Bioscientist: Jurnal Ilmiah Biologi
https://e-journal.undikma.ac.id/index.php/bioscientist

June 2026 Vol. 14, No. 2
e-ISSN: 2654-4571
pp. 906-916

Assessment of Carbon Storage and Ecological Functions of Beach Sheoak (*Casuarina equisetifolia*) in Muara Cemara, Pantai Panjang, Bengkulu City

[1*]Putri Lisya Anggraini, [2]Darmi, [3]Rizwar, [4]Meliya Wati, [5]Siti H. Norfahmi
[1,2,3,4]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Bengkulu, Bengkulu, Indonesia.
[5]Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Bengkulu, Bengkulu, Indonesia.
*Corresponding Author e-mail: planggraini@unib.ac.id
Received: December 2025; Revised: May 2026; Accepted: June 2026; Published: June 2026

Abstract: This study aimed to estimate the aboveground biomass, carbon stock, and carbon dioxide (CO_2) sequestration of coastal she-oak (*Casuarina equisetifolia*) stands in Muara Cemara, Pantai Panjang, Bengkulu City, and to describe their ecological functions based on field observations. The study was conducted in September 2025 using a non-destructive method based on the allometric equation ln Y = –2.177 + 2.523(ln DBH). Data were collected from 17 systematically established plots, each measuring 20 m × 20 m. The results showed that the stands had an aboveground biomass of 2.37 ± 0.63 t ha^{-1}, a carbon stock of 1.09 ± 0.20 t C ha^{-1}, and CO_2 sequestration of 4.01 ± 1.06 t CO_2 ha^{-1}. The 21–30 cm diameter class contributed the largest proportion of total biomass and carbon stock, indicating the important role of medium-sized trees in carbon accumulation. Ecologically, *C. equisetifolia* may contribute to reducing coastal erosion, stabilizing sandy substrates, improving microhabitat conditions, and supporting coastal habitat functions. These findings indicate that *C. equisetifolia* stands have potential as a complementary component of coastal carbon storage, climate change mitigation, and ecosystem-based coastal management in sandy coastal environments.
Keywords: Biomass; *Casuarina equisetifolia*; carbon stock; coastal ecosystem; ecological function

How to Cite: Anggraini, P. L., Darmi, Rizwar, Wati, M., & Norfahmi, S. H. (2026). Assessment of Carbon Storage and Ecological Functions of Beach Sheoak (Casuarina equisetifolia) in Muara Cemara, Pantai Panjang, Bengkulu City. *Bioscientist: Jurnal Ilmiah Biologi*, *14*(2), 906–916. https://doi.org/10.33394/bioscientist.v14i2.18906

https://doi.org/10.33394/bioscientist.v14i2.18906

INTRODUCTION

Coastal ecosystems play a vital role in shoreline protection, habitat provision, and carbon storage. These ecosystems form a dynamic interface between terrestrial and marine environments, where vegetation structure strongly influences sediment stability, microhabitat conditions, and coastal resilience. Over the past two decades, coastal vegetation has received increasing attention as part of blue carbon research and as a nature-based solution for climate change mitigation (McLeod et al., 2011; Lovelock & Duarte, 2019; Seddon et al., 2020). However, blue carbon studies have largely focused on mangrove ecosystems, while non-mangrove coastal vegetation has received comparatively limited attention (Choudhary et al., 2024; Pang et al., 2024). This imbalance limits a broader understanding of the carbon storage potential and ecological contribution of vegetation types that occur outside typical mangrove habitats, particularly along sandy coastal zones.

One of the dominant species in sandy coastal ecosystems is beach she-oak (*Casuarina equisetifolia*). This species is highly tolerant of coastal environmental stresses, including salinity, drought, nutrient-poor substrates, and strong winds. Because of these adaptive traits, *C. equisetifolia* can establish and persist in exposed coastal environments where many other woody species are less successful. It is therefore widely used as a coastal greenbelt to reduce erosion and stabilize sandy substrates. In addition to its shoreline protection function, *C. equisetifolia* can improve soil fertility through its association with nitrogen-fixing bacteria and has the potential to store carbon in aboveground biomass (Fan et al., 2021; Ravi et al., 2025). Studies in Asian coastal regions have shown that *Casuarina* forests contribute to shoreline stabilization while also supporting carbon accumulation in coastal ecosystems (Li et al., 2023). These characteristics indicate that *C. equisetifolia* may provide multiple ecosystem services, combining physical coastal protection with carbon-related ecological functions.

In Indonesia, studies on non-mangrove coastal vegetation remain limited, although coastal areas are increasingly exposed to anthropogenic pressures and climate change impacts. This knowledge gap is particularly important because many Indonesian coastal landscapes consist not only of mangroves, but also sandy beaches, estuaries, coastal greenbelts, and mixed non-mangrove vegetation. Recent research has shown that coastal ecosystem conservation plays an important role in strengthening the socio-ecological resilience of coastal areas (Analuddin et al., 2024). At the global scale, blue carbon is increasingly recognized as an ecological asset that supports sustainable development (Bertram et al., 2021; Lee et al., 2025). Therefore, expanding carbon-related studies to include non-mangrove coastal vegetation is essential for developing more comprehensive coastal conservation and climate mitigation strategies.

Most previous studies have examined carbon estimation and coastal protection functions separately. Consequently, data on the biomass, carbon stocks, and ecological functions of *C. equisetifolia* in sandy estuarine ecosystems remain scarce, particularly on Sumatra Island. In Bengkulu City, where coastal areas are subject to erosion, land-use pressure, and environmental change, such information is needed to support evidence-based management of coastal vegetation. Therefore, this study aimed to estimate aboveground biomass, carbon stocks, and potential carbon dioxide sequestration in *Casuarina equisetifolia* stands at Muara Cemara, Pantai Panjang, Bengkulu City. In addition, this study describes the ecological functions of these stands as a scientific basis for sustainable coastal ecosystem management and conservation.

METHOD

This study employed a descriptive quantitative approach using a field-based ecological assessment design to estimate biomass, carbon stock, carbon dioxide (CO_2) sequestration potential, and to describe the ecological functions of *Casuarina equisetifolia* stands in an estuarine ecosystem. This approach was selected because it enables direct, non-destructive measurement of stand structure and is relevant for assessing the potential of coastal vegetation as a component of data-driven ecosystem management. Non-destructive approaches are widely used in coastal vegetation carbon studies because they provide efficient biomass estimates without damaging the stands (Pendleton et al., 2012; Fan et al., 2021).

The study was conducted in September 2025 in the Muara Cemara area of Pantai Panjang, Bengkulu City, within a sandy coastal estuarine zone that is generally exposed to coastal abrasion and anthropogenic activities. Geographically, the study site is located at approximately 3°48′53.50″ S and 102°16′10.07″ E. The observation area included naturally growing *C. equisetifolia* stands within the coastal vegetation belt of Muara Cemara. The study boundaries were determined based on the dominant distribution of the stands and field accessibility within a relatively homogeneous observation zone.

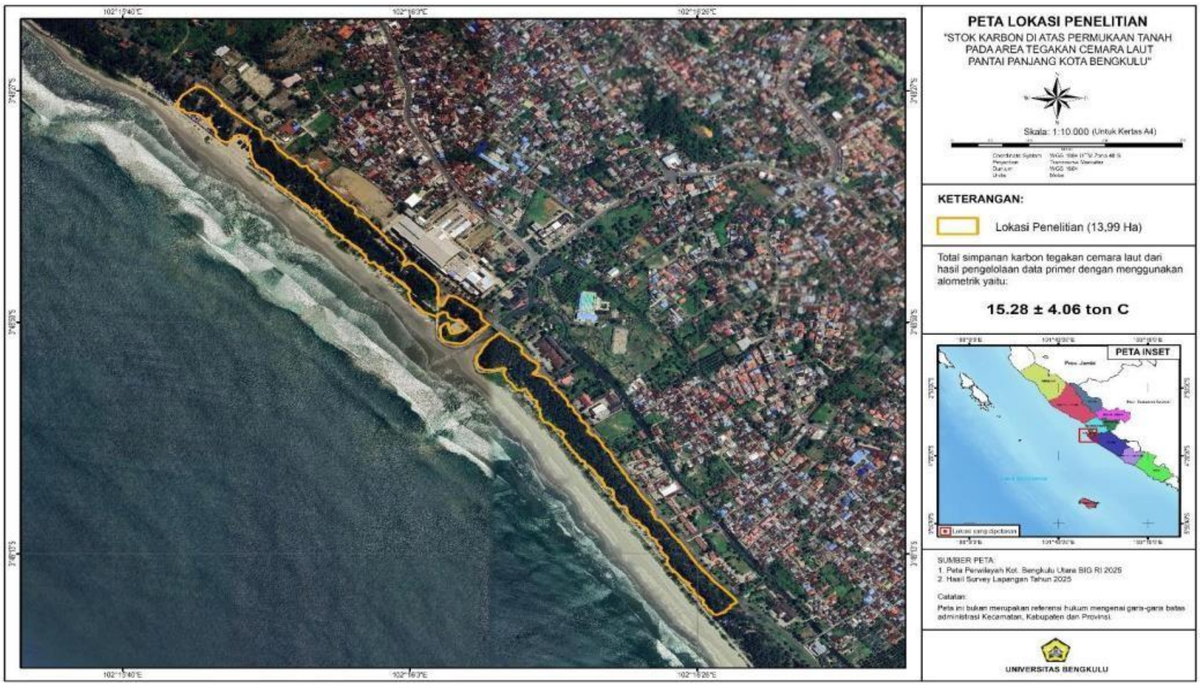

Figure 1. Study location

The research object was the naturally growing *C. equisetifolia* stand in the study area. Sampling was conducted using a systematic sampling method, with 20 m × 20 m plots (400 m²) as the main observation units. A total of 17 plots were systematically established across the study area at uniform intervals to obtain representative data distribution and reduce spatial bias. The number of plots was determined by considering the extent of the study area, stand homogeneity, and the need to capture variation in stand structure at the site level. All individual trees within each plot with a measurable diameter at breast height (DBH) were recorded as analytical units, with DBH measured at 1.3 m above the ground surface.

DBH was measured on the main stem using a diameter tape. For branched or leaning trees, measurements were conducted according to standard field procedures. In branched trees, DBH was measured on the main stem below the branching point. In leaning trees, DBH was measured at 1.3 m following the stem axis, with adjustments made to ensure that the measurement point accurately represented the diameter of the main stem. When stem irregularities were encountered, measurements were recorded consistently to ensure comparability among plots.

The use of allometric equations is a common method in biomass studies of *Casuarina* stands (Dudley & Fownes, 1992; Wang et al., 2013). The allometric equation used in this study was as follows:

$$\ln Y = -2.177 + 2.523 \times \ln(DBH)$$

Where Y represents oven-dry biomass and DBH represents diameter at breast height, expressed in centimeters. Biomass values were subsequently converted into carbon stock using a conversion factor of 0.46, while CO_2 sequestration potential was calculated using a conversion factor of 3.67. All results were expressed in standard units, namely ton ha^{-1} for biomass, ton C ha^{-1} for carbon stock, and ton CO_2 ha^{-1} for CO_2 sequestration potential.

Field data were collected using a diameter tape, GPS, compass, measuring tape, and field recording sheets. Data were analyzed quantitatively to calculate biomass, carbon stock, and CO_2 sequestration potential per plot and per hectare. These values were then averaged to obtain stand-level estimates. Diameter class distribution was analyzed to identify the diameter class contributing most substantially to carbon storage.

The ecological functions of *C. equisetifolia* were described using a qualitative-descriptive approach based on field observations supported by relevant literature. The observed aspects included indications of the role of vegetation in reducing coastal abrasion, stabilizing sandy substrates, maintaining coastal habitat conditions, and improving the physical characteristics of the surrounding environment. Accordingly, the interpretation of ecological functions was based on direct field observations and strengthened by relevant scientific references. The field inventory approach used in this study may also support the development of remote sensing-based stand mapping in future research (Lin et al., 2023).

RESULTS AND DISCUSSION

Stand Structure of *Casuarina equisetifolia* and Regeneration Dynamics in the Coastal Ecosystem

A total stand density of 474 individuals ha^{-1} of *Casuarina equisetifolia* was recorded in the Muara Cemara area of Pantai Panjang, with an uneven distribution across diameter classes. The 21–30 cm diameter class had the highest density, with 135 individuals ha^{-1}, followed by the 11–20 cm class with 118 individuals ha^{-1} and the 1–10 cm class with 115 individuals ha^{-1}. In contrast, the density of individuals in the >41 cm diameter class was relatively low, with only 43 individuals ha^{-1}.

Table 1. Stand structure of *Casuarina equisetifolia* based on diameter class

Diameter class (cm)	Density (individuals ha^{-1})	Proportion (%)
1–10	115	24.3
11–20	118	24.9
21–30	135	28.5
31–40	63	13.3
>41	43	9.1
Total	474	100

The dominance of intermediate diameter classes indicates that the *C. equisetifolia* stand is in an active and productive growth phase. This diameter-class structure is ecologically important because it reflects the continuity of natural regeneration and suggests that the stand may maintain its protective and carbon-storage functions over time, provided that disturbance pressures remain controlled. The relatively low density of trees in the >41 cm diameter class may indicate the limited presence of older trees or mortality associated with coastal environmental stress. Field observations showed that several large-diameter trees had fallen, with exposed roots and erosion observed in areas directly adjacent to the shoreline.

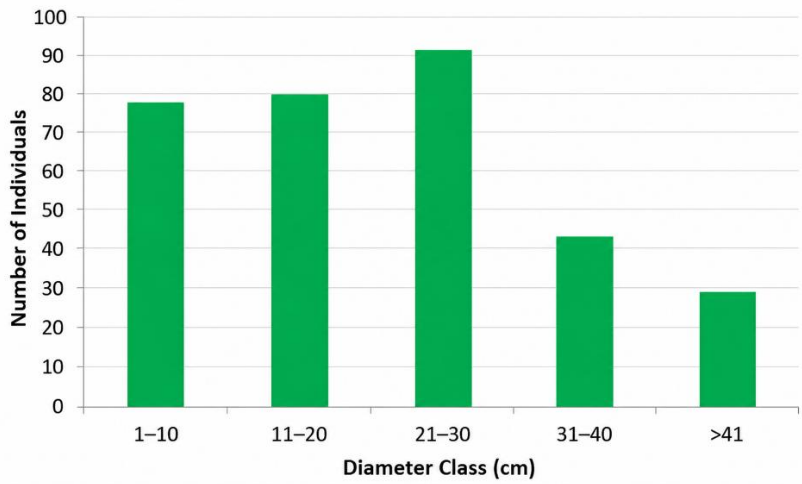

Figure 4. Distribution of *Casuarina equisetifolia* tree density by diameter class in Muara Cemara, Pantai Panjang

This pattern differs from that commonly observed in inland forest stands, which are often characterized by a higher proportion of larger-diameter trees. However, it is consistent with the characteristics of coastal shelter forests growing on sandy substrates under high environmental stress, including wind exposure, salt spray, and sediment movement (Fan et al., 2021). Ravi et al. (2025) reported that the dominance of intermediate diameter classes in *C. equisetifolia* stands reflects the adaptive capacity of this species in dynamic coastal environments that frequently experience natural disturbances. Similar patterns of stand development and biomass accumulation have also been reported in coastal *Casuarina* forests in China and India (Wang et al., 2013; Ravi et al., 2025).

Therefore, the stand structure observed in Muara Cemara can be interpreted as a regenerating coastal shelter stand with the potential to support long-term ecological functions, particularly shoreline protection, habitat support, and aboveground carbon storage. The presence of young to mature diameter classes further indicates that natural regeneration is still occurring, suggesting that the long-term persistence of the stand can be maintained. This condition is important for supporting coastal protection functions and sustaining coastal ecosystem services.

Biomass Distribution Based on Diameter Class

The total aboveground biomass of *C. equisetifolia* stands in Muara Cemara, Pantai Panjang, was 2.37 ± 0.63 t ha^{-1}. Biomass distribution showed that the 21–30 cm diameter class contributed the largest proportion to total stand biomass.

Table 2. Biomass distribution based on diameter class

Diameter class (cm)	Density (individuals ha^{-1})	Biomass (t ha^{-1})	Contribution (%)
1–10	115	0.255	10.7
11–20	118	0.556	23.4
21–30	135	0.811	34.2
31–40	63	0.428	18.0
>41	43	0.324	13.7
Total	**474**	**2.374**	**100**

The highest biomass contribution from the 21–30 cm diameter class indicates that stand-level biomass accumulation is determined not only by individual tree size but also by the density of individuals within each diameter class. Although trees in the >41 cm diameter class generally have greater biomass per individual, their relatively low density reduced their overall contribution to total stand biomass.

This finding is consistent with Fan et al. (2021), who reported that biomass and carbon accumulation in coastal *Casuarina* plantations are strongly influenced by stand density and site conditions. Wang et al. (2013) also showed that biomass accumulation in *C. equisetifolia* coastal shelterbelt plantations varies according to stand age, density, and environmental conditions. In coastal ecosystems, environmental stressors such as unstable sandy substrates, salt exposure, strong winds, and abrasion may limit the development of large-diameter trees, making medium-sized trees an important component of stand-level biomass accumulation.

The relatively low biomass value recorded in this study should be interpreted in relation to the ecological setting of Muara Cemara. The study site is located in a sandy coastal-estuarine area exposed to abrasion and anthropogenic pressure; therefore, its biomass potential may be lower than that of older, denser, or more intensively managed shelterbelt plantations. This condition highlights the importance of maintaining natural regeneration and reducing local disturbances to support future biomass accumulation.

From a management perspective, the high contribution of the 21–30 cm diameter class suggests that conservation should not focus solely on large trees. Protecting young and intermediate trees is equally important because these diameter classes represent the future carbon-storage capacity of the stand. Maintaining regeneration also supports the continuity of ecological functions, including wind buffering, substrate stabilization, and habitat provision.

Carbon Stock Potential and CO_2 Sequestration

The carbon stock of *C. equisetifolia* stands in Muara Cemara, Pantai Panjang, was 1.09 ± 0.20 t C ha^{-1}, with an estimated CO_2 sequestration potential of 4.01 ± 1.06 t CO_2 ha^{-1}.

Table 3. Distribution of carbon stock and CO_2 sequestration by diameter class

Diameter class	Carbon (t C ha^{-1})	CO_2 (t CO_2 ha^{-1})	Contribution (%)
1–10 cm	0.117	0.431	10.7
11–20 cm	0.256	0.938	23.4
21–30 cm	0.373	1.369	34.2
31–40 cm	0.197	0.723	18.0
>41 cm	0.149	0.546	13.7
Total	**1.092**	**4.007**	**100**

The 21–30 cm diameter class accounted for approximately one-third of the total stand carbon stock. This result indicates that the intermediate growth phase represents the most productive stage for biomass and carbon accumulation in the observed stand. This finding supports Rahman (2022), who reported that *Casuarina equisetifolia* stands make a measurable contribution to carbon storage in tropical coastal areas.

Compared with mangrove ecosystems, the carbon stock estimated in this study is relatively low. This difference is reasonable because mangrove ecosystems generally store substantial amounts of carbon not only in aboveground biomass but also in belowground biomass and organic-rich sediments (Donato et al., 2011; Alongi, 2023). In contrast, the present study estimated only aboveground biomass carbon and did not include root biomass, litter, dead wood, or soil organic carbon. Therefore, the carbon value reported here should be interpreted as a partial estimate of ecosystem carbon storage rather than a complete carbon stock assessment.

Nevertheless, non-mangrove coastal vegetation such as *C. equisetifolia* has an important complementary role in tropical coastal landscapes. Unlike mangroves, which are generally restricted to intertidal muddy or muddy-sandy environments, *C. equisetifolia* can grow on sandy coastal substrates where mangrove establishment is limited. This ecological characteristic allows *C. equisetifolia* stands to support carbon storage and coastal protection functions in areas that are not suitable for mangrove ecosystems. In this context, non-mangrove coastal vegetation may complement blue carbon-oriented conservation strategies, particularly in sandy beach and coastal shelterbelt systems (McLeod et al., 2011; Duarte et al., 2013; Pang et al., 2024).

Assuming that the Muara Cemara area covers approximately 14 ha, the total aboveground carbon stored in the stand is estimated at about 15.29 t C, with an equivalent CO_2 sequestration potential of 56.09 t CO_2. Although the per-hectare carbon stock is modest, the landscape-scale contribution remains ecologically relevant, especially when combined with the stand's coastal protection and habitat-supporting functions. Future studies should include belowground biomass, litter, dead organic matter, and soil organic carbon to provide a more comprehensive estimate of ecosystem carbon stocks. Standardized carbon assessment protocols for coastal and forest ecosystems recommend the inclusion of these carbon pools to improve the accuracy and comparability of carbon stock estimates (Kauffman & Donato, 2012; Howard et al., 2014).

Ecological Functions of *Casuarina equisetifolia* in Coastal Conservation and Management

Casuarina equisetifolia has a dual ecological role as a carbon-storing species and a physical protector of sandy coastal environments. Field observations showed that the stands form a vegetation belt parallel to the shoreline and function as a natural barrier against sea winds. In several locations, relatively thick litter accumulation was observed, along with a more diverse understory vegetation community compared with nearby open areas. These observations suggest that *C. equisetifolia* may improve local microhabitat conditions by increasing shade, contributing organic matter through litterfall, and providing structural complexity for coastal organisms.

The root system of *C. equisetifolia* develops within sandy substrates and may contribute to soil stabilization and reduced sediment loss caused by surface erosion. In addition, the tree canopy creates a more shaded microclimate, which may support the presence of insects, birds, and understory vegetation. However, because this study did not directly measure erosion rates, sediment movement, wind speed reduction, or shoreline change, the role of *C. equisetifolia* in reducing abrasion should be interpreted as an ecological indication based on field observation and supported by previous studies, rather than as a directly quantified effect.

Coastal vegetation is widely recognized as part of nature-based coastal defense because it can reduce wave energy, stabilize sediments, and enhance coastal resilience when vegetation structure and site conditions are suitable (Barbier et al., 2011; Narayan et al., 2016; Menéndez et al., 2020; Rezaie et al., 2020). These field observations are also consistent with Li et al. (2023), who reported that coastal shelter forests play an important role in maintaining shoreline stability, improving habitat quality, and contributing to coastal soil carbon storage. The ecological function of coastal shelter forests is particularly important in areas such as Bengkulu, where coastal abrasion and human pressure periodically affect shoreline stability.

In addition to their protective function, the presence of litter and understory vegetation under *C. equisetifolia* stands indicates that these stands may support ecological processes beyond carbon storage, including nutrient cycling and habitat formation. Soil carbon in coastal shelter forests has also been reported as an important but often overlooked component of coastal carbon storage (Li et al., 2023). Therefore, the ecological value of *C. equisetifolia* should not be assessed solely from aboveground carbon stock, but also from its broader contribution to coastal ecosystem stability and habitat quality.

At the global scale, blue carbon ecosystems face increasing pressure from land-use change, coastal development, and other anthropogenic disturbances (Hamilton & Friess, 2018; Alongi, 2023). Although blue carbon studies have traditionally focused on mangroves, seagrasses, and salt marshes, sandy coastal vegetation and shelter forests should not be overlooked because they provide complementary ecosystem services in coastal zones where typical blue carbon habitats may not occur. From an ecosystem-based coastal management perspective, *C. equisetifolia* stands in Muara Cemara can therefore be positioned as part of a conservation strategy for sandy coastal areas.

This management approach should integrate carbon storage, shoreline protection, habitat provision, and socio-ecological resilience. For Muara Cemara, conservation priorities should include protecting existing stands, maintaining natural regeneration, controlling activities that damage root zones, and monitoring shoreline change over time. Such measures would strengthen the role of *C. equisetifolia* as a coastal conservation component and support the sustainable management of sandy coastal ecosystems in Bengkulu (Analuddin et al., 2024).

CONCLUSION

The *Casuarina equisetifolia* stands in the Muara Cemara area of Pantai Panjang, Bengkulu City, had an aboveground biomass of 2.37 ± 0.63 ton ha^{-1}, a carbon stock of 1.09 ± 0.20 ton C ha^{-1}, and a carbon dioxide sequestration potential of 4.01 ± 1.06 ton CO_2 ha^{-1}. The 21–30 cm diameter class contributed the most to biomass, carbon stock, and CO_2 sequestration, indicating that the intermediate growth stage represents the most productive component of stand-level carbon accumulation. In addition to functioning as a carbon sink, field observations and literature-based assessments indicate that *C. equisetifolia* may support coastal ecological functions through the stabilization of sandy substrates, reduction of coastal abrasion, and provision of habitat for coastal organisms. These findings demonstrate that non-mangrove coastal vegetation has important ecological value and can contribute to ecosystem-based conservation and coastal management efforts. However, this study was limited to the estimation of aboveground biomass and did not include belowground carbon, soil carbon, or seasonal temporal variation. Further studies are therefore needed to integrate belowground carbon components, soil properties, and coastal environmental dynamics to obtain a more comprehensive estimate of carbon stocks as a basis for conservation planning and coastal ecosystem rehabilitation.

RECOMMENDATION

Future research should calibrate local allometric equations to improve the accuracy of biomass estimation for *C. equisetifolia* in Bengkulu. Subsequent studies should also include measurements of root biomass, soil carbon, abrasion parameters, and understory vegetation to enable a more comprehensive assessment of the ecological functions of *C. equisetifolia*. In addition, remote sensing-based mapping of

C. equisetifolia cover is needed to determine the spatial distribution of stands and to support more targeted planning for coastal conservation and rehabilitation.

ACKNOWLEDGMENT

The authors express their gratitude to the Faculty of Mathematics and Natural Sciences, Universitas Bengkulu, for providing research funding through the Non-Tax State Revenue scheme under contract number 4537/UN30.12/HK/2025. The authors also extend their appreciation to all parties who contributed to the implementation of this research, including field data collection, data processing, and administrative support, which enabled the study to be completed successfully.

REFERENCES

Alongi, D. M. (2023). Current status and emerging perspectives of coastal blue carbon ecosystems. *Carbon Footprints, 2*, 12. https://doi.org/10.20517/cf.2023.04

Analuddin, K. A. K., Helmi, M. H., Pribadi, R. P., Adrianto, L. A. L., Jaya, L. M., Iba, W., Adi, N. S., Septiana, A., Nadaoka, K., & Nakamura, T. N. (2024). Mangrove vulnerability and blue carbon storage in the Coral Triangle Areas, Southeast Sulawesi, Indonesia. *Frontiers in Ecology and Evolution, 12*, Article 1420827. https://doi.org/10.3389/fevo.2024.1420827

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs, 81*(2), 169–193. https://doi.org/10.1890/10-1510.1

Bertram, C., Quaas, M. H., Reusch, T. B. H., Vafeidis, A. T., Wolff, C., Rickels, W., & Lenk, C. (2021). The blue carbon wealth of nations. *Nature Climate Change, 11*, 704–709. https://doi.org/10.1038/s41558-021-01089-4

Choudhary, B., Dhar, V., & Pawase, A. S. (2024). Blue carbon and the role of mangroves in carbon sequestration: Its mechanisms, estimation, human impacts and conservation strategies for economic incentives. *Journal of Sea Research, 199*, 102504. https://doi.org/10.1016/j.seares.2024.102504

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

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

Fan, Y., Wang, F., Sayer, E. J., Chen, J., Li, Q., & Mo, Q. (2021). Nutrient addition enhances soil carbon sequestration but not plant biomass in a coastal shelter plantation. *Land Degradation & Development, 32*(1), 68–78. https://doi.org/10.1002/ldr.4078

Hamilton, S. E., & Friess, D. A. (2018). Global carbon stocks and potential emissions due to mangrove deforestation from 2000 to 2012. *Nature Climate Change, 8*, 240–244. https://doi.org/10.1038/s41558-017-0068-1

Howard, J., Hoyt, S., Isensee, K., Telszewski, M., & Pidgeon, E. (Eds.). (2014). *Coastal blue carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses*. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature.

Kauffman, J. B., & Donato, D. C. (2012). *Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests*. CIFOR. https://doi.org/10.17528/cifor/003749

Lee, S. L., Chee, S. Y., Huxham, M., Jamilah, M., Choo, J., Kaur, C. R., Amir, A. A., Ooi, J. L. S., Rozaimi, M., Omar, H., Sharma, S. S., Moritz, M., & Then, A. Y.-H. (2025). Blue carbon ecosystems in Malaysia: Status, threats, and the way forward for research and policy. *The Journal of Environment & Development, 34*(1). https://doi.org/10.1177/10704965241284366

Li, Y., Fu, C., Wang, W., Zhang, J., & Chen, Z. (2023). An overlooked soil carbon pool in vegetated coastal ecosystems: National-scale assessment of soil organic carbon stocks in coastal shelter forests of China. *Science of the Total Environment, 876*, 162823. https://doi.org/10.1016/j.scitotenv.2023.162823

Lin, L., Hao, Z., Post, C. J., Chen, X., & Wang, J. (2023). Protection of coastal shelter forests using UAVs: Individual tree detection and height estimation in *Casuarina equisetifolia* forests. *Forests, 14*(2), 233. https://doi.org/10.3390/f14020233

Lovelock, C. E., & Duarte, C. M. (2019). Dimensions of blue carbon and emerging perspectives. *Biological Reviews, 94*(2), 929–954. https://doi.org/10.1111/brv.12474

McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H., & Silliman, B. R. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment, 9*(10), 552–560. https://doi.org/10.1890/110004

Menéndez, P., Losada, I. J., Torres-Ortega, S., Narayan, S., & Beck, M. W. (2020). The global flood protection benefits of mangroves. *Scientific Reports, 10*, 4404. https://doi.org/10.1038/s41598-020-61136-6

Narayan, S., Beck, M. W., Reguero, B. G., Losada, I. J., van Wesenbeeck, B., Pontee, N., Sanchirico, J. N., Ingram, J. C., Lange, G.-M., & Burks-Copes, K. A. (2016). The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLOS ONE, 11*(5), e0154735. https://doi.org/10.1371/journal.pone.0154735

Pang, S., Abdul Majid, M., Perera, H. A. C. C., & Li, Y. (2024). Global trends in blue carbon research and sustainable development: A bibliometric analysis (2012–2023). *Sustainability, 16*(6), 2473. https://doi.org/10.3390/su16062473

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

Rahman, M. M. (2022). Carbon sequestration capacity of *Casuarina equisetifolia* in the coastal areas of Cox's Bazar, Bangladesh. *International Journal of Advances in Engineering and Management, 4*(8), 830–838. https://doi.org/10.35629/5252-0408830838

Ravi, R., Buvaneswaran, C., & Saravanan, S. (2025). Carbon sequestration potential of *Casuarina equisetifolia* plantations at harvest age in a tropical region of India. *Plant Science Today, 12*(2), 1–11. https://doi.org/10.14719/pst.5987

Rezaie, A. M., Loerzel, J., & Ferreira, C. M. (2020). Valuing natural habitats for enhancing coastal resilience: Wetlands reduce property damage from storm surge and sea level rise. *PLOS ONE, 15*(1), e0226275. https://doi.org/10.1371/journal.pone.0226275

Seddon, N., Smith, A., Smith, P., et al. (2020). Understanding the value and limits of nature-based solutions to climate change and other global challenges.

Philosophical Transactions of the Royal Society B: Biological Sciences, 375(1794), 20190120. https://doi.org/10.1098/rstb.2019.0120

Wang, F., Xu, X., Zou, B., Guo, Z., Li, Z., & Zhu, W. (2013). Biomass accumulation and carbon sequestration in four different aged *Casuarina equisetifolia* coastal shelterbelt plantations in South China. *PLOS ONE, 8*(10), e77449. https://doi.org/10.1371/journal.pone.0077449