rather than a scale-dependent measurement artifact. The site-level carbon density analysis at the 500 m buffer scale in 2024 reveals that all four monitoring sites maintain ecologically substantial AGC stocks, yet with meaningful inter-site differentials that reflect the contrasting disturbance histories and vegetation structural conditions described throughout this section. SOSOWO records the highest mean AGC density of 198.71 tC/ha with a corresponding CO₂ equivalent of 2,100.01 tCO₂e/ha, followed by WOSTULO at 195.42 tC/ha and 2,083.21 tCO₂e/ha, WEDABAY at 188.88 tC/ha and 2,049.86 tCO₂e/ha, and SAGEA recording the lowest values of 178.91 tC/ha and 1,998.99 tCO₂e/ha, a ranking consistent with the NDVI-based vegetation health hierarchy established from the long-term Landsat time series presented in Figure 4.

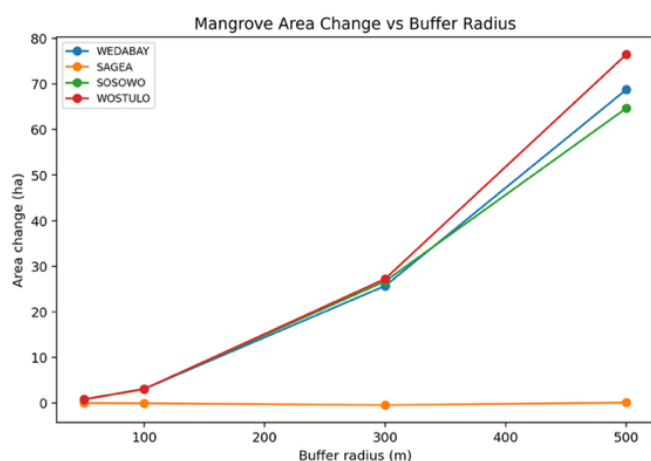


Figure 10. Net mangrove area change (ha) from 2018 to 2024 across four buffer radii (50 m, 100 m, 300 m, 500 m) at four comparative monitoring sites (WEDABAY, SAGEA, SOSOWO, WOSTULO) in the Halmahera coastal zone.

Source: Authors' processing using Google Earth Engine (GEE) based on Sentinel-2 Surface Reflectance Harmonized annual median composites with Normalized Difference Vegetation Index (NDVI)-based mangrove mask; net area change computed as the difference between 2024 and 2018 mangrove-classified pixel area within each circular buffer zone; chart generated in Python (pandas/matplotlib); compiled by the authors.

The CO₂e versus buffer radius relationship reveals a site-specific crossing pattern between WEDABAY and WOSTULO, wherein WEDABAY consistently records higher CO₂e values than WOSTULO at small buffer radii (50–100 m) but falls below WOSTULO at the 300–500 m scale, suggesting that the innermost mangrove core at WEDABAY retains relatively high carbon density while broader-scale expansion at WOSTULO is associated with proportionally higher carbon accumulation in peripheral zones. SAGEA maintains a persistently lower CO₂e trajectory across all buffer radii, recording a minimum of approximately 1,944 tCO₂e/ha at the 100 m buffer before partially recovering to 1,999 tCO₂e/ha at 500 m, a profile that reflects both the lower NDVI values documented throughout the 2013–2024 Landsat series and the site's near-zero mangrove area expansion. The convergence of lower carbon density, stagnant area change, and persistently low NDVI trajectories at SAGEA establishes this northeastern site as the most ecologically compromised within the Halmahera comparative monitoring network, with direct implications for its potential contribution to blue carbon offset portfolios. Collectively, the multi-scale spatiotemporal analysis of mangrove cover dynamics and blue carbon stock changes in Weda Bay reveals a system under progressive industrial pressure, wherein declining total stocks and shrinking valid vegetated area at the landscape scale coexist with paradoxical per-hectare density gains in surviving stands, site-level heterogeneity in area expansion trajectories, and persistent inter-site carbon density differentials that reflect the differentiated ecological trajectories of the four Halmahera coastal monitoring sites across the 2013 to 2024 observation window.

4.2 Blue carbon offsets from mangroves: Implications for Indonesia's Nationally Determined Contributions implementation

The multi-temporal carbon stock decline documented across the IWIP landscape in Section 4.1 generates spatially explicit blue carbon data that directly addresses a critical gap in Indonesia's Nationally Determined Contribution reporting, particularly within the Agriculture, Forestry, and Other Land Use sector. Analyses of NDC transparency among developing country parties have identified the Agriculture, Forestry and Other Land Use (AFOLU) sector as consistently underreported, with inconsistencies in methodological approaches and incomplete progress indicators constraining the credibility and comparability of land-based carbon accounting in national greenhouse gas inventories [12]. Global assessments of countries' commitments to land-based carbon sequestration in NDCs have further revealed that only a minority of signatory nations include specific, quantified targets for soil and ecosystem organic carbon, leaving substantial potential carbon pools systematically excluded from formal climate pledges despite their recognized mitigation significance [15]. The cumulative blue carbon stock losses quantified in this study, amounting to -0.53 MtCO₂e in the CORE zone and -2.23 MtCO₂e in BUF_20 km over the 2019 to 2024 period, represent precisely the type of site-specific, temporally disaggregated carbon flux data that current NDC reporting frameworks struggle to incorporate, and whose inclusion would substantially improve the comprehensiveness of Indonesia's land-use sector accounting. The multi-scale zonal analysis applied in this study, combining landscape-level stock aggregation with site-level carbon

density profiling across four monitoring sites, offers a reproducible methodological template that could be extended to other mangrove-bearing regencies along the eastern Indonesian coastline, thereby progressively filling the spatial gaps in AFOLU-sector carbon monitoring at the subnational level. Integrating remote sensing-derived blue carbon estimates from industrially pressured coastal sites such as Weda Bay into Indonesia's NDC monitoring and reporting framework would not only improve the accuracy of national greenhouse gas inventories but also establish verifiable baseline emission factors for future conservation-based carbon crediting at the site level.

The spatiotemporal dynamics of mangrove blue carbon documented in this study carry direct relevance for Indonesia's LCDI, which explicitly frames nature-based carbon sinks as strategic contributors to the country's decoupling of economic growth from greenhouse gas emissions trajectories. Analyses of Indonesia's post-Paris Agreement low carbon development paradigm have demonstrated that the LCDI's foundational rationale centers on integrating forest and land-use sector contributions with energy-sector decarbonization to achieve inclusive, sustainable growth outcomes, recognizing that social justice dimensions of the transition must be addressed alongside carbon accounting objectives [16]. Comparative assessments of net-zero compatible development pathways across major emerging economies including Indonesia, have established that short-term policy packages must operationalize land-use sector contributions as part of country-driven strategies, particularly where energy transition timelines are constrained by existing infrastructure dependencies and financing gaps [17]. The annualized carbon stock loss rates documented in this study, ranging from $-0.107 \text{ MtCO}_2\text{e/year}$ in the CORE zone to $-0.446 \text{ MtCO}_2\text{e/year}$ in BUF_20 km, represent measurable deviations from conservation baseline trajectories that, if reversed through targeted mangrove restoration and protection interventions, could generate quantifiable carbon stock increments directly attributable to LCDI-aligned conservation management. The contrast between SAGEA's near-zero mangrove area expansion and the substantial recovery trajectories observed at WEDABAY, SOSOWO, and WOSTULO further illustrates that the carbon offset potential of coastal mangrove systems in North Maluku is highly site-specific, reinforcing the LCDI's emphasis on spatially disaggregated, site-calibrated carbon accounting rather than aggregate national-level emission factor assumptions. Translating the blue carbon stock dynamics documented at Weda Bay into LCDI-compatible offset values requires an integrated monitoring architecture that connects satellite-derived carbon estimation with ground-truthed verification, community-level land tenure arrangements, and subnational policy instruments capable of operationalizing conservation incentives at the regency scale.

Indonesia's structural dependence on carbon-intensive fossil fuels and the persistent financing gaps constraining its energy sector transition collectively reinforce the strategic importance of nature-based blue carbon solutions as a near-term, cost-effective mitigation complement within the country's overall NDC architecture. Assessments of Indonesia's energy transition prospects have concluded that while the country has committed to net-zero emissions by 2060, substantial structural barriers, including lower-middle-income fiscal constraints, limited capacity to attract international climate finance, and entrenched fossil fuel infrastructure dependencies, place significant uncertainty around the

achievability of energy-sector decarbonization targets within planned timelines [4]. Critical geopolitical analyses of Indonesia's response to global climate governance have further identified that the country's cognitive framing of natural resources as essential to economic power and energy security has produced a selective, two-pronged approach to climate norms that prioritizes resource extraction alongside incremental environmental commitments, thereby slowing the pace of structural transformation required for full NDC implementation [18]. Within this structural context, the mangrove blue carbon assets documented in this study, including total CO_2e stocks exceeding 159,000 tCO_2e at the WOSTULO 500 m buffer alone, represent ecologically substantial carbon reservoirs whose conservation and restoration could support future mitigation planning within shorter implementation horizons, provided that field validation, MRV safeguards, and registry requirements are fulfilled.

The documented loss of 533,217 tCO_2e from the CORE zone over only five years further quantifies the scale of emissions that would result from continued unmitigated industrial pressure on the Weda Bay mangrove system, underscoring that the opportunity cost of inaction in blue carbon conservation substantially exceeds the carbon equivalent of many short-term energy efficiency interventions currently prioritized in Indonesia's LCDI sectoral plans. Positioning mangrove blue carbon conservation at IWIP as a nature-based climate solution complementary to Indonesia's energy transition commitments would enable the country to demonstrate measurable, near-term mitigation progress aligned with NDC obligations while longer-term structural decarbonization of the energy sector proceeds on its constrained timeline.

The blue carbon offset potential quantified in this study is directly relevant to the evolving architecture of ASEAN carbon markets operating under Article 6 of the Paris Agreement, within which high-integrity, spatially verified nature-based mitigation outcomes from mangrove ecosystems could be incorporated as internationally transferable carbon credits. Analyses of ASEAN carbon market development under Article 6 have established that core provisions including corresponding adjustments, measurement, reporting and verification protocols, and centralized registries provide a structural reference for enhancing market credibility and interoperability across member states at varying stages of carbon pricing system development, creating a regional framework within which Indonesian blue carbon assets could eventually participate [19].

The results provide preliminary spatial evidence that may support the development of future MRV baselines for mangrove conservation, but they do not by themselves establish creditable mitigation outcomes under Article 6 or Indonesia's SRN-PPI framework. Verifiable carbon offsets require additional requirements, including clearly defined project boundaries, baseline scenarios, additionality, permanence, leakage control, land tenure clarity, independent verification, and registry compatibility. Therefore, the carbon-stock changes documented in this study should be understood as an initial monitoring input for offset feasibility assessment, rather than as certified or immediately tradable carbon credits.

Studies of international transfer limits under Article 6 have further demonstrated that environmental integrity safeguards, including restrictions on the transfer of mitigation outcomes that exceed independently projected emission levels, are

essential to preventing perverse incentive structures that could undermine the ambition of future NDC cycles, implications directly relevant to the design of any blue carbon crediting mechanism at Weda Bay [20]. The carbon density profiles documented across the four comparative monitoring sites in this study, with CO₂e values ranging from 1,999 tCO₂e/ha at SAGEA to 2,100 tCO₂e/ha at SOSOWO at the 500 m buffer scale, provide the site-specific measurement baselines that Article 6-compliant blue carbon crediting mechanisms require as reference levels against which additionality and permanence claims can be evaluated. However, the paradox of rising per-hectare carbon density coexisting with declining total stock in the CORE and buffer zones simultaneously highlights a critical accounting challenge for Article 6 integration, as density-based metrics alone could produce misleading additionality assessments if total vegetated area contraction is not explicitly incorporated into the reference emission factor framework applied to Weda Bay. Developing an Article 6-compatible blue carbon crediting framework for the IWIP coastal zone would require the standardization of multi-temporal remote sensing monitoring protocols, the establishment of legally recognized conservation baseline boundaries, and the institutional linkage of satellite-derived carbon estimates with Indonesia's national registry systems under the Enhanced Transparency Framework of the Paris Agreement.

The domestic policy landscape for operationalizing mangrove blue carbon offset value in Indonesia encompasses both emerging private climate governance initiatives and fiscal instruments including carbon pricing mechanisms, yet the effectiveness of these instruments in channeling conservation finance toward coastal mangrove ecosystems remains constrained by structural governance gaps. Studies of private climate governance initiatives in Indonesia and Singapore have revealed that voluntary carbon standards and transnational certification mechanisms are increasingly being appropriated by internationalized fractions of domestic capital for economic expansion rather than genuine emissions reduction, creating a governance dynamic in which private initiative proliferation does not necessarily translate into transformative climate policy outcomes at ecologically critical sites [21].

Analysis of carbon tax implementation in Indonesia through social accounting matrix modeling has demonstrated that sector-specific carbon pricing produces asymmetric distributional impacts concentrated in the electricity and energy-intensive sectors, underscoring the need for careful instrument design when extending carbon pricing signals to land-based blue carbon conservation in coastal industrial zones where production activities and ecosystem services co-occur [9]. These governance implications are directly applicable to the Weda Bay context, where the co-location of IWIP's nickel processing operations with the mangrove carbon reserve documented in this study creates a complex multi-stakeholder environment in which the credibility of any voluntary or compliance blue carbon offset scheme depends critically on transparent MRV systems capable of distinguishing genuine additionality from carbon asset appropriation without meaningful ecosystem protection. The per-hectare carbon stocks documented at the four Halmahera monitoring sites, ranging from 544 tC/ha at SAGEA to 572 tC/ha at SOSOWO in total carbon density at the 500 m buffer scale, represent economically material assets whose monetization through private carbon markets would require

enforceable land tenure protections, transparent benefit-sharing mechanisms for local coastal communities, and legally binding conservation agreements with IWIP as a key industrial stakeholder. Effective integration of Weda Bay's mangrove blue carbon into Indonesia's domestic carbon pricing and voluntary market architecture therefore requires a governance framework that aligns private initiative with public accountability, connects fiscal instrument design with ecosystem conservation incentives, and ensures that offset revenues generate genuine, permanent, and locally equitable carbon stock preservation outcomes at the site level.

The translation of Weda Bay's blue carbon offset potential into operationally credible NDC contributions ultimately depends on the capacity of subnational governance systems to bridge the persistent gap between national climate commitments and local implementation realities in Indonesia's coastal regency administrations. Comparative analysis of subnational climate regulations in Indonesia and the Philippines has documented that in both countries, provincial and regency-level climate policies consistently fall short of matching the ambition of national NDCs, with contributing factors including superficial regulatory adoption, slow transmission of policies from national to subnational levels, limited local awareness of climate change impacts, and the absence of clear frameworks for integrating non-state actors into subnational climate governance processes [22]. Systematic assessment of NDC implementation processes risks across 21 countries has further identified that short-term implementation failures are most frequently linked to insufficient political will, policy inconsistency, and weakened civil society oversight rather than to technical capacity constraints alone, and that differentiated strategies tailored to countries' institutional and political risk profiles are essential to closing the implementation gap [23]. Both risk dimensions are directly applicable to Central Halmahera Regency, where the administrative jurisdiction over the IWIP coastal zone intersects with limited local government capacity for satellite-based carbon monitoring, regulatory capture risks associated with concentrated industrial interests, and the absence of dedicated blue carbon conservation frameworks within provincial spatial planning documents. Overcoming these subnational governance constraints would require targeted capacity building for remote sensing-based carbon monitoring in local government technical units, the formal integration of blue carbon conservation objectives into Central Halmahera's medium-term development plans, and the establishment of inter-agency coordination mechanisms linking the Ministry of Environment and Forestry's national mangrove restoration program with IWIP's corporate environmental compliance obligations at the site level. The spatiotemporal carbon dynamics documented across this study collectively constitute a scientifically robust, policy-relevant evidence base that positions Weda Bay as a priority site for blue carbon conservation investment within Indonesia's NDC implementation framework and LCDI, provided that the governance, monitoring, and institutional preconditions for credible offset accounting are systematically established at the subnational level.

4.3 Regulatory gaps in weda bay blue carbon: Legal framework for Nationally Determined Contributions implementation

Indonesia's NEK framework provides the national legal basis for linking carbon trading, greenhouse gas emission

control, and NDC implementation. Baskara's analysis of Indonesia's carbon exchange framework shows that carbon trading involves project developers, business actors, the National Registry System for Climate Change Control (SRN-PPI), and the Carbon Exchange under OJK supervision [24]. At the national level, Perpres 110/2025 strengthens the NEK framework and provides a broader legal foundation for carbon pricing, carbon trading, and greenhouse gas emission control [25]. Law No. 4 of 2023 further supports this framework by recognizing carbon units as securities, thereby creating a legal basis for carbon units to be recorded, owned, and traded within the national registry and financial system [26]. In the context of Weda Bay, these instruments are relevant because remotely sensed mangrove carbon indicators may support future MRV baseline development, although they cannot yet be treated as certified carbon credits without field validation and formal registry procedures.

Several derivative regulations further operationalize Indonesia's national carbon governance framework. Permen LHK 21/2022 regulates procedures for implementing NEK, including carbon trading, performance-based payments, MRV, and SRN-PPI registration [27]. Permen LHK 7/2023 specifically regulates carbon trading in the forestry sector, including reporting obligations through SRN-PPI and the role of forestry authorities in supervising carbon-related activities [28]. Permen ESDM 16/2022 regulates NEK implementation in the power plant subsector, including emission control, efficiency obligations, and carbon-related transactions in the electricity sector [29]. Permen LHK 12/2024 regulates the implementation of Indonesia's NDC in climate change management by linking mitigation, adaptation, climate finance, and registry mechanisms to national climate targets [30]. Together, these regulations form an interconnected framework for MRV, carbon financing, and emissions control; however, their sectoral coverage differs, making provincial-level synchronization essential to avoid overlapping mandates or regulatory gaps.

For Weda Bay, this regulatory architecture creates both an opportunity and an implementation challenge. Mangrove conservation falls mainly under forestry and blue carbon-related governance, while IWIP-related emissions are more closely linked to energy and industrial emission control. Without clear coordination, mangrove carbon monitoring and industrial emission governance may operate through separate regulatory channels. This is important because the carbon-stock decline documented in this study cannot automatically be translated into offset claims unless project boundaries, baselines, additionality, permanence, leakage control, land tenure, MRV procedures, and registry compatibility are clearly established. Therefore, the remote sensing results should be understood as preliminary evidence for carbon monitoring and policy planning, rather than as direct proof of creditable mitigation outcomes.

At the provincial level, no clearly identifiable, dedicated NEK, GRK, or blue carbon implementation rules for North Maluku were found within the scope of this study [31]. This does not mean that all climate-related functions are absent from provincial governance, but it indicates that the pathway for translating Weda Bay's mangrove carbon monitoring outputs into SRN-PPI-compatible MRV and NEK instruments remains unclear. Provincial governments need supporting instruments such as integration of NDC targets into Regional Medium-Term Development Plan (RPJMD) and Regional Annual Development Plan (RKPD), Regional Budget (APBD)

allocation for mitigation and adaptation, Sistem Registrasi Nasional Pengendalian Perubahan Iklim (SRN-PPI)-based emission reporting systems, and technical capacity-building programs for local institutions. In the absence of a specific regional climate regulation, provincial authorities may need to align national regulations through derivative instruments such as gubernatorial regulations, joint decrees, Regional Climate Change Adaptation and Mitigation Roadmap (RAD API), or other regional mitigation and adaptation roadmaps.

Overall, the Weda Bay case shows that national carbon regulations alone are insufficient without subnational institutional readiness. The central government has established the legal architecture for NEK, NDC implementation, forestry-sector carbon trading, and power-sector emission control, but provincial planning must harmonize these instruments with local development priorities. If this alignment is not achieved, potential conflicts may emerge between forestry-based carbon management and energy-sector emission control. For this reason, North Maluku needs stronger institutional capacity, regional emission inventories, cross-sector coordination, and a clear mitigation/adaptation roadmap to support Indonesia's NDC commitments. Within this framework, the mangrove carbon indicators generated in this study can serve as an initial scientific input for future MRV development, conservation planning, and possible carbon governance integration, provided that field validation and legal requirements are fulfilled.

5. CONCLUSION

This study demonstrates the usefulness of multi-temporal remote sensing and GEE for monitoring mangrove carbon-stock indicators in Weda Bay, Central Halmahera Regency, North Maluku Province, Indonesia. The results show that total estimated carbon stock declined across the IWIP analytical zones from 2019 to 2024, while mean carbon density per hectare showed a modest increase in several zones. This apparent paradox suggests a possible density-area trade-off, where remaining vegetated pixels retain relatively high carbon density while valid mangrove-covered area contracts over time. However, this interpretation should be treated as a plausible remote sensing-based explanation rather than a confirmed causal mechanism.

The study also shows that remotely sensed carbon-stock indicators can support discussion of Indonesia's NDC implementation, LCDI, and NEK framework. Nevertheless, the results do not constitute certified carbon offsets or immediately creditable mitigation outcomes. Formal offset development would require additional MRV components, including field-calibrated biomass and soil carbon measurements, independent validation, baseline and additionality assessment, leakage and permanence safeguards, clear project boundaries, tenure clarification, and registry compatibility through SRN-PPI or other recognized mechanisms.

From a legal and policy perspective, the findings indicate that Indonesia's national carbon governance framework provides an important foundation for future blue carbon management, but its operational translation at the provincial and regency levels remains unclear. No clearly identifiable, dedicated provincial-level NEK, GRK, or blue carbon implementation rules for North Maluku were found within the scope of this study. Therefore, the main governance issue is

not simply the existence of national regulations, but the need to synchronize national carbon instruments with subnational planning, MRV capacity, institutional coordination, and industrial emission governance in the Weda Bay context.

Several limitations should be acknowledged. The study relies on NDVI-based and remote sensing-derived proxies rather than direct field-based carbon measurements. It does not directly quantify sediment organic carbon, below-ground biomass, or all blue carbon pools. The valid analyzed area metric also combines data-quality effects and possible ecological change, so it cannot be interpreted as degradation evidence on its own. Future research should integrate field biomass surveys, soil carbon sampling, high-resolution land-cover validation, tidal and hydrological data, and article-by-article legal analysis of relevant carbon regulations. These steps are necessary to strengthen the scientific and legal credibility of Weda Bay's mangrove carbon monitoring outputs before they can be used for formal NDC accounting or carbon market participation.

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ATTRIBUTION AND CLARIFICATION

The preparation of this manuscript utilized several supporting applications: Trinkla for academic English grammar and writing style, GEE for geospatial data processing, Python (pandas and matplotlib libraries) for data analysis and chart generation, Napkin for visualization, QGIS for geographic information system analysis, Publish or Perish for citation metrics, and Mendeley for reference management. Literature sources were primarily obtained from Taylor & Francis Online (Tandfonline). All narrative content in this article has been thoroughly edited and adjusted in accordance with the editorial guidelines established by the journal. The author takes full responsibility for the accuracy and integrity of the content presented in this manuscript.

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