BIODIVERSITAS
Volume 25, Number 8, August 2024
Pages: 2748-2755

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d250848

Species-specific and landscape carbon storage analysis of mangrove forest in Segara Anakan Lagoon, Cilacap, Central Java, Indonesia

ENDANG HILMI[1,♥], HENDRAYANA[2], SESILIA RANI SAMUDRA[3], NABELA FIKRIYYA[3], TEUKU JUNAIDI[3], TRI NUR CAHYO[2], NAFSHA ATIKA PUTRI[3], AFIDA NADZIROTUL UMMAH[3]

[1]Program of Aquatic Resources Management and Magister Program of IKL, Faculty of Fisheries and Marine Sciences, Universitas Jenderal Soedirman. Jl. Dr. Soeparno, Purwokerto Utara, Banyumas 53122, Central Java, Indonesia. Tel.: +62-281-642360, ♥email: dr.endanghilmi@gmail.com

[2]Program of Marine Science, Faculty of Fisheries and Marine Sciences, Universitas Jenderal Soedirman. Jl. Dr. Soeparno, Purwokerto Utara, Banyumas 53122, Central Java, Indonesia

[3]Program of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, Universitas Jenderal Soedirman. Jl. Dr. Soeparno, Purwokerto Utara, Banyumas 53122, Central Java, Indonesia

Manuscript received: 21 May 2024. Revision accepted: 26 August 2024.

Abstract. *Hilmi E, Hendrayana, Samudra SR, Fikriyya N, Junaidi T, Cahyo TN, Putri NA, Ummah AN. 2024. Species-specific and landscape carbon storage analysis of mangrove forest in Segara Anakan Lagoon, Cilacap, Central Java, Indonesia. Biodiversitas 25: 2748-2755.* Mangrove forests are one of the world's largest carbon pools. However, each mangrove species has a different capacity to sequester and store carbon in its biomass. Therefore, at the landscape scale, there are also differences in carbon storage and percent carbon between habitat sites influenced by dominant species and stand density due to differences in environmental conditions. This study aims to analyze each mangrove species' percent carbon and carbon storage and develop a mangrove landscape in Segara Anakan Lagoon, Cilacap District, Central Java Province, Indonesia. This study used destructive methods to collect mangrove samples. The percentage of carbon of each species was analyzed using a formulation of volatile and ash values, while carbon stock for each species was estimated using allometric equations. Landscape analysis of carbon stocks was based on mangrove stand density. The results showed that the carbon percentage of mangrove species averaged between 42.48-53.34% with *Rhizophora* spp. (*R. apiculata, R. mucronata* and *R. stylosa*) and *Bruguiera gymnorrhiza* having the highest carbon percentage of 47.1-55.6%, followed by *Sonneratia* spp. and *Avicennia* with 43.0-48.6%, *Ceriops* spp., *Aegiceras* spp., *Heritiera littoralis* and *Xylocarpus* spp. with 43.0-48.2%, and *Nypa fruticans* had the lowest carbon percentage with 39.1-41.0%. At the landscape scale, Segara Anakan had mangrove biomass between 34.83-786.61 tons/ha with carbon stock between 7.85-186.09 tons C/ha. Based on percent carbon, the mangrove landscape in Segara Anakan was dominated by *B. gymnorrhiza, R. apiculata, R. stylosa, Ceriops tagal,* and *R. mucronata. Avicennia marina, Aegiceras corniculatum, N. fruticans, R. apiculata*, and *Sonneratia alba* dominated mangrove landscapes based on carbon storage. The results of this study indicate that carbon storage in mangrove ecosystems is important to support carbon conservation because it has a high percentage of carbon and large carbon storage.

Keywords: Carbon storage, mangrove biomass, mangrove density, mangrove landscape

INTRODUCTION

The use of carbon storage potential and percentage is crucial in species and landscape-specific analysis of mangrove ecosystems to support conservation under REED+ and other schemes. Species-specific carbon stock indicates the ability of each mangrove species to sequester carbon, while landscape-specific carbon stock shows the distribution of species and carbon storage potential. Mangrove forests can absorb and store carbon per hectare up to four times more than other types of tropical forest (Alviana et al. 2023; Sugiatmo et al. 2023; S. Li et al. 2024). In particular, mangrove forest has species and landscape-specific capacity to store and sequester carbon in the form of plant biomass (Hartoko et al. 2015; Azizah et al. 2017; S. Li et al. 2024) as the result of photosynthetic activities in the leaves and roots. Carbon sequestration occurs in stems and roots where approximately 50% of tree biomass is stored (Adame et al. 2017; Njana 2020; Sharma et al. 2020). The high capacity of carbon sequestration of mangrove forests implies its important role in mitigating the impacts of climate change (Karl and Church 2017; Azman et al. 2021) and supporting conservation programs.

The potential carbon shows the amount stored that can be sequestered (Cameron et al. 2019; Kandasamy et al. 2021). Mangrove forest has a high ability to store carbon which contributes to 40-55% of the biomass (Hilmi et al. 2017, 2019b). However, carbon sequestration capacity differs among species and zones (Datta and Deb 2017; Sharafatmandrad and Mashizi 2020; Hilmi et al. 2023b). The zones have varying community structures and composition which are influenced by the adaptation of mangrove species to environmental variables, such as salinity, pH, and soil texture (Hilmi et al. 2021a, 2024a; Wintah et al. 2023). This condition impacts the distribution of mangrove species in a zone and provides information on carbon stock (Perera et al. 2018; Hilmi et al. 2019b). Furthermore, carbon storage potential is related to species-specific biomass capacity (Swangjang and Panishkan 2021), sequestration rate (Doughty et al. 2016; Sleeter et al. 2017), and the prospect of mangrove forest which is also influenced by degradation condition (Owuor et al. 2019;

Lulandala et al. 2023) and stand density (Hilmi 2018, et al. 2022a).

Segara Anakan Lagoon in Cilacap District, Central Java Province, Indonesia is considered one of the important remaining areas on Java Island which has an important role in supporting the storage carbon system (Hilmi et al. 2017; Dai et al. 2018; Azman et al. 2021). Mangrove forest in Segara Anakan is composed of various species including *Rhizophora apiculata, R. mucronata, R. stylosa, Avicennia marina, Sonneratia caseolaris, Bruguiera gymnorrhiza, Ceriops tagal,* and *Nypa fruticans* which are dominant species. Meanwhile, *Avicennia alba, Aegiceras corniculatum, A. floridum, Lumnitzera* spp., and *Xylocarpuss* spp. are co-dominant and associate species (Hilmi et al. 2017, 2021a, 2022b). The western part has a mangrove density of 166-4000 trees ha^{-1}, while the eastern part has a lower density of 133-3000 trees ha^{-1} with the dominant species being *N. fruticans* (high dominant) (Hilmi et al. 2021b), *R. stylosa, R. apiculata, A. corniculatum, Sonneratia alba* and *A. marina* (moderate dominant) (Hilmi et al. 2022b).

A study in 2016-2017 showed that the potential carbon stock in Segara Anakan and Meranti Island (Riau Province, Indonesia) reached 79.2-242.2 tonsC/ha, with the estimated economic value between 396.2 US$/ha (price 5 US$/tons) and 4360.4 US$/ha (price 18 US$/tons) (Hilmi et al. 2017). The clustering species were *Bruguiera* spp. and *Rhizophora* spp. (highest contribution), *Aegiceras* spp., and *Ceriops* spp. (moderate contribution) as well as *N. fruticans* with the lowest contribution (Hilmi et al. 2019b). Although there are previous studies on carbon stock in Segara Anakan, there is no study on the zonation and landscape of mangrove forests based on carbon percent and storage for each species. Therefore, this study aimed to analyze specific species and mangrove landscapes based on carbon percent and storage. The results are expected to provide information on mangrove zonation as the blueprint for carbon conservation of the mangrove ecosystem.

MATERIALS AND METHODS

Study area and period

This study was conducted from January-March 2024 in Segara Anakan Lagoon (western and eastern part), Cilacap District, Central Java Province, Indonesia (Figure 1 and Table 1). The lagoon is an outlet from many rivers and is pressured by sedimentation with the average reduction of water bodies averaging 61 ha yr^{-1} (Cahyo et al. 2024). The study site was composed of *N. fruticans, R. stylosa, A. corniculatum, R. apiculata, A. marina,* and *S. alba* as the major species (Hilmi et al. 2024a).

Two clusters were predominant in the study site (i) East Segara Anakan covering Donan, Sapuregel, Kalipanas, Kembang Kuning River, Sleko, Tritih, and Muara Pelawangan; as well as (ii) West Segara Anakan covering Ujung Alang, Ujung Gagak, Karang Baja, Kayu Mati, Klaces, Majingklak, Muara Cawitali, Muara Bagian, Muara Legok, and Muara Masigitela. A total of 15 observation stations were established on each western and eastern part with each station having 3 sampling plots, resulting in a total of 90 plots. The sample plots followed the river condition including the current and tidal seawater, offering insights into the potential of mangrove density.

Data collection procedures

Sampling design

Sampling to collect mangrove samples was carried out using a one-stage cluster method (Hilmi et al. 2021b). Mangrove cluster followed the indicator of density (Hilmi et al. 2021b; Cahyo et al. 2024). The clustering of mangrove sampling was developed to analyze species density, as well as potential biomass, and carbon (Hilmi et al. 2024b).

Table 1. List of observation stations in Segara Anakan, Cilacap District, Central Java, Indonesia, along with geographical coordinates

Stations	East Segara Anakan			Stations	West Segara Anakan		
	Coordinates		Number plots		Coordinates		Number plots
	Lat (S)	Lon (E)			Lat (S)	Lon (E)	
Kali Panas 1 River	07°40’22”	109°00’56”	3	Majingklak River	07°40’32”	108°48’01”	3
Kali Panas 2 River	07°40’29”	109°00’41”	3	Jongor River	07°40’23”	108°48’20”	3
Kali Panas 3 River	07°40’21”	109°00’34”	3	Muara Cawitali River	07°41’46”	108°47’41”	3
Kali Panas 4 River	07°40’18”	109°00’32”	3	Kebuyutan River	07°41’13”	108°47’45”	3
Kali Panas 5 River	07°40’41”	109°00’34”	3	Batu Macan River	07°41’38”	108°47’46”	3
Donan 1 River	07°40’34”	108°59’58”	3	Ujung Gagak River	07°40’13”	108°48’43”	3
Donan 2 River	07°40’24”	108°59’57”	3	Muara Legok River	07°39’48”	108°48’13”	3
Donan 3 River	07°41’15”	108°59’43”	3	Kayu Mati River	07°39’50”	108°48’27”	3
Donan 4 River	07°42’10”	108°59’23”	3	Lorogan River	07°40’44”	108°48’30”	3
Donan 5 River	07°42’46”	108°59’29”	3	Karang Baja River	07°40’59”	108°48’47”	3
Donan 6 (Sleko)	07°43’48”	108°59’11”	3	Klaces River	07°41’05”	108°49’47”	3
Pelawangan Timur	07°43’21”	108°58’07”	3	Inti Ujung Gagak River	07°40’34”	108°49’47”	3
Sapuregel 1 River	07°41’48”	108°57’38”	3	Muara Bagian River	07°40’58”	108°51’42”	3
Sapuregel 2 River	07°42’54”	108°57’42”	3	Muara Masigitsela River	07°41’24”	108°50’46”	3
Kembang Kuning River	07°43’13”	108°57’14”	3	Pertigaan Ujung Alang River	07°41’44”	108°51’39”	3

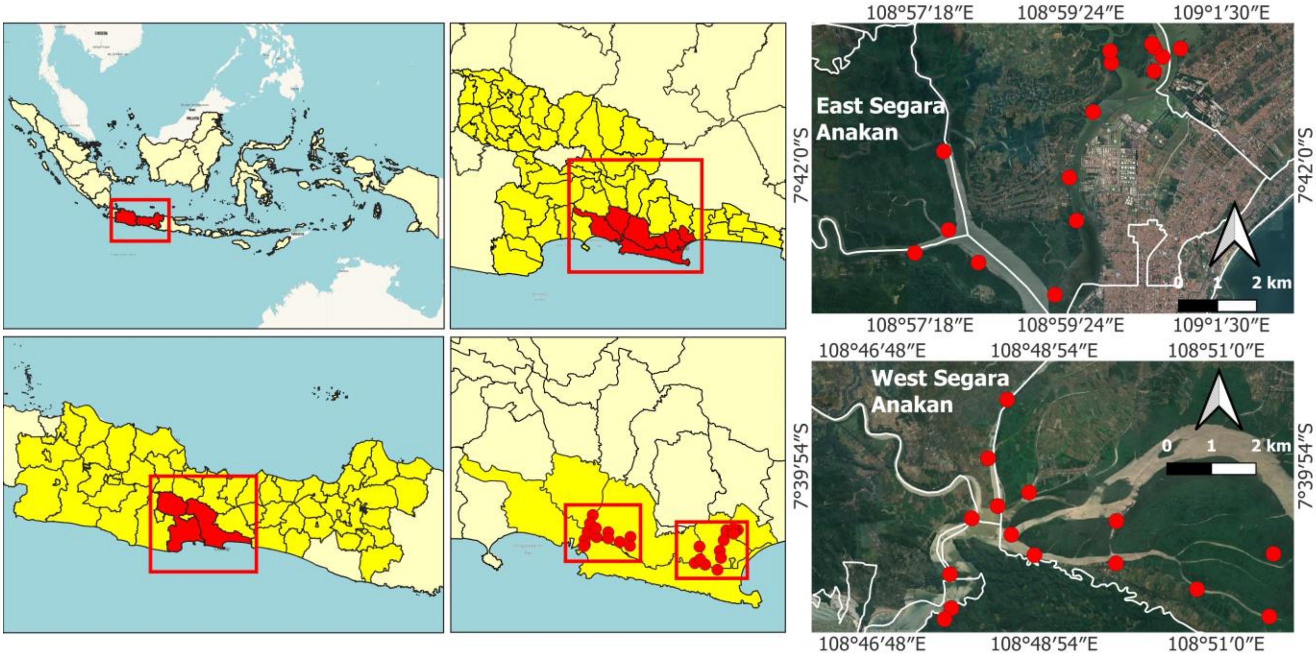

Figure 1. Map of the study area in Segara Anakan Lagoon, Cilacap District, Central Java, Indonesia, showing 30 observation stations

Table 2. Allometrics are used to estimate the above-ground biomass of each mangrove species (Komiyama et al. 2005, 2008; Fatoyinbo et al. 2008; Fatoyinbo and Simard 2011)

Spesies	Allometric equations
Avicennia marina	$W_{top} = 0.308*D^{2.11}$
Avicennia alba	$W_{top} = 0.2901*D^{2.2605}$,
Rhizophora sp.	$W_{top} = 0.128*D^{2.60}$,
Bruguiera gymnorryza	$W_{top} = 0.186*D^{2.31}$,
Ceriops tagal	$W_{top} = 0.189*D^{2.59}$,
Bruguiera parviflora	$W_{top} = 0.7749*D^{2.4167}$
General equation	$W_{top} = 0.251*P*D^{2.46}$

Note: D is the Diameter at Breast Height (DBH)

Mangrove density analysis

The analysis of mangrove density was conducted through a line transect system using a plot with a size of 10 m x 10 m based on a zone in Segara Anakan. Each plant with a diameter >4 cm was measured for the diameter and height. The mangrove tree was calculated based on (Xiong et al. 2018; Cooray et al. 2021; Hilmi et al. 2021b) as follows:

$$\text{Mangrove tree density} = \frac{mangrove\ individu\ (trees)}{mangrove\ area\ (ha)}$$

Mangrove density was then classified based on the density model developed by Hilmi et al. (2019a).

Data analysis

Biomass estimation

The diameter at breast height was measured at 1.3 m from ground level. The allometric equation was used to estimate the above-ground biomass of each mangrove species as presented in Table 2 (Cohen et al. 2013; Hilmi et al. 2017; Dutcă et al. 2020; Malakini et al. 2020).

Carbon percentage of mangrove species

The carbon percentage of mangrove species was determined through a destructive method by collecting samples including wood, root, and leaves (Chabi et al. 2016; Hilmi et al. 2019b; Malakini et al. 2020) using a plastic cover (Hartoko et al. 2015; Chabi et al. 2016). After collection, the samples of each species were analyzed for carbon percentage and wood density (Lai et al. 2023; Nascimento et al. 2023). Carbon percentage was determined using the formulation between volatile and ash values with the formulation as follows (Piponiot et al. 2016; Hilmi et al. 2017):

$$\text{Carbon percentage (\%)} = 100\% - (A + B)$$

$$\text{A is volatile value (\%)} = \frac{(a1-a2)}{a2}\ x\ 100$$

$$\text{B is ash value, (\%)} = \frac{b1}{b2}\ x\ 100$$

Where:

a_1 : Initial sample weight, gram
a_2 : Sample weight after heating, gram
b_1 : Residual ash, gram
b_2 : Sample weight, gram

Landscape analysis

Landscape analysis used the indicator carbon percentage of each species and total mangrove carbon per hectare. This analysis explains the zonation of mangroves based on the potential of carbon storage and the distribution of each species.

Data tabulation

Data tabulation used average and standard deviation analyses, as well as minimum-maximum data. The data were tabulated by table and figure.

RESULTS AND DISCUSSION

Carbon storage of mangrove species

As shown in Table 3, the mangrove ecosystem in Segara Anakan Lagoon had biomass between 34.83-786.61 tons/ha with carbon storage between 7.85-186.09 tonsC/ha. Carbon storage of each mangrove species can be divided into four groups where *S. alba* and *A. corniculatum* had the highest potential with 14.74-15.66 tonC/ha, followed by *A. marina*, *N. fruticans*, *R. stylosa* and *R. apiculata* with 7.46-10.54 tonC/ha, then *A. alba*, *B. gymnorrhiza*, *R. mucronata*, *Xylocarpus moluccensis, S. caseolaris, Avicennia officinalis* and *C. tagal* with 2.10-5.44 tonC/Ha. The last group comprised *Ceriops decandra*, *Xylocarpus granatum*, *Heritiera littoralis, A. floridum* and *Bruguiera parviflora* est with 0.17-1.74 tonC/ha. Two species, *S. alba,* and *A. corniculatum* had the highest carbon storage/ha attributed to the high density, diameter, and biomass (Table 3). On the other hand, *R. stylosa, R. apiculata, S. alba, N. fruticans,* and *A. corniculatum* had the highest density with 189-496 trees/ha.

Species presented in Table 3 have high adaptation to the environmental conditions in Segara Anakan (Hilmi et al. 2023a; Cahyo et al. 2024). Hilmi et al. (2021b, 2022b) stated that mangrove ecosystems have soil texture of clay, loam, loamy clay, mud, mud clay, water salinity 0-40 ppt, salinity 0-7.05 ppt, soil pH 5.7-6.92, water pH 5.6-7.07, pyrite 1.03-3.10%, nitrate 0.010-0.22% and phosphate between 6.85-17.65%. The *R. apiculata, R. mucronata, A. corniculatum,* and *R. stylosa* have similar environmental requirements (water salinity, substrate, and pH). The *S. alba* lives in the frontier zone of mangrove ecosystem, specifically in the border area with the Hindian Ocean in the western part of Segara Anakan. The *N. fruticans* has a specific habitat which is commonly found in estuaries and riverside.

Carbon percentage of mangrove species

The percentage of carbon in each mangrove species is influenced by stem diameter, wood density, as well as volatility, and ash value (Chabi et al. 2016; Hilmi et al. 2017). Based on the results, carbon percentage in Segara Anakan ranged between 42.48-53.34% (Table 3) with descending order of *B. gymnorrhiza* > *R. apiculata* > *R. stylosa* > *C. tagal* > *R. mucronata* > *B. parviflora. C. decandra* > *Bruguiera sexangula* > *X. granatum* > *X. moluccensis* > *S. caseolaris* > *A. marina* > *S. alba* > *A. corniculatum* > *A. floridum* > *A. officinalis* > *A. alba* > *H. littoralis* > *N. fruticans*.

Carbon percentage shows the ability of mangrove species to sequester, absorb, and accumulate carbon in the form of biomass (Soares et al. 2018; C. Li et al. 2024). This parameter is essential in enhancing carbon stock and reducing Green-House Gas (GHG) emissions (Pearson et al. 2017; Cameron et al. 2019). Tree diameter has a strong influence on carbon storage in mangrove ecosystems which is related to the ability in CO_2 absorption and carbon sequestration (Liu et al. 2016, 2024). It positively correlates with biomass, carbon, and organic compounds. The organic compound is represented as cellulose and hemicellulose where 40%-45% of wood is composed of cellulose as a linear chain of glucose (Ray et al. 2012; Chabi et al. 2016; Hilmi et al. 2021c).

Table 3. Species-specific carbon storage in the mangrove ecosystem of Segara Anakan, Cilacap District, Central Java, Indonesia

Mangrove species	Mangrove diameter (cm)	Mangrove density	Biomass (ton/ha)		Percent carbon			Carbon (ton/ha)		
			Min	Max	Min	Max	Average	Min	Max	Average
Bruguiera gymnorhiza (L.) Lam.	4.14-14.01	8-103	1.5	39.2	51.13	55.55	53.34	0.36	10.23	5.30
Rhizophora apiculata Blume	4.14-22.93	15-360	2.4	56.52	51.3	53.98	52.64	0.58	14.34	7.46
Rhizophora stylosa Griffith	4.14-14.33	10-496	1.66	78.11	50.35	52.32	51.335	0.39	19.21	9.80
Ceriops tagal (Perr.) C.B.Rob.	4.14-7.32	20-40	5.78	11.52	50.12	52.29	51.205	1.38	2.83	2.10
Rhizophora mucronata Lam.	4.14-7.96	9-187	0.75	20.2	50.09	51.86	50.975	0.18	4.92	2.55
Bruguiera parviflora (Roxb.) Wight & Arn. ex Griff.	4.46-4.78	1-4	0.08	1.37	50.02	51.01	50.515	0.02	0.33	0.17
Ceriops decandra (Griff.) Ding Hou	4.14-7.01	8-62	1.89	12.68	49.04	51.22	50.13	0.44	3.05	1.74
Bruguiera sexangula (Lour.) Poir.	4.46-11.15	6-38	1.62	21.48	49.05	50.42	49.735	0.37	5.09	2.73
Xylocarpus granatum J.Koenig	4.80-13.40	6-74	0.47	6.8	47.59	51.59	49.59	0.10	1.61	0.86
Xylocarpus moluccensis (Lam.) M.Roem.	10.10-13.40	4-10	10.6	11.25	47.23	50.15	48.69	2.35	2.65	2.50
Sonneratia caseolaris (L.) Engl.	4.10-16.60	6-153	0.6	18.28	45.02	52.12	48.57	0.13	4.48	2.30
Avicennia marina (Forssk.) Vierh.	4.14-17.20	10-298	1.09	88.28	45.41	50.23	47.82	0.23	20.84	10.54
Sonneratia alba Sm.	4.14-23.31	8-224	1.63	130.39	44.99	50.55	47.77	0.34	30.98	15.66
Aegiceras corniculatum (L.) Blanco	4.14-23.89	10-189	0.6	123.08	44.85	50.67	47.76	0.13	29.31	14.72
Aegiceras floridum Roem. & Schult.	4.10-5.40	2-20	0.64	1.23	44.92	50.55	47.735	0.13	0.29	0.21
Avicennia officinalis L.	4.1-15.90	2-20	0.65	17.73	45.32	49.05	47.185	0.14	4.09	2.11
Avicennia alba Blume	4.14-20.06	20-129	1.99	44.5	43.62	50.09	46.855	0.41	10.48	5.44
Heritiera littoralis Dryand. ex Aiton	4.46-6.05	1-7	0.1	3.18	43.59	49.87	46.73	0.02	0.74	0.38
Nypa fruticans Wurmb	4.60-7.96	10-447	0.78	100.81	41.45	43.5	42.475	0.15	20.61	10.38
Total			34.83	786.61				7.85	186.09	

Tree diameter also influences stem, canopy, leaf, branch, and roots which positively correlates with cellulose, hemicellulose, and lignin. An increase in tree diameter within mangrove forests also affects the level of organic compounds and Net Primary Production (NPP). According to Hilmi et al. (2017; 2019b) and Bolivar et al. (2018), *Rhizophora* spp. and *Bruguiera* spp. have a wood density between 0.75-0.95 which shows the potential of carbon as a basic component of protein structure developed by the photosynthesis process to create organic compound of cellulose and hemicellulose. Mangrove species and diameter have a relationship with specific gravity, wood chemical compound (hemicellulose, cellulose, and extractive matter) dust degree (calcium, potassium, and magnesium) volatile degree, and matter (aliphatic, terpene, and phenolic compound) as the main variables to analyze carbon percentage (Bolivar et al. 2018; Hilmi et al. 2019b).

Landscape analysis of mangrove species based on carbon percentage

The zonation of mangrove landscape provides insights into composition, carbon percentage, and species-specific (Chen et al. 2024; Zhu et al. 2024). Based on the results, *B. gymnorrhiza, R. apiculata, R. stylosa, C. tagal,* and *R. mucronata* were positioned at the first zone of mangrove landscape with carbon percentage between 50.97-53.34 %. Meanwhile, *B. parviflora, C. decandra, B. sexangula, X. granatum, X. moluccensis,* and *S. caseolaris* were in the second zone with carbon percentage between 48.6-50.5%. *A. marina, S. alba, A. corniculatum, A. floridum, A. officinalis, A. alba,* and *H. littoralis* were in the third zone with carbon percentage of 46.7-47.82. The *N. fruticans* was in the fourth zone with carbon percentage of 42.48% (Figure 2).

Carbon percentage in each mangrove species correlates with organic compound, water degree, wood density, extractive matter, cellulose, hemicellulose, tannin, and lignin. *Rhizophora* spp., *Bruguiera* spp., and *Ceriops* spp. belong to hardwood species with higher organic compounds, wood density, extractive matter, cellulose, hemicellulose, tannin, and lignin compared to softwood species such as *Avicennia* spp., *Sonneratia* spp., *Aegiceras* spp., *Xylocarpus* spp., *Aegiceras* spp., and *N. fruticans* (Subandriyo and Setianingsih 2016; Abdullah and Lee 2017; Hilmi et al. 2017). Landscape analysis of carbon storage explains the distribution of mangrove species based on the carbon percentage of each species. This analysis is different from other studies which were based on tannin (Hilmi et al. 2021c), as well as the reduction of heavy metal pollution, intrusion disasters, coastal disasters, and sedimentation. Landscape analysis using carbon percentage might be useful to inform efforts related to conservation in mangrove forest.

This study estimated that biomass and carbon stock in mangrove forests was between 34.83-786.61 ton/ha (biomass) and 7.85-186.09 tonC/ha (carbon storage) respectively. The potential of carbon storage in Segara Anakan was higher compared to coastal salt marshes in China which ranged from 4.53-8.39 tonC/ha (Chen et al. 2024), the entire Kenyan coastline with 60 tonC/ha, Mombasa (36.5 tonC/ha), Kiunga NMR (100 tonC/ha) (Cohen et al. 2013), and in the Colombian Pacific coast with 181.236±28.939 tonC/ha (Selvaraj and Gallego Pérez 2023). (Mukherjee and Ray 2012; Chen et al. 2024) also stated that mangrove forests located in estuarine of tropical rivers have highly productive carbon of 2500 $mgCm^{-2}day^{-1}$. (Cohen et al. 2013) estimated that 8-20% of annual global anthropogenic CO_2 emissions were from land-use changes occurring primarily in the tropics.

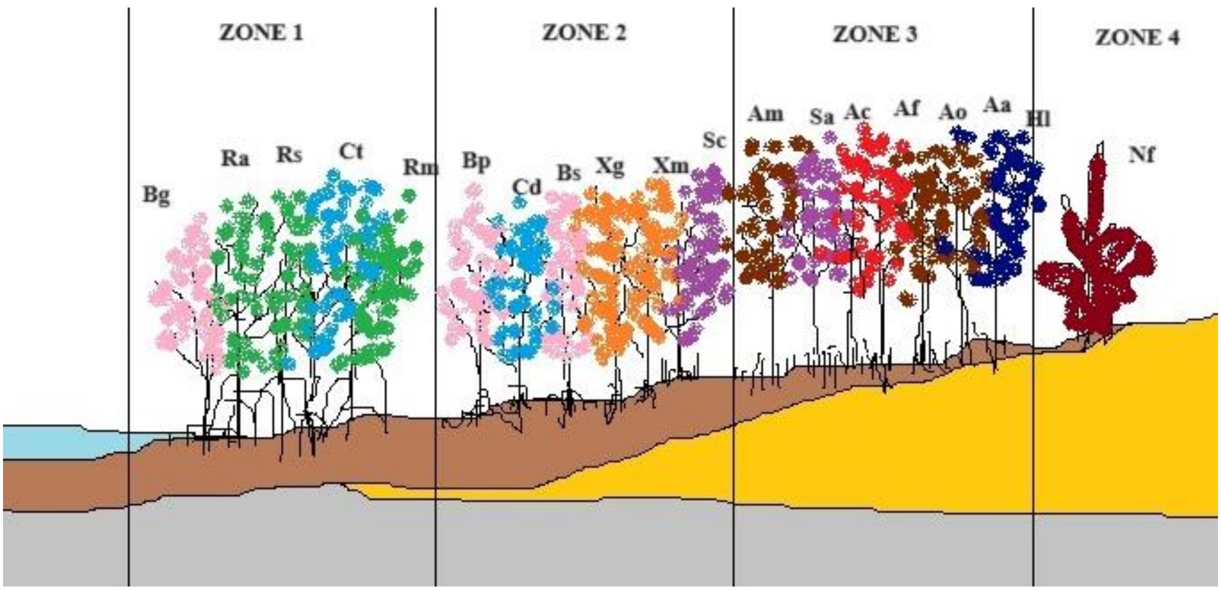

Figure 2. Landscape analysis of mangrove forest using species-specific carbon percentage as an indicator. Note: Bg: *Bruguiera gymnorrhiza*; Ra: *Rhizophora apiculata*; Rs: *Rhizophora stylosa*; Ct: *Ceriops tagal*; Rm: *Rhizophora mucronata*; Bp: *Bruguiera parviflora*; Cd: *Ceriops decandra*; Bs: *Bruguiera sexangula*; Xg: *Xylocarpus granatum*; Xm: *Xylocarpus moluccensis*; Sc: *Sonneratia caseolaris*; Am: *Avicennia marina*; Sa: *Sonneratia alba*; Ac: *Aegiceras corniculatum*; Af: *Aegiceras floridum*; Ao: *Avicennia officinalis*; Aa: *Avicennia alba*; Hl: *Heritiera littoralis*; Nf: *Nypa fruticans*

Table 4. Carbon storage based on mangrove density in Segara Anakan, Cilacap District, Central Java, Indonesia

Density category	Mangrove species	Carbon storage (tons/ha)	
		Value	STDEV
Low density	*Aegiceras corniculatum*	0.44	0.17
	Avicennia alba	1.65	1
	Avicennia marina	4.08	1.91
	Avicennia officinalis	2.68	1.39
	Bruguiera gymnorryza	1.26	0.85
	Ceriops decandra	2.96	1.49
	Ceriops tagal	0.16	0.06
	Nypa fruticans	1.15	0.81
	Rhizophora stylosa	2.9	1.47
	Rhizopora apiculata	1	0.38
	Rhizopora mucronata	1.24	0.84
	Sonneratia alba	1.6	0.6
	Sonneratia caseolaris	1.41	3.92
	Xylocarpus granatum	0.17	0.06
	Total	**22.7**	**14.95**
Moderate density	*Aegyceras corniculatum*	3.84	1.14
	Avicennia alba	11.44	3.41
	Avicennia marina	4.28	1.28
	Avicennia officcinalis	5.11	1.52
	Bruguiera gymnorryza	1.21	0.36
	Bruguiera sexangular	1.37	0.41
	Ceriops decandra	0.31	0.09
	Ceriops tagal	2.04	0.61
	Nypa fruticans	5.67	1.69
	Rhizophora apiculata	1.23	0.37
	Rhizophora mucronata	5.32	1.59
	Rhizopora stylosa	3.36	1.00
	Sonneratia alba	1.04	0.31
	Sonneratia caseolaris	4.12	1.23
	Xylocarpus granatum	10.88	3.24
	Total	**61.22**	**9.47**
High density	*Aegiceras corniculatum*	6.09	1.27
	Aegiceras floridium	1.24	0.26
	Avicennia alba	6.10	1.27
	Avicennia marina	18.91	3.95
	Bruguiera gymnorhiza	4.72	0.98
	Bruguiera sexangular	1.50	0.31
	Ceriops tagal	1.52	0.32
	Heritiera littoralis	0.20	0.04
	Nypa fruticans	7.50	1.57
	Rhizophora apiculata	12.22	2.55
	Rhizopora mucronata	2.73	0.57
	Rhizopora stylosa	8.04	1.68
	Sonneratia alba	3.74	0.78
	Sonneratia caseolaris	2,37	0,49
	Xylocarpus granatum	3.67	0.77
	Xylocarpus moluccensis	3.28	0.69
	Total	**83.81**	**12.96**
Very high density	*Aegiceras corniculatum*	21.75	4.09
	Avicennia alba	5.39	0.5
	Avicennia marina	40.69	8.78
	Bruguiera gymnorryza	4.73	0.44
	Bruguiera parviflora	1.17	0.02
	Bruguiera sexangular	1.2	0.02
	Ceriops decandra	2.21	0.21
	Ceriops tagal	1.71	0.07
	Nypa fruticans	26.57	6.54
	Rhizophora apiculata	21.22	5.04
	Rhizophora mucronata	1.3	0.12
	Rhizophora stylosa	8.4	0.78
	Sonneratia alba	21.63	1.08
	Sonneratia caseolaris	1.3	0.03
	Total	**159.27**	**27.72**

The potential of carbon storage underscores the ability of forests to accumulate carbon in tree biomass which can be developed to support sustainable mitigation measures and reduce carbon emissions programs such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) to mitigate the impact of climate change (Sasaki et al. 2016; Castillo et al. 2017; Pearson et al. 2017). The role of forests in carbon sequestration has been a crucial issue as an indicator of stability (Deng et al. 2024). Mangrove forests significantly contribute to carbon sinks in marine biota manifested as organic sedimentation, above-ground, and below-ground biomass (Deng et al. 2024; C. Li et al. 2024).

Carbon storage based on mangrove density

Carbon storage of mangrove forest in Segara Anakan based on stand density is presented in Table 4. There were four classes of carbon storage based on mangrove density namely (i) low density with carbon storage of 22.70±14.95 tonC/ha dominated by *A. marina* and *C. decandra*; (ii) moderate density with carbon storage of 61.22±9.47 tonC/ha dominated by *A. alba* and *X. granatum*; (iii) high density with carbon storage of 83.81± 12.96 tonC/ha dominated by *A. marina* and *R. apiculata*; and (iv) very-high density with carbon storage of 159.27±27.72 tonC/ha dominated by *A. marina, A. corniculatum, N. fruticans, R. apiculata*, and *S. alba*. These species influence carbon storage from mangrove forest Segara Anakan (Cameron et al. 2019; Lei et al. 2019; Sitoe et al. 2014). Carbon storage is influenced by density, percentage of carbon, and dominant species.

In conclusion, this study found that *B. gymnorrhiza, R. apiculata, R. stylosa, C. tagal,* and *R. mucronata* were mangrove species in Segara Anakan Lagoon with the highest species-specific carbon percentage, ranging from 50.98-53.43%. The potential of carbon storage was between 7.85 tonC/ton-186.09 tonC/ha. Landscape analysis showed that carbon storage in the studied area can be divided into 4 classes, namely (i) low density with carbon storage of 22.70±14.95 tonC/ha; (ii) moderate density with carbon storage of 61.22±9.47 tonC/ha; (iii) high density with carbon storage of 83.81±12.96 tonC/ha; and (iv) very-high density with carbon storage of 159.27±27.72 tonC/ha. These results underscore the need for the development of mangrove rehabilitation patterns based on carbon percentage and storage to support a blueprint for conservation in mangrove ecosystems.

ACKNOWLEDGEMENTS

The author's gratitude and appreciation go to the DRTPM Kemdikbud RI who has supported the Grand Fundamental Research DIKTI, Indonesia, with master contract number 054/E5/PG.02.00.PL/2024 and derivative contract number 20.10/UN23.35.5/PT.01.00/VI/2024. I thank the Dean of the Faculty of Fisheries and Marine Sciences, Universitas Jenderal Soedirman, Indonesia, the journal editors, the reviewer, research team, and the scientific partners that support the publication of this paper.

REFERENCES

Abdullah MM, Lee SY. 2017. Structure of mangrove meiofaunal assemblages associated with local sediment conditions in subtropical Eastern Australia. Estuar Coast Shelf Sci 198 (Part B): 438-449. DOI: 10.1016/j.ecss.2016.10.039.

Adame MF, Cherian S, Reef R, Stewart-Koster B. 2017. Mangrove root biomass and the uncertainty of belowground carbon estimations. For Ecol Manag 403: 52-60. DOI: 10.1016/j.foreco.2017.08.016.

Alviana D, Anggraini R, Hidayati JR, Karlina I, Lestari F, Apdillah D, Syakti AD, Sihite D. 2023. The estimation of carbon storage in mangrove ecosystem in Pegudangan Village, Teluk Sebong, Bintan. Jurnal Kelautan Tropis 26 (3): 464-472. DOI: 10.14710/jkt.v26i3.18326. [Indonesian]

Azizah M, Ardli ER, Sudiana E. 2017. Analysis of mangrove forest carbon stocks at various levels of damage in Segara Anakan Cilacap. Sains Natural 3 (2): 161-172. DOI: 10.31938/jsn.v3i2.66. [Indonesian]

Azman MS, Sharma S, Shaharudin MAM, Hamzah ML, Adibah SN, Zakaria RM, MacKenzie RA. 2021. Stand structure, biomass and dynamics of naturally regenerated and restored mangroves in Malaysia. For Ecol Manag 482: 118852. DOI: 10.1016/j.foreco.2020.118852.

Bolivar JM, Gutierrez-Velez VH, Sierra CA. 2018. Carbon stocks in aboveground biomass for Colombian mangroves with associated uncertainties. Reg Stud Mar Sci 18: 145-155. DOI: 10.1016/j.rsma.2017.12.011.

Cahyo TN, Hartoko A, Muskananfola MR, Haeruddin, Hilmi E. 2024. Mangrove density and delta formation in Segara Anakan Lagoon as an impact of the riverine sedimentation rate. Biodiversitas 25 (3): 1276-1285. DOI: 10.13057/biodiv/d250344.

Cameron C, Hutley LB, Friess DA, Brown B. 2019. High greenhouse gas emissions mitigation benefits from mangrove rehabilitation in Sulawesi. Indonesia. Ecosyst Serv 40: 101035. DOI: 10.1016/j.ecoser.2019.101035.

Castillo JAA, Apan AA, Maraseni TN, Salmo SG. 2017. Soil C quantities of mangrove forests, their competing land uses, and their spatial distribution in the coast of Honda Bay, Philippines. Geoderma 293: 82-90. DOI: 10.1016/j.geoderma.2017.01.025.

Chabi A, Lautenbach S, Orekan VOA, Kyei-Baffour N. 2016. Allometric models and aboveground biomass stocks of a West African Sudan Savannah watershed in Benin. Carbon Balance Manag 11 (1): 16. DOI: 10.1186/s13021-016-0058-5.

Chen C, Ma Y, Yu D, Hu Y, Ren L. 2024. Tracking annual dynamics of carbon storage of salt marsh plants in the Yellow River Delta National Nature Reserve of China based on sentinel-2 imagery during 2017-2022. Intl J Appl Earth Observ Geoinfor 130: 103880. DOI: 10.1016/j.jag.2024.103880.

Cohen R, Kaino J, Okello JA, Bosire JO, Kairo JG, Huxham M, Mencuccini M. 2013. Propagating uncertainty to estimates of above-ground biomass for Kenyan mangroves: A scaling procedure from tree to landscape level. For Ecol Manag 310: 968-982. DOI: 10.1016/j.foreco.2013.09.047.

Cooray PLIGM, Jayawardana DT, Gunathilake BM, Pupulewatte PGH. 2021. Characteristics of tropical mangrove soils and relationships with forest structural attributes in the northern coast of Sri Lanka. Reg Stud Mar Sci 44: 101741. DOI: 10.1016/j.rsma.2021.101741.

Dai Z, Trettin CC, Frolking S, Birdsey RA. 2018. Mangrove carbon assessment tool: Model development and sensitivity analysis. Estuar Coast Shelf Sci 208: 23-35. DOI: 10.1016/j.ecss.2018.04.035.

Datta D, Deb S. 2017. Forest structure and soil properties of mangrove ecosystems under different management scenarios: Experiences from the intensely humanized landscape of Indian Sunderbans. Ocean Coast Manag 140: 22-33. DOI: 10.1016/j.ocecoaman.2017.02.022.

Deng R, Yang G, Wang W, Li Y, Zhang X, Hu F, Guo Q, Jia M. 2024. A new method of estimating shelterbelt carbon storage on the regional scale: Combined the single tree carbon storage with tree numbers. Ecol Indic 163: 112071. DOI: 10.1016/j.ecolind.2024.112071.

Doughty CL, Langley JA, Walker WS, Feller IC, Schaub R, Chapman SK. 2016. Mangrove range expansion rapidly increases coastal wetland carbon storage. Estuar Coasts 39: 385-396. DOI: 10.1007/s12237-015-9993-8.

Dutcă I, Mather R, Ioraș F. 2020. Sampling trees to develop allometric biomass models: How does tree selection a ff ect model prediction accuracy and precision? Ecol Indic 117: 106553. DOI: 10.1016/j.ecolind.2020.106553.

Fatoyinbo T, Simard M. 2011. Remote Sensing of Mangrove Structure and Biomass. Workshop on Tropical Wetland Ecosystems on Indonesia: Science Needs to Address Climate Change Adaption and Mitigation. Sanur Beach Hotel, Bali, 11-14th April 2011. [Indonesian]

Fatoyinbo TE, Simard M, Washington-Allen RA, Shugart HH. 2008. Landscape-scale extent, height, biomass, and carbon estimation of Mozambique's mangrove forests with Landsat ETM+ and Shuttle Radar Topography Mission elevation data. J Geophys Res: Biogeosci 113 (G2): G02S06. DOI: 10.1029/2007JG000551.

Hartoko A, Chayaningrum S, Febrianti DA, Ariyanto D, Suryanti. 2015. Carbon biomass algorithms development for mangrove vegetation in Kemujan, Parang Island Karimunjawa National Park and Demak Coastal Area - Indonesia. Procedia Environ Sci 23: 39-47. DOI: 10.1016/j.proenv.2015.01.007.

Hilmi E, Amron A, Christianto D. 2022a. The potential of high tidal flooding disaster in North Jakarta using mapping and mangrove relationship approach. IOP Conf Ser Earth Environ Sci 989: 012001. DOI: 10.1088/1755-1315/989/1/012001.

Hilmi E, Amron A, Sari LK, Cahyo TN, Siregar AS. 2021a. The mangrove landscape and zonation following soil properties and water inundation distribution in Segara Anakan Cilacap. Jurnal Manajemen Hutan Tropika 27 (3): 152-164. DOI: 10.7226/jtfm.27.3.152.

Hilmi E, Anwar N, Santosa I, Mahdiana A, Rachman TM, Wardoyo T. 2024a. Mangrove landscaping as an adaptation pattern to reduce the impact of climate change in Segara Anakan Lagoon, Cilacap Regency Indonesia. Baghdad Sci J 21: 338-357. DOI: 10.21123/bsj.2023.8828.

Hilmi E, Junaidi T, Mahadiana A, Dewi R. 2023a. The ecological risk assessment of mercury contaminant in a mangrove ecosystem of the Segara Anakan Cilacap. Indonesia. Bagdhad Sci J 20: 1266-1282. DOI: 10.21123/bsj.2023.7455.

Hilmi E, Junaidi T, Mahdiana A, Prayogo NA, Dewi R, Rahayu S. 2024b. The specific ordination and clustering of mangrove ecosystem in Segara Anakan. Indones J For Res 11 (1): 47-63. DOI: 10.59465/ijfr.2024.11.1.47-63.

Hilmi E, Parengrengi, Vikaliana R, Kusmana C, Iskandar, Sari LK, Setijanto. 2017. The carbon conservation of mangrove ecosystem applied REDD program. Reg Stud Mar Sci 16: 152-161. DOI: 10.1016/j.rsma.2017.08.005.

Hilmi E, Prayogo NA, Junaidi T, Mahdiana A, Fikriyya N. 2023b. Adaptive pattern of mangrove species and the mangrove landscaping in the heavy metal polluted area of Eastern Segara Anakan Lagoon, Indonesia. Biodiversitas 24 (5): 2927-2937. DOI: 10.13057/biodiv/d240548.

Hilmi E, Sari LK, Amron A. 2019a. Mangrove distribution and environmental factors in Cilacap Segara Anakan Mangrove Ecosystem. Prosiding Seminar Nasional "Pengembangan Sumber Daya Perdesaan dan Kearifan Lokal Berkelanjutan IX" 19-20 November 2019. [Indonesian]

Hilmi E, Sari LK, Cahyo TN, Kusmana C, Suhendang E. 2019b. Carbon sequestration of mangrove eosystem in Segara Anakan Lagoon, Indonesia. Biotropia 26: 181-190. DOI: 10.11598/btb.2019.26.3.1099.

Hilmi E, Sari LK, Cahyo TN, Muslih, Mahdiana A, Samudra SR. 2021b. The affinity of mangrove species using Association and Cluster Index in North Coast of Jakarta and Segara Anakan of Cilacap, Indonesia. Biodiversitas 22 (7): 2907-2918. DOI: 10.13057/biodiv/d220743.

Hilmi E, Sari LK, Mahdiana A, Junaidi T, Muslih, Samudra SR, Prayogo NA, Baedowi M, Cahyo TN, Putra RRD, Sari FA. 2022b. Mapping of mangrove ecosystem in Segara Anakan Lagoon using Normalized Different Vegetation Index and Dominant Vegetation Index. Omni-Akuatika 18 (2): 165-178. DOI: 10.20884/1.oa.2022.18.2.926.

Hilmi E, Sari LK, Siregar AS, Sulistyo I, Mahdiana A, Junaedi T, Muslih, Pertiwi RPC, Samudra SR, Prayogo NA. 2021c. Tannins in mangrove plants in Segara Anakan Lagoon, Central Java, Indonesia. Biodiversitas 22 (8): 3508-3516. DOI: 10.13057/biodiv/d220850.

Hilmi E. 2018. Mangrove landscaping using the modulus of elasticity and rupture properties to reduce coastal disaster risk. Ocean Coast Manag 165: 71-79. DOI: 10.1016/j.ocecoaman.2018.08.002.

Kandasamy K, Rajendran N, Balakrishnan B, Thiruganasambandam R, Narayanasamy R. 2021. Carbon sequestration and storage in planted mangrove stands of *Avicennia marina*. Reg Stud Mar Sci 43: 101701. DOI: 10.1016/j.rsma.2021.101701.

Karl DM, Church MJ. 2017. Ecosystem structure and dynamics in the North Pacific Subtropical Gyre: New views of an old ocean. Ecosystems 20: 433-457. DOI: 10.1007/s10021-017-0117-0.

Komiyama A, Ong J.E, Poungparn S. 2008. Allometry, biomass, and productivity of mangrove forests: A review. Aquat Bot 89: 128-137. DOI: 10.1016/j.aquabot.2007.12.006.
Komiyama A, Poungparn S, Kato S. 2005. Common allometric equations for estimating the tree weight of mangroves. J Trop Ecol 21: 471-477. DOI: 10.1017/S0266467405002476.
Lai Y, Liu X, Fisk C, Davies M, Wang Y, Yang J, du Plessis C, Cotton L, Zhang Y, Willmott J. 2023. Combustion inhibition of biomass charcoal using slaked lime and dolime slurries. Fire Saf J 140: 103841. DOI: 10.1016/j.firesaf.2023.103841.
Lei P, Zhong H, Duan D, Pan K. 2019. A review on mercury biogeochemistry in mangrove sediments: Hotspots of methylmercury production? Sci Total Environ 680: 140-150. DOI: 10.1016/j.scitotenv.2019.04.451.
Li C, Wang F, Yang P, Wang F-C, Hu Y-Z, Zhao Y-L, Tian L-Z, Zhao R-B. 2024. Mangrove wetlands distribution status identification, changing trend analyzation and carbon storage assessment of China. China Geol 7 (1): 1-11. DOI: 10.31035/cg2023049.
Li S, Zhu Z, Deng W, Zhu Q, Xu Z, Peng B, Guo F, Zhang Y, Yang Z. 2024. Estimation of aboveground biomass of different vegetation types in mangrove forests based on UAV remote sensing. Sustain Horizons 11: 100100. DOI: 10.1016/j.horiz.2024.100100.
Liu J, Sleeter BM, Zhu Z, Heath LS, Tan Z, Wilson TS, Sherba J, Zhou D. 2016. Estimating carbon sequestration in the piedmont ecoregion of the United States from 1971 to 2010. Carbon Balance Manag 11 (1): 10. DOI: 10.1186/s13021-016-0052-y.
Liu Y, Liu H, Xu W, Wang L, Wang Q, Ou G, Wu M, Hong Z. 2024. Advances and challenges of carbon storage estimation in tea plantation. Ecol Inform 81: 102616. DOI: 10.1016/j.ecoinf.2024.102616.
Lulandala L, Bargués-Tobella A, Masao CA, Nyberg G, Ilstedt U. 2023. The size of clearings for charcoal production in miombo woodlands affects soil hydrological properties and soil organic carbon. For Ecol Manag 529: 120701. DOI: 10.1016/j.foreco.2022.120701.
Malakini M, Makungwa S, Mwase W, Maganga AM. 2020. Allometric models for estimating above- and below- ground tree carbon for community managed miombo woodlands: A case of Miyobe village forest area in northern Malawi. Trees For People 2: 100024. DOI: 10.1016/j.tfp.2020.100024.
Mukherjee J, Ray S. 2012. Carbon cycling from mangrove litter to the adjacent Hooghly estuary, India - A modelling study. Procedia Environ Sci 13: 391-413. DOI: 10.1016/j.proenv.2012.01.036.
Nascimento MN, Beltran J, Bressers C, van Delft J, Vermeulen J, de Ron S, Bruijn A, Raczka MF, Maezumi SY, Gosling WD, Bush MB, McMichael CNH. 2023. Charcoal abundance measurements are affected by freeze-drying. Palaeogeogr Palaeoclimatol Palaeoecol 629: 111790. DOI: 10.1016/j.palaeo.2023.111790.
Njana MA. 2020. Structure, growth, and sustainability of mangrove forests of mainland Tanzania. Glob Ecol Conserv 24: e01394. DOI: 10.1016/j.gecco.2020.e01394.
Owuor MA, Mulwa R, Otieno P, Icely J, Newton A. 2019. Valuing mangrove biodiversity and ecosystem services: A deliberative choice experiment in Mida Creek, Kenya. Ecosyst Serv 40: 101040. DOI: 10.1016/j.ecoser.2019.101040.
Pearson TRH, Brown S, Murray L, Sidman G. 2017. Greenhouse gas emissions from tropical forest degradation: An underestimated source. Carbon Balance Manag 12: 3. DOI: 10.1186/s13021-017-0072-2.
Perera KARS, De Silva KHWL, Amarasinghe MD. 2018. Potential impact of predicted sea level rise on carbon sink function of mangrove ecosystems with special reference to Negombo estuary, Sri Lanka. Glob Planet Change 161: 162-171. DOI: 10.1016/j.gloplacha.2017.12.016.
Piponiot C, Cabon A, Descroix L, Dourdain A, Mazzei L, Ouliac B, Rutishauser E, Sist P, Hérault B. 2016. A methodological framework to assess the carbon balance of tropical managed forests. Carbon Balance Manag 11 (1): 15. DOI: 10.1186/s13021-016-0056-7.
Ray R, Majumder N, Chowdhury C, Jana TK. 2012. Wood chemistry and density: An analog for response to the change of carbon sequestration in mangroves. Carbohydr Polym 90 (1): 102-108. DOI: 10.1016/j.carbpol.2012.05.001.
Sasaki N, Chheng K, Mizoue N, Abe I, Lowe AJ. 2016. Forest reference emission level and carbon sequestration in Cambodia. Glob Ecol Conserv 7: 82-96. DOI: 10.1016/j.gecco.2016.05.004.
Selvaraj JJ, Pérez BEG. 2023. Estimating mangrove aboveground biomass in the Colombian Pacific coast: A multisensor and machine learning approach. Heliyon 9 (11): e20745. DOI: 10.1016/j.heliyon.2023.e20745.
Sharafatmandrad M, Mashizi AK. 2020. Investigating distribution of ecosystem services in rangeland landscapes: An approach based on weighted key functional traits. Ecol Indic 111: 105971. DOI: 10.1016/j.ecolind.2019.105971.
Sharma S, MacKenzie RA, Tieng T, Soben K, Tulyasuwan N, Resanond A, Blate G, Litton CM. 2020. The impacts of degradation, deforestation and restoration on mangrove ecosystem carbon stocks across Cambodia. Sci Total Environ 706: 135416. DOI: 10.1016/j.scitotenv.2019.135416.
Sitoe AA, Mandlate LJC, Guedes BS. 2014. Biomass and carbon stocks of Sofala Bay Mangrove Forests. Forests 5 (8): 1967-1981. DOI: 10.3390/f5081967.
Sleeter R, Sleeter BM, Williams B, Hogan D, Hawbaker T, Zhu Z. 2017. A carbon balance model for the great dismal swamp ecosystem. Carbon Balance Manag 12 (1): 2. DOI: 10.1186/s13021-017-0070-4.
Soares RHRdeM, Assunção CAde, Fernandes FdeO, Marinho-Soriano E. 2018. Identification and analysis of ecosystem services associated with biodiversity of saltworks. Ocean Coast Manag 163: 278-284. DOI: 10.1016/j.ocecoaman.2018.07.007.
Subandriyo, Setianingsih NI. 2016. Extraction process for reducing tannin of Mangrove fruit [*Bruguiera gumnorrhiza* (Lamarck. 1798)] as a raw material for food flour. Aquat Procedia 7: 231-235. DOI: 10.1016/j.aqpro.2016.07.032.
Sugiatmo, Poedjirahajoe E, Pudyatmoko S, Purwanto RH. 2023. Carbon stock at several types of mangrove ecosystems in Bregasmalang, Central Java, Indonesia. Biodiversitas 24 (1): 182-191. DOI: 10.13057/biodiv/d240122.
Swangjang K, Panishkan K. 2021. Assessment of factors that influence carbon storage: An important ecosystem service provided by mangrove forests. Heliyon 7 (12): e08620. DOI: 10.1016/j.heliyon.2021.e08620.
Wintah, Kiswanto, Hilmi E, Sastranegara MH. 2023. Mangrove diversity and its relationships with environmental conditions in Kuala Bubon Village, West Aceh, Indonesia. Biodiversitas 24 (8): 4599-4605. DOI: 10.13057/biodiv/d240864.
Xiong Y, Liao B, Proffitt E, Guan W, Sun Y, Wang F, Liu X. 2018. Soil carbon storage in mangroves is primarily controlled by soil properties: A study at Dongzhai Bay, China. Sci Total Environ 619-620: 1226-1235. DOI: 10.1016/j.scitotenv.2017.11.187.
Zhu X, Pan J, Wu X. 2024. Impact of agricultural irrigation and resettlement practices on carbon storage in arid inland river basins: A case study of the Shule river basin. Heliyon 10 (3): e25305. DOI: 10.1016/j.heliyon.2024.e25305.