BIODIVERSITAS
Volume 26, Number 6, June 2025
Pages: 2754-2761

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d260620

Comparison of carbon storage and oxygen release in various land uses in North Luwu District, South Sulawesi Province, Indonesia

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Manuscript received: 26 February 2025. Revision accepted: 26 May 2025.

Abstract. *Dicky D, Paembonan SA, Mukrimin M, Millang S, Witno W, Makkasau AR, Arty B, Ramadhan W, Rasyid A. 2025. Comparison of carbon storage and oxygen release in various land uses in North Luwu District, South Sulawesi Province, Indonesia. Biodiversitas 26: 2754-2761.* The ability of plants to absorb CO_2 from the atmosphere and store carbon in their biomass determines the success of climate change mitigation programs. This study compared the carbon storage capacity, CO_2 absorption, and oxygen release in three types of land use in North Luwu District, South Sulawesi Province, Indonesia, namely secondary natural forest, cocoa agroforestry, and oil palm plantation. The study was conducted in two stages: field activities to collect vegetation data and laboratory analysis conducted at the Faculty of Forestry, Universitas Hasanuddin, South Sulawesi. Tree biomass was estimated using allometric equations based on tree diameter and height, while understory and litter biomass were calculated using the dry weight and carbon content methods. The results show significant differences in carbon storage capacity among land uses. Secondary natural forest has the highest carbon storage capacity (264.45 tC ha^{-1}), which contributes to the absorption of 969.65 tCO_2 ha^{-1} and the release of 705.2 tO_2 ha^{-1}. High biodiversity and complex vegetation structures allow natural secondary forests to absorb more carbon through photosynthesis. Cocoa agroforestry has a carbon storage capacity of 182.43 tC ha^{-1}, absorption of 668.90 tCO_2 ha^{-1}, and release of 486.48 tO_2 ha^{-1}. This difference is due to the simpler vegetation structure of cocoa agroforestry compared to natural secondary forest. Meanwhile, oil palm plantation has the lowest carbon storage capacity (123.92 tC ha^{-1}), absorption of 454.38 tCO_2 ha^{-1}, and release of 330.46 tO_2 ha^{-1}. Our findings suggest that cocoa agroforestry is still superior to oil palm plantation because the presence of shade trees and cultivated plants, and monoculture system is less effective in mitigating climate change.

Keywords: Carbon Stock, climate change, CO_2, land uses, oxygen release

INTRODUCTION

Land use change is one of the main factors affecting ecosystem balance, especially concerning carbon storage and oxygen release, which are key indicators in climate change mitigation. According to Rodrigues et al. (2023), carbon storage in terrestrial ecosystems is important in reducing the concentration of carbon dioxide (CO_2) in the atmosphere, the main greenhouse gas causing global warming. Vegetation absorbs CO_2 through photosynthesis and stores it in above and belowground biomass (Luo et al. 2019). In addition, plants release oxygen that supports the lives of various organisms (Polutchko et al. 2022). According to Melati (2019), each forest type, plant species, and forest management has a different carbon storage capacity (Alam et al. 2022), which is influenced by various biotic factors such vegetation type, and abiotic factors like climate and soil (Miharza et al. 2023). Natural forests and natural secondary forests are the largest carbon sinks (Osuri et al. 2020). However, other tree-based vegetation covers, such as agroforestry and monoculture timber plantation, also have the potential to store carbon. Therefore, understanding various land cover types and their capacity in storing carbon and releasing oxygen is crucial in sustainable land use planning.

While often neglected, natural secondary forests have an important role as carbon storage and oxygen producer. With a complex vegetation structure and high tree density, natural secondary forests can store carbon more than agricultural systems (Karuru et al. 2021). Natural secondary forests also contain high biodiversity which contributes to ecosystem stability and optimal carbon cycling (Maure et al. 2023). On the other hand, human-made land uses generally have a lower carbon stock compared to natural secondary forest. For example, cocoa agroforestry systems, which combine cocoa plants with shade trees (Isaac et al. 2024), have lower carbon storage capacities than natural secondary forests but higher than oil palm monocultures (Karuru et al. 2021). The presence of shade trees in agroforestry increase the capacity in sequestering carbon and releasing oxygen, although it remains limited depending on the management patterns applied (Tschora and Cherubini 2020). However, cocoa agroforestry is still a more environmentally friendly option compared to monoculture systems that are more intensive in land use.

Oil palm monoculture is a more fragmented agricultural system (de Almeida et al. 2020) with lower carbon storage than natural secondary forests and cocoa agroforestry (Málaga et al. 2021). Land conversion to oil palm plantations often results in the decrease in soil carbon stocks due to the loss of forest cover and followed with intensive soil management. Although oil palm also plays a role in photosynthesis and oxygen release, its capacity is lower compared to land use systems with more complex vegetation structure and diversity (Murphy 2024). In addition, monoculture systems tend to cause long-term ecosystem degradation including soil degradation and biodiversity loss (Murphy 2024). Therefore, understanding how these three land cover types affect carbon storage and oxygen release is essential to support more sustainable environmental policies.

North Luwu District, South Sulawesi Province, Indonesia, experienced significant land conversion in the 2016-2020 period, with natural forest loss of 12,370 hectares (World Agroforestry (ICRAF) 2022). The area of natural forest continued to decline, while palm oil plantation land cover increased from 18,360 hectares in 2018 to 23,988.42 hectares in 2021, and cocoa land reached 38,435 hectares in the same year (Central Statistics Agency of North Luwu 2021). These changes reflect a shift in land use towards cocoa agroforestry and monoculture palm oil systems, which has significant implications for carbon storage capacity and overall ecosystem function. This study aims to analyze the differences in carbon storage capacity and oxygen release in three land cover types in North Luwu District: natural secondary forest, cocoa agroforestry, and oil palm monoculture plantation. The results of this study can provide scientific insights to policymakers and stakeholders in planning more sustainable land use. By understanding the differences in ecosystem capacity in storing carbon and releasing oxygen, it is hoped that more effective solutions can be found in land use management without sacrificing ecological functions and environmental sustainability. It can also help the Indonesian government in supporting FOLU Net Sink 2030. a national target to make the Forest and Other Land Use (FOLU) sector a net carbon sink by 2030, where greenhouse gas emissions from the sector are equal to or smaller than the amount of carbon sequestered.

MATERIALS AND METHODS

Study area

This study was conducted in North Luwu District, South Sulawesi Province, Indonesia (Figure 1). The first stage of this study was to identify three land uses to compare in terms of their ability to store and absorb carbon dioxide and release oxygen: secondary natural forest, agroforestry system, and oil palm plantation. Oil palm plantation is located in Bone-Bone Sub-district with altitude of 71 meters above sea level (m asl); natural forest is in Sukamaju Sub-district with altitude of 228 m asl; and cocoa agroforestry with altitude of 30 m asl. The coordinates of research sites are presented in Table 1.

The type of soil in secondary natural forests, cocoa agroforestry, and palm oil plantations is a Red Yellow Podsolic soil (RYP) from sedimentary rock parent material (Land System Indonesia 2024). According to the Schmidt and Fergusson (1951) classification, the climate of Luwu Utara District is included in Type A with rainfall of 1000-4670 mm/year (BMKG 2024). The research location is illustrated in Figure 1.

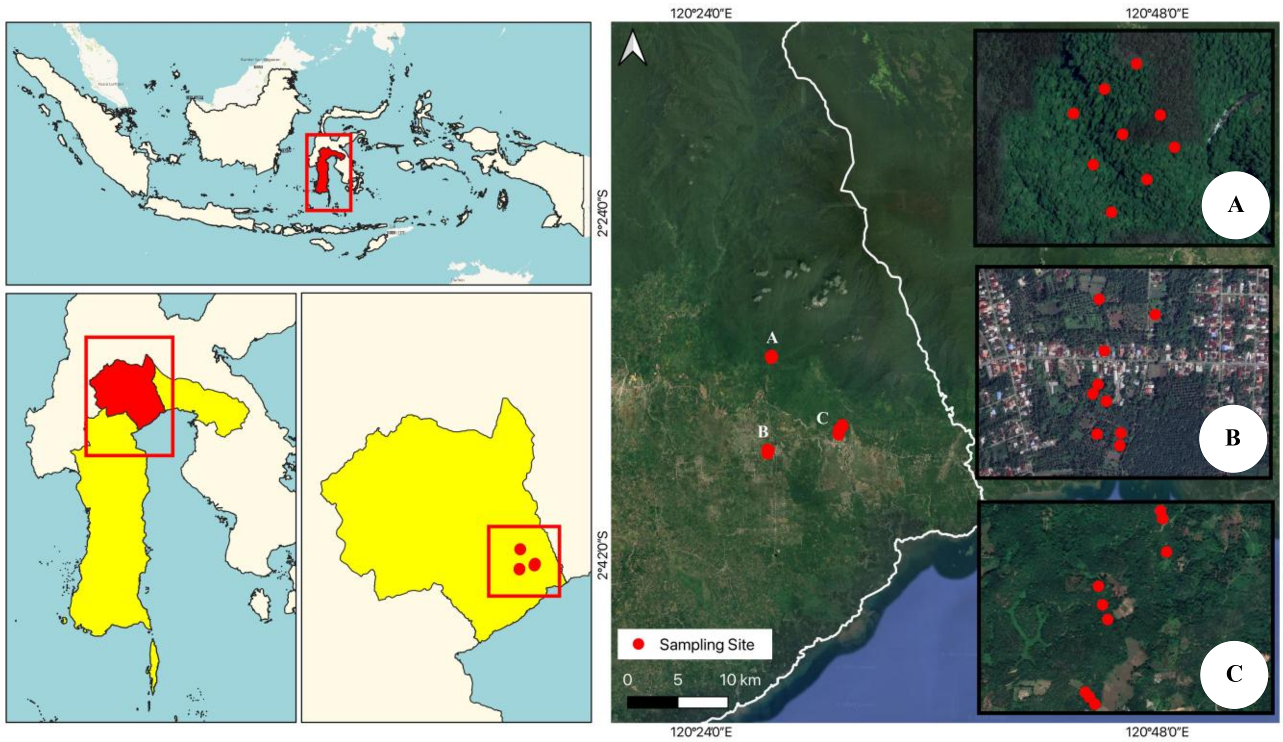

Figure 1. Map of study location showing three land use types in North Luwu District, South Sulawesi, Indonesia. A. Natural secondary forest; B. Cocoa agroforestry; C. Palm oil plantation

Table 1. Geographical coordinates of research sites in three land use types in North Luwu District, South Sulawesi, Indonesia

Station	Natural secondary forest	Cocoa agroforestry (Stand age)	Palm oil plantation (Stand age)
1	02°31′37.97″ S, 120°27′40.59″ E	02°36′39.00″ S, 120°27′30.35″ E (4 Years)	02°35′14.16″ S, 120°31′25.95″ E (5 Years)
2	02°31′35.86″ S, 120°27′42.87″ E	02°36′37.78″ S, 120°27′30.45″ E (4 Years)	02°35′08.68″ S, 120°31′25.31″ E (5 Years)
3	02°31′33.79″ S, 120°27′44.65″ E	02°36′37.87″ S, 120°27′28.12″ E (4 Years)	02°35′07.40″ S, 120°31′24.98″ E (5 Years)
4	02°31′34.91″ S, 120°27′39.42″ E	02°36′34.66″ S, 120°27′29.04″ E (7 Years)	02°35′22.87″ S, 120°31′15.40″ E (13 Years)
5	02°31′32.96″ S, 120°27′41.31″ E	02°36′33.93″ S, 120°27′27.71″ E (7 Years)	02°35′25.27″ S, 120°31′16.24″ E (13 Years)
6	02°31′31.72″ S, 120°27′43.73″ E	02°36′33.02″ S, 120°27′28.22″ E (7 Years)	02°35′19.81″ S, 120°31′14.73″ E (13 Years)
7	02°31′31.62″ S, 120°27′38.15″ E	02°36′29.73″ S, 120°27′28.84″ E (17 Years)	02°35′38.05″ S, 120°31′13.22″ E (25 Years)
8	02°31′30.05″ S, 120°27′40.14″ E	02°36′24.67″ S, 120°27′28.33″ E (17 Years)	02°35′37.23″ S, 120°31′12.55″ E (25 Years)
9	02°31′28.43″ S, 120°27′42.21″ E	02°36′26.18″ S, 120°27′33.81″ E (17 Years)	02°35′39.23″ S, 120°31′14.14″ E (25 Years)

Table 2. Formula for calculating biomass content for each type based on stand allometry

Land uses	Allometric formula	Reference
Natural secondary forest	$W = 0.0509 \times \rho \times D^2 \times H$	Chave et al. (2005)
Cocoa agroforestry	W = 0.11×ρ×D^2.62	Kettering et al. (2001)
Palm oil	W = 0.002382×D2.3385×H 0.941	Lubis (2011)

Note: W: Tree biomass (kg/tree); D: Diameter at breast height (m); H: Height (m); ρ: Specific gravity of each type of tree

Data collection

Research design

A total of nine sample plots were purposively selected for each of the three land use types: secondary natural forest, cacao agroforestry and oil palm plantation. In secondary natural forest, the nine plots represented relatively homogeneous forest conditions. For the cocoa agroforestry, nine plots were also established, consisting of three replicates for each stand age category (4, 7 and 17 years) to capture age-related variations in carbon stocks. Similarly, in oil palm plantations, nine plots were selected, with three replicates representing each age group (5, 13 and 25 years), allowing for comparative analysis of carbon dynamics across plantation maturity stages, resulting in a total of 27 sample plots. In the secondary natural forest, plots were made with a size of 20x50 m. At each sample plot, nested plots (subplots) were created to inventory plants at four levels, namely a subplot of 20x25 m was made for tree level measurements (Catuti et al. 2022), 10x10 m for pole level measurements, 5x5 m for sapling level measurements, and 1x1 for litter biomass, understory and soil organic carbon Figure 2.A. While for cocoa agroforestry and palm oil plantation, plots measuring 20x50 m were established where at each sample plot, three subplots measuring 1x1 m were delimited Figure 2.B to measure litter biomass, understory, and soil organic carbon (Indonesian National Standards Agency 2019).

Tree diameter and height measurements were carried out on each tree in the sample plot. In addition, tree density per plot was measured to estimate the amount of carbon stored per hectare. A total of 300 g of understory biomass and litter samples were taken to measure dry weight (Indonesian National Standards Agency 2019). Litter and understory biomass samples were dried in an oven at 80°C until the dry weight remained constant. Understory biomass and litter were calculated to obtain its dry weight based on the formula developed by Indonesian National Standards Agency (2019) by measuring the total fresh weight, fresh weight of the sample, and dry weight of the sample. An analysis of soil samples was carried out to determine the concentration of soil organic carbon.

Data analysis

The biomass content of each species was calculated using the allometric formula developed by several studies (Ketterings et al. 2001; Chave et al. 2005; Lubis 2011). The allometric formula was adjusted to the proximity of the previous sample stands based on the suitability of the local environment and the age range of the previous sample stands (Table 2).

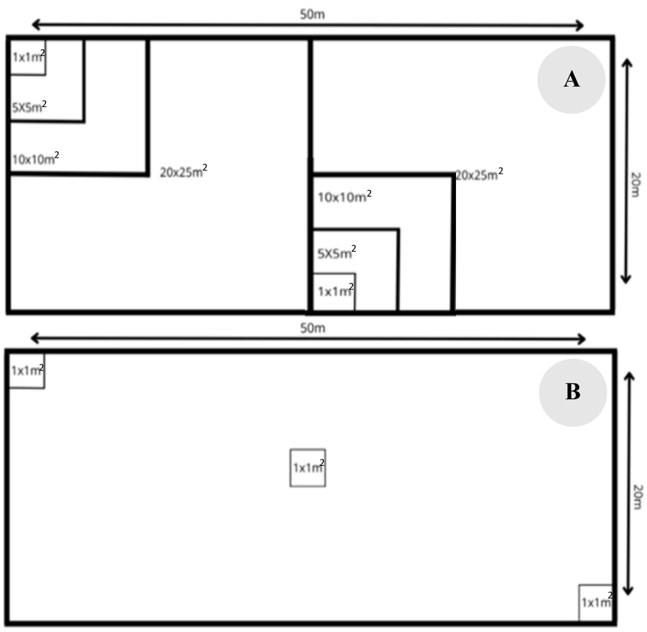

Figure 2. The diagram of sampling plot. A. Natural secondary forest; B. Cocoa agroforestry and oil palm plantation

Biomass in the form of the total dry weight of understory and litter was calculated using the formula explained by Lukito and Rohmatiah (2022) as follows:

$$W = \frac{SDW}{SFW} X\,TFW$$

Where, SDW and SFW represent dry weight and fresh weight, respectively, and TFW is the total fresh weight.

The results of standing and understory biomass and litter results were converted into carbon content using the Indonesian National Standards Agency (2019) using the following formula:

$C = W \times 0.47$

Where, 0.47 is the percentage value of carbon content in biomass, and W: aboveground biomass (Darmawan et al. 2022).

Soil carbon organic content was calculated using the following equation (Abera and Wolde-Meskel 2013):

$Ct = Sd \times \rho \times \%C$

Where, Ct: Soil organic carbon content (gr/cm^2); Sd: Soil sample depth (cm); ρ: Soil density (g/cm^3 or ton/m^3); %C: Percentage value of carbon content obtained from laboratory measurements.

Calculation of CO_2 and oxygen release

CO_2 is calculated using the comparison of the relative atomic mass of C (12) and the relative molecular mass of CO_2 (44) (Baxter and Resident 2019) using the following equation:

$CO_2 = 44/12 \times$ carbon stock

The calculation of oxygen release (net release) is based on the amount of oxygen produced during photosynthesis minus the amount of oxygen used during plant respiration. The amount of oxygen production can be estimated from carbon sequestration based on atomic weight (Baxter and Resident 2019) using the following equation:

Net O_2 = net C × 32/12

Where: Net O_2: Oxygen release; Net C: Carbon sequestration

Statistical analysis

The results of the calculation of total carbon storage observed in natural secondary forest, cocoa agroforestry, and oil palm plantation were then subjected to statistical tests using the IBM SPSS 25 application. The statistical significance test for the three types of land cover used the Welch Anova test and Post Hoc test, then the Games-Howell test was carried out to determine significant differences between each type of land use. Interpretation of the Post Hoc test was carried out by calculating the p value (Sig.)≤0.05. If the p value (sig.)≤0.05 then there is a significant difference between one land use and another, but if the p value (Sig.)>0.05 means there is no significant difference between types of land use.

RESULTS AND DISCUSSION

Biomass and carbon stock

Natural secondary forest

The biomass and carbon in secondary natural forests are stored in several components, including trees, understory, litter, and organic carbon in the soil. Carbon and biomass storage in secondary natural forest are presented in Table 3.

Table 3 shows that carbon storage in secondary natural forest is dominated by aboveground carbon. Tree carbon has the largest storage, namely 227.04 tC ha^{-1}, while carbon storage in litter and understory are 1.11 and 0.3 tC ha^{-1}, respectively. On the other hand, soil carbon is 34.4 tC ha ha^{-1}. Aboveground carbon in secondary natural forests contributes 86.99% of the total carbon stock of secondary natural forest, while belowground carbon is only 13.1%. This result is in line with the research of Marselianti (2022), which stated that soil carbon storage in the secondary forest of Tanralili Village, Sulawesi, ranges from 25-43 tC ha ha^{-1}. However, it differs from the research reported by Karuru et al. (2021), which obtained soil organic carbon of 54.4 tC ha^{-1} or 20% of the total carbon storage of secondary natural forest in East Luwu District. According to Giweta (2020), the dominance of tree species with large crowns and high density allows for a high accumulation of litter falling to the forest floor. Higher carbon stock is stored in tree stands because carbon storage is influenced by the amount of biomass in the stand. According to Rajput et al. (2017), tree biomass is influenced by the density and specific gravity of wood. In addition to stands, carbon components in natural forest is also stored in the form of soil organic carbon.

According to Zhao et al. (2023), soil organic carbon is an accumulation of biomass that has been decomposed, so it is stored in the form of soil organic carbon (Yao et al. 2023). Soil organic carbon content is also significant for forest sustainability. This is because the organic content in soil can increase soil fertility (Zhao et al. 2023), so soil organic carbon will affect the quality of forest stands through the supply of nutrients to tree stands. In line with the research of Darmawan et al. (2022), the content of soil organic carbon is influenced by the amount of litter that has undergone decomposition. The composition of forest vegetation is an essential determinant of soil carbon storage in secondary natural forest, which is influenced by various ecological and climatic factors. Heinrich et al. (2021) stated that natural secondary forest can absorb carbon at a much higher rate than primary forests, up to 20 times more carbon annually. So, the existence of secondary natural forest is essential as a carbon store to mitigate climate change.

Cocoa agroforestry

In general, biomass and carbon tend to increase with age, especially in tree category that dominate aboveground carbon storage. In addition, soil carbon contributes significantly to the total carbon of ecosystem. The relative proportion of each component to the total carbon in cocoa agroforestry is presented in the Table 4.

Table 4 shows carbon storage dynamics in cocoa agroforestry in varying ages (4, 7, and 17 years), with the main components including trees, understory, litter, and soil carbon. As age increases, there is an increase in biomass and total carbon stored, where trees are the main contributor of carbon, with 67.57%. At the age of 17 years, trees store carbon of 70.04 tC ha^{-1}, which is much higher compared to the ages of 4 years (20.42 tC ha^{-1}) and 7 years (32.82 tC ha^{-1}). Understory has a minimal contribution, only around 0.26% of the total carbon stored, indicating a minor role in carbon storage. Litter contributes around 0.56% of the total carbon, with the highest carbon value found at the age of 4 years (0.44 tC ha^{-1}). Total aboveground carbon increases significantly from 20.98 tC ha^{-1} at the age 4 to 124.76 tC ha^{-1} at the age of 17 years, indicating that the main biomass accumulation occurred during the tree growth phase in cocoa agroforestry.

Meanwhile, soil carbon contributes to 31.61% of the total carbon storage, with varying values between ages, indicating that organic decomposition and interactions with edaphic factors also influence soil carbon dynamics. Overall, the total carbon stored reach 182.43 tC ha^{-1}, with the main contribution coming from trees and soil, confirming the importance of agroforestry systems in mitigating climate change by increasing the carbon storage capacity of ecosystems. According to Lindiani et al. (2023), agroforestry systems have a great potential in storing carbon through a combination of trees, shrubs, and annual crops, with total carbon stored varies depending on the type of species and land management. In another study, Karuru et al. (2020) showed that cocoa agroforestry in East Luwu was able to store 131.31 tC ha^{-1}, which is in line with the results of this study, which showed an increase in carbon storage as the cocoa and vegetation age. In addition, research conducted by Noulèkoun et al. (2023) showed that tree-based agroforestry systems can significantly increase soil carbon stocks compared to monoculture farming systems. In this study, soil carbon can contribute up to 50% of the total carbon stock, slightly higher than the results of this study, which showed a soil organic carbon contribution of 31.61%. This difference can be caused by environmental factors such as soil texture, moisture, and microbial activity that play a role in the decomposition process of organic matter.

Furthermore, a study by Santhyami et al. (2022) confirmed that agroforestry systems increase carbon storage and provide additional benefits such as increased soil fertility, water conservation, and land degradation mitigation. In this context, agroforestry systems can be an effective alternative sustainable land management and climate change mitigation strategy, as also shown in this study which carbon storage continues to increase with vegetation growth. Overall, the results of this study support the findings of various agroforestry studies that confirm that tree-based systems have a great potential in sequestering and storing carbon. Increasing vegetation age significantly contributes to increasing biomass and soil carbon, making it an effective strategy in long-term carbon management. Therefore, agroforestry-based approaches can be adopted to increase carbon stocks, reduce greenhouse gas emissions, and improve the effectiveness of sustainable agricultural systems.

Palm oil plantation

Biomass and carbon tend to increase with the age of oil palm plantation where the largest carbon reserves are stored in tree biomass and soil carbon. The biomass and carbon content of oil palm plantation are shown in Table 5. Table 5 shows carbon storage dynamics in oil palm plantation in varying plant ages (5, 13, and 25 years), with the main components including trees, understory plants, litter, and soil carbon. As the age of the plantation increases, there is an increase in biomass and total carbon stored, where trees are the main contributor of carbon with 51.93%. At the age of 25 years, trees store carbon of 33.01 tC ha^{-1}, much higher than the ages of 5 years (11.28 tC ha^{-1}) and 13 years (20.07 tC ha^{-1}).

Table 3. Biomass and carbon storage potential of secondary natural forest in North Luwu District, South Sulawesi, Indonesia

Element	Biomass (tC ha^{-1})	Carbon (tC ha^{-1})	Relative value (%)
Trees	483.06	227.04	85.85
Understory	0.64	0.30	0.11
Litter	2.37	1.11	0.42
Aboveground total		230.05	86.99
Soil organic carbon		34.4	13.01
Total carbon		264.45	100.00

Table 4. Biomass and carbon storage of cocoa agroforestry in North Luwu District, South Sulawesi, Indonesia

Element	Biomass (tC ha^{-1})			Carbon (tC ha^{-1})			Total carbon (tC ha^{-1})	Relative value %
	Age (Years)			Age (Years)				
	4	7	17	4	7	17		
Trees	43.44	69.82	149.02	20.42	32.82	70.04	123.27	67.57
Understory	0.02	0.00	0.04	0.12	0.17	0.17	0.47	0.26
Litter	0.94	0.67	0.56	0.44	0.32	0.26	1.02	0.56
Aboveground total	44.40	70.49	149.61	20.98	33.31	70.48	124.76	68.39
Soil organic carbon	-	-	-	19.37	17.55	20.75	57.67	31.61
Total carbon							182.43	100.00

Table 5. Biomass and carbon storage potential of oil palm plantation in in North Luwu District, South Sulawesi, Indonesia

Element	Biomass			Carbon			Total carbon ($tC\ ha^{-1}$)	Relative value %
	Age (Years)			Age (Years)				
	5	13	25	5	13	25		
Trees	24.00	42.70	70.23	11.28	20.07	33.01	64.36	51.93
Understory	0.12	0.17	0.17	0.06	0.08	0.08	0.22	0.18
Litter	0.37	0.24	0.00	0.17	0.11	0.00	0.28	0.23
Aboveground total	24.48	43.11	70.41	11.51	20.26	33.09	64.86	52.34
Soil organic carbon	-	-	-	22.78	18.46	17.82	59.06	47.66
Total carbon							123.92	100.00

Understory plants make a minimal contribution, only around 0.18% of the total carbon stored, indicating that the role of understory vegetation in carbon storage is relatively low. Litter contributed about 0.23% of total carbon, with the highest carbon value found at the age of 5 years (0.17 tC ha^{-1}), which then decreased to zero at 25 years, indicating that litter accumulation decreases with increasing plant age. Total aboveground carbon increases from 11.51 tC ha^{-1} at the age of 5 years to 33.09 tC ha^{-1} at 25 years of age, dominated by carbon stored in tree biomass. Soil carbon contributes to 47.66% of total carbon storage, with a decreasing trend from 22.78 tC ha^{-1} at 5 years of age to 17.82 tC ha^{-1} at the age of 25 years, which may be due to changes in the dynamics of organic matter and microbial activity in the decomposition process. Compared with other studies at relatively similar plant ages, results were consistent or different depending on environmental conditions and land management. For example, a study by Málaga et al. (2021) showed that in 25-year-old oil palm plantations, the total carbon stored in tree biomass could reach 35-40 tC ha^{-1}, which is slightly higher compared to the findings in this study (33.01 tC ha^{-1}). This difference may be due to tree density, soil fertility, and land management activities. The study by Nabila et al. (2023) at the age of 13 also showed that the total carbon in tree biomass reached around 22-25 tC ha^{-1}, which is close to the results of this study (20.07 tC ha^{-1}). However, the slightly lower difference in this study is thought to be related to environmental factors such as nutrient availability and fertilization practices. Soil carbon in a study by Ikhsan et al. (2020) also decreased with increasing plant age, as found in this study, where soil carbon at the age of 5 years reaches 22.78 tC ha^{-1} but decreases to 17.82 tC ha^{-1} at the age of 25 years (Table 5). In addition, Bremer et al. (2022) stated that oil palm plantations in Indonesia have a total carbon storage range of 60-120 tC ha^{-1}, depending on plant age and environmental conditions. With the total carbon stored in this study reaching 123.92 ha^{-1}, his result is higher than the study (Karuru et al. 2020) on oil palm in East Luwu at 4, 8 and 10 years had a carbon storage of 100.89 tC ha^{-1}. Although there are variations in carbon storage values between studies, the general trend is that as the plantation ages, the total carbon storage above ground increases but tends to decrease in the soil. Therefore, good management strategies, including soil conservation practices, need to be considered to maintain the balance of carbon storage in oil palm plantations in supporting climate change mitigation.

Comparison of carbon storage capacity in land use

The results of the study show that the ability of each land in storing carbon varies with secondary natural forests is the largest compared to cocoa agroforestry and oil palm plantation. Based on the results of the Welch ANOVA test on three types of land use, a sig value of 0.00 was obtained (p-value (Sig.)≤0.05), indicating that there is a significant difference among land use types in carbon storage capacity. Further testing using Games Howell (Multiple Comparisons), secondary natural forests with the most extensive carbon storage have a significant difference to cocoa agroforestry of 82.43 tC ha^{-1} with a sig value of 0.00 (p-value (Sig.)≤0.05), secondary natural forests with oil palm plantations with a difference in carbon storage of 140.53 tC ha^{-1} with a sig value of 0.00 (p-value (Sig.)≤0.05). However, cocoa agroforestry with palm oil plantations has an insignificant difference in carbon storage with a difference of 58.1 tC ha^{-1} and a sig value of 0.317 (p-value (Sig.)>0.05. This shows that carbon storage is influenced by the type of land uses. This is in line with research (Maulana and Wibisono 2017). Waring et al. (2020) stated that carbon storage in natural forests is higher because the stand density is high in forested areas. On the other hand, carbon stock in cocoa agroforestry and oil palm plantation tend to be smaller (Miharza et al. 2023). This is because the vegetation structure is different; natural forests generally have a complex vegetation structure, while cocoa agroforestry has low species diversity (Murniati et al. 2022), as well as monoculture oil palm plantation (Ikhsan et al. 2020).

CO_2 absorption and oxygen release on various land uses

The results of the study show that the ability of each land use type to absorb CO_2 and release O_2 varies as presented in Figure 3.

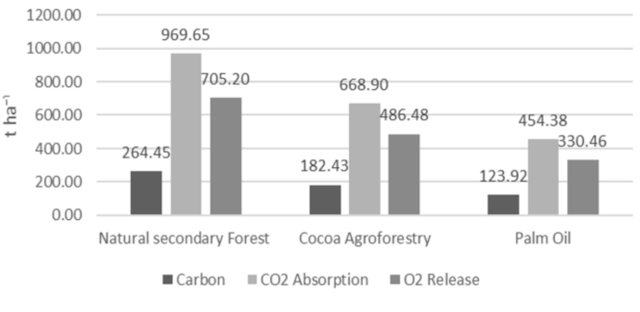

Figure 3. Comparison of the CO_2 and oxygen release on various land uses in North Luwu District, South Sulawesi, Indonesia

Figure 3 shows carbon content, carbon dioxide (CO_2), and oxygen release (O_2 release) in three land uses, namely natural secondary forests, cocoa agroforestry, and oil palm plantations. From the graph, it can be seen that natural secondary forests have the highest carbon storage capacity, which directly contributes to a greater amount of CO_2 and oxygen release compared to cocoa agroforestry and oil palm plantations.

Natural secondary forests show the highest CO_2 absorption with 969.65 tCO_2 ha^{-1}, which is directly proportional to the oxygen release of 705.2 tO_2 ha^{-1}. This is due to the high carbon content in the natural secondary forest, which reaches 264.45 tC ha^{-1}. Natural secondary forests have high biodiversity and complex vegetation structures, so they are able to absorb more carbon dioxide from the atmosphere through photosynthesis (Li et al. 2024). In this process, the absorbed carbon dioxide is converted into biomass, while oxygen is released into the atmosphere, making natural secondary forests a very effective carbon sink in mitigating climate change (Suhardono et al. 2024).

Cocoa agroforestry ranks second in carbon storage and oxygen release. With a CO_2 sequestration of 668.90 tCO_2 ha^{-1} and an oxygen release of 486.48 tO_2 ha^{-1}, cocoa agroforestry still plays a significant role in the carbon cycle even though its capacity is lower than natural secondary forests. This difference is caused by the less complex agroforestry vegetation structure and the presence of agricultural crops that have lower growth rates and carbon absorption than trees in natural secondary forests (Fahad et al. 2022; Istikorini and Sari 2022). However, agroforestry remains superior to monoculture systems because it has a combination of tree shade and crop cultivation, which contributes to carbon absorption and oxygen production.

On the other hand, palm oil plantations show the lowest CO_2 absorption value with 454.38 tCO_2 ha^{-1}, with an oxygen release of 330.46 tO_2 ha^{-1}. This low value compared to the other two land use systems can be attributed to the characteristics of palm oil vegetation, which has a lower biomass and growth that is more focused on fruit production (Málaga et al. 2021; Camacho-Valdez et al. 2022). Although palm oil still contributes to the carbon cycle, this plantation system tends to have a lower carbon absorption capacity than natural secondary forests and cocoa agroforestry.

Overall, this research shows that the higher the carbon content in an ecosystem, the greater the CO_2 and oxygen release. Therefore, land management strategies that maintain or increase vegetation biomass are essential in mitigating climate change. In the context of national policy, these data are very relevant to the Folu Net Sink 2030 program, where Indonesia targets the forestry and land use sectors to be able to absorb more carbon emissions than they release. To achieve this target, conservation and rehabilitation of natural secondary forests must be a top priority, given their high capacity to absorb carbon and release oxygen. In addition, wider implementation of agroforestry can be a solution that combines agricultural productivity with environmental conservation, helping to increase carbon stocks while reducing deforestation pressures. Palm oil plantation management also needs to be directed towards more sustainable practices to increase carbon absorption, such as implementing palm oil-based agroforestry systems, using cover crops, and optimizing organic waste management to increase soil carbon content. With this strategy, the forestry and land use sectors can contribute more to achieving the Folu Net Sink 2030, ensuring that Indonesia can achieve the target of zero net emissions from this sector and support global efforts to address the climate crisis.

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