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Total Ecosystem Carbon Stock (TECS) in Various Tropical Forest Ecosystems of South Sorong Regency, Southwest Papua Province, Indonesia

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Abstract

The significant uncertainty concerning the role of South Sorong's tropical forest ecosystem in the global carbon cycle is the lack of adequate data on the total carbon content of all its components. This study aimed to fill this data gap by calculating the total carbon stock in six forest ecosystems of South Sorong, Southwest Papua Province, Indonesia. The above-below-ground (root) carbon stock was calculated using several published allometric equations. The Walkey and Black and loss-on-ignition method analyzed soil carbon stocks. Aboveground live C-stock ranged from 51.9 to 105.5 Mg C ha^{-1} and soil C-stock from 52.91 to 1,124.3 Mg C ha^{-1}, representing the two most significant C components in all plots. The C in litter (10.5 to 49.9 Mg C ha^{-1}), dead and downed wood (0.2 to 2.9 Mg C ha^{-1}) and roots (9.2 to 58.2 Mg C ha^{-1}) accounted for less than 5.3% of the total C. The total ecosystem carbon stock ranged from 213.0 to 1,217.4 Mg C ha^{-1}. More C was found in the peat swamp forest in six forest ecosystems, where deeper soil (organic sediment) was the main support factor. Both dried lowland forest ecosystem and peat swamp forest ecosystem are unique ecosystems that need to be considered in their management so that we can benefit from those present in local, regional, and global communities.

Keywords: *carbon sequestration*, *dried lowland forest*, *peatland forest, CO_2-eq*, *south Sorong*

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Introduction

High rates of tropical deforestation and forest degradation contribute substantially to anthropogenic climate change, with recent estimates of their contribution to total atmospheric greenhouse gases ranging from 12% to 20% (Pearson et al., 2017; Mitchard, 2018). Most tropical countries' most significant sources of greenhouse gas emissions are forest loss and degradation (Pearson et al., 2017). The tropical forests of Southwest Papua have become a focus of initiatives to mitigate climate change due to their large capacity for carbon sequestration. Southwest Papua Province is located in the western part of Papua Island, a former West Papua Province division. Southwest Papua Province is known for its unspoiled natural conditions, uniqueness, and high biodiversity that spread across various natural ecosystems on land and in water (Maturbongs et al., 2014; Shaverdo et al., 2016; Sillanpää et al., 2017; Fatem et al., 2020).

According to the Regulation of the Director General of Conservation of Natural Resources and Ecosystems (KSDAE) Number P.8/KSDAE/SET.3/KUM.1/11/2020 concerning technical instructions for inventory and verification of areas with high biodiversity value outside nature reserve area, nature conservation area, and hunting park. The analysis results referring to the Director General of KSDAE above show that Southwest Papua Province, including South Sorong Regency, consists of high biodiversity values. Apart from flora and fauna diversity, this region is believed to have played an important role in sequestering carbon. Previous studies have shown that peat and mangrove ecosystems of certain areas of the region have stocked significant carbon (Taberima et al., 2014). Southwest Papua Province could benefit substantially from mechanisms that reward the conservation of forest carbon, such as proposed reduced emissions from avoided deforestation and degradation (i.e., the UNREDD program www.un-redd.org). REDD aims to create financial value for the carbon stored in forests and incentivize developing countries to reduce emissions from forested lands. However, the first step to initiating such a mechanism is accurately accounting for forest systems' carbon stock. Hence, this study aimed to investigate the total carbon stock of several ecosystem types in the South Sorong Region, Southwest Papua Province.

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Methods

Time and study area Fieldwork took place from October 29th to November 5th, 2023. The study area was located in South Sorong Regency, which is under the administrative control of Southwest Papua Province, Indonesia (Figure 1).

The South Sorong Regency covers an area of approximately 930 km^2 of primary lowland rainforest classified as tropical, wet, mixed evergreen, and mangrove forests. The soil vary and include alluvial, gleisol, kambisol, podsolik, and regosol, while the climate has seasons, with an average temperature of 27 °C and year rainfall between 4,200 and 5,200 mm, with more than 300 mm of rain each month (Faisol et al., 2022). The topography comprises fluvial and peat plains in Nakna, coastal plains in Konda, and karst hills in Wara and Boldon ranging from 0 to 132 m asl. The study was conducted in 6 different ecosystem types, as shown in Table 1.

Procedures Two purposively allocated fixed transects were designed in ArcGIS 10.02 and overlaid on a map of the Papua land cover to establish sample plots (Figure 1). In the field, transects were located by Avenza Maps (Version 5.2.1).

In dryland ecosystems (mineral soil), two line transects were placed in each ecosystem type with a minimum distance between plots of 300 m. We established at least five nested sample plots at each transect with dimensions shown in Figure 2.

Plot locations were marked with a handheld GPS and a pole stake embedded in the ground at the northwest corner. Wood poles marked the corners of the plot and subplot. Using diameter tape (d-tape), trees with a diameter at breast height (dbh) between 5 cm and 30 cm were measured in a 5 m 40 m (0.02 ha) plot. Trees with dbh > 30 cm were measured in the extended 20 m × 100 m (0.2 ha) plot (Peck et al., 2017). Aboveground live tree biomass was estimated using Equation *[1]* for wet forest stands (Chave et al., 2005; Peck et al., 2017; Mukul et al., 2020).

$$AGB_{est} = \rho.\exp(-1.499 + 2.148\ \ln(D) + 0.207\ (\ln(D))^2 - 0.0281\ (\ln(D))^3) \qquad [1]$$

note: AGB_{est} is above-ground biomass (kg), ρ is wood-specific density (g cm^3), and D is the diameter at breast height (cm).

Above-ground biomass (AGB) was estimated for all trees (excluding dbh > 30 cm) in the 0.2 ha subplots and then scaled to AGB per hectare before adding biomass for all trees (dbh > 30 cm) in both plots, also scaled to a hectare.

In swamp ecosystems (peatland), at least two transects were laid from the river or coast shoreline without knowledge of forest composition or structure. Five nested circular plots with distances of 50 m were established along each transect at 500 m intervals (Figure 3).

In a nested circular plot (Figure 4), height and diameter measurements were carried out on mangrove vegetation at tree level (dbh > 5 cm) in plots with a radius of 7 m and saplings (1.2 cm ≤ dbh ≤ 5 cm) in plots with a radius of 2 m (Dharmawan et al., 2020; Kauffman et al., 2020). Meanwhile, a seedling, a new individual with a height of < 1.3 m that grows from fruit or propagules and has not yet branched, will record the species and number in the 2 m radius sub-circular plots (Dharmawan et al., 2020; Kauffman et al., 2020). Identification of mangrove species refers to Tomlinson (2016).

For non-mangrove vegetation, live tree biomass was estimated using Equation *[1]*, whereas for mangrove live trees, above-ground biomass was estimated using general Equation *[2]* (Hidayah et al., 2022).

In dryland and swamp ecosystems, seedlings (understory) were sampled using the destructive method (Hairiah et al., 2001; Mizanur Rahman et al., 2015; Peck et al., 2017; Kauffman et al., 2020; Ragavan et al., 2021). All seedlings in the quadrat of 0.25 m^2 (Figures 2 and 4) were cut, placed in a plastic bag, and weighed to get the total field fresh weight (g 0.25 m^{-2}). The samples were then chopped and mixed well before taking subsamples and placing them in a paper bag of about 100–300 g as a subsample. Litter samples were also collected in a quadrat of 0.25 m^2, as indicated in Figures 2 and 4. In the dryland ecosystem, litter samples consisted of coarse and fine litter, whereas in the swamp ecosystem, only coarse litter was collected. Coarse litter, any tree necromass (diameter < 5 cm and length < 50 cm), undecomposed plant materials or crop residues, and all unburned leaves and branches were collected and then placed in a plastic bag and weighed to get total field fresh weight (g 0.25 m^{-2}). Before collecting, all weeds and brushes were cleared. Subsequently, fine litter in the organic layer (0–5 cm above the mineral soil layer) in the same quadrat (including all woody roots) and dry sieve of the origins was partly decomposed, and dark litter was also collected. Like seedlings, place about 100–300 g as a subsample in a paper bag. All subsamples were then dried in the oven at 85 °C for 48 hours for their dry weight (Hairiah et al., 2001; Mizanur Rahman et al., 2015; Peck et al., 2017; Kauffman et al., 2020; Ragavan et al., 2021).

The biomass of standing dead trees (SDT) was determined based on decay status, as shown in Figure 5. As can be seen in Figure 5, the first status was that those trees with fine branches still attached were estimated to use live tree equations. The second status was calculated using the same

Table 1 Six ecosystem types have been the target of the study in South Sorong Regency

No	Ecosystem	Coordinate		Abbreviation
A.	Dry lowland forest ecosystem			
1.	Alluvial lowland forest of Nakna	E132°3'1.988"	S1°33'56.458"	ALLF-N
2.	Lowland karst forest of Boldon	E132°6'54.395"	S1°25'23.912"	LLKF-B
3.	Lowland limestone forest of Wara	E132°2'9.278"	S1°29'53.888"	LLLF-W
B.	Peat swamp forest ecosystem			
1.	Alluvial swamp forest of Konda	E131°53'5.983"	S1°39'0.733"	ASF-K
2.	Peat swamp forest of Nakna	E132°3'40.898"	S1°36'6.990"	PSF-N
3.	Mangrove forest of Konda	E131°58'16.187"	S1°35'41.604"	Mgrv-K

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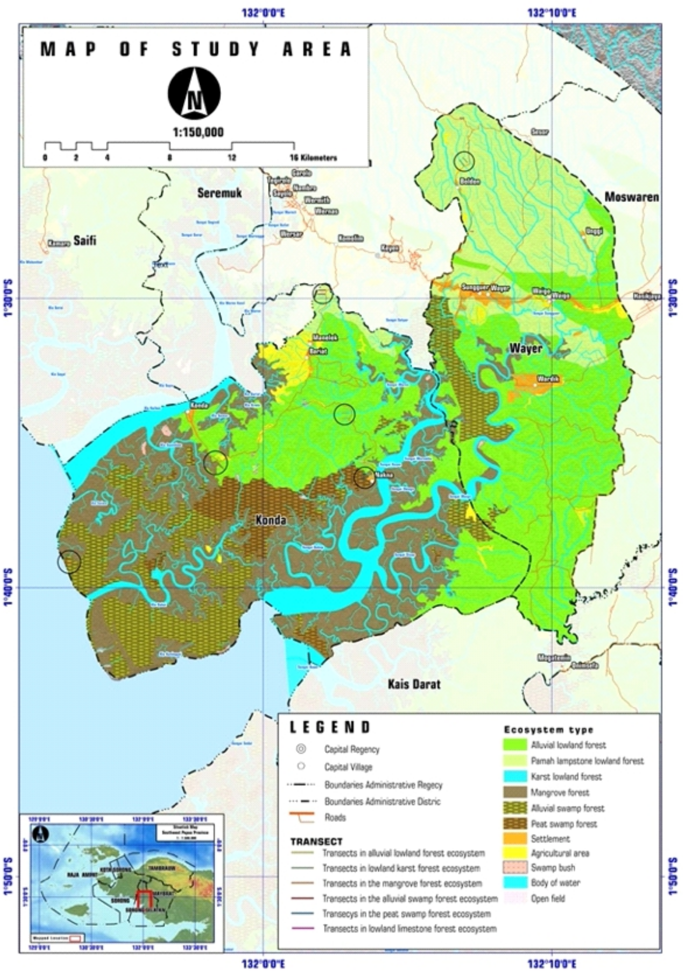

Figure 1 Aboveground and belowground biomass sampling plots within the Study area in South Sorong Regency, Southwest Papua Province.

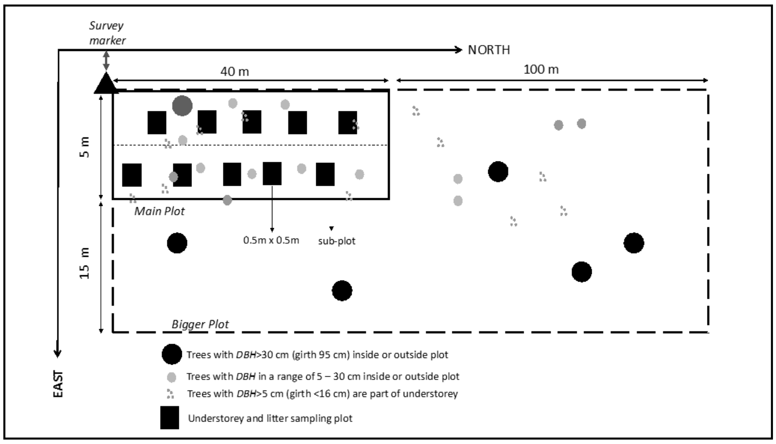

Figure 2 Nested plot design for sampling in the forest ecosystem, adopted from Hairiah et al. (2001) and Mukul et al. (2020).

equation as a live tree and subtracting 10–20% of biomass (accounting for leaves and some branches). Whereas for those trees with decay status 3, the remaining tree's volume was calculated using an equation for a frustum (truncated cone). The top diameter was estimated with a taper equation using the base diameter and height measurements. The Equations *[2]* and *[3]* were used in calculating the top diameter of a broken-topped standing dead tree (Chave et al., 2005; Peck et al., 2017; Chen et al., 2018; Kauffman et al., 2020; Mukul et al., 2020; Hidayah et al., 2022).

$$d_{top} = d_{base} - [100.ht\,((d_{base}\ dbh)/130)] \qquad [2]$$

note: d_{top} is the estimated diameter at the top of the tree (cm), d_{base} is the measured basal diameter (cm), *ht* is the tree height

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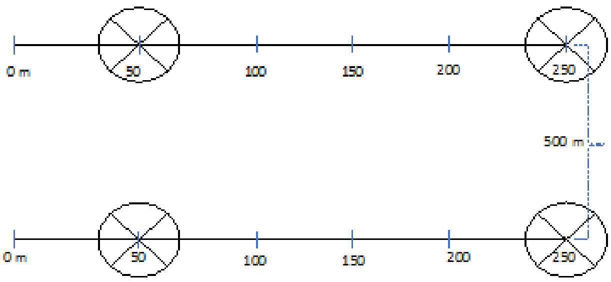

Figure 3 Plot sampling for wetland ecosystem forest (Dharmawan, 2021; Kauffman et al., 2020).

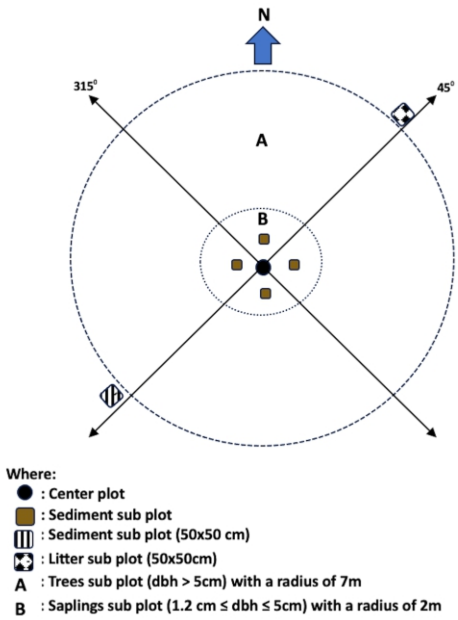

Figure 4 Nested plot dimensions of mangrove ecosystem (Chen et al., 2018; Kauffman et al., 2020; Wicaksono et al., 2016).

(m), and *dbh* is the diameter at breast height (cm).

$$V = [(.100.ht)/12].[(d_{base}^2 + d_{top}^2 + (d_{top}.d_{base})] \quad [3]$$

note: V is the volume of fine, small, and medium of wood debris (WD), ht is tree height (m), d_{base} is the basal diameter (cm), and d_{top} is the diameter at the top (cm).

The carbon stock of standing dead tree biomass (g) was then calculated by multiplying volume (cm^3) by wood density ($g\ cm^{-3}$) and the carbon concentration of dead wood by 50% (Peck et al., 2017; Kauffman et al., 2020).

Furthermore, dead and downed wood or woody debris (WD) within the plot of 200 m^2 (5 m × 40 m) and the plot radius of 7 m (Figures 2 and 4), including woody debris and trunks (unburned part), dead standing trees, dead trees on the ground, and stumps that have a diameter > 5 cm and a length > 0.5 m, were also collected. The biomass of woody debris was calculated using the Equations *[4]*, *[5]*, and *[6]* (Peck et al., 2017; Kauffman et al., 2020).

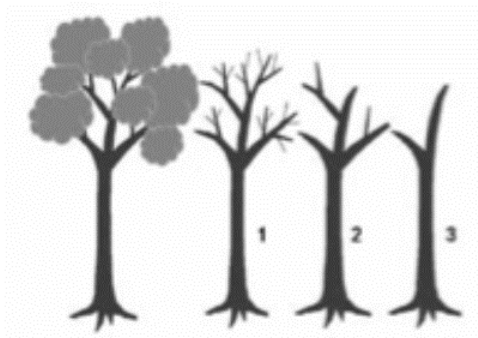

Figure 5 The dead tree decay status classes for tropical trees (Kauffman & Donato, 2012).

$$QMD = [(d_i^2)/n] \quad [4]$$

note: QMD is the quadratic mean diameter (cm); d_i is the diameter of each WD (cm); n is the number of WDs.

$$V = \pi^2 [(Ni.QMD_i^2)/8.L] \quad [5]$$

note: V is the volume of fine, small, and medium (< 7.6 cm) WD; N_i is the count of intersecting woody debris pieces in size class-i; QMD_i is the quadratic mean diameter of size class-i (cm); L = transect length (m).

$$V = \pi^2.[(d_1^2 + d_2^2 + d_3^2 + ... + d_n^2)/8.L] \quad [6]$$

note: V is the volume of large downed wood (diameter > 7.6 cm) ($m^3\ ha^{-1}$); d_1, d_2, etc. = diameters of intersecting pieces of sizeable dead wood (cm); L = the length of the transect line for large size class (m).

Wood biomass was then calculated as the volume multiplied by its mean specific gravity (mass). Finally, the downed wood biomass is converted to carbon mass by multiplying by 50%, which is an acceptable default value based on carbon concentrations of dead wood in tropical forests (Kauffman et al., 2020).

In the dryland ecosystem (mineral soil), composite soil samples were collected in the two 0.5 m × 0.5 m small plots within the 40 m × 5 m transect (Figure 2). Using a soil auger, composite samples were dug at specific soil depths of 0–10, 10–20, and 20–30 cm. Organic litter layers were removed and mixed, and a 500 g subsample was taken for further laboratory analysis. In determining soil bulk density, undisturbed mineral soil was also collected using a ring sampler at 010 cm and 2030 cm (Figure 6a). Meanwhile, in the swamp ecosystem (organic soil), five 4 cm sub-samples were collected, representing depth intervals 0–15, 15–30, 30–50, 50–100, and 100–300 cm. Soil samples were taken using a Russian peat borer (Figure 6b).

Analysis of the chemical and physical properties of soil samples was carried out at the Silviculture Laboratory, Faculty of Forestry, University of Papua, Manokwari, and the Soil Laboratory of IPB, Bogor, Indonesia. Analysis methods for soil samples are shown in Table 2.

Soil bulk density ($g\ m^{-3}$) was determined by dividing the oven-dry soil sample (g) by its volume (m^{-3}) (Walter et al., 2016; Xu et al., 2016; Nengi-Benwari et al., 2022; Sukamto & Rahmat, 2023).

The concentration of soil organic matter (SOM) in

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samples from peat swamp forest ecosystem (PSFE) was determined using Equation *[7]* (Dayathilake et al., 2021).

$$SOM\ (\%) = [[\text{weight}_{80C}\ (g) - \text{weight}_{550C}\ (g)]/[\text{weight}_{80C}\ (g)]].100 \quad [7]$$

Soil organic carbon (SOC) stock per area was obtained by multiplying the SOM concentration by both the bulk density and soil depth per each sampled depth per Equation *[8]*.

$$C\ (\text{Mg C ha}^{-1}) = [\text{soil bulk density (g cm}^{-3}).\text{soil depth (cm). SOC concentration}].100 \quad [8]$$

Mean SOC stock per hectare and depth of soil were determined by averaging the SOC stock (Mg C ha^{-1}) across all plots. The results were then extrapolated to the total area of the study site to obtain the SOC stock per depth. The total SOC stock of the wetland was determined by combining the resultant values of all depth intervals.

Belowground (root) biomass was estimated through non-destructive methods. To calculate total biomass, non-mangrove species' root volume and biomass were estimated as a fraction of the aboveground biomass. Such an equation is widely used to assess the belowground biomass of tropical rain forests as 0.37 aboveground biomass (IPCC, SNI 7724) (Boonman et al., 2020). To calculate the tree belowground biomass and carbon stock of mangrove species, Equations *[9]* and *[10]* were used (Komiyama et al., 2008).

$$B_{tbg} = 0.199\rho^{0.899}dbh^{2.22} \quad [9]$$

$$C_{tbg} = 0.39B_{tbg} \quad [10]$$

note: B_{tbg} is tree belowground biomass (kg); ρ is wood density (g cm^{-3}), dbh is tree diameter at breast height (cm); 0.39 is the carbon fraction; and C_{tbg} is the carbon of the tree belowground (root) (Mg C ha^{-1});

The aggregates of all the sources of carbon pools were added to obtain the total ecosystem carbon stock (TECS) in each ecosystem type, as shown in Equation *[11]*.

$$TECS = C_t + C_u + C_l + C_{ddw} + C_{tbg} + C_s \quad [11]$$

note: *TECS* is total ecosystem carbon stock (Mg C ha-1), *Ct* is carbon of live trees, *Cu* is carbon of understory (seedlings), *Cl* is litter's carbon, *Cddw* is carbon in dead and downed woods, *Cr* is carbon tree belowground (roots), and *Cs* is carbon in soil.

The total C-stock in the whole area is calculated by multiplying the C-stock per unit area (Mg ha^{1}) with the area size (ha) (Kauffman et al., 2020). In addition, the $CO_{2\text{-eq}}$ of the total carbon stock was obtained by multiplying the carbon stock by 3.67 (Dayathilake et al., 2021; Kauffman et al., 2020).

Data analysis Differences in the TECS of each ecosystem and the carbon stock of each carbon pool in each ecosystem were statistically analyzed using an SPSS version 29 software package. Analysis of variance (ANOVA) was carried out using a significance level of 0.05 after verifying the additivity (Tukey's test) and homogeneity of variance (Bartlett's test) of the data.

Results and Discussion

Dried lowland forest ecosystem (DLFE) Sampling generated 345 individual stems from a total area of approximately 1.2 ha. We identified 95 species, 78 genera, and 66 tree

Figure 6 Collecting undisturbed mineral soil (a); taking organic soil samples (b).

Table 2 Soil chemical and physical analysis methods in estimating stored carbon

Parameter	Metode	References
Total C-mineral soil (%)	Walkey and Black	Sukamto and Rahmat (2023); Aziz et al. (2017)
Total C-organic soil	Loss on Ignition (LOI)	Hoogsteen at al. (2015); Steinmuller et al. (2024);
Bulk density (g cm^{-3})	Gravimetry	Walter et al. (2016); Xu et al. (2016)

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families of these. The dried lowland forest ecosystem contains different main types in the growth phases of trees, poles, and saplings. The *Vatica rassak* rasak (Korth) Blume. was the most dominant species (INP = 46.49%), followed by *Gymnacranthera farquhariana* (Wall. ex Hook. f. & Thomson) Warb. (INP = 24.41%). The other dominant species are *Spathiostemon javensis* Blume, *Hopea papuana* Diels., *Syzygium malaccense* P. Browne ex Gaertn., *Anisoptera thurifera* (Blance) Blume., *Haplolobus lanceolatus* H.J.Lam., *Gironniera subaequalis* Planch., *Itoa staphii* Sleumer., and *Pimelodendron amboinicum* Hassk, with INP ranging from 5.91% to 18.80%. Furthermore, results also show that *V. rassak* presented the highest BA of 7.3 m^2 ha^{-1} (p-value < 0.05). It is followed *by V. rassak, G. farquhariana, H. papuana, S. malaccense*, *S. javensis*, *Fagraea racemosa* Jack., *H. lanceolatus, A. thurifera*, *Ardisia crenata* Sw., and *Calophyllum costatum* L., with basal area (BA) ranging from 0.90 to 5.31 m^2 h^{-1}.

This study indicates that, in terms of diameter classes, the majority (76%) of tree diameters in these DLFEs in South Sorong Regency, Southwest Papua Province, were between 5 cm, which has been the dominant vegetation growth phase in all six ecosystem types (Figure 7). This indicates that the DLFEs in South Sorong, Southwest Papua, are categorized as comparatively young forests with relatively moderate growth dynamics (Clarke, 1993; Petter et al., 2021). Interestingly, the population of trees with a diameter greater > 40 cm is tiny.

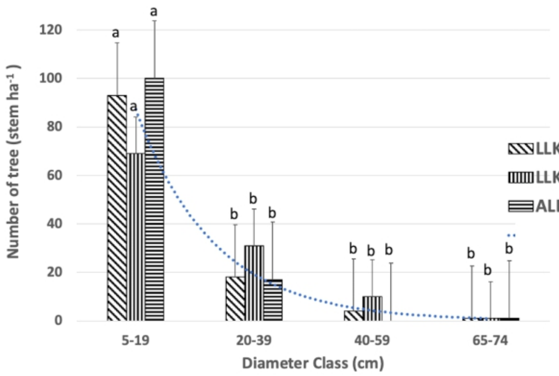

Figure 7 Distribution of tree size-class diameters of trees > 5 cm in the dried lowland forest ecosystem (DLFE), South Sorong Regency, Southwest Papua Province. Letters above the bars of measured total ecosystem carbon stocks represent a significant difference (p-value ≤ 0.05) between the forest ecosystems.

This indicates that the stands in this dried lowland forest ecosystem have abnormal growth (Clarke, 1993; Petter et al., 2021). This anomaly could be caused by illegal logging activities in this ecosystem area.

Furthermore, as shown in Figure 7, the pattern of dbh classes of the tree species in this region's inverted J-shaped distribution indicates a forest dominated by young trees. Only a few trees with dbh more than 60 cm, including *H. lanceolatus*, *G. farquhariana*, and *F. racemosa*. This pattern suggests a favorable potential for the reproduction and recruitment of the forests and the development of secondary forests (Robiansyah 2018; Geng et al. 2019; Ardiyaningrum et al. 2021). Likewise, almost all ecosystem types do not have trees with a diameter class of > 60 cm. This anomaly is probably due to small-scale logging activities that have been going on in these lowland primary forests. A one-way ANOVA analysis found a significant difference (p-value > 0.05) in the C-stock of dead and downed wood (DDW) and soil pool in the DLFE in the South Regency (Table 3).

Data from SOC analysis shows that the average C-organic density of soil samples in the ALLF-N and LLLF-W forests is twice as high (97.9 Mg C ha^{-1}) as the SOC density of soil samples in the LLKF-B ecosystem (52.9 Mg C ha^{-1}). This has direct implications for higher soil carbon density in an area. It is also suspected that ALLF-N and LLLF-W forests produce higher organic matter that contributes to forming higher soil carbon density (Russell et al., 2015; Keller & Medvedeff, 2016; Sokol et al., 2019; Gerke, 2022). Field observations indicated that the soil sampling location (transect) of Kampung Wara is located between two hills, which allows for the buildup (accumulation) of litter and organic material, affecting the SOC content. In addition, tree-felling activities inherited unused logs, providing more downed wood biomass in ALLF-N and LLLF-W. These actions produced significantly higher DDW biomass, eventually enhancing the soil organic matter (Russell et al., 2015). In addition, higher carbon densities in Wara Village to local topographical features, such as hill proximity of that promotes organic matter accumulation, and to anthropogenic impacts like residual downed wood from logging. This connection provides a mechanistic understanding of how landscape and disturbance influence carbon storage, supported by Gerke (2022) and Russell et al. (2015).

In comparison to other neighbouring lowland forests, the DLFE in South Sorong has significantly higher TECS compared to TECS values of climax vegetation in old-growth forests in Malaysia (194 Mg C ha^{-1}) (Kho & Jepsen, 2015)

Table 3 Total ecosystem carbon stock (Mg C ha^{-1}) with 95% confidence limits of dried lowland forest ecosystem (DLFE) of the South Sorong Regency

Ecosystem type	Total C-stock (Mg C ha^{-1})						
	Tree	Understory	Litter	Dead and downed wood	Root	Soil	Total
ALLF-N	29.3(1.9) a	74.5(4.4) a	22.0(0.6) a	2.9(0.1) a	8.7(1.0) a	96.3(27.7) a	233.6(30.4) a
LLLF-W	37.5(3.9) a	66.9(1.3) a	34.2(1.8) a	2.9(0.1) a	12.1(0.9) a	99.6(21.4) a	238.8(25.1) a
LLKF-B	39.4(2.7) a	52.6(3.1) a	34.2(1.7) a	0.1(0.1) b	12.1(1.3) a	52.9(09.2) b	194.1(11.8) a

Notes: Means within a column followed by the same lowercase letter are not significantly different at a 5% significance level using the least significant difference (LSD) test. Numbers in parentheses are standard error (SE).

and Khe Nuoc Trong forest, north-central Vietnam (196.1 Mg C ha^{-1}) (Stas et al., 2020). However, as shown in Table 2, even though there was a significant difference in the C-stock of dead and downed wood (DDW) and the soil's pool, it did not affect the TECS of these three forest ecosystems, as they shared similar total carbon stock (p-value < 0.05). These three ecosystems comprise 194 Mg ha^{-1} to 238 Mg ha^{-1} (average = 229.8 Mg ha^{-1}) of total carbon, derived mainly from soil and understories (36% and 28%, respectively). The average C-stock in this area is within the value of the total carbon stock in tropical forests of 161300 Mg C ha^{-1}. The results showed that South Sorong's DLFE, with an average of 229.8 Mg C ha^{-1} (95% CI 136.8–328.8), has a slightly lower TECS than the global mean for tropical rainforests (247 Mg C ha^{-1}), representing three continents (Latin America, Africa, and Southeast Asia) (Saatchi et al., 2011), and much lower than regional rainforest TECS values estimated for central Panama, South America (271.5 Mg C ha^{-1}) (Jones et al., 2019), Nyungwe tropical montane rainforest, southwestern Rwanda, Africa (321.5 Mg C ha^{-1}) (Nyirambangutse et al., 2017), tropical Sal forest in the Terai Arc Landscape of Nepal, South Asia (264.35 Mg C ha^{-1}) (Gurung et al., 2015). Factors such as the lower basal area and diameter classes observed in South Sorong's DLFE are the case. Imani et al. (2017), Mensah et al. (2020), Cieszeweski et al. (2021), and Seiwa et al. (2023) found that high tree diameter contributes to the higher basal area, significantly affects aboveground biomass, and eventually affects the AGC.

Table 3 also shows that those three forest ecosystems shared similar carbon stock values originating from live trees with a diameter above 5 cm, seedlings, and litter. The final results show that the proportion of average AGCs (60%) is slightly lower than that of the average belowground carbon stock (BGCs) (40%) of these three forest ecosystems (Figure 8). One-way ANOVA revealed that the three forest ecosystems shared similar AGC (Figure 8). Meanwhile, there was a difference in carbon stock in the BGCs pool. The difference in the total amount of BGCs in this ecosystem is greatly influenced by the contribution of carbon storage in the soil.

Furthermore, the top 10 tree species, in terms of AGC, contributed 55.02% of tree C-stock (Table 3). The most significant contributor to tree C-stock (16.45%) in the plots was *V. rassak*, followed by species *G. farquhariana*, *S. javensis*, and *H. papuana*, with a proportion of tree C-stock of 8.63%, 6.69%, and 6.47%, respectively.

As can be seen from Table 4, the top ten species with higher BA, including *F. racemosa, A. crenata,* and *C. costatum*, do not perform high tree c-stock. It is suspected that they presented fewer stem densities in their ecosystem site. The value of carbon stock in plants is strongly correlated with the amount of biomass in the plants, particularly tree biomass. Banuwa et al. (2019) state that tree biomass is the most significant contributor to carbon due to its higher level of carbon storage than seasonal crops. Plants absorb large quantities of atmospheric carbon dioxide (CO_2) by photosynthesis, which is then converted into oxygen (O_2) that is emitted back to the surrounding environment and glucose ($C_6H_{12}O_6$) for its growth. At the same time, the excess of food is stored as biomass (Banuwa et al., 2019).

Peat swamp forest ecosystem (PSFE) Sampling generated 199 individual stems from a total area of 1.72 ha. We identified 46 species, 44 genera, and 21 tree families of these. The dried lowland forest ecosystem contains different main types in the growth phases of trees, poles, and saplings. The *Metroxylon sagu* Rottb. (INP = 122.4% and BA = 28.4 m^2 h^{-1}), *Bruguiera gymnorhiza* (L.) Lam. (INP = 43.75% and BA = 13.7 m^2 h^{-1}) and *Xylocarpus granatum* K.D Koenig (INP = 34.37% and BA = 10.7 m^2 h^{-1}) are the top three species

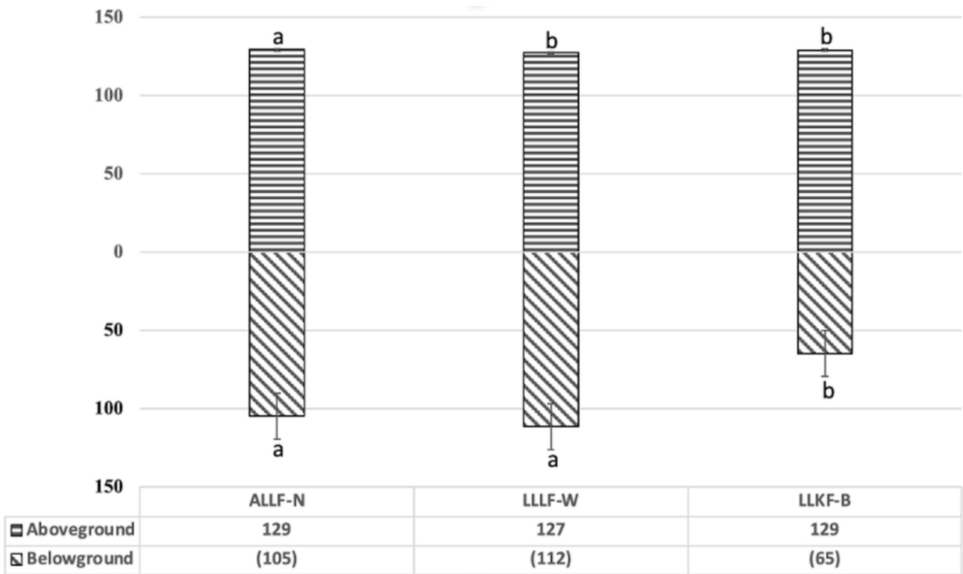

Figure 8 Comparison of estimates of total carbon stored (c-stock) (Mg C ha^{-1}) aboveground and belowground in dried lowland forest ecosystem (DLFE) of the South Sorong Regency, Southwest Papua. Letters above and below the bars of measured ecosystem carbon stocks represent a significant difference (p-value ≤ 0.05) between the forest ecosystems.

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Scientific Article
ISSN: 2087-0469

(important species) in these ecosystems. The other main species are *P. amboinicum, Nauclea orientalis* L., *Endospermum moluccanum* (Teijsm. & Binn.) Kurz., *Intsia bijuga* (Colebr.) Kuntze., *Macaranga tessellata* Gage, *Rhizophora apiculata* (Blume.), and *Rhus lamprocarpa* Merr. & L.M.Perry with INP and BA ranging from 4.85% and 0.68 m^2 h^{-1} to 5.76% and 2.79 m^2 h^{-1}.

As shown in Figure 9, unlike in the DLFE, the distribution of trees in the PSFE of South Sorong Regency, Southwest Papua Province, is quite normal in all diameter classes. This indicates that the stands in this wetland ecosystem are relatively old forests with comparatively fast to moderate growth dynamics (Clarke, 1993; Petter et al., 2021). Similar to DLFE, overall, the pattern of dbh classes of the tree species in this PSFE also formed a J-shaped distribution with almost no giant trees (dbh > 60 cm) present. This pattern suggests a good potential for reproducing and recruiting forests and developing secondary forests (Robiansyah 2018; Geng et al. 2019; Ardiyaningrum et al. 2021). The absence of more enormous trees in PSFE is probably due to small-scale logging activities that have been going on in these lowland primary forests. These patterns indicate a relatively young forest affected by past illegal logging activities, which is consistent with findings by Petter et al. (2021). This interpretation helps clarify the forest's growth dynamics and structural characteristics.

One-way ANOVA analysis showed a significant difference (p-value < 0.05) in mean TECS, with the highest stocks for ASF-K (1,217.4 ± 1.9 Mg C ha^{-1}) and Mgrv-K (1,118.2 ± 5.5 Mg C ha^{-1}) and the lowest for PSF-N (471.2 ± 2.4 Mg C ha^{-1} in South Regency, Southwest Papua Province, Indonesia (Table 5).

Table 5 shows that the contribution of carbon content at the research location comes from the carbon content in non-woody necromass (coarse and fine litter), understory (seedlings), woody necromass (dead and downed trees), live trees (including pole and sapling levels), subsurface (roots), and soil. The TECS in these three wetland forest ecosystems ranges from 471.2 Mg C ha^{-1} to 1,217.4 Mg C ha^{-1} with an average of 941.9 Mg C $ha^{-1,}$ in which ASF-K has the significantly highest TECS (p-value < 0.05). Soil organic carbon (SOC) (average = 825.8 Mg C ha^{-1}) has played a

Table 4 Top 10 tree species ranked on contribution to tree c-stock in dried lowland forest ecosystem (DLFE) of South Sorong Regency

Species	Family	C-stock (Mg C ha^{-1})	Proportion (%)
Vatica rassak	Dipterocarpaceae	15.50	16.45
Gymnacranthera farquhariana	Dipterocarpaceae	8.14	8.63
Spathiostemon javensis	Euphorbiaceae	6.27	6.65
Hopea papuana	Dipterocarpaceae	6.10	6.47
Syzygium malaccense	Myrtaceae	3.55	3.76
Anisoptera thurifera	Dipterocarpaceae	3.16	3.35
Haplolobus lanceolatus	Burseraceae	2.52	2.67
Gironniera subaequalis	Cannabaceae	2.45	2.60
Itoa staphii	Salicaceae	2.20	2.33
Pimelodendron amboinicum	Euphorbiaceae	1.97	2.09

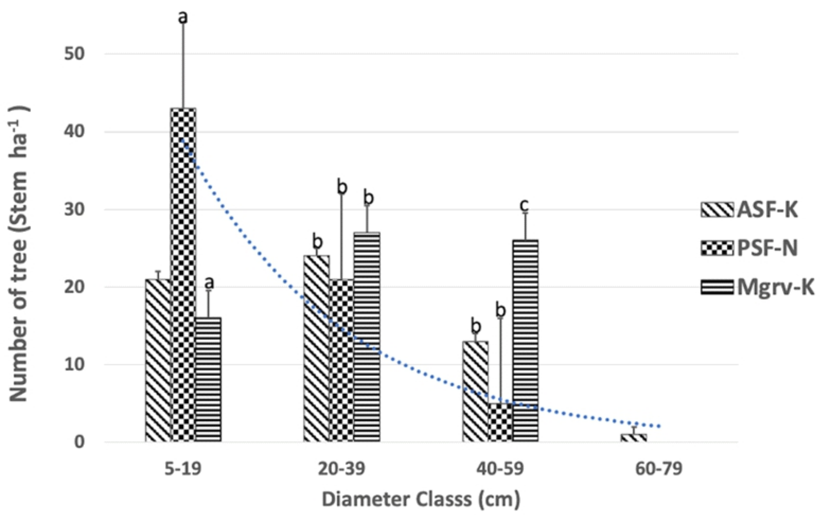

Figure 9 Distribution of tree size-class diameters of trees > 5 cm in the peat swamp forest ecosystems (PSFEs), South Sorong Regency, Southwest Papua Province. Letters above the bars of measured total ecosystem carbon stocks represent a significant difference (p-value ≤ 0.05) between the forest ecosystems.

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significant role in topping up the TECS in this wetland ecosystem of South Sorong Regency. Results indicated that the average SOC density in the wetland forest ecosystem in this region (825.8 Mg C ha^{-1}) is higher than that found in global, national, and regional similar ecosystems. Adame et al. (2015), Dayathilake et al. (2021), Carnell et al. (2018), and Ma et al. (2015) found that the mangrove and peatland in the Encrucijada Biosphere Reserve (LEBR), Chiapas, south Pacific coast of Mexico, in the Kolonnawa wetland and the Thalawathugoda wetland park are distributed within the Colombo city, and in the organic wetland of the Southeastern Atlantic Coastal Plain, USA, in the state of Victoria, Australia. China's palustrine wetland has only an average of 753 Mg C ha^{-1}, 527 Mg C ha^{-1}, 533 Mg C ha^{-1}, 290 Mg C ha^{-1}, and 96 Mg C ha^{-1}, respectively. The mangrove in Bunaken National Park, North Sulawesi, has only an average of 822.1 Mg C ha^{-1} (Murdiyarso et al., 2009), and the mangrove forest in Teminabuan District, Southwest Papua (average = 822.1 Mg C ha^{-1}) (Taberima et al. 2014). It has been suspected that the wetland ecosystem of South Sorong Regency has a much deeper organic soil layer than similar ecosystems in a specific part of the globe (De Feudis et al., 2022). On the other hand, the SOC of the wetland ecosystem of South Sorong Regency is still slightly lower than the average SOC density of the mangrove substrate in the mangrove, swamp forests, marshes, and grazed wetlands of Veracruz, Tabasco/ Campeche, and Chiapas states, Mexico (1,400 Mg C ha^{-1}) (Sjögersten et al., 2021), Tanjung Puting National Park (average = 1,059.2 Mg C ha^{-1}) (Murdiyarso et al., 2009), Bintuni and Timika, Papua, with average substrate carbon densities of 1,032 Mg C ha^{-1} and 964.9 Mg C ha^{-1}, respectively, in which deeper soil (organic sediment) was the main support factor (Taberima et al., 2014).

The PSFE measured in this study had large TECS with values for mangroves and peat swamps almost five times as high as those measured in DLFE. TECS within PSFE (mean of 941.9 ± 17.6 Mg C ha^{-1}; maximum of 1,219.3 Mg C ha^{-1}) were much higher than another similar ecosystem around the world, such as in Vietnam (762.2 ± 57.2 MgC ha^{-1}) (Tue et al., 2014), the Dominican Republic (853 Mg C ha^{-1}) (Kauffman et al., 2014), Yucatan, Mexico (663 ± 176 Mg C ha^{-1}) (Adame et al., 2015), and Northwest Madagascar (367–593 Mg C ha^{-1}) (Jones et al., 2019). Especially in Mgrv-K, the TECS of this mangrove ecosystem (1,181.2 ± 5.5 Mg C ha^{-1}) is slightly higher than that of the national value of 1,083 ± 378 Mg C ha^{-1} (Murdiyarso et al., 2015). However, the TECS of PSFE of this region is still much lower compared to that found by Saragi-Sasmito et al. (2019), who invented a means of TECS in the secondary tropical peat swamp forest in Central Kalimantan (1,752 ± 401 Mg C ha^{-1}), of which 93% was stored in belowground organic peat soils.

Furthermore, as previously explained, the amount of carbon storage is greatly influenced by the contribution of SOC from this ecosystem. This causes the proportion of BGCs to be much higher (91%) than AGCs (Figure 10).

Figure 10 shows that the overall proportion of AGCs to BGCs (9%:91%) indicates that this ecosystem's lower parts (SOC and roots) store much higher carbon. This finding is similar to Saragi-Sasmito et al.'s (2019) finding that 93% of BGCs were stored in belowground organic soils in Central Kalimantan, Indonesia. This finding is slightly different from previous studies on identical ecosystem types. Taberima et al. (2014), Kusumaningtyas et al. (2018), and Meng et al. (2021) reported that the proportion of AGS to BGS in the coastline of southeast China, Papua (Bintuni, Teminabuan, and Timika), Indonesia, and in the Berau region, East Kalimantan, Indonesia, was 27% to 73%, 82% to 12%, and 79% to 21%.

Furthermore, as can be seen from Figure 10, there was a significant difference (p-value < 0.05) in AGCs and BGCs among PSFEs in South Regency, Southwest Papua Province, Indonesia. Mgrv-K and ASF-K presented significantly higher BGCs than PSF-N. Higher BGCs at Mgrv-K and ASF-K of South Sorong Regency, as shown by the present study, could mainly be attributed to the deeper organic layer contributing to higher SOC (De Feudis et al., 2022). Results show that the average soil organic layer of Mgrv-K and ASF-K was 150 cm compared to 50 cm in PSF-N. The elevated of TECS in the peat swamp forest ecosystem (PSFE), were explained by the presence of deeper organic soil layers and higher soil organic carbon content, which distinguish this ecosystem from the DLFE and align with studies by De Feudis et al. (2022) and Saragi-Sasmito (2019). The significant role of large trees such as Metroxylon sagu in carbon sequestration was further elaborated to underscore species-specific biomass contributions.

The top 10 tree species, in terms of C-stock, contributed 80.45% of the AGC (Table 6). The most significant contributor to tree C-stock (40.75%) in the plots, *M. sagu*, was also the most abundant species, with the second most abundant species, *B. gymnorhiza*, contributing 14.58% to tree C-stock. A single, large individual of *X. granatum* contributed the third-highest tree C-stock–highlighting the disproportionate importance of large trees in carbon sequestration.

Sago (*M. sagu*) is an essential indicator species grown in

Table 5 Total carbon stock (Mg C ha^{-1}) with 95% confidence limits for the peat swamp forest ecosystems (PSFEs), South Sorong Regency, Southwest Papua Province

Ecosystem type	Total C-stock (Mg ha^{-1})						
	Tree	Understory	Litter	Dead and downed wood	Root	Soil	Total
Mgrv-K	45.2(2.3) a	30.0(3.8) a	47.3(0.6) a	45.2(0.02) a	58.1(0.0) a	955.4(44.0) a	1,181.2(5.5) b
ASF-K	38.6(0.4) a	31.6(1.4) a	10.5(1.8) a	0.2(0.0) b	11.9(0.0) b	1,124.7(137.4) a	1,217.4(1.9) a
PSF-N	30.1(1.6) a	21.8(0.9) a	12.6(1.7) a	0.2(0.0) b	9.2(0.0) b	397.3(27.7) b	471.2(2.4) c

Notes: Means within a column followed by the same lowercase letter are not significantly different at a 5% significance level using the least significant difference (LSD) test. Numbers in parentheses are standard error (SE).

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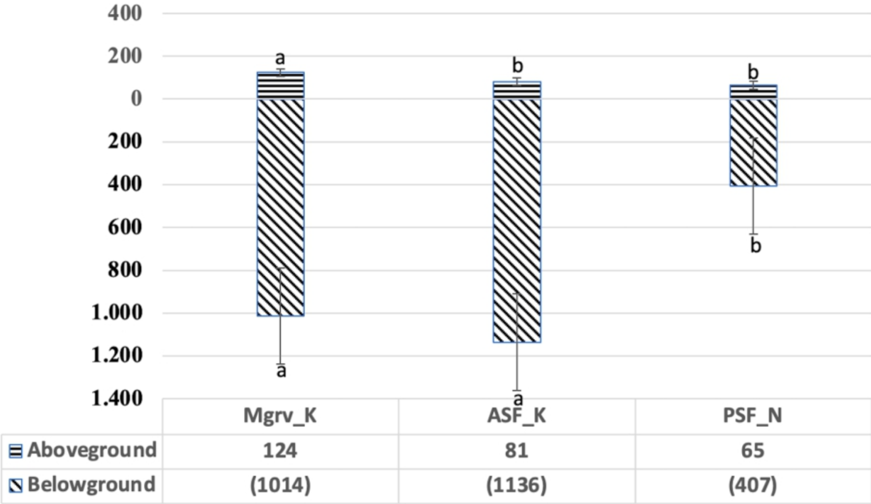

Figure 10 Comparison of AGCs and BGCs (Mg C ha^{-1}) estimates in peat swamp forest ecosystem (PSFE) of the South Sorong Regency, Southwest Papua Province, Indonesia. Letters above and below the bars of measured ecosystem carbon stocks represent a significant difference (p-value ≤ 0.05) between the forest ecosystems.

Table 6 Top 10 tree species ranked on contribution to tree C-stock (AGCs) in peat swamp forest ecosystem (PSFE) of South Sorong Regency

Species	Family	C-stock (Mg C ha^{-1})	Proportion (%)
Metroxylon sagu	Arecaceae	41.79	40.75
Bruguiera gymnorhiza	Rhizophoraceae	14.96	14.58
Xylocarpus granatum	Meliaceae	12.77	12.45
Pimelodendron amboinicum	Euphorbiaceae	1.97	1.92
Nauclea orientalis	Rubiaceae	1.95	1.90
Endospermum moluccanum	Euphorbiaceae	1.89	1.84
Intsia bijuga	Fabaceae	1.88	1.84
Macaranga tessellata	Euphorbiaceae	1.85	1.81
Rhizophora apiculata	Rhizophoraceae	1.80	1.75
Rhus lamprocarpa	Anacardiaceae	1.66	1.62

peatland. Taberima et al. (2014) found that the sago species was the major contributor (BA = 2.13 m^2 ha^{-1}) to the carbon stock in Bintuni Bay, West Papua, Indonesia. In addition, the findings in Table 5 are supported by Hilmi et al. (2017), who reported that *B. gymnorhiza* is one of the leading carbon sinks of mangrove species.

Conclusion

The data presented in this study show that PSFEs stored exceptionally high TECS compared to dried DLFEs. Within DLFEs, the quantities of carbon were held mostly (60%) in the aboveground pool (tree, seedling, litter, and dead and downed wood), whereas within PSFEs, it was held mainly in the belowground pool (root and soil). In PSFEs, Mgrv-K, and ASF-K stored much more TECS than PSF-N, mainly because they have a thicker layer of organic soil. Another critical point is that the SOC contributed 88% of the total TECS in the South Sorong region. In addition, in both DLFEs and PSFEs, soil holds twofold the carbon content compared to vegetation biomass. However, live trees also contributed significantly to the C-stock of both ecosystem types. *V. rassak, M. sagu*, and *B. gymnoriza* were the main contributors to the biomass of live trees.

Recommendation

The findings underscore the urgent need to protect mature forests and peat soils in South Sorong to maintain biodiversity and maximize carbon sequestration. Integrated conservation efforts targeting illegal logging and soil preservation are essential for enhancing forest resilience and supporting climate change mitigation.

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References

Adame, M. F., Santini, N. S., Tovilla, C., Vázquez-Lule, A., Castro, L., & Guevara, M. (2015). Carbon stocks and soil sequestration rates of tropical riverine wetlands. *Biogeosciences*, *12*(12), 3805–3818. https://doi.org/10.5194/bg-12-3805-2015

Ardiyaningrum, I, Budiastuti, M. T. S., & Komariah, K. (2021). Short Communication: Species composition and diversity of vegetation in dryland agricultural landscape. *Biodiversitas*, *22*(1), 65–71. https://doi.org/10.13057/biodiv/d220109

Aziz, M. A., Hazra, F., Salma, S., & Nursyamsi, D. N. (2017). Soil chemical characteristics of organic and conventional agriculture. *Journal of Tropical Soils*, *21*(1), Article 1. https://doi.org/10.5400/jts.2016.v21i1.19-25

Banuwa, I. S., Afriliyanti, R., Utomo, M., Yusnaini, S., Riniarti, M., Sanjaya, P., Suroso, E., & Hidayat, W. (2019). Short communication: Estimation of the above- and below-ground carbon stocks in University of Lampung, Indonesia. *Biodiversitas Journal of Biological Diversity*, *20*(3), Article 3. https://doi.org/10.13057/biodiv/d200309

Boonman, C. C. F., van Langevelde, F., Oliveras, I., Couédon, J., Luijken, N., Martini, D., & Veenendaal, E. M. (2020). On the importance of root traits in seedlings of tropical tree species. *New Phytologist*, *227*(1), 156–167. https://doi.org/10.1111/nph.16370

Carnell, P. E., Windecker, S. M., Brenker, M., Baldock, J., Masque, P., Brunt, K., & Macreadie, P. I. (2018). Carbon stocks, sequestration, and emissions of wetlands in south eastern Australia. *Global Change Biology*, *24*(9), 4173–4184. https://doi.org/10.1111/gcb.14319

Chave, J., Chust, G., Condit, R., Aguilar, S., Hernandez, A., Lao, S., & Perez, R. (2005). Error propagation and scaling for tropical forest biomass estimates. In Y. Malhi, & O. Phillips (Eds.), *Tropical forests and global atmospheric change* (pp. 155–163). https://doi.org/10.1093/acprof:oso/9780198567066.003.0013

Chen, S., Chen, B., Sastrosuwondo, P., Dharmawan, I. W. E., Ou, D., Yin, X., Yu, W., & Chen, G. (2018). Ecosystem carbon stock of a tropical mangrove forest in North Sulawesi, Indonesia. *Acta Oceanologica Sinica*, *37*(12), 85–91. https://doi.org/10.1007/s13131-018-1290-5

Clarke, K. R. (1993). Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology*, *18*(1), 117–143. https://doi.org/10.1111/j.1442-9993.1993.tb00438.x

Dayathilake, D. D. T. L., Lokupitiya, E., & Wijeratne, V. P. I. S. (2021). Estimation of soil carbon stocks of urban freshwater wetlands in the Colombo Ramsar Wetland City and their potential role in climate change mitigation. *Wetlands*, *41*(2), Article 29. https://doi.org/10.1007/s13157-021-01424-7

De Feudis, M., Falsone, G., Vianello, G., Agnelli, A., & Vittori Antisari, L. (2022). Soil organic carbon stock assessment in forest ecosystems through pedogenic horizons and fixed depth layers sampling: What's the best one? *Land Degradation & Development*, *33*(9), 1446–1458. https://doi.org/10.1002/ldr.4253

Dharmawan, I. W. E. (2021). Mangrove health index distribution on the restored post-tsunami mangrove area in Biak Island, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *860*(1), Article 012007. https://doi.org/10.1088/1755-1315/860/1/012007

Dharmawan, I. W. E., Suyarso, Ulumuddin, Y. I., Prayudha, B., & Pramuji (2020). *Panduan monitoring struktur komunitas mangrove di Indonesia*. Bogor: PT Media Sains Nasional.

Faisol, A., Indarto, Novita, E., & Budiyono. (2022). Assessment of agricultural drought based on CHIRPS data and SPI method over West Papua–Indonesia. *Journal of Water and Land Development*, *52*, *44–52*. https://doi/org/ 10.24425/jwld.2021.139942

Fatem, S. M., Djitmau, D. A., Ungirwalu, A., Wanma, A. O., Simbiak, V. I., Benu, N. M. H., Tambing, J., & Murdjoko, A. (2020). Species diversity, composition, and heterospecific associations of trees in three altitudinal gradients in Bird's Head Peninsula, Papua, Indonesia. *Biodiversitas Journal of Biological Diversity*, *21*(8), Article 8. https://doi.org/10.13057/biodiv/d210824

Geng, S. Shi, P., Song, M., Zong, N. Zu. J., & Zhu, W. (2019). Diversity of vegetation composition enhances ecosystem stability along elevational gradients in the Taihang Mountains, China. *Ecological Indicators*, *104*, 594–603. https://doi.org/10.1016/j.ecolind.2019.05.038

Gerke, J. (2022). The central role of soil organic matter in soil fertility and carbon storage. *Soil Systems*, *6*(2), Article 2. https://doi.org/10.3390/soilsystems6020033

Gurung, M. B., Bigsby, H., Cullen, R., & Manandhar, U. (2015). Estimation of carbon stock under different management regimes of tropical forest in the Terai Arc Landscape, Nepal. *Forest Ecology and Management*, *356*, 144–152. https://doi.org/10.1016/j.foreco.2015.07.024

Hairiah, K., Dewi, S., Agus, F., Velarde, S., Andree, E., Rahayu, S., & van Noordwijk, M. (2001). *Measuring carbon stocks*. World Agroforestry Centre.

Hidayah, Z., Rachman, H. A., & As-Syakur, A. R. (2022). Mapping of mangrove forest and carbon stock estimation of east coast Surabaya, Indonesia. *Biodiversitas*, *23*(9), 4826–4837. https://doi.org/10.13057/biodiv/d230951

Hilmi, E., Parengrengi, Vikaliana, R., Kusmana, C., Iskandar, Sari, L. K., & Setijanto. (2017). The carbon conservation of mangrove ecosystem applied REDD program. *Regional Studies in Marine Science*, *16*, 152–161. https://doi.org/10.1016/j.rsma.2017.08.005

Hoogsteen, M. J. J., Lantinga, E. A., Bakker, E. J., Groot, J. C. J., & Tittonell, P. A. (2015). Estimating soil organic carbon through loss on ignition: Effects of ignition conditions and structural water loss. *European Journal of Soil Science*, *66*(2), 320–328. https://doi.org/10.1111/ejss.12224

Imani, G., Boyemba, F., Lewis, S., Nabahungu, N. L., Calders, K., Zapfack, L., Riera, B., Balegamire, C., & Cuni-Sanchez, A. (2017). Height-diameter allometry and above ground biomass in tropical montane forests: Insights from the Albertine Rift in Africa. *PLoS ONE*, *12*(6), Article e0179653. https://doi.org/10.1371/journal.pone.0179653

Jones, I. L., DeWalt, S. J., Lopez, O. R., Bunnefeld, L., Pattison, Z., & Dent, D. H. (2019). Above- and belowground carbon stocks are decoupled in secondary tropical forests and are positively related to forest age and soil nutrients respectively. *Science of The Total Environment*, *697*, Article 133987. https://doi.org/10.1016/j.scitotenv.2019.133987

Kauffman, J. B., Adame, M. F., Arifanti, V. B., Schile-Beers, L. M., Bernardino, A. F., Bhomia, R. K., Donato, D. C., Feller, I. C., Ferreira, T. O., Jesus Garcia, M. del C., MacKenzie, R. A., Megonigal, J. P., Murdiyarso, D., Simpson, L., & Hernández Trejo, H. (2020). Total ecosystem carbon stocks of mangroves across broad global environmental and physical gradients. *Ecological Monographs*, *90*(2), Article e01405. https://doi.org/10.1002/ecm.1405

Kauffman, J. B., & Donato, D. C. (2012). Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working Paper No. 86. Bogor: Center for International Forestry Research. https://doi.org/10.17528/cifor/003749

Kauffman, J. B., Heider, C., Norfolk, J., & Payton, F. (2014). Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. *Ecological Applications*, *24*(3), 518–527. https://doi.org/10.1890/13-0640.1

Keller, J. K., & Medvedeff, C. A. (2016). Soil organicmatter. In *Wetland soils* (2nd ed.). CRC Press.

Kho, L. K., & Jepsen, M. R. (2015). Carbon stock of oil palm plantations and tropical forests in Malaysia: A review. *Singapore Journal of Tropical Geography*, *36*(2), 249–266. https://doi.org/10.1111/sjtg.12100

Komiyama, A., Ong, J. E., & Poungparn, S. (2008). Allometry, biomass, and productivity of mangrove forests: A review. *Aquatic Botany*, *89*(2), 128–137. https://doi.org/10.1016/j.aquabot.2007.12.006

Kusumaningtyas, M., Hutahaean, A., Fischer, H., Perez, M., Ransby Née Pittauer, D., & Jennerjahn, T. (2018). Variability in the organic carbon stocks, sources, and accumulation rates of Indonesian mangrove ecosystems. *Estuarine, Coastal and Shelf Science*, *218*, 310–323. https://doi.org/10.1016/j.ecss.2018.12.007

Ma, K., Liu, J., Zhang, Y., Parry, L. E., Holden, J., & Ciais, P. (2015). Refining soil organic carbon stock estimates for China's palustrine wetlands. *Environmental Research Letters*, *10*(12), Article 124016. https://doi.org/10.1088/1748-9326/10/12/124016

Maturbongs, R. A., Dransfield, J., & Baker, W. (2014). *Calamus kebariensis* (Arecaceae)—A new montane rattan from New Guinea. *Phytotaxa*, *163*(4), 235–238. https://doi.org/10.11646/PHYTOTAXA.163.4.4

Meng, Y., Bai, J., Gou, R., Cui, X., Feng, J., Dai, Z., Diao, X., Zhu, X., & Lin, G. (2021). Relationships between above- and below-ground carbon stocks in mangrove forests facilitate better estimation of total mangrove blue carbon. *Carbon Balance and Management*, *16*(1), Article 8. https://doi.org/10.1186/s13021-021-00172-9

Mensah, S., Noulèkoun, F., & Ago, E. E. (2020). Aboveground tree carbon stocks in West African semi-arid ecosystems: Dominance patterns, size class allocation and structural drivers. *Global Ecology and Conservation*, *24*, Article e01331. https://doi.org/10.1016/j.gecco.2020.e01331

Mitchard, E. T. A. (2018). The tropical forest carbon cycle and climate change. *Nature*, *559*(7715), 527–534. https://doi.org/10.1038/s41586-018-0300-2

Mizanur Rahman, Md., Nabiul Islam Khan, Md., Fazlul Hoque, A. K., & Ahmed, I. (2015). Carbon stock in the Sundarbans mangrove forest: Spatial variations in vegetation types and salinity zones. *Wetlands Ecology and Management*, *23*(2), 269–283. https://doi.org/10.1007/s11273-014-9379-x

Mukul, S. A., Halim, Md. A., & Herbohn, J. (2020). Forest carbon stock and fluxes: Distribution, biogeochemical cycles, and measurement techniques. In W. Leal Filho,

A. M. Azul, L. Brandli, A. Lange Salvia, & T. Wall (Eds.), *Life on land* (pp. 1–16). Springer International Publishing. https://doi.org/10.1007/978-3-319-71065-5_23-1

Murdiyarso, D., Donato, D., Kauffman, J. B., Kurnianto, S., Stidham, M., & Kanninen, M. (2009). Carbon storage in mangrove and peatland ecosystems: A preliminary account from plots in Indonesia. Working Paper No. 48. Bogor: Center for International Forestry Research.

Murdiyarso, D., Purbopuspito, J., Kauffman, J. B., Warren, M. W., Sasmito, S. D., Donato, D. C., Manuri, S., Krisnawati, H., Taberima, S., & Kurnianto, S. (2015). The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change*, *5*(12), 1089–1092. https://doi.org/10.1038/nclimate2734

Nengi-Benwari, A. O., Udom, B. E., & Orji, O. A. (2022). Clay conten, bulk density and carbon storage relationships in mangrove and rainforest soils during dry and wet seasons. *Journal of Global Ecology and Environment*, *15*(2), Article 2. https://doi.org/10.56557/jogee/2022/v15i27511

Nyirambangutse, B., Zibera, E., Uwizeye, F. K., Nsabimana, D., Bizuru, E., Pleijel, H., Uddling, J., & Wallin, G. (2017). Carbon stocks and dynamics at different successional stages in an Afromontane tropical forest. *Biogeosciences*, *14*(5), 1285–1303. https://doi.org/10.5194/bg-14-1285-2017

Pearson, T. R. H., Brown, S., Murray, L., & Sidman, G. (2017). Greenhouse gas emissions from tropical forest degradation: An underestimated source. *Carbon Balance and Management*, *12*(1), 3. https://doi.org/10.1186/s13021-017-0072-2

Peck, M. R., Kaina, G. S., Hazell, R. J., Isua, B., Alok, C., Paul, L., & Stewart, A. J. A. (2017). Estimating carbon stock in lowland Papua New Guinean forest: Low density of large trees results in lower than global average carbon stock. *Austral Ecology*, *42*(8), 964–975. https://doi.org/10.1111/aec.12525

Petter, G., Kreft, H., Ong, Y., Zotz, G., & Cabral, J. S. (2021). Modelling the long-term dynamics of tropical forests: From leaf traits to whole-tree growth patterns. *Ecological Modelling*, *460*, Article 109735. https://doi.org/10.1016/j.ecolmodel.2021.109735

Ragavan, P., Kumar, S., Kathiresan, K., Mohan, P. M., Jayaraj, R. S. C., Ravichandaran, K., & Rana, T. S. (2021). Biomass and vegetation carbon stock in mangrove forests of the Andaman Islands, India. *Hydrobiologia*, *848*(20), 4673–4693. https://doi.org/10.1007/s10750-021-04651-5

Robiansyah, I. (2018). Diversity and biomass of tree species in Tambrauw, West Papua, Indonesia. *Biodiversitas*, *19*(2), 377–386. https://doi.org/10.13057/biodiv/d190204

Russell, M. B., Fraver, S., Aakala, T., Gove, J. H., Woodall, C. W., D'Amato, A. W., & Ducey, M. J. (2015). Quantifying carbon stores and decomposition in dead wood: A review. *Forest Ecology and Management*, *350*, 107–128. https://doi.org/10.1016/j.foreco.2015.04.033

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T. A., Salas, W., Zutta, B. R., Buermann, W., Lewis, S. L., Hagen, S., Petrova, S., White, L., Silman, M., & Morel, A. (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences*, *108*(24), 9899–9904. https://doi.org/10.1073/pnas.1019576108

Saragi-Sasmito, M. F., Murdiyarso, D., June, T., & Sasmito, S. D. (2019). Carbon stocks, emissions, and aboveground productivity in restored secondary tropical peat swamp forests. *Mitigation and Adaptation Strategies for Global Change*, *24*(4), 521–533. https://doi.org/10.1007/s11027-018-9793-0

Seiwa, K., Sasaki, T., & Masaka, K. (2023). Important role of a few large-diameter tree species in basal area and its increase in an old-growth deciduous broadleaf forest in Japan. *Trees, Forests and People*, *13*, Article 100421. https://doi.org/10.1016/j.tfp.2023.100421

Shaverdo, H., Panjaitan, R., & Balke, M. (2016). A new, widely distributed species of the Exocelina ekari-group from West Papua (Coleoptera, Dytiscidae, Copelatinae). *ZooKeys*, *554*, 69–85. https://doi.org/10.3897/zookeys.554.6065

Sillanpää, M., Vantellingen, J., & Friess, D. A. (2017). Vegetation regeneration in a sustainably harvested mangrove forest in West Papua, Indonesia. *Forest Ecology and Management*, *390*, 137–146. https://doi.org/10.1016/j.foreco.2017.01.022

Sjögersten, S., de la Barreda-Bautista, B., Brown, C., Boyd, D., Lopez-Rosas, H., Hernández, E., Monroy, R., Rincón, M., Vane, C., Moss-Hayes, V., Gallardo-Cruz, J. A., Infante-Mata, D., Hoyos-Santillan, J., Vidal Solórzano, J., Peralta-Carreta, C., & Moreno-Casasola, P. (2021). Coastal wetland ecosystems deliver large carbon stocks in tropical Mexico. *Geoderma*, *403*, Article 115173. https://doi.org/10.1016/j.geoderma.2021.115173

Sokol, N. W., Sanderman, J., & Bradford, M. A. (2019). Pathways of mineral-associated soil organic matter formation: Integrating the role of plant carbon source, chemistry, and point of entry. *Global Change Biology*, *25*(1), 12–24. https://doi.org/10.1111/gcb.14482

Stas, S. M., Le, T. C., Tran, H. D., Hoang, T. T. H., van

Kuijk, M., Le, A. V., Ngo, D. T., van Oostrum, A., Phillips, O. L., Rutishauser, E., Spracklen, B. D., Tran, T. T. A., Le, T. T., & Spracklen, D. V. (2020). Logging intensity drives variability in carbon stocks in lowland forests in Vietnam. *Forest Ecology and Management*, *460*, Article 117863. https://doi.org/10.1016/j.foreco.2020.117863

Steinmuller, H. E., Breithaupt, J. L., Rovai, A. S., Engelbert, K. M., Smoak, J. M., Chambers, L. G., Radabaugh, K. R., Moyer, R. P., Chappel, A., Vaughn, D. R., Bianchi, T. S., Twilley, R. R., Pagliosa, P. R., Cifuentes-Jara, M., & Torres, D. (2024). Using loss-on-ignition to estimate total nitrogen content of mangrove soils. *Geoderma*, *448*, Article 116956. https://doi.org/10.1016/j.geoderma.2024.116956

Sukamto, S., & Rahmat, A. (2023). Evaluation of FTIR, macro and micronutrients of compost from black soldier fly residual: In context of its use as fertilizer. *ASEAN Journal of Science and Engineering*, *3*(1), Article 1. https://doi.org/10.17509/ajse.v3i1.42798

Taberima, S., Nugroho, Y. D., & Murdiyarso, D. (2014, September 17–18). *The distribution of carbon stock in selected mangrove ecosystem of wetlands Papua: Bintuni, Teminabuan, and Timika Eastern Indonesia* [Conference presentation]. International Conference on Chemical, Environment & Biological Sciences (CEBS-2014), Kuala Lumpur, Malaysia.

Tomlinson, P. B. (2016.) *The botany of mangroves* (2nd ed.). Cambridge University Press.

Tue, N. T., Dung, L. V., Nhuan, M. T., & Omori, K. (2014). Carbon storage of a tropical mangrove forest in Mui Ca Mau National Park, Vietnam. *CATENA*, *121*, 119–126. https://doi.org/10.1016/j.catena.2014.05.008

Walter, K., Don, A., Tiemeyer, B., & Freibauer, A. (2016). Determining soil bulk density for carbon stock calculations: A systematic method comparison. *Soil Science Society of America Journal*, *80*(3), 579–591. https://doi.org/10.2136/sssaj2015.11.0407

Wicaksono, P., Danoedoro, P., Hartono, & Nehren, U. (2016). Mangrove biomass carbon stock mapping of the Karimunjawa Islands using multispectral remote sensing. *International Journal of Remote Sensing*, *37*(1), 26–52. https://doi.org/10.1080/01431161.2015.1117679

Xu, L., He, N., & Yu, G. (2016). Methods of evaluating soil bulk density: Impact on estimating large scale soil organic carbon storage. *CATENA*, *144*, 94–101. https://doi.org/10.1016/j.catena.2016.05.001