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Assessment of Carbon Capture and Storage in Plantation and Garden Agroecosystems in Tuntang Hulu Sub-Watershed

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ABSTRACT

Agroecosystems such as gardens and plantations play a crucial role in climate change mitigation through carbon capture and storage (CCS). This study aimed to analyze the carbon storage potential of these two agroecosystem types in the Tuntang Sub-Watershed and to examine the factors influencing it. A quantitative-descriptive approach was employed, involving biomass measurement both above and below round, along with analyses of soil physical and chemical properties at 41 sampling points. Results showed that the average CCS capacity in plantation areas reached 380.51 tons/ha, slightly higher than that of gardens at 333.30 tons/ha, although the difference was not statistically significant. Contributing factors to carbon storage capacity included vegetation type, soil pH, soil texture, and bulk density. Plantations were dominated by perennial woody crops producing higher biomass, whereas gardens were more commonly planted with annual crops. Therefore, well-planned vegetation management, particularly mixed agroforestry systems, has the potential to enhance CCS efficiency. These findings serve as an important foundation for planning sustainable agroecosystem management as a strategy for climate change adaptation and mitigation.

1. INTRODUCTION

Carbon plays a crucial role in regulating climate change and maintaining soil fertility, with its function reflected in the carbon cycle within ecosystems. The carbon cycle is a biogeochemical process in which carbon is exchanged among the geosphere, biosphere, atmosphere and hydrosphere, thereby influencing ecosystem balance, the Earth's climate system, soil fertility, and regulating the concentration of carbon dioxide (CO_2) in the atmosphere. Therefore, the carbon cycle not only affects the continuity of life on Earth but also helps maintain overall environmental stability (Sarwono, 2016). One of the forms of carbon that strongly influences ecosystems is CO_2, as it plays a significant role in driving global warming. The excessive release of carbon dioxide into the atmosphere can lead to a rise in global temperatures, which is closely associated with climate change and may have harmful effects on both the environment and human life. On the other hand, CO_2 plays an essential role for plants as it is required for the process of photosynthesis (Kartika *et al.*, 2017). In addition, carbon stored in the soil in the form of soil organic carbon also contributes to improving soil fertility. To maintain carbon balance within ecosystems, various types of agroecosystems play a role in capturing and storing carbon, including garden and plantation agroecosystems. Both of these agroecosystems are dominated by perennial plants or trees, which have a high capacity for carbon absorption. In the context of carbon cycle sustainability, agroecosystems play a vital role as one of the natural mechanisms that support carbon balance on Earth.

An agroecosystem refers to a human modified ecosystem designed to fulfill food and clothing needs by combining biological and physical components within an agricultural setting (Mooduto *et al*., 2024). In this context, there are various types of agroecosystems, including garden agroecosystems and plantation agroecosystems. Garden agroecosystems are typically cultivated on small to medium plots, combining a variety of crops such as food and horticultural plants. They are often managed through agroforestry practices by individuals or small community groups on household owned land. Management is carried out to meet the needs of local communities, relying on traditional or semi modern practices and characterized by limited technological input (Indrawati *et al.*, 2022). In contrast, plantation agroecosystems are generally organized on an extensive scale and are typically overseen by large enterprises or institutions specializing in the cultivation of high-value crops such as oil palm, rubber wood, tea, and coffee (Parinduri & Parinduri, 2020; Widodo & Mahagiyani, 2022). Garden and plantation agroecosystems both involve cultivation systems shaped by biotic and abiotic factors. However, despite these similarities, they differ in characteristics such as scale, crop types, and management practices. These distinctions influence their capacity to capture and store carbon through the Carbon Capture and Storage (CCS) mechanism. The differing characteristics of garden and plantation agroecosystems also have implications for their respective capacities to absorb and store carbon, which are closely linked to the CCS mechanism.

Carbon Capture and Storage (CCS) is a natural process in which carbon dioxide is absorbed by plants through photosynthesis, converted into oxygen, and partially stored as biomass in trees, grasses, and shrubs. Meanwhile, carbon retained in the soil is referred to as soil organic carbon, which contributes to enhancing soil fertility (Parinduri & Parinduri, 2020). In both garden and plantation agroecosystems, intensive and diverse cultivation practices may exert positive or negative effects on soil carbon. Therefore, the CCS capacity in agroecosystems is influenced by multiple factors. These include the type of vegetation cultivated, vegetation age, vegetation density, soil conditions, and cultivation techniques employed (Farrasati *et al.*, 2019).

Various types of agroecosystems, including gardens and plantations, possess distinct characteristics that influence their carbon sequestration capacity. Mixed gardens generally contribute larger carbon reserves compared to monoculture plantations. This is due to the application of agroforestry systems in mixed gardens, which enable greater biomass accumulation through species diversity and complex vegetation structures, while also providing stronger carbon storage capacity than monoculture systems (Violetta *et al.*, 2024). Agroforestry dominated by perennial or woody plants offers greater carbon storage potential than agricultural crops, which store relatively small and temporary amounts of carbon. Alongside the decline in forest quality and the growing public awareness of tree planting, agroforestry practices on private lands hold considerable potential to support the functions of protected and conservation areas. Studies indicate that carbon reserves in cacao-based agroforestry systems are higher than in cacao monocultures, while soil organic carbon stocks in mixed gardens also surpass those in monoculture lands, highlighting that polyculture practices can enhance soil carbon content (Sitohang *et al.*, 2022). This is particularly relevant in the context of agroecosystems in the Tuntang Sub-Watershed, where diverse garden and plantation systems are likely to have varying CCS capacities.

Management system of gardens and plantations in the Sub DAS Tuntang region is predominantly based on agroforestry. Multiple factors influencing CCS capacity are also evident in the agroecosystems of Tuntang Sub-Watershed, Semarang Regency. This area hosts diverse agroecosystems, including mixed gardens owned by local communities with crops such as sengon and coffee, as well as state-owned plantations dominated by rubber wood and coffee cultivated in both monoculture and mixed systems. The variation in topography further affects the capacity of each agroecosystem to sequester carbon. Garden and plantation agroecosystems play a role in carbon capture and storage through the CCS mechanism, yet their capacity differs according to vegetation type, management practices, and environmental conditions (Anika *et al*., 2024). Sub DAS Tuntang is also an industrial zone with high CO_2 emissions, highlighting the need for studies on the contribution of gardens and plantations to CCS in this area. Although mixed gardens have greater potential for carbon storage than monoculture plantations, empirical data on CCS in Sub DAS Tuntang remain limited. Research on specific factors influencing differences in carbon storage capacity in this region is also scarce. Meanwhile, several studies have identified that carbon storage variability is determined by a combination of biophysical factors, such as vegetation type, soil texture, moisture, and pH, as well as land management practices (Xu *et al.*, 2020). In Indonesia, most CCS research has focused on peatlands or mangrove ecosystems due to their significant role in the national carbon cycle (Juliano *et al.*, 2024). Garden and plantation agroecosystems in Tuntang Sub-Watershed, however, have received little in-depth investigation. Therefore, this study aims to assess CCS capacity in these agroecosystems and to identify the factors contributing to differences in carbon storage capacity between them. The findings are expected to provide valuable insights for developing sustainable agroecosystem management strategies and optimizing their role in climate change mitigation.

2. MATERIALS AND METHODS

2.1. Research Time and Location

This research was conducted from July to November 2024. Sampling was carried out in the Upper Tuntang Sub-watershed, located at coordinates 10° 15′ 50″ E – 110° 33′ 20″ E and 06° 51′ 25″ S – 07° 26′ 40″ S, which is traversed by two tributaries, namely the Senjoyo River (120 km²) and the Bancak River (140 km²). The total area of the Tuntang watershed is 108,973.04 ha. This region encompasses garden and plantation agroecosystems, which are the primary focus in assessing the capacity of Carbon Capture and Storage (CCS).

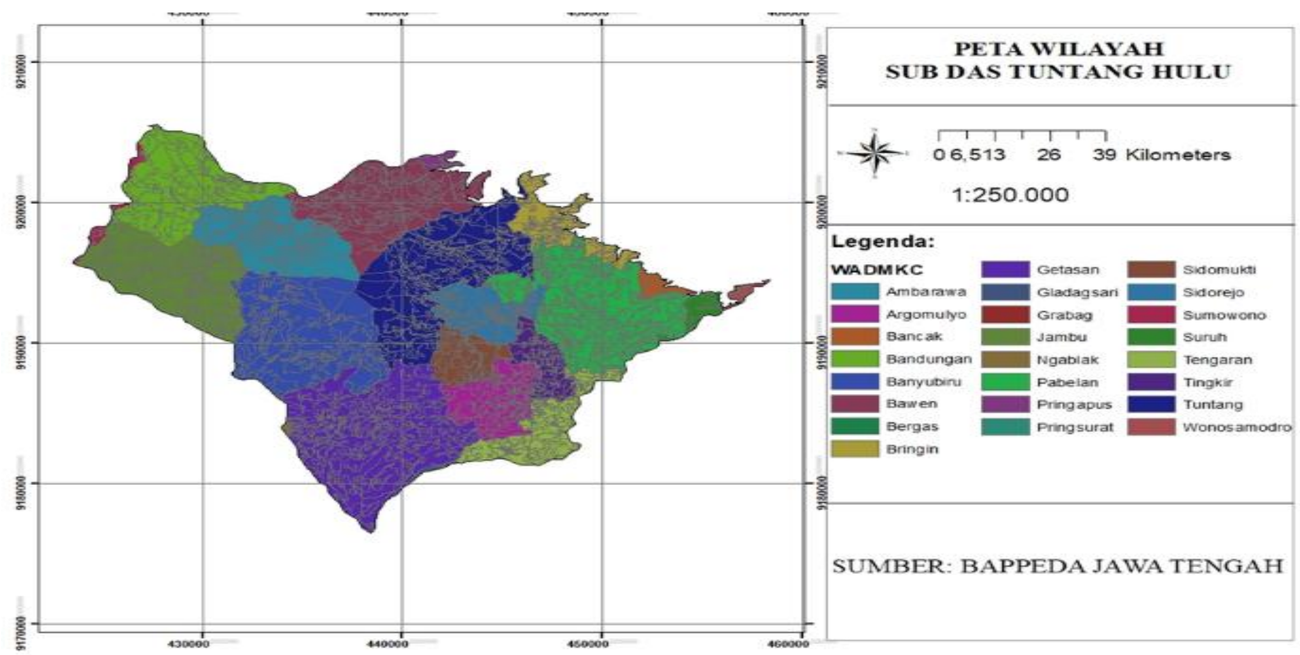

Figure 1. Administrative map of the Tuntang Sub-Watershed

2.2. Method

This study employed a quantitative descriptive design using observation and laboratory analysis to describe the phenomenon of Carbon Capture and Storage in both garden and plantation agroecosystems. Prior to fieldwork, several preparatory steps were carried out, including the collection of secondary data on land use, topography, and agroecosystem management practices in the Upper Tuntang Sub-watershed, to gain an initial understanding of the research site's characteristics. Sampling points were determined using probability sampling with a stratified random sampling technique. This method was selected because it provides a more accurate representation of a heterogeneous population by dividing it into strata based on agroecosystem factors, ensuring that each category within the ecosystem is proportionally represented (Obenu, 2020). Materials used to determine the sampling points included soil maps, topographic maps, land use maps, DEM (Digital Elevation Model), and Sentinel imagery. These maps were analyzed using ArcGIS 10.8 (2019) with supervised classification. Supervised classification was applied to identify land use (agriculture and non-agriculture). The results were further analyzed to classify land into gardens and plantations, and to calculate the area of each agroecosystem as well as estimate carbon storage potential using NDVI (Normalized Difference Vegetation Index). A total of 41 sampling points were selected across the Tuntang Sub-Watershed. These consisted of 28 points for gardens and 13 points for plantations (Figure 2). Sampling locations were systematically selected to represent land characteristics in the study area, so that the results could provide a comprehensive overview of environmental conditions in the Tuntang Sub-Watershed.

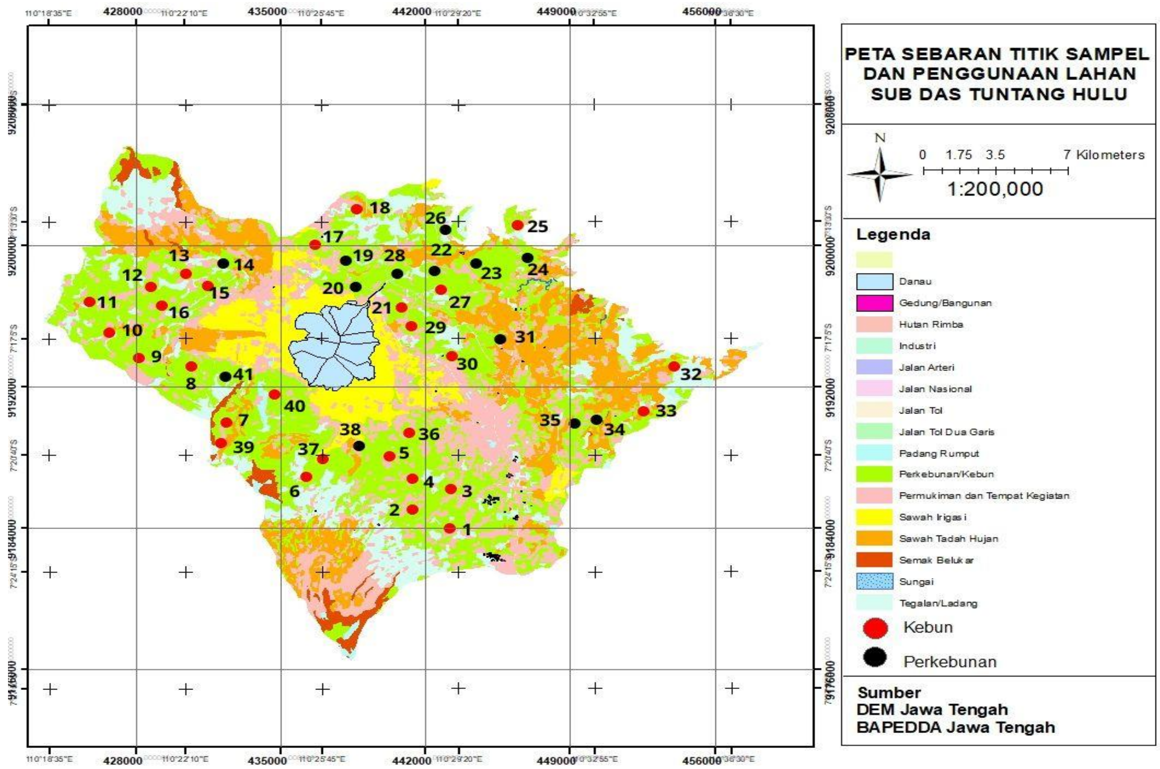

Figure 2. Distribution map of sampling points and land use in the Tuntang Sub-Watershed

Table 1. Sampling location for land utilization unit of garden and plantation

Sample No.	Land Use	Coordinates		Sample No.	Land Use	Coordinates	
		(X-Longitude)	(Y-Longitude)			(X-Longitude)	(Y-Longitude)
1	Garden	110.48230	7.38208	22	Plantation	110.47920	7.24816
2	Garden	110.45623	7.38076	23	Plantation	110.49672	7.24598
3	Garden	110. 48112	7.36872	24	Plantation	110.51390	7.24515
4	Garden	110.28092	7.21243	25	Garden	110.51632	7.22704
5	Garden	110.27260	7.20372	26	Plantation	110.48305	7.22793
6	Garden	110.42072	7.35715	27	Garden	110.48240	7.26069
7	Garden	110.23091	7.19441	28	Plantation	110.27513	7.14537
8	Garden	110.37390	7.29958	29	Garden	110.46658	7.27874
9	Garden	110.34947	7.29484	30	Garden	110.48776	7.29514
10	Garden	110.33671	7.28191	31	Plantation	110.50892	7.28571
11	Garden	110. 32718	7.24871	32	Garden	110.58016	7.29556
12	Garden	110.35162	7.25784	33	Garden	110.57114	7.32151
13	Garden	110.36915	7.25374	34	Plantation	110.54940	7.32581
14	Plantation	110.23051	7.14483	35	Plantation	110.54075	7.3269
15	Garden	110.37866	7.25708	36	Garden	110.46801	7.33260
16	Garden	110.35826	7.26950	37	Garden	110.42468	7.34489
17	Garden	110.25444	7.14119	38	Plantation	110.44820	7.20190
18	Garden	110.26407	7.13003	39	Garden	110.38561	7.33793
19	Plantation	110.44301	7.244911	40	Garden	110.40855	7.31253
20	Plantation	110.26282	7.14409	41	Plantation	110.23167	7.18189
21	Garden	110.46316	7.26522				

2.3. Procedure

2.3.1. Biomass Carbon Measurement

A total of 41 observation plots were established within plantation and garden agroecosystems distributed across the Tuntang Sub-Watershed. The plots were laid out as square plots (Figure 3) and adjusted to the growth stage of vegetation. Plot sizes included: (i) 20 m × 20 m for trees (diameter ≥ 10 cm, measured at breast height/DBH = 1.3 m), (ii) 10 m × 10 m for poles (diameter 2–10 cm), (iii) 5 m × 5 m for saplings (height > 1.5 m and diameter < 2 cm), and (iv) 2 m × 2 m for seedlings (height < 1.5 m). The subdivision of plots followed standard vegetation analysis methods commonly applied in tropical forest ecology (Salviana *et al*., 2024).

Data collection was conducted directly through field exploration. Plant species found in each subplot were recorded, and vegetation parameters were measured. Data collected included DBH measurement, species identification, and the number of trees in each plot.

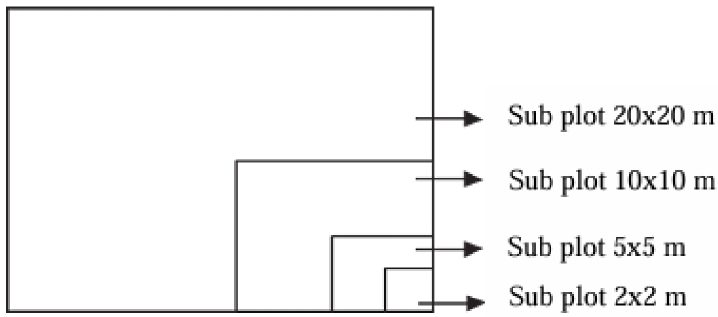

Figure 3. Sampling plot design

Vegetation analysis was conducted quantitatively to determine species dominance by calculating the Importance Value Index (IVI), which is obtained from the sum of Relative Density (RD), Relative Frequency (RF), and Relative Dominance (RDo) of each species.

$$INP = KR + FR + DR \tag{1}$$

The IVI results were used to identify dominant species. These stand data were then used for biomass calculation and tree carbon estimation at the plot scale (Melaponty *et al*., 2019).

2.4. Below ground Carbon Measurement

2.4.1. Soil Sampling

At each sampling point, soil samples were collected using a soil ring at a depth of 30 cm topsoil to determine bulk density. Each sampling point consisted of several subsamples that were combined into a composite sample to represent one observation plot. Samples were taken from a depth of 0–15 cm during moderately dry soil conditions. The collected samples were air-dried for 7 days The composite soil was then sieved to obtain data on texture, pH, and C-organik % (Gebre, 2018).

2.4.2. Laboratory Sampel Preparation

Soil samples were air-dried in a shaded area, then sieved using a 2 mm mesh to separate coarse materials. The homogenized samples were stored in sealed containers prior to further analysis.

2.4.3. Laboratory Analysis

Physical and chemical properties of soil including pH, EC, EH, C-organic, soil texture, and bulk density were analyzed properly. Table 1 summarized methods and equipment used for the analysis.

Table 2. Laboratory analysis methods

No	Parameter	Analysis Method	Reference
1	pH	Solvent H_2O	(Yanti & Kusuma, 2021)
2	EC (µS/cm)	EC meter	(Swardana *et al.*, 2022)
3	EH (mV)	EH meter	
4	C-organic (%)	Walkey and Black	(Farrasati *et al.*, 2019)
5.	Soil Texture	Bouyoucos Hydrometer	(Cenkseven *et al.*, 2017)
6.	Soil bulk density	Ring sample	(Gebre, 2018)

2.5. Data Analysis

Data analysis was conducted using the biomass method (IPCC, 2008). The association between soil organic carbon content and soil physicochemical properties was assessed. Statistical analyses were performed, with the t-test applied to identify significant differences among land-use types. The findings were then compared with previous research to provide deeper insights into the role of plantation and garden agroecosystems in carbon storage within the Tuntang Sub-Watershed.

3. RESULTS AND DISCUSSION

3.1. Soil Characteristics

The soils in the study area, which fall within garden and plantation agroecosystems, are predominantly classified as *Hapludands Dystrudepts*. This soil type belongs to the Andisol order, with Hapludands formed from volcanic ash as the parent material (Harahap *et al.*, 2020). *Hapludands Dystrudepts* are typically found in dry agricultural lands and are characterized by the physical and chemical properties presented in Table 3.

Table 3. Soil chemical and physical characteristics

No	Parameter	Analysis Method	Value (Mean±Standard Deviation)	
			Plantation	Garden
A	Chemical			
	pH	Solvent H_2O	6.1 (slightly acidic)±0.21	6.2 (slightly acidic)±0.26
	EC (µS/cm)	EC meter	54.3±33.5	108.4±263.16
	EH (mV)	EH meter	54.09±13.6	45.21±16.29
	C-organic (%)	*Walkey* and *Black*	5.33±1.71	5.53±2.06
B	Physical			
	Soil Texture			
	Sand (%)	*Bouyoucos Hydrometer*	21.19	20.43
	Dust (%)		65.14	65.54
	Clay (%)		13.68	14.02
	Soil bulk density	Sample ring	1.27	1.17

Soil Chemical Characteristics

In addition to measuring soil carbon, several soil physicochemical parameters were analyzed to describe the environmental conditions that influence the accumulation and dynamics of organic carbon. These parameters included soil pH, electrical conductivity (EC), redox potential (Eh), soil texture, and organic carbon content. Soil chemical properties can be reflected by pH values, which serve as indicators of soil chemical fertility. Soil pH represents the concentration of hydrogen (H^+) and hydroxyl (OH^-) ions, directly affecting microbial activity in decomposing organic matter. Microbial activity is highly dependent on pH conditions that support their growth (Wang *et al.*, 2019). The pH values observed in plantation agroecosystems were 6.1 (slightly acidic) and in garden agroecosystems 6.2 (slightly acidic), as presented in Table 2. An increase in pH toward neutral can enhance carbon and nitrogen mineralization, thereby supporting more active microbial growth. However, under acidic conditions, microbial activity remains low and the decomposition of organic matter becomes suboptimal (Neina, 2019). In soils with low pH, microbial growth is inhibited, leading to slower decomposition rates. When pH rises beyond a certain threshold, microbial activity increases, but this may also cause carbon loss due to excessive mineralization. Conversely, under near-neutral pH conditions, intensification may reduce microbial biomass and growth efficiency, so less intensive management practices may be more favorable for enhancing microbial growth efficiency and soil carbon storage (Malik *et al.*, 2018). The electrical conductivity (EC) values indicated that gardens had higher values of 108.4±263.16 µS/cm compared to plantations with 54.3±33.5 µS/cm. This difference is presumed to be related to the accumulation of dissolved ions due to more intensive fertilization in garden systems, while EC values in plantations tended to remain stable across seasons. Low redox potential (Eh <200 mV) was observed in both land uses, with 45.21±16.29 mV in gardens and 54.09±13.6 mV in plantations. These values indicate anaerobic conditions or low oxygen environments. Under such conditions, the decomposition of organic matter occurs more slowly, allowing carbon to accumulate in more stable forms (Mattila, 2024).

The organic carbon content differed significantly between gardens and plantations, with higher values in gardens at 5.53±2.06% compared to plantations at 5.33±1.71%. This is presumably due to gardens having mixed vegetation and greater organic input, such as litter. Although plantations are dominated by woody plants, their lower organic carbon content is likely due to slower decomposition or more controlled fertilization. This difference reflects the complex relationship between vegetation type, soil properties, and land management practices in influencing soil carbon accumulation (Farrasati *et al.*, 2019).

Soil Physical Characteristics

The soil texture in both agroecosystems was silt loam, dominated by silt (> 60%). The soil texture in both agroecosystems indicated good water-holding capacity, but drainage and aeration may not be optimal. The advantage of this soil texture is that it tends to be fertile and efficient in storing nutrients. Bulk density values indicated soil compaction levels. The relatively low bulk density in gardens (1.17 g/cm³) and plantations (1.27 g/cm³) reflects loose soils with high organic matter content. Looser soil allows better air and water penetration, which supports microbial activity and the decomposition of organic matter, thereby enhancing soil carbon content (Nguyen *et al.*, 2024).

3.2. Carbon Capture and Storage (CCS)

Table 4 shows the vegetation in plantation agroecosystems in the Tuntang Hulu Sub-watershed is dominated by woody plants such as coffee (*Coffea* sp.), rubber wood (*Hevea brasiliensis*), cacao (*Theobroma cacao* L.), durian (*Durio zibethinus*), and sengon (*Albizia chinensis*). Woody plants in plantation systems have greater above-ground biomass accumulation potential, allowing them to absorb and store carbon (carbon sequestration) through photosynthesis and retain it in biomass such as stems, branches, twigs, roots, and leaves, with longer lifespans (Novita *et al*., 2021). Conversely, gardens are dominated by annual crops or herbaceous vegetation such as elephant grass (*Pennisetum purpureum*), cassava (*Manihot esculenta*), and cosmos (*Cosmos caudatus*). Annual crops have shorter life cycles and relatively lower biomass compared to perennial plants. Although understory vegetation provides lower results, these findings suggest that variations in carbon stocks in understory vegetation are strongly influenced by factors such as plant age, soil type, and land management practices (Shang *et al.*, 2024).

Soil organic matter (SOM) is an important indicator of soil fertility, functioning as a carbon source, improving soil structure, enhancing water and nutrient retention, and supporting soil microbial life. Soil organic matter in the dry season was recorded at 207.504 tons/ha in plantations and 184.356 tons/ha in garden (Table 5). Although plantations had higher SOM than gardens, the difference was not significant. In the rainy season, SOM decreased to 196.898 tons/ha in plantations and 177.129 tons/ha in gardens, also showing no significant difference. This difference may be influenced by the slower decomposition rate during the dry season due to lower soil moisture, leading to higher SOM accumulation compared to the rainy season. Conversely, in the rainy season, high moisture can increase microbial activity, accelerating decomposition. However, excessive moisture can create anaerobic conditions that hinder aerobic microbial activity and reduce carbon storage efficiency (Yanti & Kusuma, 2021).

Table 4. Dominant vegetation in plantation and garden agroecosystems

Agroecosystem	Dominant Vegetation
Agroforestry Garden	Elephant grass, Cosmos, Peanuts, Cassava, Coffee
Monoculture Plantation	Coffee, Rubber wood, Sengon, Cacao, Durian

Table 5. Average soil organic matter, below ground biomass, and above ground biomass in dry and rainy seasons

Component	Seasons	Plantation (ton/ha)	Garden (ton/ha)	Standard Deviation		*p-value*	Significant
				Plantation	Garden		
SOM	Dry Season	207.504	184.356	73.129	61.839	0.331	Not Significant
	Rainy Season	196.898	177.129	61.308	70.650	0.425	Not Significant
BGB	Dry Season	2.703	1.831	1.087	0.829	0.011	Significant
	Rainy Season	2.168	1.825	1.282	0.776	0.320	Not Significant
AGB	Dry Season	10.394	7.042	4.180	3.189	0.011	Significant
	Rainy Season	8.340	7.018	4.932	2.984	0.320	Not Significant

Note: SOM = Soil organic matter; BGB = Below Ground Biomass; AGB = Above Ground Biomass;

The Below Ground Biomass (BGB) values showed significant difference (*p-value* = 0.011) in the dry season, with 2.703 tons/ha in plantations and 1.831 tons/ha in garden (Table 4). In the rainy season, BGB values in plantations (2.168 tons/ha) and gardens (1.825 tons/ha) were not significantly different, possibly due to sufficient water availability that balances biomass allocation to roots in both land types. This indicates that plantation systems support greater root biomass growth compared to gardens. Root biomass plays an important role in long-term soil carbon storage as roots significantly contribute to soil carbon accumulation through decomposition and carbon stabilization associated with coarse and fine roots. Furthermore, increased root biomass can enhance soil carbon storage capacity sustainably and support the resilience of agricultural and natural ecosystems (Hirte *et al.*, 2017). Plant roots contribute to soil organic carbon stabilization through organic inputs such as root litter and rhizodeposition that interact with soil minerals (Dijkstra *et al*., 2021; Huang *et al.*, 2021).

Above Ground Biomass (AGB) in the dry season was 10.394 tons/ha in plantations and 7.042 tons/ha in gardens. The differences between the two agroecosystems were significant (*p-value* = 0.011). In the rainy season, AGB in plantations (8.340 tons/ha) and gardens (7.018 tons/ha) were also not significantly different, though plantations still showed higher values. Significant differences were only observed in the dry season, indicating that drier conditions highlighted productivity differences between the two agroecosystems. Meanwhile, in the rainy season, more favorable environmental conditions resulted in relatively comparable productivity between the two systems. AGB serves as an indicator for assessing the potential of atmospheric carbon sequestration, as it includes total above-ground plant biomass such as stems, leaves, and harvests (IPCC, 2008). Carbon storage in plant biomass is positively impacted by higher AGB values in plantations. Agroforestry systems store more carbon in both above- and below-ground biomass compared to conventional farming and grassland systems. This highlights that increasing above-ground biomass (AGB) in plantation areas can significantly enhance carbon storage within plant biomass (Sambou *et al.*, 2024).

Figure 4 shows that garden and plantation agroecosystems in the Tuntang Sub-Watershed display varying capacities for carbon capture and storage during both the dry and rainy seasons. Overall, plantations tend to exhibit higher levels of biomass, total carbon storage (TCS), and total carbon capture (TCC) compared to gardens, especially in dry season. Although there is a slight decrease during the rainy season, the seasonal differences are not very pronounced, indicating that seasonal changes have not yet strongly influenced fluctuations in soil carbon reserves and vegetation biomass. The variations in Total Biomass (TB), TCS, and TCC between the dry and rainy seasons can be explained by the physiological responses of plants to environmental conditions. During the dry season, plants generally allocate more energy toward developing permanent structures such as stems and large roots as an adaptation to water scarcity. The greater intensity of sunlight during this season also enhances photosynthesis, resulting in increased biomass accumulation and higher carbon storage compared to the rainy season (Hermialingga *et al.*, 2020).

Table 6. Average total biomass, total carbon capture, and total carbon storage

Component	Season	Plantation (ton/ha)	Garden (ton/ha)	Standard Deviation		*p-value*	Significant
				Plantation	Garden		
Total Biomass	Dry Season	220.60	193.230	75.44	63.11	0.262	Not Significant
	Rainy Season	207.406	185.972	64.323	72.268	0.400	Not Significant
Total Carbon Storage	Dry Season	103.682	90.817	35.455	29.663	0.262	Not Significant
	Rainy Season	97.481	87.407	30.232	33.996	0.400	Not Significant
Total Carbon Capture	Dry Season	380.514	333.300	130.119	108.863	0.262	Not Significant
	Rainy Season	357.755	320.782	110.951	124.655	0.400	Not Significant

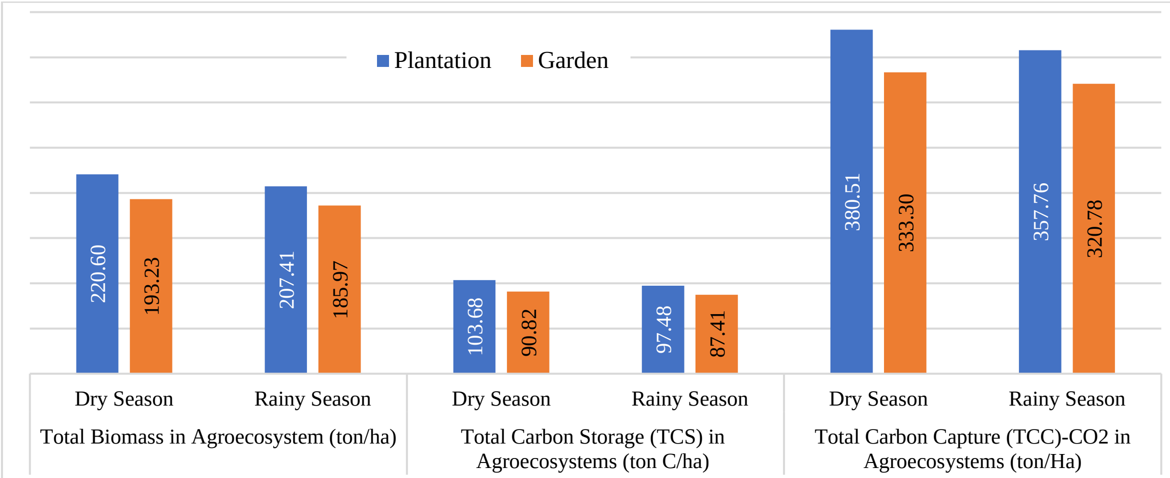

Figure 4. Carbon capture storage in garden and plantation agroecosystems

The reduction in carbon storage capacity during the rainy season is likely influenced by ecological factors, such as higher soil moisture levels that accelerate organic matter decomposition, thereby releasing more carbon into the atmosphere as CO_2. Heavy rainfall can also lead to nutrient leaching, which reduces the activity of soil microorganisms responsible for carbon fixation. In addition, increased respiration from plants and soil organisms contributes to lower net carbon storage, causing TCS and TCC values to be lower in the rainy season compared to the dry season. Another contributing factor is the prevalence of fine roots that grow rapidly but also die quickly during the rainy season, while in the dry season, plants tend to develop more durable structures such as large roots and stems, which are more effective for long term carbon storage (Putra *et al.,* 2020). On the other hand, although high soil moisture during the rainy season may temporarily enhance microbial activity, excess water often creates anaerobic conditions that inhibit the performance of aerobic microorganisms, ultimately lowering carbon storage efficiency (Tomar & Baishya, 2020; Hao *et al.*, 2021). Thus, seasonal climatic dynamics play an important yet complex role in the processes of carbon capture and storage within agricultural ecosystems.

4. CONCLUSION AND RECOMMENDATION

Agroecosystems comprising gardens and plantations in Tuntang Sub-Watershed help to collect and store carbon. The average CCS capacity in the two agroecosystems was 380.51 tons/ha in plantations and 333.30 tons/ha in gardens. During the dry season, there were significant differences in below-ground biomass (BGB: 2.703 tons/ha in plantations and 1.831 tons/ha in gardens) and above-ground biomass. Plantations showed greater carbon storage capacity compared to gardens, particularly in the dry season, which is likely influenced by the dominance of woody perennial crops capable of producing higher biomass. Soil characteristics such as acidity (pH), texture, bulk density, moisture, and redox conditions also affected soil microbial activity and the rate of organic matter decomposition, thereby determining the level of carbon accumulation.

Enhancing CCS can be achieved through the application of agroforestry systems that integrate woody perennials with annual crops, regulation of vegetation density, and soil fertility management to maintain a near-neutral pH. This strategy is expected to optimize carbon capture and storage while strengthening the role of agroecosystems in climate change mitigation in the Tuntang Sub-Watershed.

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