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Biodiversity and carbon dynamics in sustainable social forestry management in West Papua Province

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Abstract

The Indonesia FOLU Net Sink 2030, launched by the Ministry of Environment and Forestry, aims to reduce greenhouse gas (GHG) emissions and increase soil carbon sequestration to achieve net zero emissions at the site level by 2030, thereby sustaining the forestry sector. However, biodiversity and carbon dynamics in Social Forestry have yet to be studied to determine their effectiveness in preserving carbon stocks and reducing GHG emissions. Systematic stratified sampling was used to create a 1 ha rectangular tract. The destructive method was applied to the understorey, litter, necromass, and soil, while biomass was measured using non-destructive sampling (an allometric equation). The biodiversity found lower INP dominance, suggesting medium to high levels across all growth phases. An H' value over 3, species richness over 100 species per hectare, and evenness index (E) above 0.8 at each phase indicate a high category and uniform distribution. The potential carbon of aboveground biomass (AGB) and belowground biomass (BGB) in Mubradiba Village was 140.85 tC/ha and 68.32 tC/ha, respectively, with AGB above 100 tC/ha and BGB exceeding 30 tC/ha. Low understory carbon was 0.33 tC/ha, below 1.5 tC/ha. There was 2.67 tC/ha of litter carbon, within the median range of 2-5. Due to its 10.67 tC/ha necromass carbon, it meets the high criterion. The soil carbon potential at 1 meter is 171.75 tC/ha, within the medium criteria range of 100-250 tC/ha. Mubradiba Village has 606.24 tC/ha of total carbon, above 500 tC/ha. Carbon is 70% above and 30% below the surface.

Keywords: Social Forestry; Biodiversity; Carbon Stock; Destructive Sampling; Non-Destructive Sampling

1 Introduction

This social forestry initiative has recorded an area of 5,522,164.64 ha from its inception in 2016 to May 2023, with a target of 12.7 million ha. It is anticipated that by 2025, it will have achieved 70% of the total target [1]. In December 2022, 9,985 social forestry business organizations were registered. Agroforestry enterprises (35%), non-timber forest products (14%), ecotourism (10%), and coffee (10%). In contrast, 30% of enterprises comprise silvopastoral, sugar palm, bamboo, rattan, silvofishery (mangrove fisheries), fruits, and honey [2,3,4]. West Papua Province is estimated to have 78,385 ha of Village Forest scheme, 16,299 ha of Customary Forest, and 1,628 ha of Community Forest as of 2023, according to data from the Indicative Map of Social Forestry Areas [5].

Social forestry in Indonesia faces numerous issues and hurdles that hinder its effective implementation and long-term sustainability. A significant difficulty is the inadequate focus on ecological aspects, especially biodiversity conservation, in Social Forestry projects. In many cases, program implementation has been predominantly driven by social and economic objectives, such as poverty alleviation, improving livelihoods, and securing tenure for local communities. At the same time, ecological integrity and biodiversity protection are often treated as secondary priorities or even neglected completely [6,7,8]. This mismatch compromises the ecological sustainability of forest regions and threatens

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the resilience of ecosystems vital for the long-term welfare of the communities. Without integrating biodiversity conservation as a core component of social forestry, these initiatives risk contributing to forest degradation, habitat loss, and a decline in ecosystem services, which may undermine the social and economic gains they aim to achieve [9,10,11].

Regulatory limitations and policy discrepancies in the forestry industry prevent numerous farmer organizations from acquiring forest management permits, particularly for community forests. Consequently, streamlining the management of forest permissions, particularly for community forests, is crucial to addressing the challenges farmers face in securing permits [12,13].

A notable barrier in the execution of social forestry in Indonesia is the ongoing difficulty in addressing conflicts arising from the intricate and overlapping matters of forest gazettlement, land administration, and population movement. The historical process of forest gazettlement in Indonesia, which involves the formal establishment of forest boundaries by the state, has often been characterized by ambiguous demarcations, inconsistencies, and inadequate engagement of local communities in decision-making processes [14]. These deficiencies have established a legacy of ambiguity regarding land status, with numerous communities living within or near state forest regions lacking legal clarity or formal acknowledgment of their customary rights. Moreover, voluntary or state-directed internal migration has exacerbated land tenure conflicts, as new populations inhabit wooded regions, confounding existing rights and overlapping land uses [15]. Resolving these conflicts necessitates legal and administrative clarity and culturally sensitive, participatory mechanisms to equitably address community claims and safeguard indigenous peoples' and local communities' rights, interests, and traditional knowledge.

Institutional barriers and a lack of progress in achieving policy outcomes have resulted from the involvement of other bureaucracies that are not aligned with the objectives of social forestry policy, a consequence of the expansion of the social forestry bureaucracy. The bureaucratic structure and design of social forestry are the primary factors contributing to the partial results and unfulfilled promises. Many bureaucracies have integrated their interests into social forestry policies, frequently surpassing the anticipated objectives, as numerous studies indicate [16,17,18].

In Indonesia, including Manokwari Regency, West Papua Province, numerous social forests have not been effectively managed in terms of strategies and efforts to enhance community welfare through product downstreaming and the advantages of carbon trading, aiming to prevent deforestation and preserve the surrounding areas [19,20]. In addition, the Ministry of Environment and Forestry has implemented Indonesia's FOLU Net Sink 2030 program to sustain the forestry sector by reducing greenhouse gas (GHG) emissions and increasing carbon absorption at the site level to a level that exceeds the amount emitted or sink in 2030. The four primary strategies for accomplishing this are the prevention of deforestation, the preservation and restoration of peatlands, the conservation and sustainable management of forests, and enhancing carbon sequestration [21]. The community is also expected to participate in these activities and benefit from the outcomes of carbon offsetting or initiatives aimed at preventing deforestation.

To mitigate climate change and guarantee ecosystem services, it is imperative to implement biodiversity and carbon management at the site level in sustainable social forestry [22]. In the context of climate change, sustainable forest management requires an understanding of the dynamics of forest biodiversity and biomass, atmospheric carbon, and land-use change. Consequently, this investigation concentrates on concerns regarding the biodiversity and total ecosystem carbon stock (TECS) in the social forestry of Mubradiba Village, Manokwari Regency.

2 Material and methods

2.1 Study area

The Regulation of the Minister of Environment and Forestry Number 9 of 2021, dated April 1, 2021, concerning Social Forestry Management, governs the area of Social Forestry in Mubradiba Village, Manokwari Regency. With a total area of 353 hectares, the geographical location is situated at the coordinates 133° 55' 26.991" E and 0º 44' 53.349" S. Protected forests, which span an area of 256 ha, and production forests, which span 97 ha, dominate the forest function status. The topography is primarily characterized by steep conditions, which account for 39.22% of the total. Slightly steep conditions (23.68%), level conditions (15.97%), sloping conditions (15.56%), and very steep conditions (5.57%) follow. The altitude is primarily dominated by classes 101-200 masl (51.82%) and 201-300 masl (29.90%), with the remaining classes being 0-100 masl (16.50%) and >300 masl (1.78%). The number of recorded residents is 114 for men and 86 for women. The community's primary sources of income are agriculture (80 people), trade (20 people), and the state civil apparatus (2 people).

Pometia pinnata and Instia bijuga are the predominant tree species. Rattan, matoa, areca nut, coconut, taro, banana, rambutan, longan, and mango are among the non-timber forest products distributed at the seedling, stake, pole, and tree levels. Bonsai ecotourism is a recognized environmental service. Turtles, birds of paradise, and king cockatoos are among the uncommon creatures that have been discovered.

The biodiversity and total ecosystem carbon stock (TECS) potential data in this study were systematically collected by establishing 100 permanent measurement sites, each with a plot size of 10 m x 10 m, encompassing an overall research area of 1 hectare (Figure 1). The design and distribution of these plots were carefully chosen to ensure that they accurately represented the diverse vegetation structures and habitat conditions prevalent in the study area. The permanent nature of these plots enables the accumulation of baseline data and long-term ecological monitoring to evaluate changes in carbon stock, forest structure, and biodiversity composition over time.

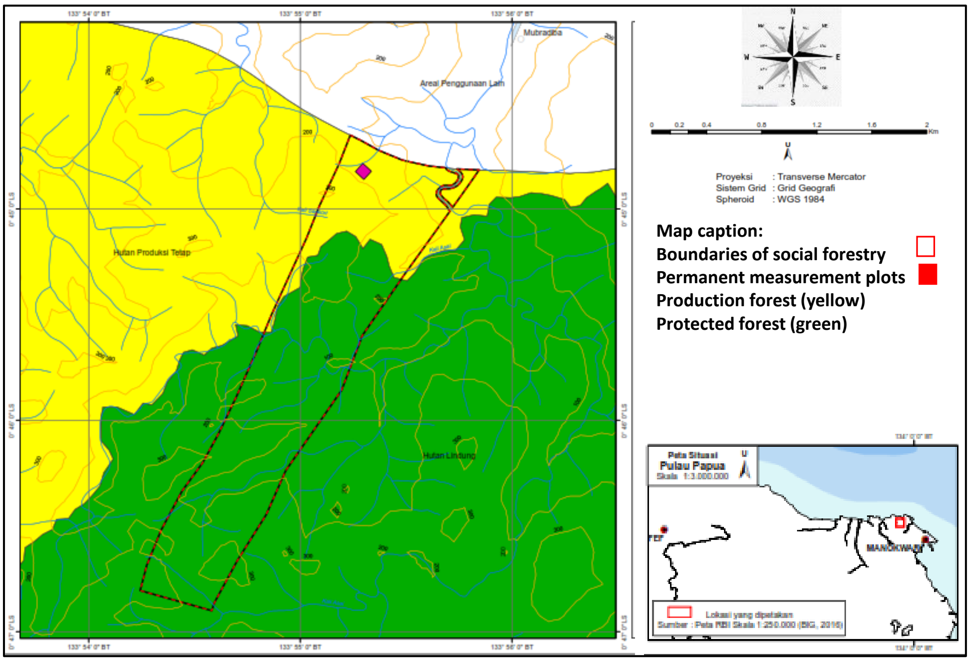

Figure 1 Social Forestry research location in Mubradiba Village

2.2 Method of data analysis

To evaluate the biodiversity and carbon stock potential within the social forestry production forest located in Mubradiba Village, Manokwari Regency, this study adopted a carefully designed sampling approach to ensure data accuracy and ecological representativeness. A purposive sampling strategy was initially employed to select the overall research area, targeting locations that reflect typical ecological conditions and land-use patterns within the social forestry landscape. Following this, a simple random sampling technique was employed as the primary method for plot establishment to reduce sampling bias and ensure that all portions of the selected area had an equal probability of being included in the study. In total, 100 sample plots were established, each with dimensions of 10 meters by 10 meters, systematically distributed across a 1-hectare permanent measuring plot using the quadratic plot measurement method to facilitate standardized data collection (Figure 2).

To improve the accuracy of vegetation stratification and carbon stock assessment, various plot sizes were employed according to the growth stage or size class of the observed vegetation. For tree-level observations, a 20 m x 20 m plot was utilised to encompass larger specimens and precisely measure tree density, biomass, and species diversity. In the pole group, comprising smaller woody plants generally in initial growth phases, 10 m x 10 m plots were employed. Observations of saplings, indicative of adolescent trees, were carried out within 5 m x 5 m plots, and 2 m x 2 m plots were allocated for documenting seedling quantity and regeneration capacity. This hierarchical plot design adheres to standardised forestry research protocols, ensuring that data collection is suitable for the size and ecological function of each vegetation stratum, thus yielding comprehensive and reliable information on biodiversity and carbon storage potential within the study area [23,24].

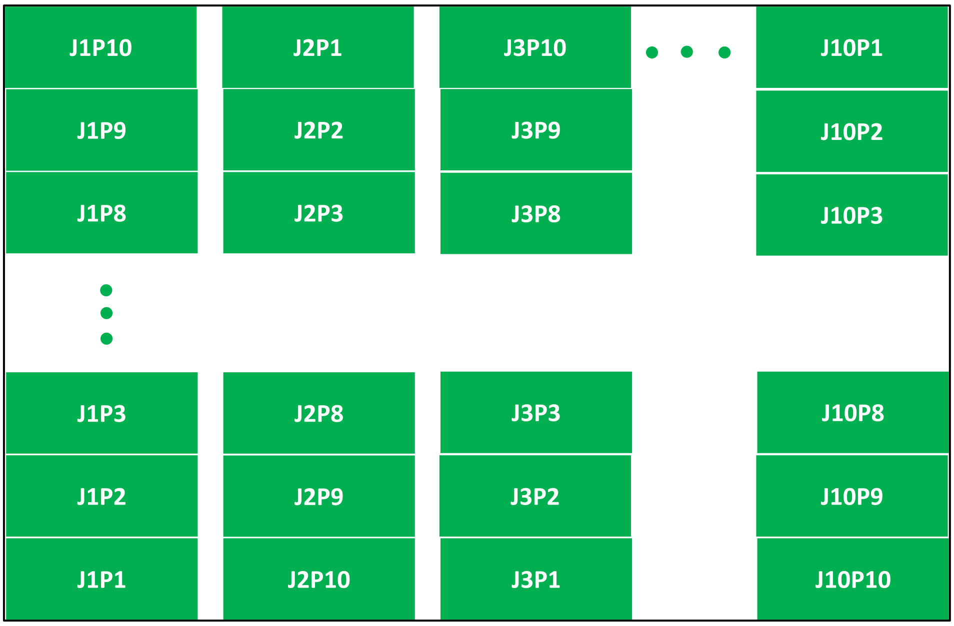

Figure 2 Permanent measurement plot plan for social forestry vegetation stand inventory in Mubradiba Village

2.2.1 Biodiversity

The structure and composition of vegetation at each growth phase can be grouped into the Importance Vegetation Index (IVI) [25] and then determined as high, medium, and low dominance with the following formula:

$$\text{Density (D)} = \frac{\text{number of individuals}}{\text{area of measurement plot}} \quad \ldots\ldots \quad 1$$

$$\text{Relative Density (RD)} = \frac{\text{density of a species}}{\text{density of all species}} \quad \ldots\ldots \quad 2$$

$$\text{Frequency (F)} = \frac{\text{number of plots where a species is found}}{\text{total number of plots}} \quad \ldots\ldots \quad 3$$

$$\text{Relative Frequency (FR)} = \frac{\text{frequency of a type}}{\text{frequency of all plots}} \quad \ldots\ldots \quad 4$$

$$\text{Dominance (Do)} = \frac{\text{area of the base of a type}}{\text{area of the plot}} \quad \ldots\ldots \quad 5$$

$$\text{Relative Dominance (RDo)} = \frac{\text{dominance of a species}}{\text{dominance of the entire plot}} \quad \ldots\ldots \quad 6$$

$$\text{IVI} = \text{RD} + \text{FR} + \text{RDo} \quad \ldots\ldots \quad 7$$

Species diversity index (H' value) is employed in biodiversity analysis to evaluate the variation patterns of abundance measurements among species [26]. Shannon-Wiener formula [27] is utilized to calculate the species diversity index:

$$H' = -\sum (pi \times \ln pi) \quad \ldots\ldots \quad 8$$

with H : the species diversity index, $\sum$: the total number of species inside the community, and Pi : the proportion of species i relative to the overall number of individual species in the community (N). The H-index value requirement is classified as follows: high (> 2.0), medium (1.6 < < 2.0), low (< 1.6), and very low (< 1.0) [28].

Species richness is the total number of species that are present in a community or ecosystem, regardless of the extent of any individual species population. [29] posits that this is an essential indicator of biodiversity, particularly concerning the species composition of a designated area. The richness value of a region increases with the discovery of additional species. Assessment criteria: high category (3) for species with a population exceeding 100; medium category (2) for species with a population between 30 and 100; and low category (1) for species with a population below 10 [30].

Evenness pertains to the degree of homogeneity in the distribution of individual species within a community. The evenness rating indicates the homogeneity of individual distribution across all existing species. If all species have almost equivalent populations, the evenness score will approach 1 (maximum). If one or more species demonstrate significant dominance, the evenness score will approach 0 (minimum) [31,32]. The formula for Evenness (E) is delineated below:

$$E = H'/\ln S \quad \ldots\ldots \quad 9$$

with E : the Evenness value, H' : the Shannon-Wiener diversity index, and S : the number of species. The E value criteria are delineated as follows: <0.25 is classified as extremely low, 0.26-0.50 as low, 0.51-0.75 as moderate, and 0.76-1.0 as high [33].

2.2.2 *Total Ecosystem Carbon Stock (TECS) Analysis*

Aboveground Biomass (AGB) and Belowground Biomass (BGB)

Carbon calculations from aboveground biomass (AGB) and belowground biomass (BGB) calculations were obtained using the allometric formula with the equation developed by [34]; referring to the allometric formula developed by [35] and [36]. The allometric formula can be seen as follows:

$$AGB = \exp\{-2.364 + 0.946 \ln(\rho_w D^2 H)\} \quad \ldots\ldots \quad 10$$
$$BGB = \exp\{-1.6603 + 0.9429 \ln(AGB)\} \quad \ldots\ldots \quad 11$$
$$TB = AGB.c_f + BGB.c_f \quad \ldots\ldots \quad 12$$

whit AGB : the estimated aboveground biomass (kg per tree, including stem and branch wood and leaf biomass), ρw : the wood density (g cm−3), D : the stem diameter (DBH in cm), H : the total tree height (m), BGB : the estimated belowground biomass (kg per tree), TB : the total carbon biomass (tC ha−1), and cf : the non-dimensional conversion factor value from biomass to carbon [37], value of 0.5).

Understorey

To estimate the carbon stock contributed by understorey vegetation within the study area, randomly selected plots measuring 2 m x 2 m were established along each designated transect path. The selection of these plots followed a systematic approach whereby an odd number of plots was consistently positioned along each transect to ensure adequate spatial representation and avoid sampling bias. This strategy was designed to capture the variability of understorey vegetation distribution along different sections of the forest area, which may be influenced by microhabitat conditions, canopy cover, and human disturbance [38].

The understorey component in this context refers to all herbaceous plants, shrubs, small saplings, ferns, and other low-growing vegetation that typically occupy the forest floor and play a crucial role in ecosystem functioning, including soil protection, biodiversity maintenance, and carbon sequestration. The biomass of these understorey plants was harvested within each 2 m × 2 m plot using standardized procedures, with samples subsequently dried and weighed to determine dry biomass values. These dry biomass measurements were then converted into carbon stock estimates by applying a generally accepted carbon conversion factor. The calculation of carbon stock from understorey vegetation was performed using the following formula [39]:

$$B = B(u).A.c_f \quad \ldots\ldots \quad 13$$

with B : the estimated understorey carbon (tC/ha), B(u) : the dry weight of understorey plants (t/m^2), A : the area (m^2/ha), and cf : the non-dimensional conversion factor from biomass to carbon [37], valued at 0.5).

Litter

Carbon sampling for litter was conducted within a 2 m x 2 m subplot, strategically placed alongside the understorey sampling plots to maximize efficiency and ensure spatial consistency in the data collection process. The litter component in this study refers to the layer of organic material that has accumulated on the forest floor, including fallen leaves, twigs, small branches, bark fragments, and other plant debris. This layer plays a crucial role in nutrient cycling, enhancing soil fertility, and temporarily storing carbon within forest ecosystems [40].

The collected litter was then cleaned of soil and other contaminants, followed by oven drying at a constant temperature to remove its moisture content. Once dried, the litter was weighed to determine its dry biomass, which serves as the basis for calculating the carbon stock contained within this forest floor component. The carbon stock of litter was estimated using the following formula, which has been widely applied in forest carbon assessment research [41]:

$$L = L(u).A.c_f \qquad 14$$

with L : the estimated carbon from litter, branches, and twigs (tC/ha), L(u) : the dry weight of litter, branches, and twigs (t/m^2), A : the area (m^2/ ha), and cf : the non-dimensional conversion factor from biomass to carbon [37], with a value of 0.5.

Utilize the following equation in the meantime for trees that have died and are in the process of decomposing [42]:

$$V_{km} = 0.25\pi(\frac{(d_p+d_u)}{2x100})^2.p \qquad 15$$

$$B_{km} = V_{km} \times \rho \qquad 16$$

with V_{km} : the volume of dead wood (m^3), dp : the diameter at the base of the dead wood (cm), du : the diameter at the tip of the dead wood (cm), p : the length of the dead wood (m), B_{km} : the biomass of dead wood (kg), and ρ : the specific gravity of dead wood (kg/m^3) [37].

Soil

Soil carbon sampling in this study was conducted within a 2 m x 2 m subplot, which was strategically established in the same area as the understorey and litter sampling plots to maintain consistency and spatial representativeness across all carbon measurement components. The selection of these subplots was based on a systematic approach to ensure that they adequately captured the overall characteristics of the soil within the research area, while avoiding areas with visible disturbances such as erosion scars, animal burrows, or footpaths. The soil within the study area was observed to be relatively uniform in terms of texture, structure, and composition, a condition that increases the reliability and representativeness of the soil carbon data obtained from these subplots [43]. The following equation expresses the computation of soil carbon:

$$S = c_f \rho_s d. 100 \qquad 17$$

where S : soil carbon (t/ha), ρs : soil density (g/cm^3), cf : the non-dimensional conversion factor from biomass to carbon [37], equivalent to 0.5), d : the vertical distance beneath the ground surface (cm), and 100 : the conversion factor.

3 Results and discussion

3.1 Biodiversity

The calculation of the Shannon-Wiener Species Diversity Index (H') for each growth phase is presented in Table 1. The table indicates that H' > 3 is present during all growth phases, signifying substantial species diversity. H' suggests that individuals across each growth phase are uniformly distributed and exhibit a significant level of species richness [44,45,46].

Table 1 Shannon-Wiener diversity index (H')

Growth Phase	H'	Criteria
Seedling	3,95	High
Sapling	3,98	High
Pole	4,28	High
Tree	3,63	High

The species diversity (richness) in social forestry of Mubradiba Village is evident from the presence of 90 species across 34 families during the seedling phase. Subsequently, there were the sapling phase, comprising 98 species from 36 families; the pole phase, encompassing 97 species from 36 families; and the tree phase, featuring 56 species belonging to 33 families. Additional research indicates that the Ile Flores Protected Forest in NTT comprises 26 species and 21 families during the pole phase, and 31 species and 22 families during the tree phase [47]. Research conducted in the

KPHL Model Protected Forest in Sorong City identified 275 species across 68 families in the seedling phase, whereas 225 species were observed in the tree phase [48].

The cumulative number of species identified during the seedling, sapling, pole, and tree stages amounted to 341 species. The species variety in Mubraidiba Village is categorised as high (criterion 3), with specific areas exceeding 100 species per hectare. This signifies favourable ecological conditions, conservation, and management of natural resources by demonstrating the degree of ecosystem health and biological complexity. These conditions are frequently observed in tropical rainforests located in the Amazon, Congo, and Indonesia, particularly Papua [49,50,51]. The diversity of forest species is influenced by climate, altitude, soil composition and nutrients, natural disturbances (such as fires, storms, and volcanic eruptions), and human activities (including deforestation, degradation, and monoculture planting) [52,53,54].

The species evenness (E) of the seedling, sapling, pole, and tree levels can be shown in Table 2. All growth phases are classified as high, indicating an equitable distribution of individuals among all current species. A high level of evenness signifies ecological stability and community resistance to external disruptions, such as environmental stresses and human activity. In West Papua's social forestry sector, community management measures, such as conserving traditional mixed gardens, significantly enhance species composition and structure [55]. Moreover, elevated evenness values strengthen the delivery of several ecosystem functions, encompassing environmental services such as carbon sequestration, soil and water conservation, and the preservation of local biodiversity.

Table 2 Evenness (E) in social forestry of Muradiba Village

Growth Phase	E	Criteria
Seedling	0,88	High
Sapling	0,87	High
Pole	0,93	High
Tree	0,90	High

3.2 Total Ecosystem Carbon Stock (TECS)

3.2.1 Total Biomass

The carbon dynamics during the pole phase identified 97 species and 36 families, predominantly represented by *Pimelodendron amboinicum* (IVI 15.00), *Litsea timoriana* (IVI 14.44), *Pometia pinnata* (IVI 12.12), and *Sterculia macrophylla* (IVI 11.24). These species are classified as least concern, with their availability in nature being stable, unknown, or decreasing. The INP is identified in superior species, specifically *Pterygota horsfieldii* (IVI 7.76), *Diospyros papuana* (IVI 7.75), *Elaeocarpus angustifolius* (IVI 7.68), *Celtis philippensis* (IVI 7.39), *Maasia sumatrana* (IVI 7.04), *Inocarpus fagifer* (IVI 6.74), *Artocarpus altilis* (IVI 6.49), *Mallotus philippensis* (IVI 6.33), and *Dracontomelon dao* (IVI 6.14), all classified as of least concern, with their availability in nature being stable, unknown, or diminished. High and medium IVI correlate with elevated carbon content.

Low IVI identified four species classified as vulnerable: *Horsfieldia sylvestris*, *Syzygium anomala*, *Koordersiodendron pinnatum*, and *Pterocymbium beccarii*, whose presence in the wild is uncertain and has diminished. Furthermore, there are three species classified as endangered: *Pandanus furcatus*, *Drypetes sp*., and *Sloanea pulei*, whose presence in the wild remains uncertain. The remaining species are classified as near threatened (*Canarium decumanum*), with their natural availability being uncertain. Meanwhile, 76 other species are categorized as of Least Concern, exhibiting steady, unknown, or declining availability in nature [56]. The carbon stock capacity during the sapling period is 12.92 tC/ha. This value lies within the range of sapling and tree phases. The mean increase in diameter and height during the sapling phase is 13.4 cm and 7.1 m, respectively, which undoubtedly enhances carbon stock capacity in this phase.

Carbon recapitulation during the tree phase was conducted on 56 species across 33 families, characterised by high and medium INP, specifically *Pometia pinnata* (IVI 40.27), *Ficus benjamina* (IVI 21.70), *Pimelodendron amboinicum* (IVI 17.55), and *Elaeocarpus angustifolius* (INP 15.10), all classified as least concern with stable or declining populations in the wild. Four varieties of IVI identified as vulnerable include *Koordersiodendron pinnatum, Garcinia picrorhiza, Syzygium anomala*, and *Pterocymbium beccarii*, whose natural abundance is uncertain and has diminished. Other species classified as near threatened include *Canarium decumanum*, whose natural availability remains doubtful, while 47 more species are categorised as least concern, exhibiting steady, unknown, or declining availability in nature [56].

The estimated total biomass carbon stock during the tree phase was determined to be 209.18 tC/ha, comprising aboveground biomass (AGB) and belowground biomass (BGB) values of 140.85 and 68.32 tC/ha, respectively. The AGB value in social forestry of Mubradiba Village is categorised as high, exceeding 100 tC/ha, while the BGB is likewise rated as high, above 30 tC/ha [57]. Research on aboveground biomass (AGB) carbon potential in various locations indicates 269.2 tC/ha in Bukit Tigapuluh National Park, Sumatra [58], 112.39 tC/ha in the Pesanggrahan Malang forest area [59], 140.02 tC/ha in KGPAA Mangkunagoro Grand Forest Park [60], and 174.95 tC/ha in primary forest in Seram, Maluku [61]. The biomass carbon value remains within the range of carbon values seen in the world's tropical forests, which is between 87 to 387 tC/ha [62].

3.2.2 Understorey

The seedling phase was used to estimate carbon in understory plants. The dominance of high and medium IVI was determined in several varieties, including *Palaquium amboinense* (IVI 19.76), *Pometia pinnata* (IVI 16.77), *Pimelodendron amboinicum* (IVI 11.98), and *Haplolobus lanceolatus* (IVI 7.19). These varieties are classified as having a low concern status, and their availability in nature is stable, unknown, or decreasing. The destructive sampling method was employed to calculate the wet weight of understory carbon on a 1 m x 1 m plot in several designated odd plots. The damp weight was subsequently dried in the Forestry Research and Development Laboratory at 80°C for three days. The carbon content of the dried weight was determined using Equation 13. The understory carbon results in the social forestry of Mubradiba Village were 0.33 tC/ha (Figure 3).

The carbon potential of understorey vegetation refers to the capacity of various plant species, including shrubs, herbs, grasses, ferns, and tree seedlings, to bind or assimilate carbon. These plants are located beneath the primary forest canopy. The carbon absorption capacity and biomass quantity of this potential category are typically categorized as high, medium, or low [63, 64, 65]. The carbon potential value of understory plants in the social forestry of Mubradiba Village is classified as low, with a value of less than 1.5 tC/ha. This suggests a problem associated with the regeneration of trees, shrubs, vegetation, and grasses in disturbed social forest conditions at the nursery stage. Note: high criteria (> 5 tC/ha) and medium criteria (1.5 – 5 tC/ha).

3.2.3 Litter

Litter carbon measurements were acquired by collecting decaying leaves, branches, and twigs on the lower floor, which were sourced from the sapling, pole, and tree phase levels. The destructive sampling method was also employed for litter collection, which involved collecting decomposing materials on a 2 m x 2 m plot in several randomly selected odd-numbered plots. Litter is frequently discovered in areas where decaying wood is present, with a dry weight of 1,011.67 gr after being desiccated at the Forestry Research and Development for three days at a temperature of 80°C. The range of dried weight values reaches 399.35 gr in regions where there is no decaying wood. Additionally, equation 16 is employed to determine the carbon content of the debris by calculating its dry weight. In the PS Kampung Mubraidiba area, the carbon in refuse results were 2.67 tC/ha (Figure 3). The refuse carbon potential results are classified as moderate, with a carbon range of 2-5 tC/ha. Note: high criteria (> 5 tC/ha) and medium criteria (2-5 tC/ha).

The medium category litter carbon value suggests that the ecological function is still functioning effectively, as the litter carbon content contributes to the recycling of soil nutrients, serves as an energy source for microorganisms, and provides short-term carbon storage. Nevertheless, this value is not optimal when compared to natural forests or pure conservation. Consequently, there is still potential for development through litter conservation practices, such as refraining from burning and frequently cleaning up litter. Thus, the ecosystem is likely to remain relatively healthy; however, it is still susceptible to disturbances such as land clearance or other forms of agricultural intensification, as decomposition activities have been ongoing. The magnitude of litter carbon value in community forests in Gunung Kidul, Jogjakarta is 2.1-2.9 tC/ha [66]. Additionally, mangrove rehabilitation in Ngurah Rai Grand Forest Park, Bali is 3.7-4.2 tC/ha [67], Social Forestry rubber agroforestry in Jambi is 2.4-3.2 tC/ha [68], and Village Forests in Central Maluku are 1.8-2.6 tC/ha [69].

3.2.4 Necromass

The decaying wood and branches (necromass) in the social forestry of Mubradiba Village are primarily characterised by the discovery of approximately nine large logs (diameter > 50 in and length exceeding 5 m) and the collapse of several large trees. The estimated wood density for decaying wood is 0.3. The necromass was discovered in plots J1P1, J1P5, J1P7, J2P5, J3P5, J5P9, J6P5, J7P7, and J9P5.

The diameter of the tip, base, and middle, as well as the length of the decaying wood, were measured non-destructively during the sampling process. Subsequently, the prospective value of necromass carbon was determined by utilising equations 17 and 18. The necromass carbon result in the location was 10.67 tC/ha (Figure 3). Consequently, the total carbon potential of understory vegetation, litter, and necromass was determined to be 13.67 tC/ha, which is close to the carbon content of global tropical forests, which range from 14 to 138 tC/ha [62].

The high criteria include the potential value of necromass carbon in the research area, which exceeds 10 tC/ha. This suggests the presence of large trees that perish naturally and a natural decomposition process that is crucial for nutrient cycles, carbon storage, and habitats for biodiversity, including decomposing insects and soil microorganisms. Also, it indicates high forest productivity. A forest system that remains intact is characterized by necromass, which serves as a temporary carbon storage container before being released into the atmosphere through decomposition. Nevertheless, the presence of an excessive amount of necromass for an extended period without regeneration can also serve as an indicator of ecosystem stress, such as drought, wind, or disease [70].

The natural secondary forest in Lore Lindu National Park (Central Sulawesi) has a necromass carbon content of 9.2-11.5 tC/ha [71], community forests in Gunung Kidul (Jogjakarta) have a necromass carbon content of 2.3-4.8 tC/ha [66], rubber agroforestry (Jambi) has a necromass carbon content of 3.1-6.5 tC/ha [68], and Kapuas Hulu Village Forest (West Kalimantan) has a necromass carbon content of 6.7-9.8 tC/ha [72]. Note: median criteria (5-10 tC/ha) and low criteria (<5 tC/ha).

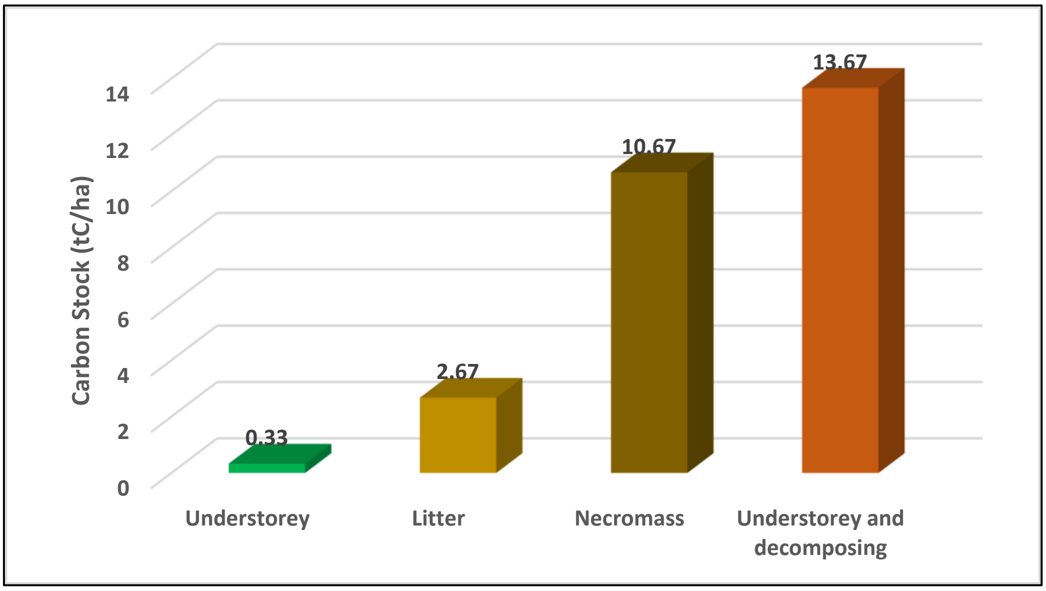

Figure 3 Understorey and decaying carbon stocks in the social forestry of Mubradiba Village

3.2.5 Soil

Several sample points were obtained from five plots in the social forestry-production forest, including J1P1, J1P10, J5P5, J1P1, and J10P10, representing the front, rear, and middle sections. The potential of organic carbon in the soil was 12.23% at these locations. This sampling was conducted on a 1 m x 1 m plot in the selected plot using a destructive method to create a soil profile at a depth of 1 m. Additionally, an average of two layers of soil were extracted from each stratum, which varied in color. The carbon content was obtained from the Forestry Laboratory of the University of Papua, and the soil carbon potential was calculated using equation 19. This equation also necessitates the soil density, which was determined from laboratory results. The average soil density was 0.67 g/cm^3. With each %C content per stratum of soil depth, a carbon potential of 171.75 tC/ha was determined (Figure 4). The high soil carbon value is a result of the substantial quantity of decaying litter in the field, which facilitates the incorporation of carbon into the soil, resulting in a high percentage of carbon (%C).

The soil carbon potential value of 100-250 tC/ha in Mubraidiba Village is classified as moderate at a depth of 1 m. This value indicates that the soil continues to store substantial quantities of carbon, which is crucial for preserving ecosystem structure, enhancing soil productivity, and mitigating climate change. This condition remains highly pertinent to Social Forestry, as it demonstrates that community management practices have effectively preserved soil quality and contributed to carbon stocks. Nevertheless, this value is also susceptible to a decline in the event of land conversion, fire, or intensive processing, which can result in the release of carbon in the form of CO_2 into the atmosphere. Research conducted in other locations has demonstrated that peat village forests in Kapuas Hulu (West Kalimantan) have a carbon content of 280-400 tC/ha [72], rubber agroforestry (Jambi) have a carbon content of 150-220 tC/ha [68], village forests in Central Maluku have a carbon content of 160-230 tC/ha [69], and community forests in Gunung Kidul (Jogjakarta) have a carbon content of 120-170 tC/ha [66]. Note: medium criteria (100-250 tC/ha) and low criteria (<100 tC/ha).

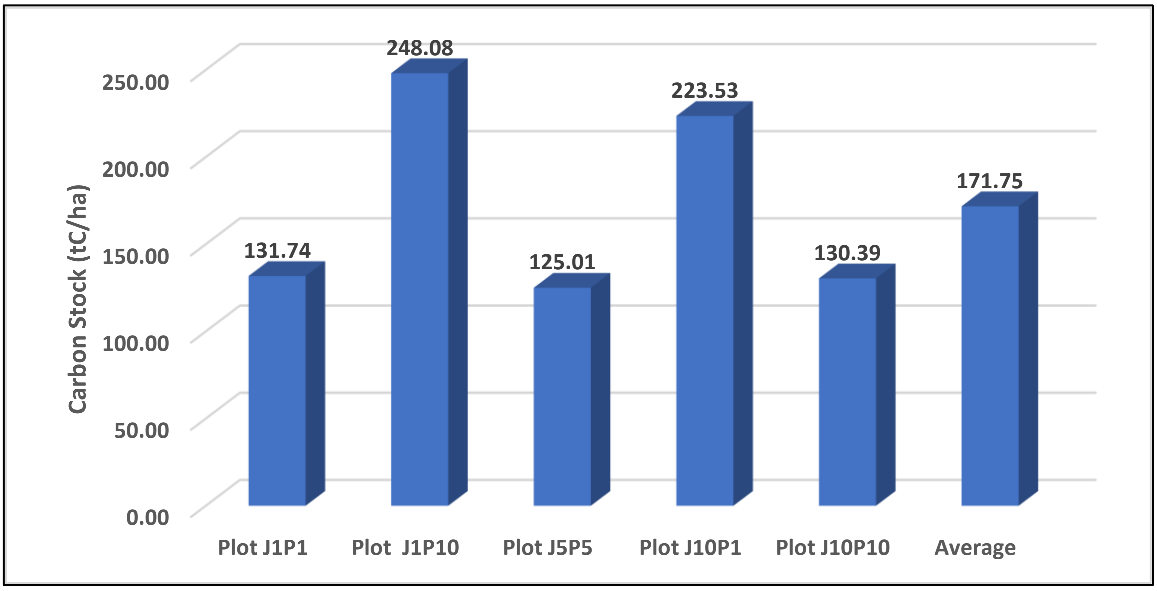

Figure 4 Soil carbon stocks in the social forestry of Mubradiba Village

3.2.6 Total Ecosystem Carbon Stock (TECS)

The total carbon potential in social forestry of Mubradiba Village is 606.24 tC/ha, which is derived from the total biomass, understory, detritus, necromass, and soil (Figure 5). The total biomass and soil are the primary sources of carbon, accounting for 69.41% and 28.33%, respectively. The carbon proportions that remain are 1.76%, 0.44%, and 0.05% in necromass, debris, and understory, respectively. Consequently, the ratio of carbon between the above-ground and below-ground regions is 70:30. This proportion is frequently observed in agroforestry forests, old secondary forests, or regions with high decomposition. This value is also observed in rubber agroforestry areas in Jambi, where the proportion of ABG is 70% and BGB is 30% [68]. ABG and BGB proportions of 60-70% and 30-40%, respectively, were achieved in community forests in Gunung Kidul (Jogjakarta) [66]. ABG and BGB proportions of 70% and 30%, respectively, were also achieved in industrial plantation forests in Perhutani Java [73]. The proportions of AGB and BGB in the world's tropical plantation forests (teak and Eucalyptus) are nearly identical, at 60-75% and 25-40%, respectively [74].

The site's total carbon potential is classified as elevated, exceeding 500 tC/ha. This value indicates that the ecosystem is highly effective in mitigating climate change, as it can store substantial quantities of carbon in both biomass and soil. Consequently, this region may be a priority for conservation or protection. In the context of Social Forestry, this demonstrates the efficacy of community management in preserving ecological sustainability and the potential to secure carbon incentives (e.g., through voluntary carbon initiatives or REDD+).

Additionally, other studies have demonstrated that the total potential value of carbon in rubber agroforestry PS in Jambi is 220-350 tC/ha [68], community forests in Gunung Kidul (Jogjakarta) are 180-250 tC/ha [66], lowland natural forests in Papua are 600-850 tC/ha [67], tropical rainforests in Brazil are 400-700 tC/ha [75], and tropical rainforests in Congo are 450-600 tC/ha [76]. Note: median criteria (200–500 tC/ha) and low criteria (< 200 tC/ha).

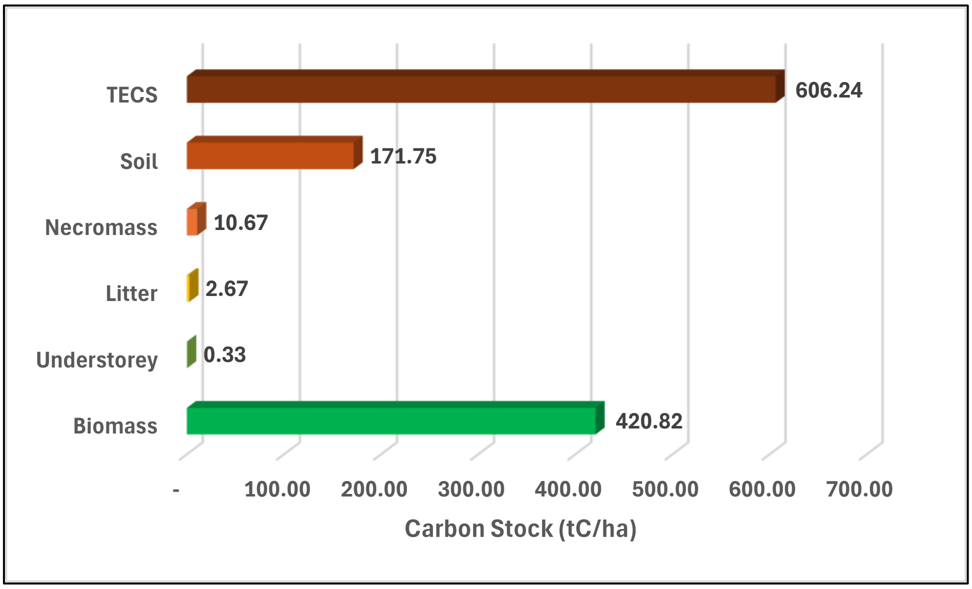

Figure 5 TECS in social forestry of Mubradiba Village

4 Conclusion

The identification of species diversity in PS Kampung Mubraidiba revealed that INP dominated at a lower level, then medium and high levels in all growth phases. This suggests that the stand structure has not yet attained a climax or is not yet balanced, which could be a result of logging. The species diversity of the H' value > 3, the number of species (richness) > 100 species/ha, and E > 0.8 in each phase indicate a high category and are evenly distributed.

The carbon potential of aboveground biomass (AGB) and belowground biomass (BGB) in PS Kampung Mubraidiba was determined to be 140.85 and 68.32 tC/ha, respectively. The AGB value is classified as high when it exceeds 100 tC/ha, and the BGB value is classified as high when it exceeds 30 tC/ha. The understory carbon results were 0.33 tC/ha, which falls within the low category, with a value of less than 1.5 tC/ha. The carbon range of 2-5 tC/ha is classified as moderate for litter carbon, which is attained at 2.67 tC/ha. Necromass carbon was measured at 10.67 tC/ha, which meets the high criteria of a value exceeding 10 tC/ha. 171.75 tC/ha is classified as moderate soil carbon potential at a depth of 1 meter, with a value of 100-250 tC/ha. Therefore, the total carbon produced at PS Kampung Mubraidiba is classified as high, with a value of 606.24 tC/ha, which exceeds the threshold of 500 tC/ha. The ratio of carbon above and below the surface is 70:30.

Compliance with ethical standards

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Disclosure of conflict of interest

There is no conflict of interest.

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