Results in Engineering 21 (2024) 101716

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

A comparative study on carbon sequestration potential of disturbed and undisturbed mangrove ecosystems in Kannur district, Kerala, South India

Manoj K *, Thangavelu Arumugam, Adithya Prakash

Department of Environmental Studies, Kannur University, Kannur, Kerala, 670567, India

A R T I C L E I N F O

Keywords:
Carbon
Sequestration
Mangroves
Climate change

A B S T R A C T

In this study attempts have been made to assess the carbon sequestration potential of conserved mangrove ecosystems and anthropogenic mangrove ecosystems. The investigation used a non-destructive method of biomass estimation to determine carbon sequestration potential. The CO_2 equivalent, or carbon sequestration potential, of the Edat mangrove ecosystem is 286.88 t C/ha, and Valapattanam is 212.20 t C/ha. The CO_2 equivalent of the Edat mangrove ecosystem is higher than that of Valapattanam. Avicenna officinal contributes to the higher carbon sequestration potential. The present study reveals that conserved mangrove ecosystems have the highest carbon sequestration potential compared to anthropogenic-interfering mangrove ecosystems. The Valapattanam mangrove ecosystem frequently faces illegal encroachment, land reclamation, industrialization, sand mining, and coastal erosion.

1. Introduction

Mangrove forests are among the most carbon-rich habitats in the biosphere [1–4]. Carbon sequestration in mangrove ecosystems helps reduce environmental pollution, plays a major role in ecosystem balance, helps overcome climate change issues, and provides a good environmental condition for a good and better future [5–8]. Carbon dioxide (CO_2) from the atmosphere can be sequestrated and stored in the soil and biomass [9–11]. Compared to tropical highland forests, mangroves can store up to five times as much organic carbon. [12]; Chatting et al., 2022). Carbon sequestration in mangroves accounts for almost half of the total global mangrove biomass present in Southeast Asia. Globally, the mangroves are estimated to occupy an area of approximately 152, 361 km^2 [13–15]. Long-term carbon sequestration, or carbon capture, is one of the most important ways to mitigate global warming and climate change [14,16,17].

Environmental restoration is a major tool for long-term carbon capture. More vegetation helps capture more carbon dioxide from the atmosphere over the long term, and the carbon dioxide is converted into biomass [18–20]. India's mangrove cover is estimated at 4639 km^2, which is 3 % of the total global mangrove (FAO, 2007; Forest Survey of India, 2009). Mangrove forests are considered potential sinks that store rooms of atmospheric carbon, and mangrove forests play an important role in the global carbon cycle [7,21]. The mangrove plants are highly productive, and the mangrove ecosystem provides high productivity [22,23]. The loss of mangrove ecosystems could have an effect on the ecological stability of coastal zones because they are crucial connectors between land systems and coastal habitats [24].

Mangrove forests are considered the most carbon-rich ecosystems among the tropics and subtropical regions of the world [16,25,26]. The mangrove forests or mangrove ecosystem sequester three or four times more carbon per unit area than the terrestrial forests of the tropics [27, 28]). Reducing the atmospheric carbon dioxide level through carbon sequestration appears to be a more important and viable solution [19, 29]. The lesser carbon stock or carbon sequestration in mangrove ecosystems may lead to global warming and climate change [22,30]. Carbon dioxide emissions in the environment cause several issues, like environmental pollution, global warming, climate change, etc. Overpopulation or population exploitation is another reason for increasing carbon dioxide emissions in the environment [31–33]. Environmental restoration is a major tool for long-term carbon capture. More vegetation helps capture more carbon dioxide from the atmosphere over the long term, and the carbon dioxide is converted into biomass [18,34].

Mangroves have the capacity to sequester carbon in a higher ratio, and the carbon is stored in the form of biomass on their roots and other plant parts for the long term [10]. Mangrove ecosystems soil can store more carbon in the long term, which is also beneficial for mangrove ecosystems and associated species [35,36]. Most of the natural

* Corresponding author. Department of Environmental Studies, Kannur University, Kannur, Kerala, 670567, India.
E-mail address: manojk@kannuruniv.ac.in (M. K).

https://doi.org/10.1016/j.rineng.2023.101716
Received 18 October 2023; Received in revised form 20 December 2023; Accepted 24 December 2023
Available online 29 December 2023

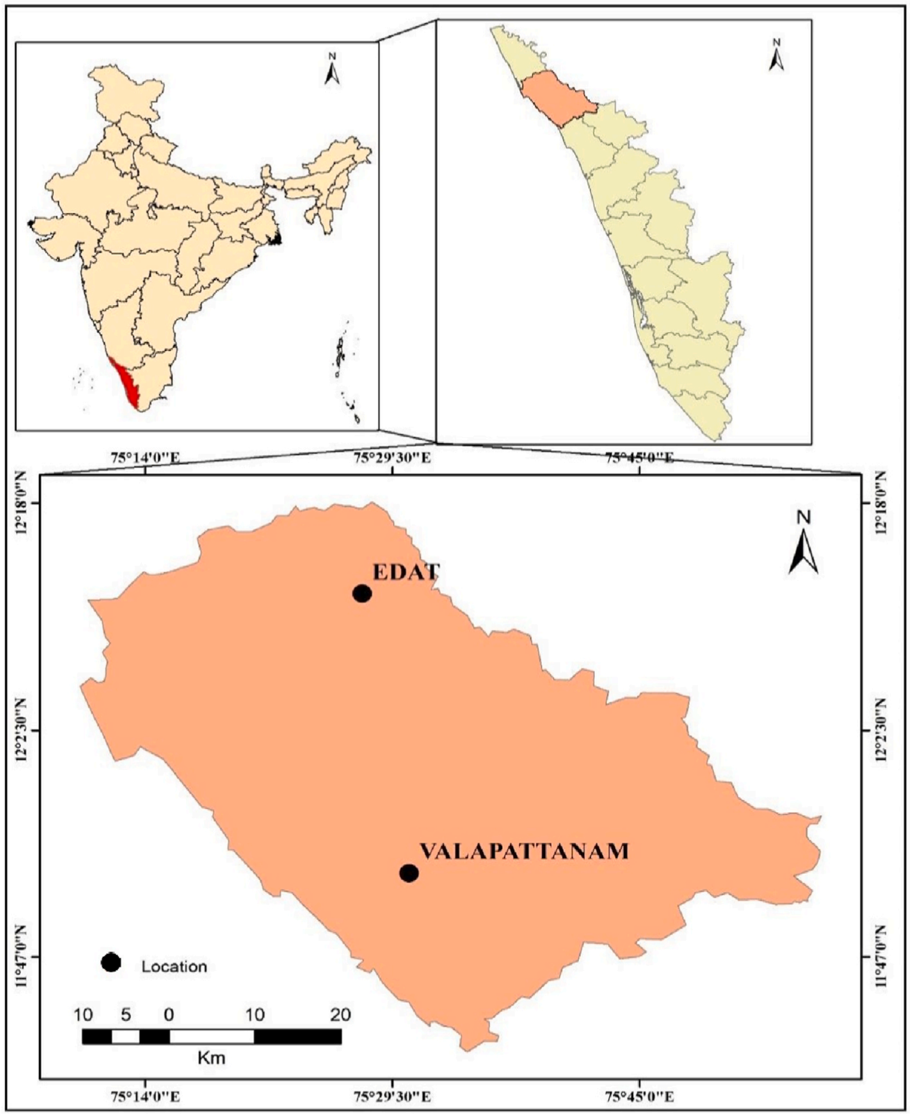

Fig. 1. Study area Map.

vegetation and resources are depleted due to human activity, which directly affects the carbon sequestration of ecosystems [32]. The study reveals that conserved mangrove ecosystems have the highest carbon sequestration potential compared to anthropogenic-interfering mangrove ecosystems in Kannur District.

2. Materials and methods

2.1. Study area

The study area was selected from the mangrove ecosystems of Kannur district, Kerala. Kannur district lies between latitude 11.8745° North and longitude 75.3704° East. The district is bound by the Western Ghats in the east. Kannur experiences a tropical monsoon climate. The vegetation types in Kannur district were Moist deciduous forest, West Coast tropical evergreen forest, and West Coast semi evergreen. 5.5 % of the area is covered with forest, which is 163.17 km^2 (forest and biodiversity, Kannur District). Kerala Forest Research Institute (1999–2000). In Kerala state, Kannur district has the largest mangrove ecosystem. Kannur district covers almost 80 % of the total area of the mangrove ecosystem in the state. A total of 20 sampling plots (10 plots in each study site) of size 10 m × 10 m quadrates were established for non-destructive assessment of biomass and soil carbon stock. The total sampling area covered was 2 ha. The global positioning system GPS (Garmin etrex 32) was used to record the study site's geographic location, as shown in Fig. 1.

2.2. Assessment of above ground biomass and below ground biomass carbon stock using allometric equations

All mangrove trees greater than 10 cm in girth were measured. The girth is measured at breast height (GBH), which is approximately 1.37 m. And the GBH was recorded in centimeters. The diameter of the mangrove tree was calculated by dividing its girth by pi (π) (Brock et al., 2006; [10].). The allometric equations developed by Ref. [37] are used to estimate or assess the above-ground biomass (Wtop) and below-ground biomass (WR) equation (1).

$$W\ (top) = 0.251 \times \rho \times W_{(R)} = 0.199 \times \rho^{0.899} \times D^{2.22} \quad (1)$$

Where ρ is the wood density of species and D is the diameter. The wood density of species is the ratio of the total wood mass to the wood volume at certain moisture content, and it is species-specific. The wood density of the species was obtained from the World Agroforestry Database (Chave et al., 2009). The total biomass of the plots is the sum of the

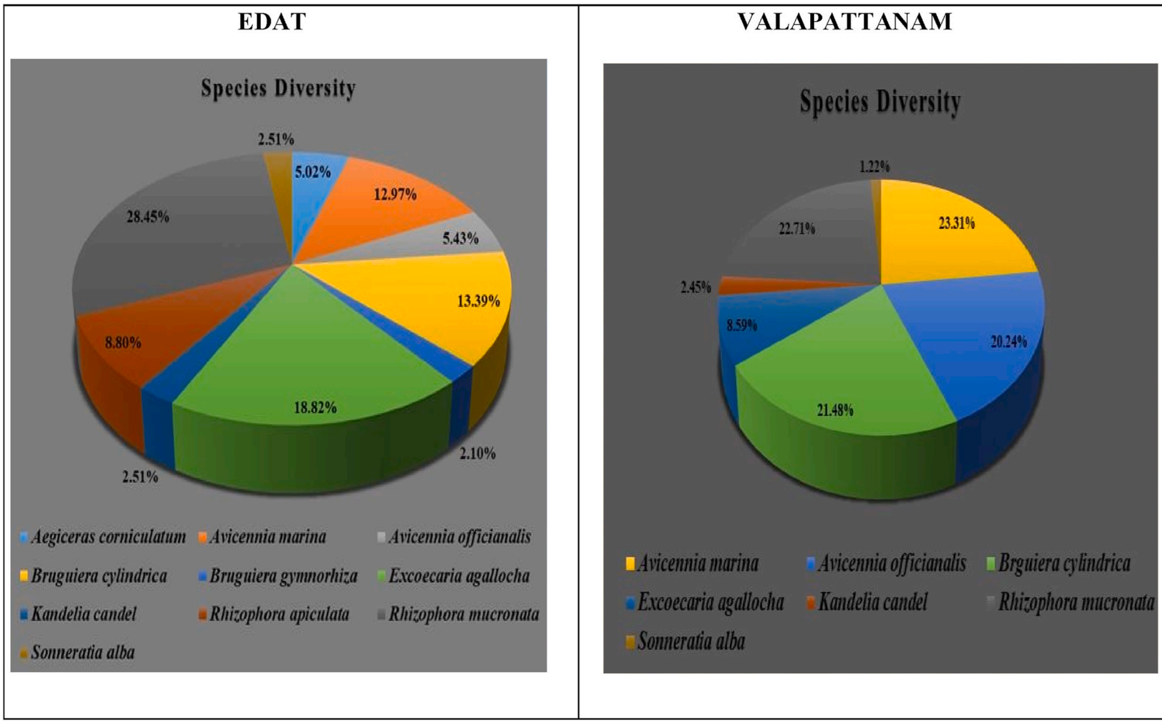

Fig. 2. Species diversity.

values of above-ground biomass and below-ground biomass, and the total biomass is expressed in tons per hectare.

The carbon content of the plot was calculated by multiplying the individual tree biomass with a conversion factor of 0.5 (IPCC 2006) in equation (2).

$$\text{Total biomass} = \text{Individual tree biomass} \times 0.5 \tag{2}$$

2.3. Assessment of soil carbon stock

For the assessment of soil carbon stock, a PVC core is used to collect the soil. The PVC core of 60 cm length and 2 cm radius was used to collect the soil sample. Soil carbon stocks (SCS) in each layer were determined by equation (3):

$$\text{SCS}\left(\text{t}\frac{\text{C}}{\text{ha}}\right) = C \times T \times BD \tag{3}$$

Where C is the soil organic carbon concentration (%), T is the layer thickness of the soil (m), and BD Bulk density (kg/m^3) Total organic carbon in soil is determined by potassium dichromate and sulfuric acid using the wet digestion method (Walkley and Black method, 1934). Bulk density is defined as the weight of the soil in a given volume, and it is expressed in g/cm^2. It is inversely related to pore space. Soil with high bulk densities has low permeability.

The carbon stock of the study area is expressed as equation (4):

$$\text{Total carbon stock}\left(\frac{\text{t}}{\text{C}}\text{ha}\right) = \text{C treeAGB} + + \text{C treeBGB} + \text{C Soil} \tag{4}$$

Where C tree AGB is the carbon content in above-ground biomass and C tree BGB is the carbon content in below ground biomass and C soil is the soil carbon stock. This total carbon stock was then converted into CO_2 equivalents by multiplying with the factor 3.67. The factor was derived on the basis ratio of molecular weights between carbon and carbon dioxide [38].

2.4. Major soil nutrients estimation

The major soil nutrients Available nitrogen was estimated using the alkaline permanganate method. Available phosphorus and Available potassium were determined using the colorimetric method in the study area.

3. Result and discussion

The study area of the mangrove ecosystem represents a variety of mangrove species occurring in Kerala. For a comparative assessment, choose one conserved mangrove ecosystem and one anthropogenic-interfering mangrove ecosystem. Site 1 Edat is a conserved mangrove ecosystem owned and protected by the Wild Life Trust of India. Edat has longitude 12.1006° North and latitude 75.2306° East. Mangrove ecosystems in Edat are conserved by the Wild Life Trust of India, and until November 2016, the Wild Life Trust of India, and Site 2 is Valapattanam; it is an anthropogenic-interfering mangrove ecosystem. Valapattanam has a longitude of 11.9262° North and 75.3500° East. The natural mangrove ecosystems in Valapattanam were very famous. Mangroves are harboring the banks of the Valapattanam River, and the area covered is 30.542 ha [interactive mangrove map of Kannur District, created by Kannur Kandal Project (2016).

4. 1. species diversity

In the Edat mangrove ecosystem, *Rhizophora mucronata* has shown the highest species diversity (28.45 %) and the lowest is *Kandelia candel* (2.10 %), and in the Valapattanam mangrove ecosystem, *Rhizophora mucronata* shows the highest species diversity (22.71 %), and Sonneratia alba has the lowest species diversity (1.22 %). The conserved mangrove ecosystem in Edat consists of more species than the human-interfering mangrove ecosystem in Valapattanam, as shown in Fig. 2. The Edat mangrove ecosystem harbors a variety of species of mangrove plants, such as *Aegiceras corniculatum*, *Avicenna marina*, Avicennia officianalis, *Bruguiera cylindrica*, Bruguiera gymnorhiza, *Excoecaria agallocha*, *Kandelia candel*, *Rhizophora apiculata*, *Rhizophora mucronata*, and Sonneratia

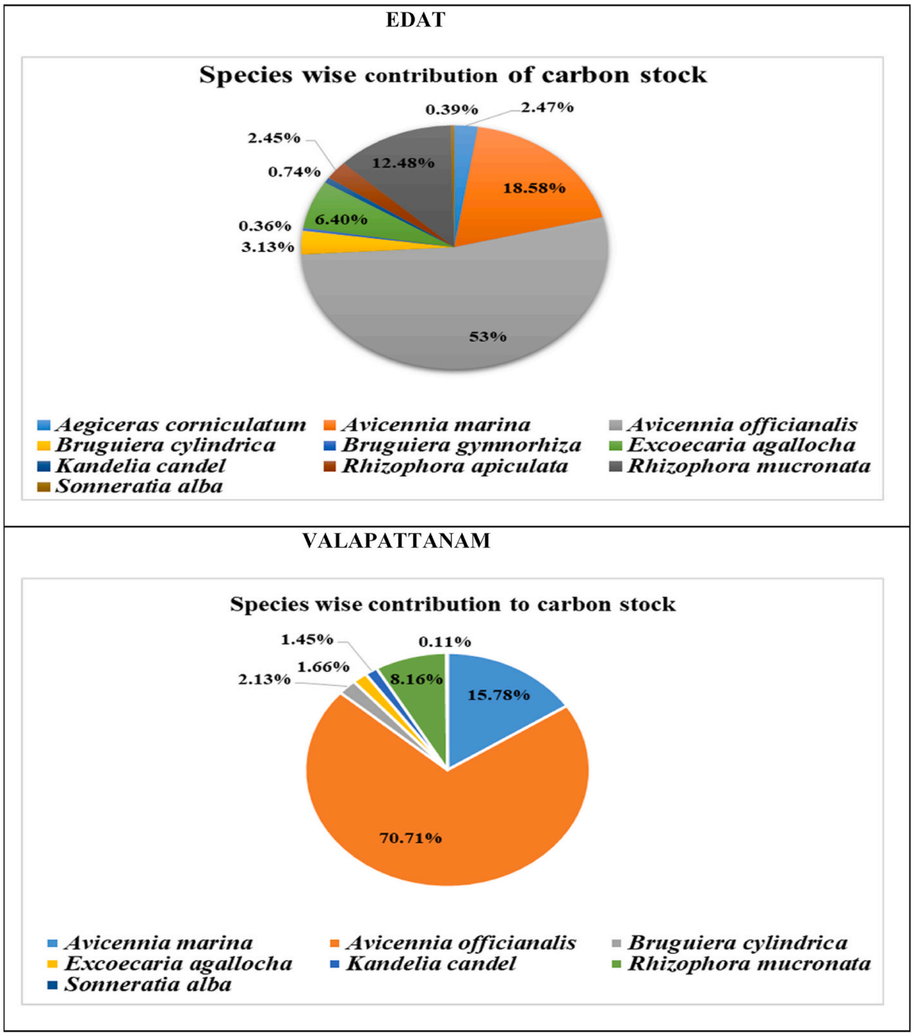

Fig. 3. Species wise contribution of carbon stock.

alba. Valapattanam mangrove ecosystem harbors a variety of species such as *Avicennia marina*, Avicennia officianalis, *Bruguiera cylindrica*, *Excoecaria agallocha*, *Kandelia candel*, *Rhizophora mucronata*, and Sonneratia alba.

4.1. Species wise contribution of carbon stock

In the conserved mangrove ecosystem in Edat, Avicennia officianalis contributes 53 % of the carbon stock, and this species contributes the highest carbon stock. *Kandelia candel* contributes only 0.36 %, which is a small amount. The anthropogenic interference in the ecosystem in Valapattanam, Avicennia officianalis, has contributed 70.71 % of the carbon stock in Valapattanam, and this is the highest. *Excoecaria agallocha* contributes the lowest carbon stock of 1.45 %, as presented in Fig. 3.

4.2. Carbon stock and CO_2 equivalent-soil carbon stock

The soil carbon stock of the Edat mangrove ecosystem is 52.18 t CO_2/ha, and the soil carbon stock of Valapattanam is 38.59 t CO_2/ha. The highest value of soil organic carbon in Edat is 1.76 %, and the lowest value is 1.4 %. The highest value of soil organic carbon in Valapattanam is 1.77 %, and the lowest value is 0.32 %. The average soil organic carbon in Edat is 1.64 %. The average soil organic carbon in Valapattanam is 1.10 %. It is very clear that the soil organic carbon is higher in Edat, which is a conserved mangrove ecosystem, and the soil organic carbon is lower in Valapattanam, which is an anthropogenic-interfering mangrove ecosystem. The highest bulk density in Edat is 1 g/cm^3, and the lowest is 0.25 g/cm^3. The highest bulk density in Valapattanam is 0.83 g/cm^3, and the lowest is 0.06 g/cm^3. The average bulk density of Edat was 0.64 g/cm^3, and the average bulk density of Valapattanam was 0.47 g/cm^3, as shown in Table 1.

Table 1
Soil organic carbon and Bulk density.

Location	Soil organic carbon (%)		Bulk density (g/cm^3)	
	Total	Average	Total	Average
Edat	16.39	1.63	6.4	0.64
Valapattanam	11.07	1.10	4.71	0.47

4.3. Major soil nutrients

The highest concentration of nitrogen (N) in Edat is 401.41 kg/ha, and the lowest is 100.35 kg/ha. The highest concentration of phosphorus (P) in Edat was 38.21 kg/ha, and the lowest was 17.82 kg/ha. The highest concentration of potassium (K) in Edat is 2436 kg/ha, and the lowest is 688.8 kg/ha. The highest concentration of nitrogen (N) in Valapattanam is 250.88 kg/ha, and the lowest is 75.26 kg/ha. The highest concentration of phosphorus (P) in Valapattanam was 78.49 kg/ha, and the lowest was 23.64 kg/ha. The highest concentration of

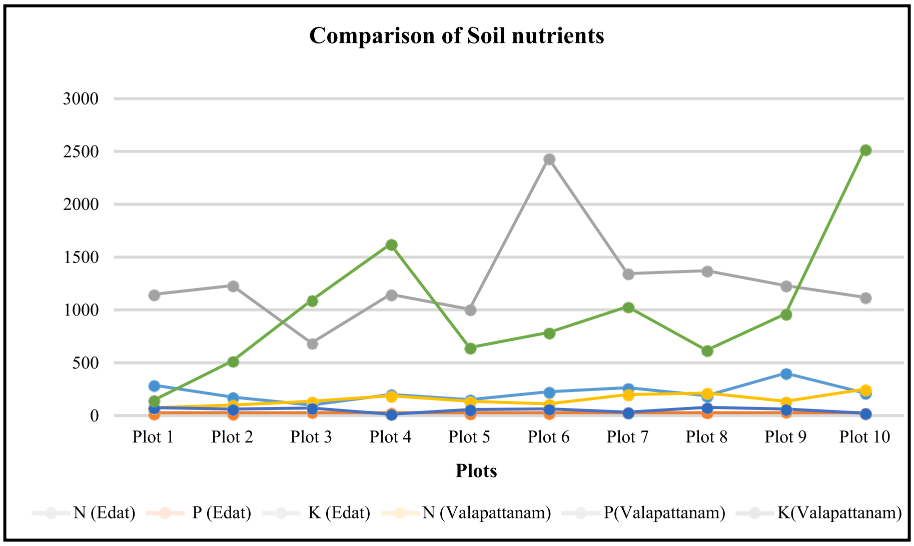

Fig. 4. Major soil nutrients.

Table 2
Carbon stock and CO_2 equivalent.

Location	Caron stock	Vegetation carbon stock (t C/ha) CO_2	Soil carbon stock (t C/ha) CO_2	Ecosystem carbon stock (t C/ha) CO_2	CO_2 Equivalent (t CO_2/ha)
Edat	Total carbon stock	25.98	52.18	78.17	286.88
	Average carbon stock	2.60	5.22	7.81	28.68
Valapattanam	Total carbon stock	19.23	38.59	57.82	212.20
	Average carbon stock	1.92	3.85	5.78	21.22

potassium (K) in Valapattanam is 2520 kg/ha, and the lowest is 145.6 kg/ha. The average concentration of nitrogen in Edat is 220.77 kg/ha, and the average concentration of nitrogen in Valapattanam is 155.54 kg/ha, as shown in Fig. 4.

The average concentration of phosphorous in Edat is 26.50 kg/ha, and the average concentration of phosphorous in Valapattanam is 54.26 kg/ha. The average concentration of potassium in Edat is 1272.992 kg/ha, and the average concentration of potassium in Valapattanam is 995.33 kg/ha. This study found that the concentrations of nitrogen and potassium were higher in the Edat mangrove ecosystem than the Valapattanam mangrove ecosystem, and the concentration of phosphorous was higher in the Valapattanam mangrove ecosystem than the Edat mangrove ecosystem.

Generally, mangrove ecosystems have higher concentrations of major soil nutrients than other areas. The main reason for this higher soil nutrient concentration was the retention capacity of mangroves. The high retention capacity helps keep nutrients in sediments. The soil nutrient enrichment helps with the growth of shoots and roots in mangroves. The mangrove growth accelerated with the enrichment of soil nutrients. The mangrove ecosystem and soil nutrients are positively correlated. The concentration of nitrogen and potassium is higher in the Edat mangrove ecosystem than the Valapattanam mangrove ecosystem, and the concentration of phosphorous is higher in the Valapattanam mangrove ecosystem than the Edat mangrove ecosystem. Also, carbon concentration and organic matters in ecosystems contribute to nutrient retention; major soil nutrients and ecosystem carbon were positively correlated, as presented in Table 2.

The vegetation carbon stock of the mangrove species in Edat was found to be 25.98 t C/ha, and the vegetation carbon stock of the mangrove species in Valapattanam was found to be 19.23. The species-wise contribution in Edat is Avicennia officianalis > *Avicenna marina* > *Rhizophora mucronata* > *Excoecaria agallocha* > *Bruguiera cylindrica* > Bruguiera gymnorhiza > *Rhizophora apiculata* > *Aegiceras corniculatum* > *Kandelia candel* > Sonneratia alba. The species-wise contribution of carbon stock in Valapattanam is as follows: Avicennia officianalis, *Avicennia marina*, *Rhizophora mucronata*, Bruguiera cylindrical, *Excoecaria agallocha*, *Kandelia candel*, and Seneratia alba. The vegetation carbon stock of the Edat mangrove ecosystem is higher than that of the Valapattanam mangrove ecosystem. The soil carbon stock of the Edat mangrove ecosystem was found to be 52.18 t C/ha, and the soil carbon stock of the Valapattanam mangrove ecosystem was found to be 38.59 t C/ha. The soil carbon stock in Edat is greater than that in Valapattanam.

The Edat Mangrove Ecosystem is conserved and protected by the Wild Life Trust of India. There are no conservation plans for the Valapattanam mangrove ecosystem at this time. Valapattanam mangrove ecosystem is an anthropogenic interfered ecosystem, and it was found that illegal encroachment, land reclamation, industrialization, sand mining etc. are the major threat to the Valapattanam mangrove ecosystem and which is the reason for lesser carbon sequestration potential in Valapattanam. In photographs of Valapattanam, first one is the glassware waste dumped in the mangrove ecosystem, and second photograph a lot of plastic waste was dumped into the mangrove ecosystem; and the third image indicates the destruction of the mangrove ecosystem. The photographs of the Edat mangrove ecosystem indicate that healthy mangroves, in Edat are conserved and protected.

The ecosystem carbon stock is the sum of soil carbon stock and vegetation carbon stock. The ecosystem carbon stock of the Edat mangrove ecosystem was found to be 78.17 t C/ha. The ecosystem carbon stock of Valapattanam mangroves was found to be 57.56 t C/ha. The ecosystem carbon stock of Edat is higher than that of Valapattanam. The CO_2 equivalent, or carbon sequestration potential of the Edat mangrove ecosystem is 286.88 t CO_2/ha. The CO_2 equivalent, potential, of Valapattanam is 212.20 t CO_2/ha. The CO_2 equivalent of the Edat mangrove ecosystem is higher than that of Valapattanam. Here, we found that the conserved mangrove ecosystem has a higher carbon sequestration potential than the anthropogenic-interfering mangrove ecosystem. Land reclamation, industrialization, sand mining, etc. are the major threats to the Valapattanam mangrove ecosystem. For this study, the predominant plant species in mangrove forests are typically shrubs or evergreen trees that occur along beaches, brackish estuaries, or delta habitats. Mangrove ecosystems are easily recognized because they are located on tideland mud or sand flats that are frequently flooded with sea water. They are necessary to keep coastal ecosystems healthy and to give coastal residents substantial economic benefits.

5. Conclusion

In the present study, we observed the carbon sequestration potential of the mangrove ecosystem in Kannur district, Kerala. For this comparative study, we selected conserved mangrove ecosystems (Edat) and anthropogenic-interfering mangrove ecosystems (Valapattanam). In this study, the researcher adopted various methods for investigation, i.e., reviews of literature, field surveys, soil analyses, etc. The mangrove ecosystem stores a large amount of atmospheric carbon dioxide in the form of biomass. This study found that the carbon sequestration potential of the Edat mangrove ecosystem is 286.88 t CO_2/ha. The carbon sequestration potential of Valapattanam is 212.20 t CO2/ha. The CO_2 equivalent of the Edat mangrove ecosystem is higher than that of Valapattanam. The main reason for higher carbon sequestration potential in the Edat mangrove ecosystem is conservation of mangroves, and the reason for lower carbon sequestration potential in the Valapattanam mangrove ecosystem is anthropogenic interference and a lack of conservation and restoration activities. The conserved mangrove ecosystem in Edat has the highest carbon sequestration potential. We found that land reclamation, industrialization, sand mining, etc. are the major threats to the Valapattanam mangrove ecosystem, which is the reason for the lesser carbon sequestration potential in Valapattanam. Carbon concentration and organic matter in ecosystems contribute to nutrient retention; major soil nutrients and ecosystem carbon were positively correlated. Carbon sequestration plays a major role in controlling atmospheric carbon dioxide emissions and mitigating global warming and climate change.

CRediT authorship contribution statement

Manoj K: Writing - review & editing, Writing - original draft, Investigation. **Thangavelu Arumugam:** Writing - review & editing, Visualization, Methodology, Data curation. **Adithya Prakash:** Visualization, Resources, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Manoj K reports a relationship with Kannur University that includes: employment. Thangavelu Arumugam reports a relationship with Kannur University that includes: non-financial support. There is no conflict of Interest.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank Kannur University and Wildlife Trust of India for providing all the necessary support for the successful completion of the work.

References

[1] C.M. Duarte, S. Agustí, D. Vaqué, N.S.R. Agawin, J. Felipe, E.O. Casamayor, J. M. Gasol, Experimental test of bacteria-phytoplankton coupling in the Southern Ocean, Limnol Oceanog 50 (2005) 1844–1854.
[2] Azyleah C. Abino, Castillo Jose Alan A, Young Jin Lee, Species diversity, biomass and carbon stock assessments of a natural mangrove forest in Palawan, Philippines, Pak. J. Bot. 46 (6) (2014) 1955–1962.
[3] F. Sidik, B. Supriyanto, H. Krishnawati, M.Z. Muttaqin, Mangrove conservation for climate change mitigation in Indonesia WIREs Clim, Change 9 (2018), https://doi.org/10.1002/wcc.529.
[4] Y. Zeng, D.A. Friess, T.V. Sarira, K. Siman, L.P. Koh, Global potential and limits of mangrove blue carbon for climate change mitigation, Curr. Biol. 31 (2021) 1737, https://doi.org/10.1016/j.cub.2021.01.070, e–1743.e.
[5] A.K. Das, D.K. Jha, M. Prashanthi Devi, B.K. Sahu, N.V. Vinithkumar, R. Kirubagaran, Post tsunami mangrove evaluation in coastal vicinity of Andaman Islands, India, J. Coast Conserv. 18 (2014) 249–255, https://doi.org/10.1007/s11852-014-0312-5.
[6] D. Murdiyarso, J. Purbopuspito, J.B. Kauffman, M.W. Warren, S. Sasmito, D. C. Donato, S. Manuri, H. Krismawati, S. Taberima, S. Kurnianto, The potentials of Indone-sian mangrove forests for global climate change mitigation, Nature Clim. Change 5 (2015) 1089–1092, https://doi.org/10.1038/nclimate2734.
[7] R.D. Ward, D.A. Friess, R.H. Day, R.A. Mackenzie, Impacts of climate change on mangrove ecosystems: a region by region overview, Ecosyst. Heal. Sustain. 2 (2016) e01211, https://doi.org/10.1002/ehs2.1211.
[8] S. Sreelekshmi, Bijeesh Kozhikkodan Veettil, S. Bijoy Nandan, M. Harikrishnan, Mangrove forests along the coastline of Kerala, southern India: Current status and future prospects, Regional Studies in Marine Science 41 (2021) 101573, https://doi.org/10.1016/j.rsma.2020.101573. ISSN 2352-4855.
[9] P. Gnanamoorthy, V. Selvam, R. Ramasubramanian, S. Chakraborty, D. Pramit, A. Karipot, Soil organic carbon stock in natural and restored mangrove forests in Pichavaram, south-east coast of India, Indian J. Mar. Sci. 48 (5) (2019) 801–808.
[10] K.M. Harishma, S. Sandeep, V.B. Sreekumar, Biomass and carbon stocks in mangrove ecosystems of Kerala, southwest coast of India, Ecological Processes 9 (1) (2020) 1–9.
[11] F. Wang, C.J. Sanders, I.R. Santos, J. Tang, M. Schuerch, M.L. Kirwan, et al., Global blue carbon accumulation in tidal wetlands increases with climate change, Natl. Sci. Rev. 8 (2020) nwaa296, https://doi.org/10.1093/nsr/nwaa296.
[12] D.A. Marchio, M. Savarese, B. Bovard, W.J. Mitsch, Carbon sequestration and sedimentation in mangrove swamps influenced by hydrogeomorphic conditions and urbanization in Southwest Florida, Forests 7 (6) (2016) 116.
[13] C. Giri, J. Long, S. Abbas, R.M. Murali, F.M. Qamer, B. Pengra, D. Thau, Distribution and dynamics of mangrove forests of South Asia, J. Environ. Manag. 148 (2015) 101–111, https://doi.org/10.1016/j.jenvman.2014.01.020.
[14] P. Taillardat, D.A. Friess, M. Lupascu, Mangrove blue carbon strategies for climate change mitigation are most effective at the national scale, Biol. Lett. 14 (2018) 2018025, https://doi.org/10.1098/rsbl.2018.0251.
[15] T. Inoue, Carbon sequestration in mangroves, in: Blue Carbon in Shallow Coastal Ecosystems, Springer, Singapore, 2019, pp. 73–99.
[16] S.D. Sasmito, M. Silanpää, M.A. Hayes, S. Bachri, M.F. Saragi-Sasmito, F. Sidik, et al., SWAMP Dataset-Mangrove Soil Carbon-West Papua-2019, V2. Bogor, Center for International Forestry Research (CIFOR, 2019, https://doi.org/10.17528/CIFOR/DATA.00192.
[17] N. Saintilan, N.S. Khan, E. Ashe, J.J. Kelleway, K. Rogers, C.D. Woodroffe, et al., Thresholds of mangrove survival under rapid sea level rise, Science 368 (2020) 1118–1121, https://doi.org/10.1126/science.aba2656.
[18] D.J. Farrelly, C.D. Everard, C.C. Fagan, K.P. McDonnell, Carbon sequestration and the role of biological carbon mitigation: a review, Renewable and sustainable energy reviews 21 (2013) 712–727.
[19] D.R. Richards, B.S. Thompson, L. Wijedasa, Quantifying net loss of global mangrove carbon stocks from 20 years of land cover change, Nat. Commun. 11 (2020) 4260, https://doi.org/10.1038/s41467-020-18118-z.
[20] P. Macreadie, M. Costa, T. Atwood, D. Friess, J. Kelleway, H. Kennedy, et al., Blue carbon as a natural climate solution, Nat. Rev. Earth Environ. 2 (2021) 826–839, https://doi.org/10.1038/s43017-021-00224-1.
[21] N. Matsui, J. Suekuni, M. Nogami, S. Havanond, P. Salikul, Mangrove rehabilitation dynamics and soil organic carbon changes as a result of full hydraulic restoration and re-grading of a previously intensively managed shrimp pond, Wetlands Ecol Manag 18 (2010) 233–242.
[22] D.M. Alongi, Carbon cycling and storage in mangrove forests, Ann. Rev. Mar. Sci 6 (2014) 195–219.
[23] P.M.M. Soares, J.A.M. Careto, R.M. Cardoso, K. Goergen, R.M. Trigo, Land-atmosphere coupling Regimes in a future climate in Africa: from model evaluation to projections based on CORDEX-Africa, J. Geophys. Res. Atmos. 124 (2019) 11118–11142, https://doi.org/10.1029/2018JD029473.
[24] M. Chatting, L. Le Vay, M. Walton, M.W. Skov, H. Kennedy, S. Wilson, et al., Mangrove carbon stocks and biomass partitioning in an extreme environment, Estuar. Coast Shelf Sci. 244 (2020) 106940, https://doi.org/10.1016/j.ecss.2020.106940.
[25] D.R. Aryal, D.E.M. Ruiz, C.N.T. Marroquín, R.P. Ruiz, F.G. Hernández, J.A. V. Venegas, et al., Soil organic carbon depletion from forests to grasslands conversion in Mexico: a review, Agriculture 8 (11) (2018) 181, https://doi.org/10.3390/agriculture8110181.
[26] J.Z. Sippo, C.E. Lovelock, I.R. Santos, C.J. Sanders, D.T. Maher, Mangrove mortality in a changing climate: an overview, Estuar. Coast Shelf Sci. 215 (2018) 241–249, https://doi.org/10.1016/j.ecss.2018.10.011.

[27] D.C. Donato, J. Boone Kauffman, D. Murdiyarso, S. Kurnianto, M. Stidham, M. Kanninen, Mangroves among the most carbon-rich forests in the tropics, Nat. Geosci. 4 (2011) 293–297.
[28] C. Cameron, L.B. Hutley, D.A. Friess, B. Brown, High greenhouse gas emissions mitigation benefits from mangrove rehabilitation in Sulawesi, Indonesia, Ecosyst. Serv. 40 (2019) 101035, https://doi.org/10.1016/j.ecoser.2019.101035.
[29] K. Vinod, P.K. Asokan, P.U. Zacharia, C.P. Ansar, G. Vijayan, A. Anasukoya, M. Nikhiljith, Assessment of biomass and carbon stocks in mangroves of Thalassery estuarine wetland of Kerala, south west coast of India, J. Coast Res. 86 (SI) (2019) 209–217.
[30] M. Sinclair, A. Ghermandi, A.M. Sheela, A crowdsourced valuation of recreational ecosystem services using social media data: an application to a tropical wetland in India, Sci. Total Environ. 642 (2018) 356–365, https://doi.org/10.1016/j.scitotenv.2018.06.056, 2018.
[31] H.S. Suresh, D.M. Bhat, N.H. Ravindranath, R. Sukumar, Carbon stocks and sequestration potential of Indian Mangroves, Trop. Ecol. 58 (3) (2017) 547–553.
[32] J. Fang, G. Yu, L. Liu, S. Hu, F.S. Chapin, Climate change, human impacts, and carbon sequestration in China, Proc. Natl. Acad. Sci. USA 115 (16) (2018) 4015–4020.
[33] J. Sanderman, T. Hengl, G. Fiske, K. Solvik, M.F. Adame, L. Benson, et al., A global map of mangrove forest soil carbon at 30 m spatial resolution, Environ. Res. Lett. 13 (2018) 055002, https://doi.org/10.1088/1748-9326/aabe1c.
[34] A. Thangavelu, K. Manoj, K. Sapna, C.K. Jyothin, K.P. Prashanth, Investigation of Land use cover patterns of sea shore vegetation of Kannur Coast of Northern Kerala, India Using GIS, Ecology, Environment and Conservation, EM International 27 (2021) S225–S235.
[35] M.F. Adame, R.M. Connolly, M.P. Turschwell, C.E. Lovelock, T. Fatoyinbo, D. Lagomasino, et al., Future carbon emissions from global mangrove forest loss, Glob. Chang. Biol. 27 (2021) 2856–2866, https://doi.org/10.1111/gcb.15571.
[36] P.L.I.G.M. Cooray, K.A.S. Kodikara, M.P. Kumara, U.I. Jayasinghe, S. K. Madarasinghe, F. Dahdouh-Guebas, et al., Climate and intertidal zonation drive variability in the carbon stocks of Sri Lankan mangrove forests, Geoderma 389 (2021) 114929.
[37] A. Komiyama, S. Poungparn, S. Kato, Common allometric equations for estimating the tree weight of mangroves, J. Trop. Ecol. 21 (2005) 471–477.
[38] J.B. Kauffman, D.C. Donato, Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests, Working Paper 86, CIFOR, Bogor, Indonesia (2012) 40.

Further reading

[39] D.M. Alongi, S.K. Mukhopadhyay, Contribution of mangroves to coastal carbon cycling in low latitude seas, Agric. For. Meteorol. 213 (2015) 266–272.
[40] J. Bai, Y. Meng, R. Gou, J. Lyu, Z. Dai, X. Diao, G. Lin, Mangrove diversity enhances plant biomass production and carbon storage in Hainan island, China, Funct. Ecol. 35 (3) (2021) 774–786.
[41] G. Bindu, P. Rajan, E.S. Jishnu, K.A. Joseph, Carbon stock assessment of mangroves using remote sensing and geographic information system, The Egyptian Journal of Remote Sensing and Space Science 23 (1) (2020) 1–9.
[42] S. Das, R. Vincent, Mangroves protected villages and reduced death toll during Indian super cyclone, Proc. Natl. Acad. Sci. USA (2009) 1–4.
[43] G. George, P. Krishnan, K.G. Mini, S.S. Salim, P. Ragvan, et al., Structure and regeneration status of mangrove patches along the estuarine and coastal stretches of Kerala, India J. For. Res. 30 (2018) 517–518, https://doi.org/10.1007/s11676-018-0600-2.
[44] K. Kandasamy, N. Rajendran, B. Balakrishnan, R. Thiruganasambandam, R. Narayanasamy, Carbon sequestration and storage in planted mangrove stands of Avicennia marina, Regional Studies in Marine Science 43 (2021) 101701.
[45] I. Kasawani, J. Kamaruzaman, M.I. Nurun-Nadhirah, Biological diversity assessment of Tok Bali mangrove forest, Kelantan, Malaysia, WSEAS Trans. Environ. Dev. 3 (2) (2007) 37–44.
[46] K. Kathiresan, N. Rajendran, Coastal mangrove forests mitigated tsunami. Estuarine, Coastal and Shelf Science 65 (2005) 601–606.
[47] J.B. Kauffman, C. Heider, J. Norfolk, F. Payton, Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic, Ecol. Appl. 24 (2014) 518–527.
[48] J.B. Kauffman, V.B. Arifanti, A.F. Bernardino, T.O. Ferreira, D. Murdiyarso, M. C. Cifuentes, J. Norfolk, And details for land-use carbon footprints arise from quantitative and replicated studies, Front. Ecol. Environ. 1749 (2018) 12–13, https://doi.org/10.1002/fee.1749.
[49] C. Cameron, B. Kennedy, S. Tuiwawa, N. Goldwater, K. Soapi, C.E. Lovelock, High variance in community structure and ecosystem carbon stocks of Fijian mangroves driven by differences in geomorphology and climate, Environ. Res. 192 (2021) 110213.
[50] C.M. Duarte, J.J. Middelburg, N. Caraco, Major role of marine vegetation on the oceanic carbon cycle, Biogeosciences 2 (1) (2005) 1–8.
[51] M.N.I. Khan, R. Suwa, A. Hagihara, Carbon and nitrogen pools in a mangrove stand of Kandelia obovata (S.L.) Yong: vertical distribution in the soil-vegetation system, Wetl. Ecol. Manag. 15 (2) (2007) 141–153.
[52] A. Komiyama, J.E. Ong, S. Poungparn, Allometry, biomass, and productivity of mangrove forests: a review, Aquat. Bot. 89 (2) (2008) 128–137.
[53] C.E. Lovelock, M.C. Ball, K.C. Martin, C. Feller I, Nutrient enrichment increases mortality of mangroves, PLoS One 4 (5) (2009) e5600.
[54] Chatting Mark, Ibrahim Al-Maslamani, Walton Mark, W. Skov Martin, Hilary Kennedy, Y. Sinan Husrevoglu, Lewis Le Vay, Future mangrove carbon storage under climate change and deforestation, Front. Mar. Sci. 9 (2022). ISSN=2296-7745.
[55] A. Mitra, K. Sengupta, K. Banerjee, Standing biomass and carbon storage of above-ground structures in dominant mangrove trees in the Sundarbans, For. Ecol. Manag. 261 (7) (2011) 1325–1335.
[56] B. Murray, L. Pendleton, W. Jenkins, S. Sifleet, Green Payments for Blue Carbon: Economic Incentives for Protecting Threatened Coastal Habitats, Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, NC, 2011.
[57] C. Nellemann, E. Corcoran, C.M. Duarte, L. Valdes, C. De Young, L. Fonseca, G. Grimsditch, Blue carbon: the role of oceans as carbon sinks, in: Blue Carbon: the Role of Healthy Oceans in Binding Carbon: A Rapid Response Assessment, Nairobi: UNEP; Arendal, Norway: GRID-Arenda, 2009.
[58] C.P. Onuf, J.M. Teal, I. Valiela, Interactions of nutrients, plant growth and herbivory in a mangrove ecosystem, Ecology 58 (3) (1977) 514–526.
[59] X. Ouyang, S.Y. Lee, Improved estimates on global carbon stock and carbon pools in tidal wetlands, Nat. Commun. 11 (1) (2020) 1–7.
[60] C.N. Pandey, R. Pandey, Carbon sequestration by mangroves of Gujarat, India, Int. J. Bot. Res. 3 (2) (2013) 57–70.
[61] S.D. Roy, P. Krishnan, Mangrove stands of Andamans vis-à-vis tsunami, Curr. Sci. 89 (2005) 1800–1804.
[62] S.C. Sahu, Manish Kumar, N.H. Ravindranath, Carbon stocks in natural and planted mangrove forests of Mahanadi mangrove wetland, east coast of India, Curr. Sci. 110 (12) (2016) 2253–2260.
[63] J. Schahczenski, H. Hill, Agriculture, Climate Change and Carbon Sequestration, ATTRA, Melbourne, 2009, pp. 14–18.
[64] L.M. Schile, J.B. Kauffman, S. Crooks, J.W. Fourqurean, J. Glavan, J.P. Megonigal, Limits on carbon sequestration in arid blue carbon ecosystems, Ecol. Appl. 27 (3) (2017) 859–874.
[65] M.A. Sheikh, M. Kumar, R.W. Bussmann, Altitudinal variation in soil organic carbon stock in coniferous subtropical and broadleaf temperate forests in Garhwal Himalaya, Carbon Bal. Manag. 4 (2009) 6.
[66] K. Vinod, A. Anasu Koya, V.A. Kunhikoya, P.G. Shilpa, P.K. Asokan, P.U. Zacharia, K.K. Joshi, Biomass and carbon stocks in mangrove stands of Kadalundi estuarine wetland, south-west coast of India, Indian J. Fish. 65 (2) (2018) 89–99.
[67] K. Vidyasagaran, V.K. Madhusoodanan, Distribution and plant diversity of mangroves in the west coast of Kerala, India, J. Biodivers. Environ. Sci. (JBES) 4 (5) (2014) 38–45.
[68] A. Walkley, I.A. Black, An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method, Soil Sci. 37 (1934) 29–38.
[69] C.D. Woodroffe, Studies of a mangrove basin, Tuff Crater, New Zealand: I. Mangrove biomass and production of detritus, Estuar. Coast Shelf Sci. 20 (1985) 265–280.
[70] World Agroforestry Centre, Databases, World Agroforestry Centre, Nairobi, Kenya, 2011. http://www.worldagroforestrycentre.org/our_products/databases. (Accessed 11 May 2011).
[71] M. Wu, Z. He, S. Fung, Y. Cao, D. Guan, Y. Peng, S.Y. Lee, Species choice in mangrove reforestation may influence the quantity and quality of long-term carbon sequestration and storage, Sci. Total Environ. 714 (2020) 136742.
[72] D.A. Marchio, M. Savarese, B. Bovard, W.J. Mitsch, Carbon sequestration and sedimentation in mangrove swamps influenced by hydrogeomorphic conditions and urbanization in southwest Florida, Forest@ 7 (6) (2016) 116, https://doi.org/10.3390/f7060116.
[73] M. Yoshiro, M. Michimasa, K. Motohiko, N.H. Phan, Mangroves as a coastal protection from waves in the Tong Kind delta, Vietnam, Mangroves Salt Marshes 1 (1997) 127–135.