Borneo Journal of Resource Science and Technology (2026), 16(1): 10-22
DOI: https:doi.org/10.33736/bjrst.10918.2026

Assessing the Impact of ENSO Events on Mangrove Carbon Stock Using Landsat-8: A Case Study in Sungai Kakap, West Kalimantan

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Received: 23 September 2025 Accepted: 01 April 2026 Published: 30 June 2026

ABSTRACT

Climate change poses a significant threat to mangrove ecosystems, which play a vital role in carbon sequestration. This study analyses the impact of El Niño phenomena on mangrove carbon stocks in Sungai Kakap, West Kalimantan, using Landsat-8 imagery data from normal (2013), very strong El Niño (2015), and weak El Niño (2019) years. The methodology included mangrove cover classification, NDVI-based biomass estimation, and carbon stock calculation using a 0.47 conversion factor. The results revealed that during very strong El Niño conditions, mangrove vegetation density, biomass, and carbon stocks significantly declined, despite an increase in spatial coverage. In contrast, a partial recovery was observed during the weak El Niño year, though values did not return to normal baseline levels. The results demonstrate a clear linkage between reduced vegetation density and declines in biomass and carbon storage capacity, highlighting the sensitivity of mangrove structural dynamics to climate-driven disturbances. These findings underscore that spatial extent alone is insufficient to evaluate ecosystem recovery or carbon sequestration potential. Instead, climate-adaptive management should priorities integrated monitoring frameworks that combine satellite-based observations with structural ecological assessments to enhance the protection and resilience of mangrove carbon stocks in ENSO-prone regions.

Keyword: Biomass, El Niño, mangrove carbon stock, tropical coastal ecosystems, vegetation indices

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INTRODUCTION

Climate change poses a significant threat to coastal ecosystems, particularly mangrove forests, which play a crucial role in climate change mitigation due to their exceptional capacity to store carbon in both biomass and sediments (Jennerjahn *et al*., 2017; Friess *et al*., 2022). However, climatic variability, such as the El Niño-Southern Oscillation (ENSO), can disrupt mangrove productivity and health by altering rainfall patterns, temperature regimes, and water availability (Duke *et al*., 2022; Zhang *et al*., 2025). Regions like West Kalimantan in Indonesia, including the Sungai Kakap area, are highly vulnerable to El Niño-induced extreme droughts (Rifai *et al*., 2019), which may lead to significant reductions in mangrove carbon stocks (Sasmito *et al*., 2019).

Despite the recognised importance of mangroves as carbon sinks, a critical research gap remains in understanding how ENSO-driven extreme climate conditions affect their carbon storage at local scales, particularly in tropical regions such as West Kalimantan (Sasmito *et al*., 2019; Krawczyk *et al*., 2020). Existing studies have primarily examined the broad-scale impacts of climate anomalies on mangrove carbon stocks, often neglecting finer-scale assessments in areas such as Sungai Kakap (Feng *et al*., 2024). Moreover, empirical data quantifying these impacts remain scarce. Traditional field-based carbon stock assessments, while valuable, are labour-intensive and lack the temporal resolution needed to capture rapid changes induced by ENSO variability. Satellite remote sensing, particularly Landsat-8, offers a promising alternative for continuous monitoring, yet its potential for assessing ENSO-related fluctuations in mangrove carbon stocks remains underexplored (Hickey *et al*., 2021).

Previous research has advanced our understanding of mangrove monitoring through remote sensing, including carbon stock estimation (Simard *et al*., 2019; Bindu *et al*., 2020; Mariano *et al.*, 2024) and the linkage between climatic variability and mangrove productivity (Ward *et al.*, 2016). However, few studies have integrated El Niño data, remote sensing, and carbon stock modelling, particularly in dense mangrove regions like West Kalimantan. Recent advancements in vegetation indices (e.g., NDVI derived from Landsat-8) show promise for detecting mangrove stress caused by climate variability (Sunkur *et al.*, 2024; Vasquez *et al.*, 2024), yet their application for assessing ENSO-driven changes in carbon stocks remains limited.

While mangroves are acknowledged as vital carbon sinks, the specific effects of climatic variability (e.g., El Niño) (Alongi, 2022) on their carbon dynamics are not yet fully understood (Adame *et al.*, 2021). This study addresses two key research questions: (1) How do El Niño events influence mangrove cover and health in Sungai Kakap? (2) Are there significant differences in mangrove carbon stocks between El Niño periods and normal climatic conditions?

This study aims to analyse the impacts of ENSO events on mangrove cover in Sungai Kakap using Landsat-8 data and estimate changes in carbon stocks during El Niño compared to normal conditions. The research is significant as it (1) enhances understanding of mangrove vulnerability to climate variability, particularly El Niño, and (2) provides a scientific basis for targeted mangrove conservation strategies in El Niño-prone regions.

MATERIALS & METHODS

Study Sites

The study area is located along the coastal region of Sungai Kakap Subdistrict, Kubu Raya Regency, West Kalimantan (Figure 1). Geographically, it extends between 0°03′12.5″–0°20′44.7″ South Latitude and 109°04′19.6″–109°11′17.4″ East Longitude.

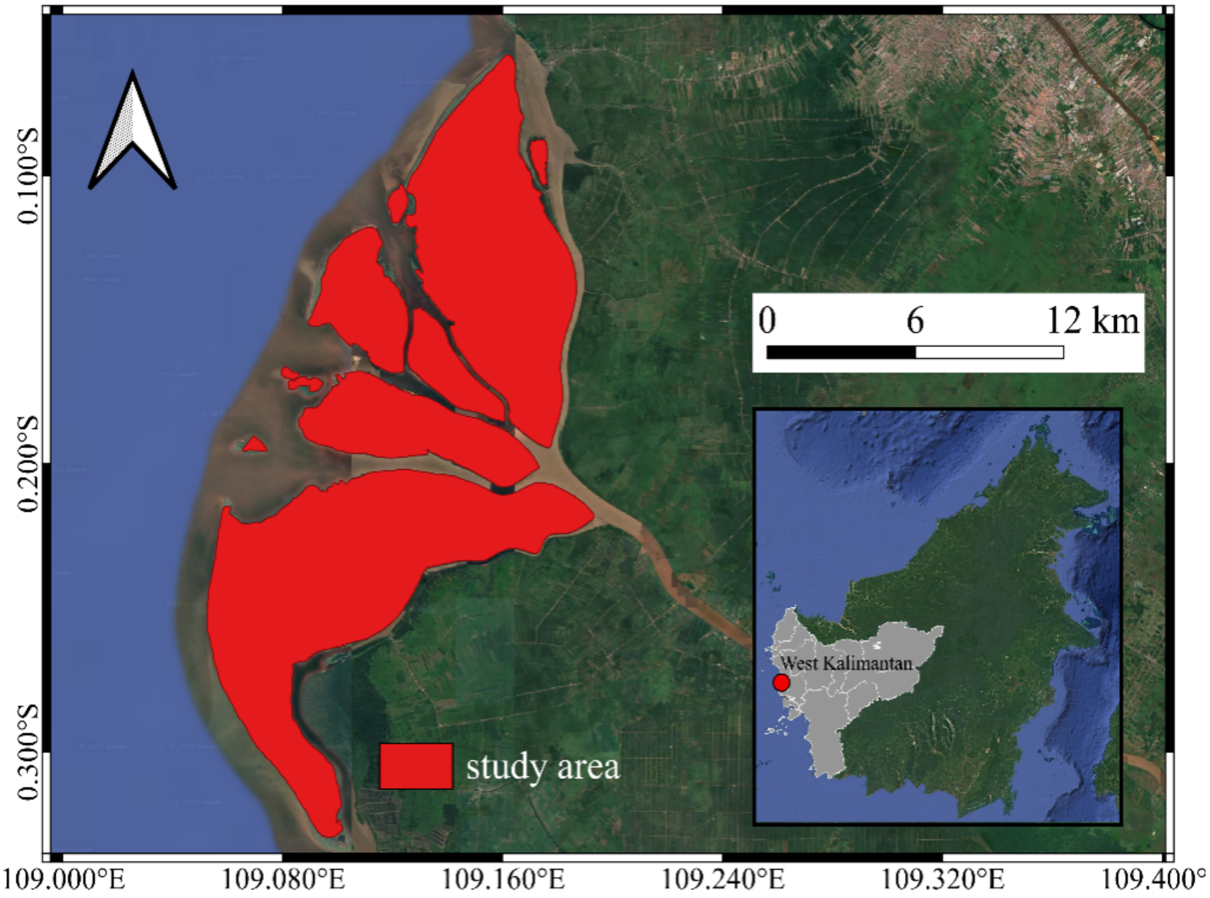

Figure 1. Study area

Data Analysis

This research employed Landsat 8 satellite imagery accessed via the Google Earth Engine (GEE) platform to analyse carbon stocks within the mangrove ecosystems of Sungai Kakap District, Kubu Raya Regency, West Kalimantan. To ensure that the study area accurately represents mangrove ecosystems, a mangrove distribution map provided by Sugiarto *et al.* (2024) was used as validation data for year 2021. The integration of these datasets is intended to enhance the accuracy of both mapping and carbon stock assessment in the mangrove ecosystems of Sungai Kakap District.

RESEARCH PROCEDURES

Mangrove Area Classification Process

Landsat 8 satellite imagery for the years 2013 (normal climatic conditions), 2015 (extreme El Niño), and 2019 (weak El Niño) was acquired and processed using the Google Earth Engine (GEE) platform, constrained to the coastal boundaries of Sungai Kakap District, Kubu Raya Regency. Cloud masking was performed using the MaxCloud Probability method with a ≤10% threshold to ensure that only cloud-free pixels were used in the analysis (Tigabu & Gessesse, 2025). Annual Landsat 8 image composites were generated using median values of cloud-free observations to minimize the influence of outliers and residual atmospheric effects. Three vegetation indices Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI), and Normalized Difference Water Index (NDWI) were calculated to characterize vegetation condition and moisture content. These indices were incorporated to enhance discrimination between mangrove forests, other coastal vegetation, and water bodies in the study area.

Supervised classification was conducted using the Support Vector Machine (SVM) algorithm (Okwuashi & Ndehedehe, 2020). Training samples were generated using geometric points within GEE and classified into three land-cover classes, mangrove, non-mangrove, and water bodies. In the SVM classification process, NDVI, SAVI, and NDWI were included as input bands together with spectral information to improve class separation, particularly between mangrove forests and other coastal vegetation under complex coastal conditions. The dataset was divided into 70% for training and 30% for validation, and classification results were retained for further analysis only when the overall accuracy reached at least 90%.

Mangrove Area, Biomass, and Carbon Stock Estimation

The spatial extent of mangrove areas was quantified through pixel-based calculation of the validated SVM classification outputs. Mangrove above-ground biomass was estimated using an NDVI-based allometric approach, in which biomass density is expressed as a function of NDVI values following a general exponential relationship Eq. (1):

$$\mathrm{AGB} = a \times e^{(b \times \mathrm{NDVI})} \qquad \text{Eq. (1)}$$

where AGB denotes above-ground biomass (tons/ha), NDVI is the Normalized Difference Vegetation Index derived from Landsat imagery representing vegetation greenness and canopy density, a is an empirical scaling coefficient representing baseline biomass, and b is an empirical coefficient describing the rate of biomass increase with increasing NDVI values. The coefficients a and b were adopted from field-calibrated allometric relationships reported in previous studies (Bindu *et al.*, 2020).

Subsequently, carbon stocks were estimated by multiplying AGB by a carbon conversion factor of 0.47, which represents the typical carbon content of mangrove biomass. To assess the influence of climatic variability, a comparative spatio-temporal analysis of mangrove area, biomass, and carbon stock was undertaken across three distinct climatic conditions: 2013 (normal conditions), 2015 (very strong El Niño), and 2019 (weak El Niño).

RESULTS

Normalized Difference Vegetation Index (NDVI)

In 2013, under normal climatic conditions, the vegetation distribution map (Figure 2) shows dense vegetation (dark green) across the coastal areas of Sungai Kakap District. Moderately dense vegetation, represented by light blue, also covered a considerable area, while sparse vegetation, represented by yellow, was only found in some peripheral parts of the vegetation zone. Areas without vegetation, represented by dark purple, were relatively limited and mostly located around water bodies and open areas. These conditions suggest that the study area's vegetation density remained well maintained under normal climate conditions.

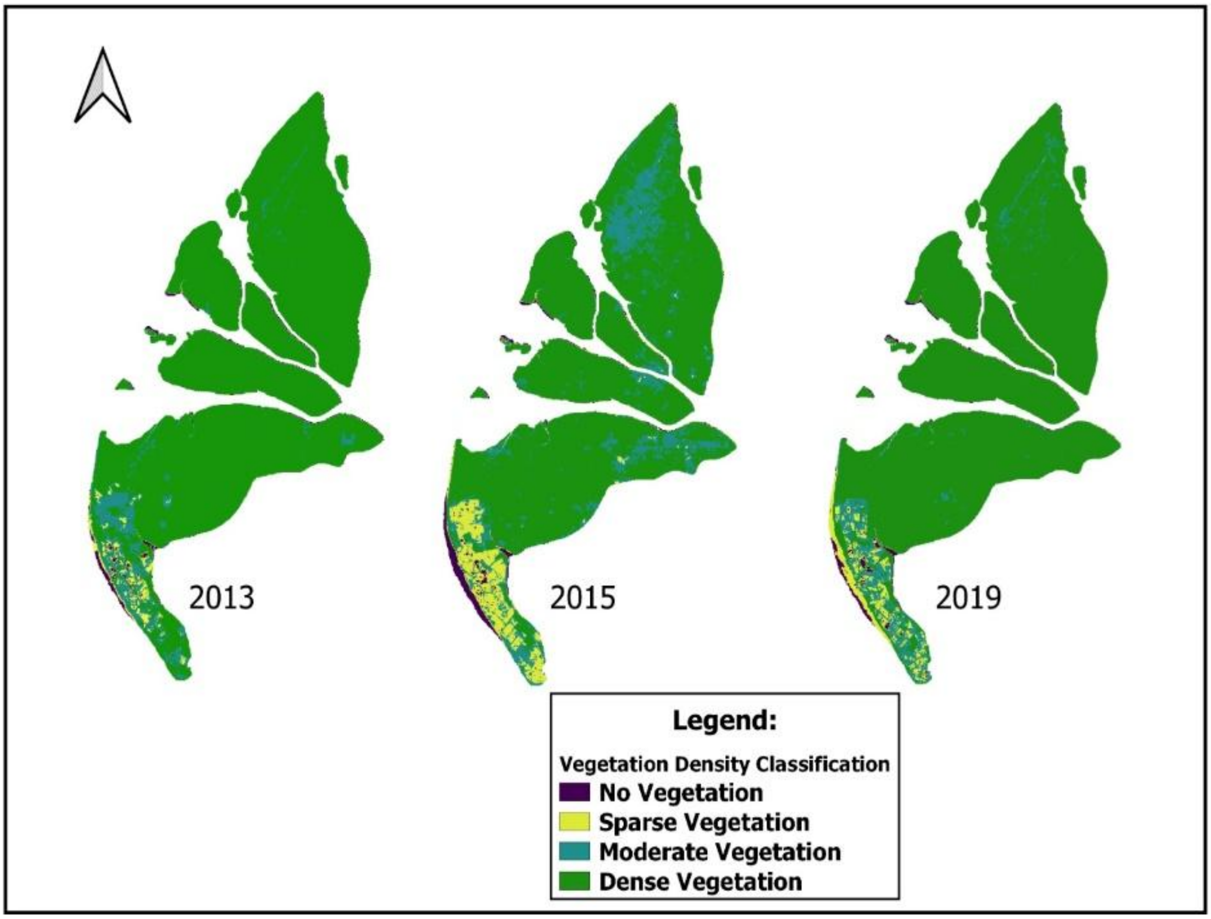

Figure 2. Vegetation density based on NDVI

In 2015, coinciding with a very strong El Niño event, the map revealed significant changes in vegetation distribution. Dense vegetation, indicated by dark green, declined substantially and shifted to moderately dense vegetation (light blue) and sparse vegetation (yellow). In addition, areas without vegetation (dark purple) expanded, particularly along the coastal sections directly adjacent to the sea. This pattern reflects vegetation stress associated with prolonged drought, elevated temperatures, and increased salinity during extreme El Niño events, which are known to suppress photosynthetic activity and reduce mangrove canopy density.

By 2019, which was influenced by a weak El Niño, vegetation distribution began to show signs of recovery compared to 2015. Figure 2 illustrates an increase in dense vegetation (dark green), although not as extensive as in the normal year of 2013. Moderately dense vegetation (light blue) still dominated much of the area, while sparse vegetation (yellow) was more evenly distributed along the coastal edges of Sepuk Laut village near the sea. Meanwhile, areas without vegetation (dark purple) persisted in several coastal locations near the sea in Sepuk Laut. Overall, the 2019 condition indicates a recovery trend following the very strong El Niño in 2015, although vegetation density had not yet fully returned to the levels observed in the normal year of 2013.

Soil Adjusted Vegetation Index (SAVI)

The Soil-Adjusted Vegetation Index (SAVI) was used to minimise the influence of soil background in vegetation analysis. In 2013, the SAVI classification results (Figure 3) showed dense vegetation dominance, consistent with the

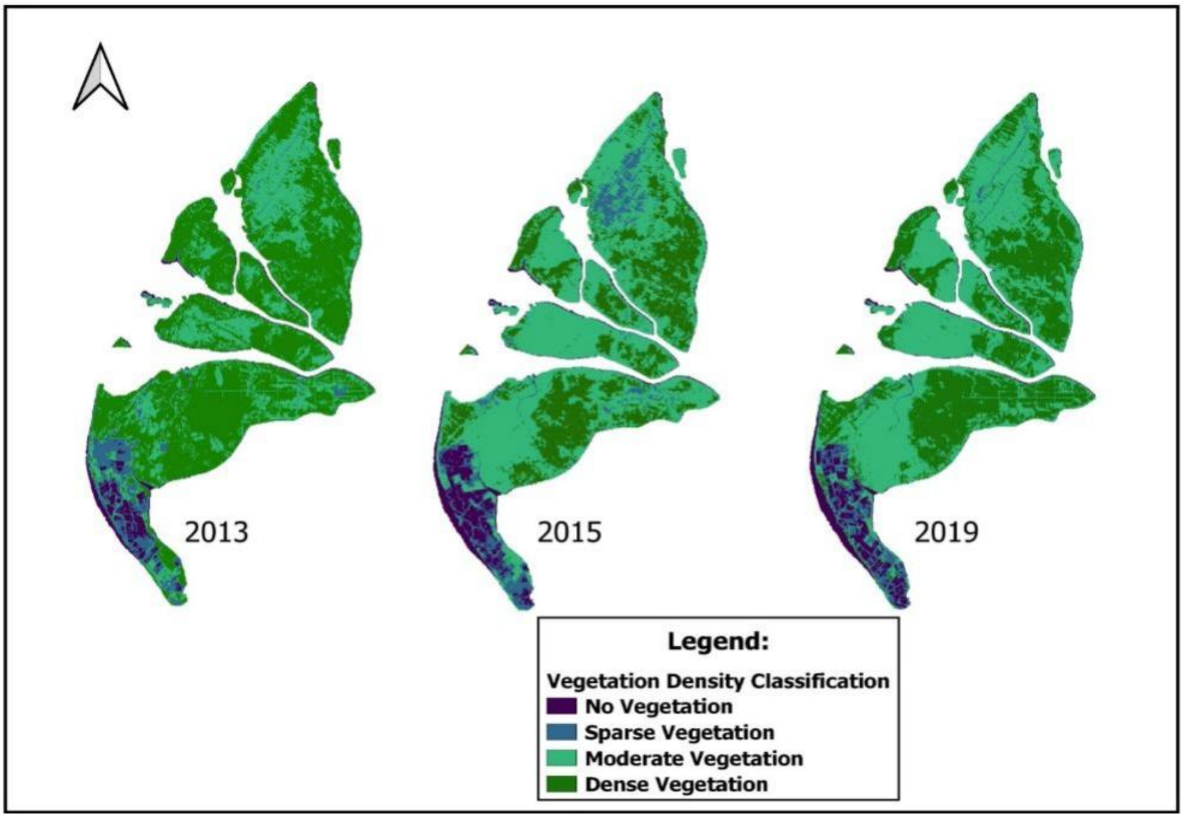

Figure 3. Vegetation density based on SAVI

NDVI findings. However, SAVI was more sensitive in detecting areas with sparse vegetation, particularly along the coastal edges. This indicates that although overall mangrove condition was generally good, certain transitional zones already exhibited mixed vegetation–soil characteristics.

In 2015, the strong impact of El Niño became increasingly evident. Areas of dense vegetation decreased drastically, with many regions shifting into sparse to moderate vegetation classes. Compared to NDVI, SAVI more clearly highlighted canopy thinning and vegetation degradation, emphasizing the exposure of soil surfaces under drought-induced stress conditions.

In 2019, the SAVI results showed an improving trend, with an increase in moderate to dense vegetation areas, although some regions were still dominated by sparse vegetation. This suggests that while the weak El Niño still impacted on the ecosystem, its effect did not result in severe degradation as observed in 2015.

Normalized Difference Water Index (NDWI)

NDWI was used to assess vegetation moisture by combining the green and near-infrared (NIR) bands. In 2013, the NDWI classification results (Figure 4) indicated the dominance of moderate to very high moisture across most vegetation areas. This reflects adequate water availability and favorable tidal and freshwater inputs supporting healthy mangrove physiological processes. However, during the very strong El Niño event in 2015, NDWI showed an increase in areas categorized as “dry” to “slightly moist,” particularly in coastal regions. The reduction in vegetation moisture corresponds with prolonged drought and reduced freshwater input, which are characteristic of extreme El Niño events and contribute directly to vegetation stress and biomass decline.

In 2019, vegetation moisture showed better conditions compared to 2015. Most areas returned to the moderate moisture category, although some regions still exhibited low moisture. This indicates that during a weak El Niño, the impact of reduced vegetation moisture was more limited.

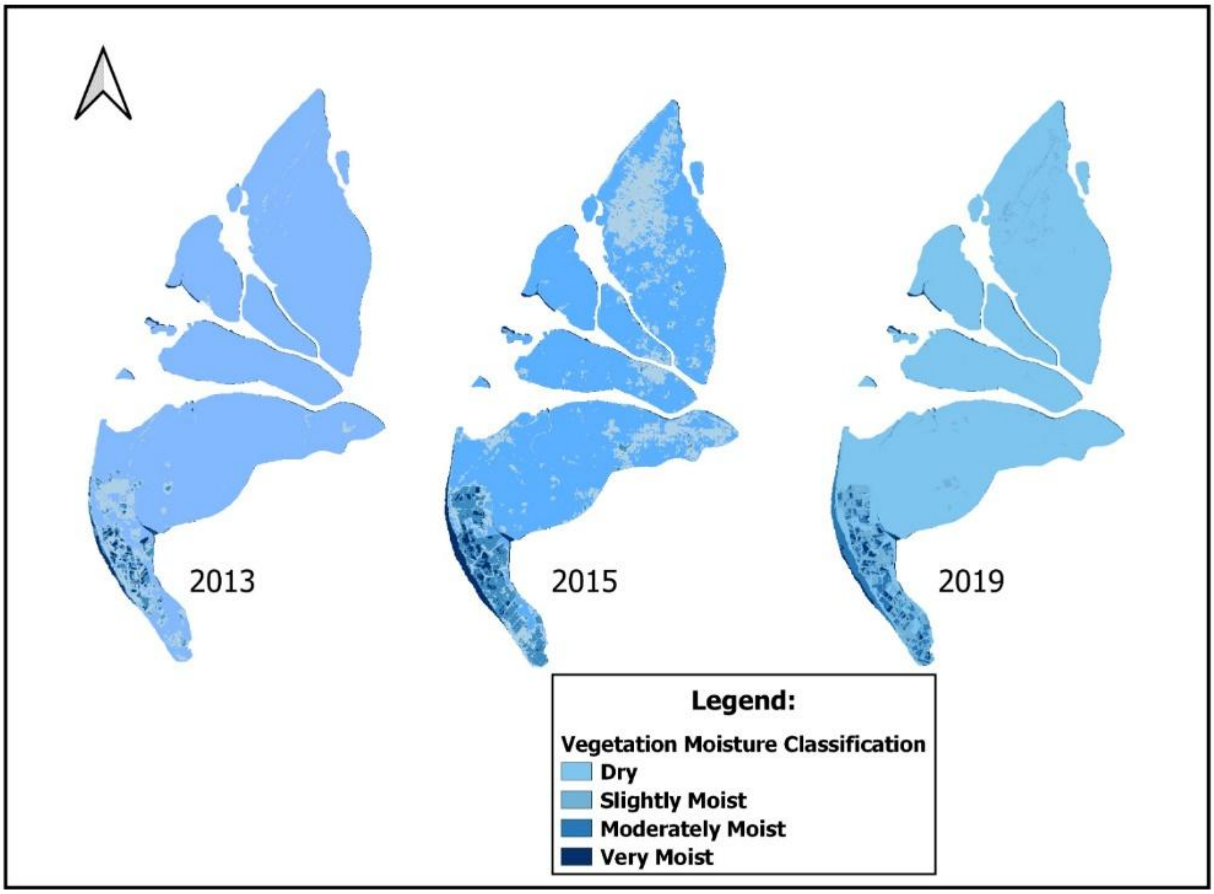

Figure 4. Vegetation moisture based on NDWI

Mangrove Area Classification in the Coastal Zone of Sungai Kakap

The classification of mangrove areas along the coast of Sungai Kakap Subdistrict was carried out using supervised classification with the SVM algorithm. The process began with creating training sample points for three main classes, namely mangrove, non-mangrove, and water bodies, based on Landsat 8 image interpretation and local knowledge. The SVM model was then built and tested until it reached a minimum accuracy of 90% (≥0.9). The validated classification results were used to calculate cover area, biomass estimation, and carbon stock. Validation was conducted by comparing the 2024 estimation results with reference data, which showed good agreement between the classification-based carbon stock values (2,823.3 tons/ha; density 5.51 ha) and the reference data (2,656.6 tons/ha; density 5.20). This method was then consistently applied throughout the study period, namely in the normal year 2013, the very strong El Niño year 2015, and the weak El Niño year 2019. The classification results (Figure 5a) successfully identified the distribution of mangroves in Sepuk Laut and Tanjung Saleh Villages. Additional validation with the 2021 reference map (Sugiarto *et al*., 2024) (Figure 5b) showed a high level of agreement, where the mangrove areas in the classification results (green color) matched the reference map. Thus, the SVM-based classification method proved to be accurate and can serve as a valid basis for analyzing the dynamics of mangrove ecosystem area, biomass, and carbon stock along the coast of Sungai Kakap Subdistrict.

The classification of mangrove distribution based on Landsat imagery (Figure 6) reveals the spatial dynamics of mangrove areas along the coast of Sungai Kakap District in 2013, 2015, and 2019. In 2013, mangrove areas appeared extensive and dominant, with relatively dense and evenly distributed cover along the coast, particularly in Sepuk Laut and Tanjung Saleh villages. This condition indicates that, under normal climatic conditions, the mangrove ecosystem was healthy and had not yet experienced significant fragmentation.

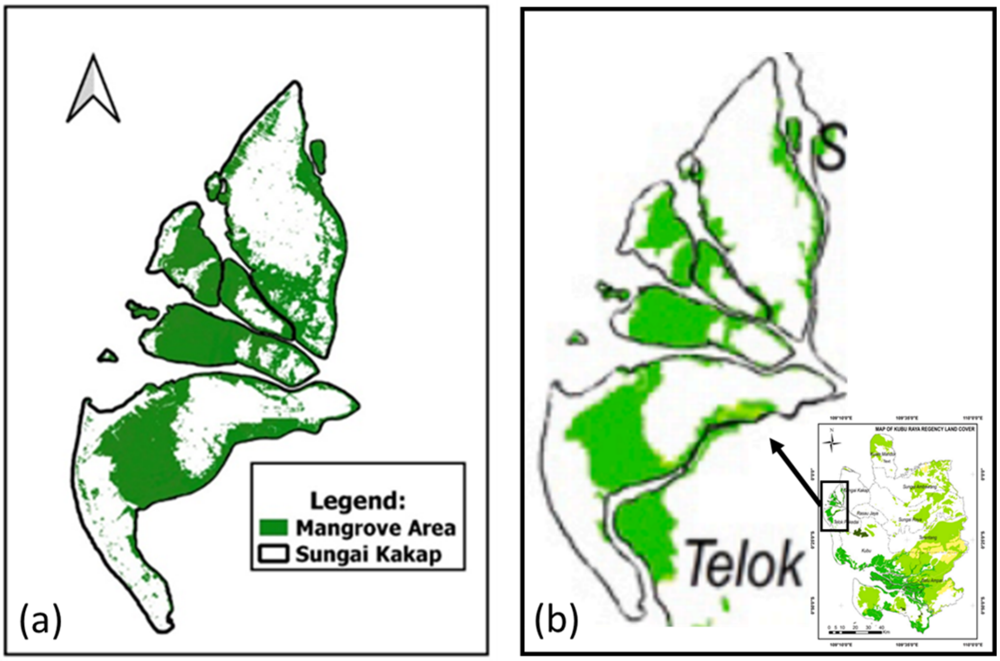

Figure 5. Map of mangrove areas in the coastal region of Sungai Kakap subdistrict, (a) Satellite classification results in 2021, (b) Validation data of mangrove areas in 2021 (Source: Sugiarto *et al*., 2024)

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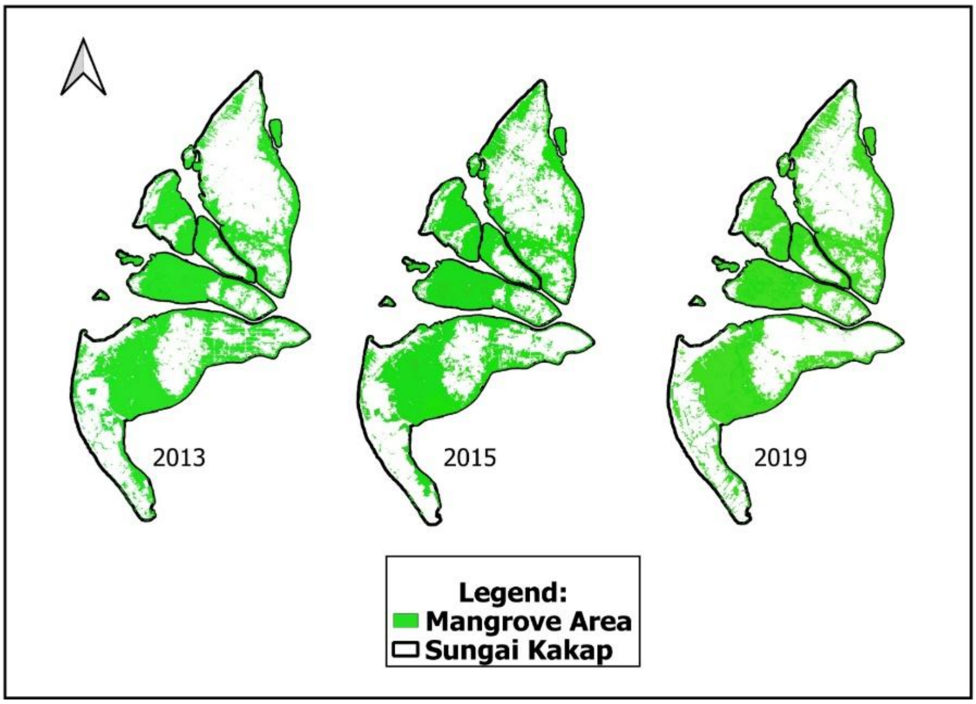

Figure 6. Mangrove areas along the coast of Sungai Kakap Subdistrict

However, in 2015, coinciding with a strong El Niño event, mangrove cover declined. The classification results showed a reduction in mangrove extent in several coastal areas, particularly in zones directly adjacent to the sea. In 2019, which was influenced by a weak El Niño, the condition of mangrove areas began to show an increasing trend. Mangrove cover expanded again in several locations, especially around deltas and river mouths. Nevertheless, its extent had not fully returned to the level observed in 2013, and open areas were still present in several coastal sections. This suggests that the recovery of mangrove ecosystems following the strong El Niño in 2015 occurred gradually.

Mangrove Density in the Coastal Area of Sungai Kakap District, West Kalimantan

The mangrove density classification map in the coastal area of Sungai Kakap Subdistrict, particularly in Sepuk Laut and Tanjung Saleh Villages, shows a dynamic change in mangrove density during the periods of normal conditions in 2013, the strong El Niño event in 2015, and the weak El Niño event in 2019 (Figure 7). In the normal year of 2013, mangrove cover was dominated by dense mangrove, represented by dark green color. This condition indicates that the mangrove forest in the area was still relatively well-preserved, with a large extent and low level of degradation. Sparse or moderate mangrove cover was almost absent during this period.

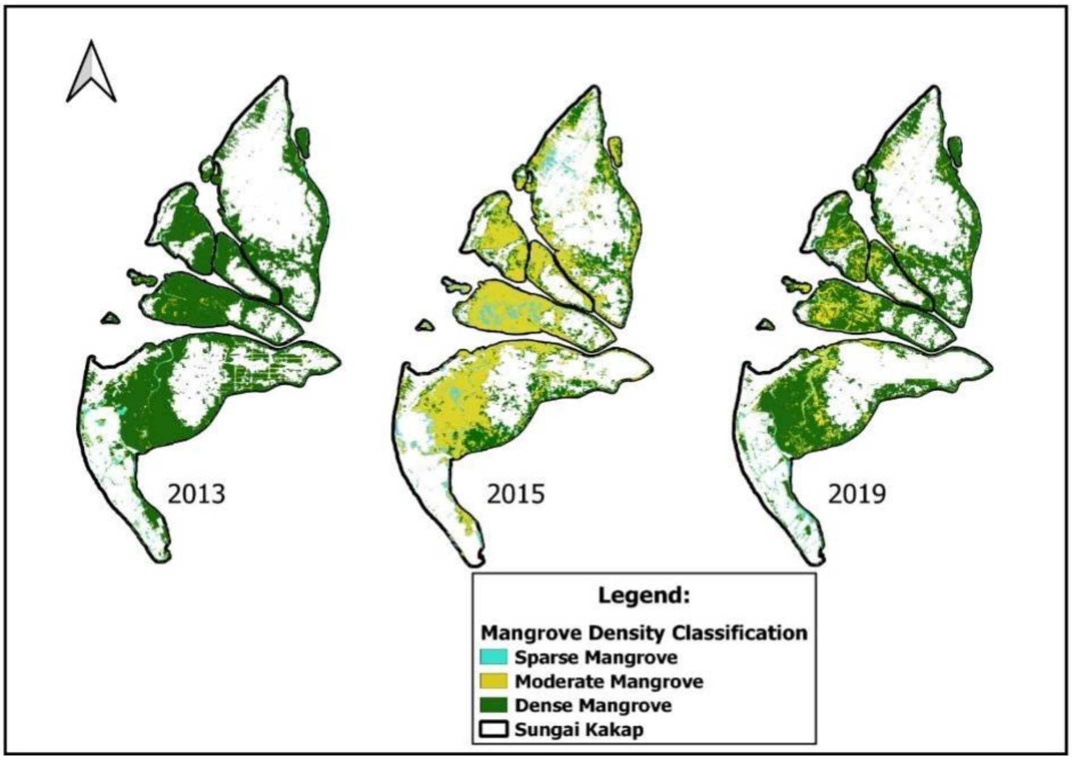

Figure 7. Mangrove density classification in the coastal area of Sungai Kakap subdistrict

Significant changes were observed in 2015, during a strong El Niño event. During this period, most areas of dense mangrove experienced a reduction in canopy density and transitioned to moderate mangrove, represented in yellow, and sparse mangrove, represented in light blue. This phenomenon occurred primarily along the southern coastal portion of Sepuk Laut Village and in certain areas of Tanjung Saleh Village. These conditions indicate that the mangrove ecosystem was under considerable stress. In 2019, during a weak El Niño event, mangrove cover showed an increase in density. This was indicated by the expansion of moderate mangrove areas (yellow), as well as the persistence of some dense mangrove areas (dark green), although not to the same extent as in 2013. Meanwhile, sparse mangrove areas (light blue) remained present but did not dominate the landscape. The mangrove area within the study site remained well maintained, as illustrated in Figure 8.

Figure 8. The mangrove forest ecosystem in the coastal area of Sungai Kakap Sub-District. (Source: Field survey, 2024)

Mangrove Area, Biomass, and Carbon Stock in the Coastal Area of Sungai Kakap Subdistrict

Table 1. The analysis of mangrove area and biomass was carried out to understand the spatial dynamics and vegetation productivity of mangroves in the coastal areas of Sepuk Laut and Tanjung Saleh Villages, Sungai Kakap Subdistrict, West Kalimantan, during the normal year of 2013, the strong El Niño year of 2015, and the weak El Niño year of 2019. In the normal year of 2013, mangrove area reached its highest value at 8,035.35 ha, with a distribution extending evenly from the southern to the northern part of the region. In the same year, total biomass was also recorded as the highest at 669,825.92 tons, indicating the dominance of dense mangrove cover and healthy vegetation. In the strong El Niño year of 2015, the mangrove

area increased significantly to 8,605.08 ha. However, the total biomass decreased to 540,309.80 tons, indicating that the expansion of the mangrove area was not accompanied by high vegetation quality.

Meanwhile, in the weak El Niño year of 2019, the mangrove area was recorded at 8,115.14 ha with a total biomass of 616,017.58 tons. This condition reflects an improvement in vegetation quality compared to 2015, although the mangrove area was not as extensive as in that period. These findings suggest that the restoration of mangrove structural complexity after extreme climatic stress occurs over extended temporal scales.

Table 1. Mangrove area and biomass in Sepuk Laut and Tanjung Saleh Villages, Sungai Kakap subdistrict

Year / Climate Condition	Mangrove Area (ha)	Total Biomass (tons)
2013 (Normal)	8,035.35	669,825.92
2015 (Strong El Niño)	8,605.08	540,309.80
2019 (Weak El Niño)	8,115.14	616,017.58

The analysis of mangrove carbon stock in the coastal area of Sungai Kakap Subdistrict, particularly in Sepuk Laut and Tanjung Saleh Villages, shows dynamic changes influenced by climatic conditions during the observation period (Figure 8). In the normal year of 2013, the total carbon stock was the highest at 314,818.18 tons, with an average of 3.50 tons/ha. This value indicates that, under normal climatic conditions, the mangrove ecosystem was relatively healthy and stable, with dense vegetation cover. In the strong El Niño year of 2015, the total carbon stock declined significantly to 253,945.60 tons, averaging only 2.64 tons/ha. This decrease suggests degradation in mangrove quality, presumed to be caused by the extreme El Niño event, which is known to result in higher temperatures, reduced rainfall, and seawater intrusion, all of which affect mangrove vegetation density.

In the weak El Niño year of 2019, the carbon stock increased again to 289,528.26 tons, with an average of 3.19 tons/ha. This condition reflects an improvement in the mangrove ecosystem after the strong El Niño period, although it had not yet reached the optimal level recorded in 2013. The increase also demonstrates that mangroves possess a considerable capacity for natural regeneration, enabling them to partially restore their ecological function in carbon storage. Overall, the dynamics of mangrove carbon stock in 2013, 2015, and 2019 indicate that climate variability, particularly the El Niño phenomenon, plays an important role in influencing the carbon storage capacity of mangrove ecosystems.

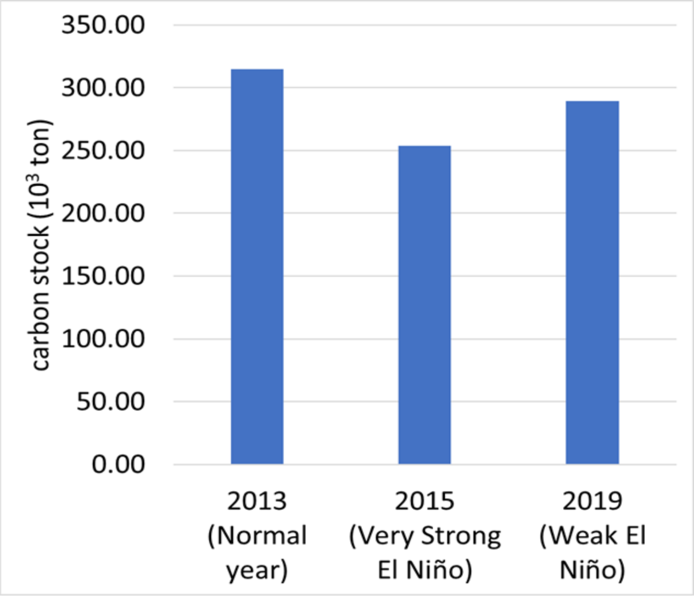

Figure 8. Mangrove Carbon Stock under different climate conditions

DISCUSSION

The carbon stock graph demonstrates a clear declining trend from the normal climatic conditions in 2013 to the period of very strong El Niño in 2015, followed by a partial recovery in 2019 during a weak El Niño phase. This pattern indicates a decoupling between mangrove spatial expansion and structural carbon storage capacity. In other words, increases in areal extent do not necessarily correspond to higher carbon stocks, as these dynamics are strongly influenced by changes in stand structure and environmental conditions associated with extreme climatic disturbances.

In 2015, mangrove area increased but was dominated by sparse to moderately dense stands. Ecologically, this suggests that spatial expansion was likely driven by early-stage regeneration or colonisation by younger individuals. Stands in early successional stages typically consist of smaller trees with less developed structural biomass, thereby contributing less to overall carbon storage compared to mature forests. Recent studies emphasise that mangrove carbon stocks are more strongly governed by structural attributes such as stem diameter, tree height, and wood density rather than areal extent alone (Simard *et al*., 2019; Zaman *et al*., 2023).

The very strong El Niño event in 2015 likely played a key role in driving these structural ecosystem changes. ENSO-related climatic variability is known to reduce regional precipitation, increase air temperature, and elevate sediment salinity due to reduced freshwater inputs. These conditions impose physiological drought stress on mangroves, constraining photosynthetic activity and secondary growth, and thereby limiting biomass accumulation (Lovelock *et al*., 2017; Duke *et al*., 2022). Furthermore, prolonged hydrological stress may increase mortality among mature trees and lead to canopy thinning, resulting in lower-density stands with reduced carbon storage capacity. As a consequence, even when vegetation cover remains spatially extensive, woody biomass accumulation and long-term carbon storage may decline. Similar patterns have been reported globally, where extreme climatic disturbances drive structural forest degradation without necessarily causing substantial loss of spatial extent (Sasmito *et al*., 2019; Goldberg *et al*., 2020).

By 2019, the observed increase in carbon stock reflects signs of ecosystem recovery as ENSO intensity weakened. More stable hydroclimatic conditions likely enhanced primary productivity and facilitated stand densification, leading to increased biomass and carbon storage. This finding aligns with recent studies indicating that mangrove ecosystems exhibit considerable resilience to climatic disturbances, although carbon stock recovery strongly depends on hydrological stability and local sediment dynamics (Goldberg *et al*., 2020; Adame *et al*., 2021).

Overall, the integration of carbon stock dynamics with changes in mangrove density highlights vegetation structure as a key driver of interannual variability in carbon storage. Spatial expansion without corresponding increases in stand density or structural maturity may produce an ecological paradox in which forest area expands while carbon storage capacity declines. These findings underscore the importance of adopting multidimensional approaches when evaluating mangrove ecosystem dynamics, integrating spatial, structural, and functional metrics to better understand ecosystem responses to extreme climate variability.

CONCLUSION

This study demonstrates that ENSO-driven climate variability exerts a significant influence on mangrove vegetation structure, biomass, and carbon stock dynamics in Sungai Kakap, West Kalimantan. The very strong El Niño event in 2015 resulted in a substantial decline in biomass and carbon stocks despite an increase in mangrove spatial extent, highlighting a decoupling between areal expansion and structural carbon storage capacity. The partial recovery observed in 2019 during a weak El Niño phase indicates that mangrove ecosystem responses to climatic disturbances are dynamic and strongly dependent on hydroclimatic stability and stand density. These findings underscore the importance of climate-adaptive management strategies that integrate long-term satellite-based monitoring with vegetation structural assessments to safeguard mangrove carbon storage functions in ENSO-prone regions. Future research should prioritise the integration of multitemporal field observations, high-resolution remote sensing, and coupled climate–ecosystem modelling to better understand mechanisms of mangrove structural recovery and their implications for long-term carbon stock stability.

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