Jurnal Ilmu Kehutanan
https://jurnal.ugm.ac.id/v3/jik/
ISSN: 2477-3751 (online); 0126-4451 (print)

Assessing Carbon Dioxide (CO_2) Absorption Potential of Forests Around Landslides Along the Trans Palopo-Toraja Highways

Kajian Potensi Penyerapan Karbon Dioksida (CO_2) Hutan Sekitar Longsor di Sepanjang Tol Trans Palopo-Toraja

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RESEARCH ARTICLE DOI:

DOI: 10.22146/jik.v18i1.9782

MANUSCRIPT:
Submitted : 6 September 2023
Revised : 4 January 2024
Accepted : 18 January 2024

KEYWORD
biomass, CO_2, carbon storage, carbon absorption, landslide.

ABSTRACT

Forests are crucial in absorbing carbon dioxide (CO_2) from the atmosphere through photosynthesis and storing the carbon in its biomass. This research aimed to assess the potential for CO_2 absorption of forests around landslides along the Trans Palopo-Toraja highways. This research employed a destructive sampling to measure understorey and litter biomass. Furthermore, it measured the biomass of understorey plants and litter with a destructive method. The 12 measurement plots were purposively placed on the landslide points to represent various vegetation conditions. The results revealed the presence of 77 plant species, totaling 554 individuals on the measurement plots. Plot 4 and Plot 1 showed the highest and lowest carbon absorption potential at 790.39 tons/ha and 199.63 tons/ha, respectively. The estimated average absorption of 12 plots was 461.75 tons/ha. Tree-level vegetation had the highest carbon absorption value due to its bigger diameter and CO_2 absorption capacity than saplings and poles.

KATA KUNCI
biomassa, CO_2, simpanan karbon, serapan karbon, tanah longsor.

INTISARI

Hutan berperan dalam penyerapan carbon dioxide (CO_2) dari atmosfer melalui fotosistesis, dan menyimpan carbon tersebut dalam bentuk biomassa. Penelitian ini bertujuan untuk mengetahui potensi penyerapan CO_2 pada hutan sekitar tanah longsor sepanjang jalan Trans Palopo-Toraja. Penelitian ini menggunakan destruktif sampling untuk mengukur biomassa tumbuhan bawah dan seresah. Sebanyak 12 plot pengukuran ditempatkan secara purposive pada sebaran titik longsor untuk merepresentasikan kondisi vegetasi. Hasil penelitian menunjukkan terdapat 77 jenis tumbuhan dan 554 jumlah individu pada plot pengukuran. Potensi penyerapan karbon tertinggi terdapat pada plot 4 sebesar 790,39 ton/ha dan terendah pada plot 1 sebesar 199,63 ton/ha. Rerata serapan karbon pada 12 plot sebesar 461,75 ton/ha. Vegetasi tingkat pohon mempunyai nilai serapan karbon tertinggi karena mempunyai diameter yang lebih besar sehingga kemampuannya dalam menyerap CO_2 lebih baik dibandingkan dengan tingkat pertumbuhan pancang dan tiang.

Introduction

The rapid development of cities is a significant factor impacting society and causing environmental repercussions, commonly manifested as reduced air quality, specifically in urban areas saturated with human activities. One of the direct consequences is global warming, characterized by an increase in the earth's temperature due to accumulating heat in the atmosphere. The primary contributor to this condition includes elevated greenhouse gas (GHG) emissions, such as carbon dioxide (CO_2) and methane (CH_4), exceeding the atmospheric threshold, leading to global climate change (Asbar & Yunus 2022). Almost 75% of GHG is CO2 produced by human activities in the industrial and transportation sectors (Rawung 2015).

The abundance of motorized vehicles causes high fuel consumption, thereby increasing the release of fuel residues, leading to air pollution. Common air pollutants include Carbon monoxide (CO), Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), Hydrocarbon (HC), and particulate matter (Hannun & Abdul Razzaq 2022). The fuel residues comprise approximately 60% CO and 15% HC (Asharuddin & Basry 2023). Inhaling air contaminated with fuel residues initiates adverse health effects, such as respiratory and nervous system damage, digestive problems, cancer formation, and the onset of various other diseases (Fitri 2019).

Controlling CO_2 concentration in the atmosphere is crucial to mitigate the impact of global warming. Forests contribute significantly to this effort by absorbing CO_2 through photosynthesis, which involves chlorophyll and water (Permana et al. 2019). Photosynthesis results are stored in biomass form, contributing to the continual growth of vegetation until it reaches the physiological limit or is harvested. Generally, forests in a "net growth" phase, particularly those containing a high density of trees, can absorb more CO_2. However, mature forests store more carbon stocks without actively absorbing excess CO_2 (Obed et al. 2022). Sustainably managed forests ensure prolonged carbon storage in more significant quantities, contributing to long-term emission reduction efforts. Strategies commonly applied to achieve this include planting vegetation on bare land or rehabilitating disturbed forests to absorb excess atmospheric CO_2 (Jauhari et al. 2021).

Land exploitation contributes to deforestation in Indonesia, including landslides from the conversion process (Maryani 2020). GHG inventory to monitor emission reductions is necessary to mitigate climate change. In Indonesia, carbon emission estimation uses terrestrial and vegetation analysis by calculating differences in periodical carbon stocks (Krisnawati et al. 2015). Numerous research on carbon biomass content has occurred in natural, production, and mangrove forests Noor'an et al. 2016 (Noor'an et al. 2016; Witno et al. 2019; Hasidu et al. 2021). However, the gaps in the carbon stock of landslide areas make this research a valuable reference for the latest data on lost and recoverable carbon due to landslides.

Battang and West Battang Villages, located along the Trans Palopo-Toraja highways, experienced moderate to vulnerable categories of landslides. Previous research attributed these landslides to converting forests into vegetable and clove plantations, settlements, and roads (Latimojong 2021), significantly influencing carbon absorption and storage. The landslide incidents in this area have been relatively high between 2015 and 2021, with over 20 occurrences ranging from small to large. Therefore, this research aimed to assess the potential for CO2 absorption of forests around landslides along the Trans Palopo-Toraja highways. The information resulting from this research could become a reference indicator for necessary restoration activities.

Methods

Time and Location

This research was conducted all through April 2023 in the landslide areas along the Trans Palopo-Toraja Highways in Battang and West Battang Villages, Palopo City (Figure 1). The area possessed various characteristics, including being in a protected forest and other land uses, having an altitude between 150 m and 500 m above sea level, with a slope ranging from 15-40%, and precipitation of 2,500-2,700 mm/year. The measurement Plots were purposively placed around the landslide incidences in the two villages. The Plots were strategically positioned amidst the existing vegetation around landslide

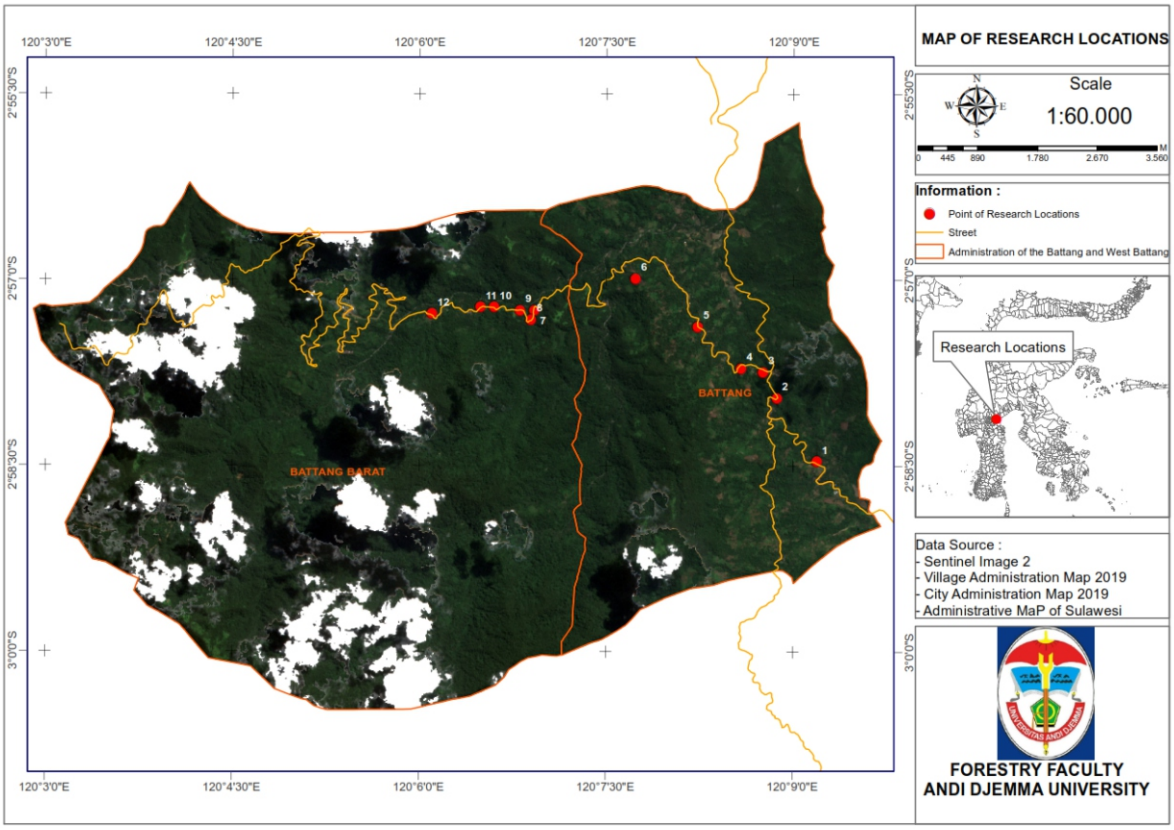

Figure 1. Location of measurement plots in the research area

incidences to estimate carbon absorption lost due to landslides. The carbon absorption value obtained from the existing vegetation indicated the quantity of carbon absorption lost due to landslides, offering valuable information for rehabilitating landslide-prone areas.

Tools and Materials

The tools used in this research included tally sheets, cameras, raffia rope, roll meters, stationery, compasses, haga meters, meter tapes, computers, and ovens. The applied materials comprised vegetation and litter from the protected forests and other land uses in Battang and West Battang Villages.

Data Collection

This research conducted field surveys to collect data, with observed parameters including plant species, the number of individuals per species, tree height, and tree circumference (converted to diameter at breast height or DBH) for saplings, poles, and trees using the Census method. The measurement Plots were purposively placed to represent vegetation conditions at growth and litter levels. The data collection from trees, poles, saplings, litter, and understorey applied 12 measurement Plots of 20 m x 20 m, 10 m x 10 m, 5 m x 5 m, and 0.5 m x 0.5 m, respectively. Moreover, the growth categories included mature and young trees with respective diameters of > 20 cm and 10 cm – 20 cm, as well as saplings with a height of > 1.5 m and a diameter of <10 cm (Hidayat & Hardiansyah 2012).

The measurement of understorey and litter biomass used the destructive method, which included direct biomass estimation by collecting sample trees and weighing each component (Krisnawati et al. 2012). Understorey samples included shrubs or seedlings with a stem diameter of <5 cm, vines, grasses, weeds, herbs, and terrestrial ferns found in three 0.5 m x 0.5 m subPlots to calculate the total wet weight (Witno et al. 2018). Subsequently, a sample of 200 grams of each Plot was put in the oven at 80°C for 48 hours to obtain the dry weight of each sample. Litter data measurement also occurred on 0.5 m x 0.5 m to obtain the wet weight of the samples. The subsequent step was oven-drying at 80°C for 48 hours to obtain the dry weight (Utami & Putra 2020).

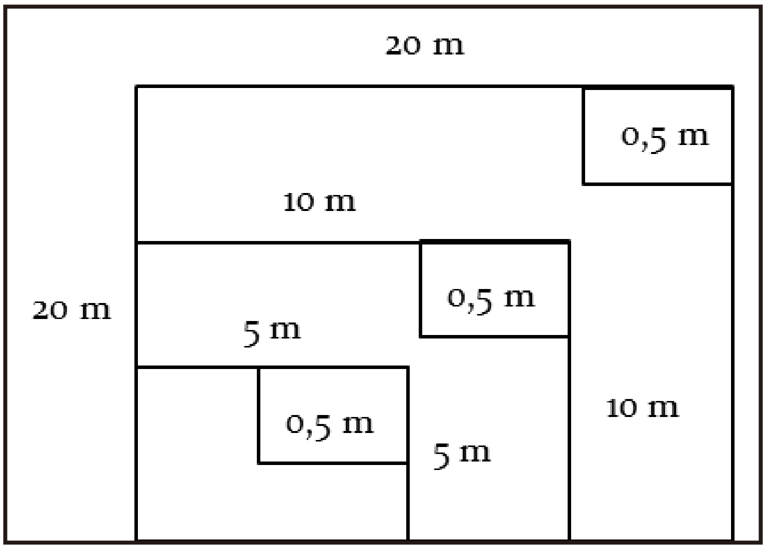

Figure 2. The measurement plot design, with three 0.5 m x 0.5 m subplots for understorey and litter biomass assessment (Witno et al. 2018)

Analysis

Vegetation Analysis

Analysis of species composition data collected from field observations used the formula from Soerinegara and Indrawan (Rambey et al. 2021).

Density (D)

$$D = \frac{\text{Number of individuals of a species}}{\text{Area of sample plots (ha)}}$$

Relative Density (RD)

$$RD = \frac{\text{The density of a species}}{\text{Densities of all species}} \times 100\%$$

Frequency (F)

$$F = \frac{\text{Number of plots found for a species}}{\text{Total number of plots}}$$

Relative Frequency (RF)

$$RF = \frac{\text{Frequency of a species}}{\text{Frequency of all species}} \times 100\%$$

Basal Area (LBDS)

$$\text{Basal Area} = 1/4.\mu.d^2$$

$$d = \textit{Circumference}/\mu$$

Dominance (C)

$$C = \frac{\text{Basal area of a tree species}}{\text{Total area of measurement plot}}$$

Relative Dominance (RC)

$$RC = \frac{\text{Dominance of a species}}{\text{Dominance of all species}} \times 100\%$$

Importance Value Index (IVI)

IVI = RD + RF + RC (for tree, pole, and sapling levels)

IVI = RD + RF (for seedling level)

The Minister of Forestry Regulation No. 200/ Kept-IV/1994 on Criteria for Unproductive Natural Production Forests regulates the criteria and classification of the IVI (Table 1).

Aboveground Biomass (AGB)

Estimation of tree AGB employed the following allometric equation (Ketterings et al. 2001):

$$Y = a.D^b$$

Description:

Y = biomass content (kg);

D= Diameter of trees at breast height (cm);

a,b = Constants, where a = 0.066 and b = 2.59.

If the research area contained tree species lacking an allometric equation, the biomass estimation used the standard equation for Indonesian tropical forest standard with rainfall between 1,500-4,000 mm per year. The equation was AGB= 0.118 $D^{2.53}$ (Brown & Ulgiati 1997)

Carbon Storage

Carbon stored in tree trunks represented 47% of the total biomass, calculated by multiplying the total biomass by 0.47 (National Standardization Agency or (BSN), 2012) according to the following equation.

$$C = Y x 0{,}47$$

Table 1. Vegetation IVI criteria and classification

No.	Tree IVI	IVI of Seedlings, Saplings, and Poles	Class
1	> 240	> 160	Very good
2	180 – 239	120 – 159	Good
3	120 – 179	80 – 119	Simply
4	60 – 119	40 – 79	Less
5	< 60	< 40	Very less

Table 2. Vegetation composition around landslide incidents along the Trans Palopo-Toraja Highways based on the growth levels

Plot	Number of Individuals			Total
	Saplings	Poles	Trees	
1	7	2	11	20
2	19	10	6	35
3	9	-	19	28
4	4	7	25	36
5	28	5	22	55
6	25	23	15	63
7	54	16	11	81
8	21	14	13	48
9	30	18	6	54
10	44	9	1	54
11	21	18	11	50
12	13	2	15	30
Total	275	124	155	554

Description:

C = Carbon Storage (kg);

Y = Tree biomass (kg);

0.47 = Carbon fraction.

Carbon Absorption

$$S = C \times 3.67$$ (SNI, 2011).

Description:

S = Carbon absorption (kg CO_2e);

C = Carbon storage (kg);

3.67 = constant, obtained from the ratio of CO_2 compound mass (44) and C atomic mass (12).

Litter and Understorey Biomass

Litter and understorey biomass calculation used the following formula.

$$Bo = \frac{\text{Dry Weight of the sample x Total wet Weight}}{\text{Wet weight of sample}}$$

Description:

Bo= Weight of organic matter (kg);

Bks= Dry weight of the sample (g);

Bbt= Total wet weight (g);

Bbs= Wet weight of the sample (g).

Result and Discussion

Species Composition

The results showed 77 plant species comprising 554 individuals identified along the landslide incidences along the Trans Palopo-Toraja Highways. These included 60, 27, and 35 species of saplings, poles, and trees, with 275, 124, and 155 individuals, respectively (Table 2). Furthermore, the distribution of individuals across different growth levels and species varied in each observation Plot. This disparity was due to the forest succession process through the disappearance or demise of certain species and the ingrowth of new species (Andewi et al. 2015). Saplings showed the highest number of individuals, attributed to the openness of the observation areas, where tall tree species with large diameters were scarce, permitting sufficient sunlight penetration. Meanwhile, poles had the lowest number, signifying the onset of competition leading to the inability of several species to survive. Plot 7 contained the highest number of individuals, totaling 81, while Plot 1 had the lowest, which was 20. Sapling and pole levels competed for sunlight and nutrients beneath the shade of tall trees, causing the diminished number of individuals in Plot 1. Large tree diameters correlated with fewer individuals (Haryadi 2017). Plot 3 indicated that intensified competition led to the lack of identifiable individuals at the pole level.

Importance Value Index (IVI)

The IVI was one of the parameters used to investigate the role of species in the plant community, where those with the highest IVI had elevated values of density, frequency, and dominance. The IVI signified species possessing a substantial number of individuals, widespread distribution, and dominance on the land surface compared to other plant types. The calculation of IVI required summing the relative density, frequency, and dominance (Utami & Putra 2020). At the sapling level, the analysis revealed that Sinangkala (*Litsea mappacea* Boerl) had the highest IVI of 14.69%, and Sleumer (*Gonocaryum* sp.) had the lowest IVI of 1.95%. At the pole level, Javanese wood (*Litsea mappacea* Boerl) had the highest IVI of 50.24%, while Javanese wood (*Lannea coromandelica*) had the lowest IVI of 5.63%. The Sinangkala (*Litsea mappacea* Boerl) had high IVI in all measurement Plots. Species with these high IVI values spread across the entire measurement Plots and vice versa (Hidayat 2018).

Magnitudes of IVI represented the level of roles that the species played in an ecosystem (Jhariya 2017); (Gunawan et al. 2015) At all growth levels, the high IVI of Sinangkala ecologically suggested superior adaptability and tolerance to surrounding environmental conditions than other species. Moreover, species with high IVI generally showed adaptation and survival in the regeneration process (Naharuddin, 2018; Siska et al. 2023). Animals significantly facilitated the regeneration of natural forests by spreading ingested seeds through faeces in the exploration area (Shilin et. al. 2023) contributing to the numerous Sinangkala stands found around the Trans Palopo-Toraja Highways.

Table 3. The IVI of each species for saplings, poles, and trees

Growth Rates	Local Name	Scientific Name	Number of Individuals	RD%	RF%	RC%	IVI%
Sapling	Angsana	*Pterocarpus indicus*	1	0.36	1.23	1.39	2.99
	Araliaceae	*Araliaceae*	1	0.36	1.23	0.71	2.31
	Aropi	*Antidesma celebica*	1	0.36	1.23	1.82	3.41
	Bangkal	*Nauclea officinalis*	1	0.36	1.23	3.75	5.35
	Banjar	*Cratoxylum fc.formosum*	4	1.45	2.47	1.93	5.85
	Banyan	*Ficus benjamina l.*	3	1.09	3.70	4.79	9.59
	Bintaro	*Cerbera manghas*	7	2.55	2.47	0.69	5.70
	Bitti	*Pitex Kopasus*	1	0.36	1.23	8.69	10.28
	Buni	*Antidesma sp.*	3	1.09	2.47	1.12	4.68
	Burkil	*Pternanda azurea*	6	2.18	2.47	0.35	5.00
	Cloves	*Syzygium aromaticum*	1	0.36	1.23	1.82	3.41
	Chocolate	*Theobroma cacao*	19	6.91	3.70	0.85	11.46
	By	*Dillenia serrata Thunb.*	4	1.45	1.23	0.71	3.40
	Durian	*Durio*	4	1.45	2.47	2.77	6.69
	Ganitri	*Elaeocarpus spaericus*	2	0.73	1.23	1.93	3.89
	Giwang	*Pimelodendron amboinicum*	2	0.73	1.23	0.18	2.14
	White teak	*Gmelina arborea*	2	0.73	1.23	4.61	6.58
	Jure	*Indicum mill*	4	1.45	1.23	0.94	3.63
	Camphor	*Cinnamomum camphora*	4	1.45	2.47	2.23	6.16
	Kapok randu	*Ceiba pentandra*	2	0.73	1.23	0.21	2.18
	Coffee	*Coffea sp.,*	2	0.73	2.47	1.63	4.83
	Kopi-kopian	*Rubiaceae*	9	3.27	1.23	0.04	4.54
	Langsat	*Lansium domesticum*	12	4.36	2.47	1.74	8.57
	Lempauang	*Beccaurea sp.,*	4	1.45	1.23	1.20	3.89
	Litchi	*Dimocarpus longan*	1	0.36	1.23	4.43	6.03
	Loba	*Symplocos sp.,*	9	3.27	1.23	0.32	4.82
	Malinjo	*Gnetum gnemon*	2	0.73	1.23	1.81	3.78
	Mareme	*Glochidion zeylanicum*	11	4.00	1.23	0.32	5.56
	Masoi	*Cryptocarya sp.,*	6	2.18	1.23	0.06	3.48
	Medang	*Litsea sp.,*	10	3.64	2.47	0.35	6.45
	Noni	*Morinda citrifolia*	9	3.27	1.23	0.19	4.70
	Mindi-mindian	*Melia azedarach*	4	1.45	1.23	0.45	3.14
	N16		9	3.27	1.23	0.26	4.76
	N19		13	4.73	1.23	0.31	6.27
	N21		5	1.82	2.47	0.26	4.54
	N26		1	0.36	1.23	5.96	7.56
	N28		2	0.73	1.23	3.59	5.55

Growth Rates	Local Name	Scientific Name	Number of Individuals	RD%	RF%	RC%	IVI%
	N36		2	0.73	1.23	0.78	2.74
	N42		2	0.73	1.23	0.18	2.14
	N46		1	0.36	1.23	6.38	7.98
	N8		1	0.36	1.23	1.60	3.19
	Nyatoh	*Palaquium obtusifolium*	5	1.82	1.23	0.37	3.42
	Palm	*Dypsis lutescens*	2	0.73	1.23	1.39	3.35
	Pampung	*Macropanax dispermus*	1	0.36	1.23	2.56	4.16
	Pumpkin tree	*Endospermum moluccanum*	1	0.36	1.23	1.82	3.41
	Legumes	*Leguminosae*	1	0.36	1.23	0.45	2.05
	Punak	*Theaceae*	1	0.36	1.23	1.60	3.19
	Puspa	*Schima wallichii*	1	0.36	1.23	2.05	3.65
	Rambutan	*Nephelium lappaceum*	7	2.55	3.70	2.56	8.81
	Sambas	*Rhodamnia sp.,*	18	6.55	2.47	0.17	9.18
	Seluang	*Luvunga sarmentosa*	1	0.36	1.23	6.38	7.98
	Sinangkala	*Litsea mappacea Boerl*	20	7.27	4.94	2.48	14.69
	Soursop	*Annona muricata*	5	1.82	1.23	0.22	3.28
	Sleumer	*Gonocaryum sp.,*	1	0.36	1.23	0.35	1.95
	Sterculia sp	*Sterculia sp.,*	5	1.82	1.23	0.33	3.38
	Tekalong	*Artocarpus elasticus*	4	1.45	1.23	0.45	3.14
	Uru	*Elmerillia ovalis*	2	0.73	2.47	2.30	5.50
	Viola	*Rinorrhea*	2	0.73	1.23	0.14	2.11
	Premna	*Premna sp*	7	2.55	1.23	0.90	4.68
	Total		275	100	100	100	300
Poles	Angsana	Pterocarpus indicus	2	1.61	2.70	6.00	10.31
	Ara-araan	Moraceae	3	2.42	2.70	1.19	6.31
	Banyan	Ficus benjamina l.	1	0.81	5.41	6.77	12.99
	Burkil	Pternandra azurea	16	12.90	2.70	0.40	16.00
	Chocolate	Theoboroma Cacao	4	3.23	2.70	0.94	6.87
	By	Dillenia serrata Thunb.	10	8.06	5.41	0.83	14.30
	Durian	Durio sp.,	3	2.42	5.41	3.56	11.39
	Eurya	Eurya nitida	4	3.23	2.70	2.27	8.19
	Java wood	Lannea coromandelica	2	1.61	2.70	1.32	5.63
	Ladiran		1	0.81	2.70	3.96	7.47
	Langsat	Lansium domesticum	12	9.68	5.41	1.03	16.12
	Loba	Symplocos sp.,	1	0.81	2.70	4.38	7.89
	Mahang	Macaranga hypoleuca	1	0.81	2.70	4.17	7.68
	Malinjo	Gletum gnemon	2	1.61	2.70	1.38	5.69
	Mareme	Glochidion zeylanicum	8	6.45	2.70	1.44	10.59
	N13		1	0.81	2.70	6.25	9.76
	N16		5	4.03	2.70	1.76	8.50
	N19		1	0.81	2.70	6.77	10.28
	N34		1	0.81	2.70	6.25	9.76
	Nutmeg	Myristica fragrans	1	0.81	2.70	4.38	7.89
	Legumes	Leguminosae	1	0.81	2.70	8.76	12.27
	Rambutan	Nephelium lappaceum	1	0.81	2.70	9.69	13.20
	Rolli	Ficus variegata Blume	1	0.81	2.70	6.25	9.76
	Seluang	Luvunga sarmentosa	1	0.81	2.70	4.17	7.68
	Sinangkala	Litsea mappacea Boerl	37	29.84	18.92	1.48	50.24
	Soursop	Annona muricata	1	0.81	2.70	3.96	7.47
	Viola	Rinorrhea	3	2.42	2.70	0.64	5.76
	Total		124	100	100	100	300
Trees	Angsana	Pterocarpus indicus	3	1.94	2.04	3.07	7.04
	Bajur	Pterospermum javanicum	1	0.65	2.04	1.79	4.48
	Bane	Aconium napellus	4	2.58	2.04	0.69	5.31
	Bangkal	Nauclea officinalis	8	5.16	2.04	0.58	7.78
	Bitti	Pitex Kopasus	2	1.29	2.04	0.54	3.88
	Bonitan	Pholyalthia lateliflora	4	2.58	2.04	2.18	6.80
	Burkil	Pternandra azurea	6	3.87	2.04	0.32	6.23
	Cloves	Syzygium aromaticum	3	1.94	2.04	0.37	4.35
	Dengen	Dillenia serrata Thunb.	3	1.94	6.12	2.30	10.35
	Durian	Durio sp.,	10	6.45	6.12	0.73	13.30
	Red Girang	Leea Indica	1	0.65	2.04	16.92	19.60
	Kacapiring	Glochidion sp.,	1	0.65	2.04	1.69	4.37
	Camphor	Cinnamomum camphora	3	1.94	2.04	4.97	8.95
	Kapuk Randu	Ceiba Pentandra	4	2.58	2.04	1.67	6.30
	Ladiran		3	1.94	4.08	3.80	9.81
	Langsat	Lansium domesticum	2	1.29	2.04	0.43	3.77
	Lempuang	Beccaurea..,	5	3.23	2.04	2.80	8.06
	Loba	Symplocos sp.,	1	0.65	2.04	1.64	4.32

Growth Rates	Local Name	Scientific Name	Number of Individuals	RD%	RF%	RC%	IVI%
	Marame	Glochidion zeylanicum	1	0.65	2.04	2.01	4.69
	Masoi	Cryptocarya sp.,	1	0.65	2.04	8.37	11.06
	N12		1	0.65	2.04	2.36	5.04
	N13		5	3.23	2.04	5.16	10.42
	N16		1	0.65	2.04	2.93	5.62
	N55		1	0.65	2.04	3.64	6.33
	Nyatoh	Palaquium obtusifolium	1	0.65	2.04	3.14	5.82
	Nutmeg	Myristica fragrans	4	2.58	2.04	0.61	5.23
	Pally	Alstonia scholaris	3	1.94	4.08	2.10	8.12
	Rambutan	Nephelium lappaceum	15	9.68	6.12	1.22	17.02
	Rolli	Ficus variegata Blume	1	0.65	2.04	3.28	5.96
	Sinangkala	Litsea mappacea Boerl	35	22.58	10.20	3.49	36.28
	Surian	Disoxylum sp.,	2	1.29	2.04	1.30	4.63
	Uru	Elmerillia ovalis	5	3.23	4.08	2.71	10.01
	Viola	Rinorrhea	12	7.74	4.08	4.39	16.21
	Total		155	100	100	100	300

Table 4. Aboveground biomass (AGB) of the measurement plots

Plot	AGB (tons/ha)			Total AGB Per Plot (tons/ha)	Aboveground Carbon Storage (tons/ha)			Total Above-ground Carbon Storage Per Plot (tons/ha)	Carbon Absorption (tons/ha)			Total Carbon Absorption Per Plot (tons/ha)
	Saplings	Poles	Trees		Saplings	Poles	Trees		Saplings	Poles	Trees	
1	14.54	10.65	90.55	115.74	6.84	5	42.56	54.4	25.09	18.36	156.18	199.63
2	79.96	45.65	155.21	280.82	37.58	21.46	72.95	131.99	137.93	78.74	267.72	484.39
3	40.81	0	237.12	277.93	19.18	0	111.4	130.63	70.4	0	409	479.4
4	17.27	33.57	407.39	458.22	8.12	15.78	191.5	215.37	29.78	57.91	702.7	790.39
5	109.03	37.82	223.32	370.16	51.24	17.77	105	173.98	188.06	65.23	385.2	638.5
6	57.34	73.61	131.48	262.43	26.95	34.6	61.79	123.34	98.9	127	226.78	452.66
7	107.79	65.97	205.61	379.37	50.66	31.01	96.63	178.3	185.92	113.8	354.65	654.37
8	15.74	46.24	292	353.98	7.4	21.73	137.2	166.37	27.15	79.75	503.67	610.57
9	101.93	85.66	23.77	211.37	47.91	40.26	11.17	99.34	175.83	147.8	41	364.59
10	53.97	44.05	87.52	185.53	25.37	20.7	41.13	87.2	93.09	75.98	150.96	320.03
11	36.42	44.86	43.98	125.26	17.12	21.08	20.67	58.87	62.82	77.38	75.86	216.06
12	19.28	13.31	158.99	191.58	9.06	6.26	74.73	90.04	33.25	22.96	274.24	330.45
Total	654.08	501.4	2056.9	3212.38	307.42	235.7	966.8	1.509.82	1128.2	864.8	3548	5541.03
Average	54.51	41.78	171.41	267.7	25.62	19.64	80.56	125.82	94.02	72.07	295.67	461.75

Aboveground Biomass (AGB)

The average AGB of the 12 measurement Plots was 267.70 tons/ha. At the sampling level, Plot 5 had the highest AGB of 109.03 tons/ha, while Plot 1 had the lowest AGB of 14.54 tons/ha. At the pole level, Plot 9 had the highest AGB, 85.66 tons/ha, and the lowest was in Plot 1 at 10.65 tons/ha. Meanwhile, at the tree growth level, the highest biomass was in Plot 4 at 407.39 tons/ha, and the lowest was in Plot 9 at 23.77 tons/ha (Table 4).

Aboveground Carbon Storage

The average aboveground carbon storage estimated in landslide incidences along the Trans Palopo-Toraja Highways was 125.82 tons/ha. Based on Table 4, the total carbon storage in the area around the landslide of the Trans Palopo-Toraja road was obtained as much as 1509.82 tons/ha with an average of 125.82 tons/ha. At the sapling level, Plot 5 had the highest aboveground carbon storage of 51.24 tons/ha, and Plot 1 had the lowest aboveground carbon storage of 6.88 tons/ha. At the pole level, Plot 9 had the highest aboveground carbon storage of 40.26 tons/ha, while Plot 1 had the lowest aboveground carbon storage of 5.00 tons/ha. At tree level, Plot 4 had the highest aboveground carbon storage of 191.47 tons/ha, and Plot 9 had the lowest aboveground carbon storage of 11.17 tons/ha (Table 4).

The numerous individuals and the high species density found in Plots 5 and 9 initiated the high carbon storage in both saplings and poles. Plot 4 had the highest aboveground carbon storage at the tree level due to 25 trees with an average DBH of 33.66 cm. Larger DBH would lead to higher aboveground carbon storage (Syamsudin Noor et al. 2020). Additionally, plant density, number of trees, and average tree diameter determined the carbon storage of each stand (Istomo & Farida 2017). Plot 1 had relatively low AGB and aboveground carbon storage at sapling and pole levels, suggesting that those variables had a proportional positive correlation (Santoso et al. 2021).

Carbon Absorption

The average carbon absorption was 461.75 tons/ha. At the sapling, poles, and tree levels, the highest carbon absorption was at 188.06 tons/ha (Plot 5), 147.76 tons/ha (Plot 9), and 702.70 tons/ha (Plot 4), respectively. The high carbon absorption in Plots 5 and 9 at sapling and pole growth levels was due to the height of the existing vegetation of 11.26 m and 26.64 m, respectively. The lowest carbon absorption at the sapling, poles, and tree levels was at 25.09 tons/ha (Plot 1), 18.36 tons/ha (Plot 1), and 41.00 tons/ha (Plot 9), respectively (Table 4). Trees above 10 m tall and with a canopy diameter of more than 10 m had ample carbon storage and absorption (Darlina et al. 2023). Additionally, vegetation possessing a large canopy or crown cover had a large number of leaves for efficient carbon absorption (Wiratman 2019). Trees had a relatively higher capacity to absorb CO2 than poles, saplings, and shrubs due to their larger basal areas. Large DBH contributed to the large basal area and carbon absorption (Handika et al. 2020).

Litter Biomass

Plot 10 showed the highest litter biomass at 10.70 tons/ha due to the possession of a reasonably high vegetation density, while the lowest was in Plot 12, with a value of 3.66 tons/ha (Table 5). Vegetation density was an environmental factor affecting litter production (Riyanto et al. 2013). The canopy or stand density influenced the fall of forest litter with direct proportionality because of competition for sunlight (Rositah et al. 2013). Additionally, trees in a relatively dense forest initiated the formation of litter by releasing branches and leaves rapidly during growth, starting from the bottom due to insufficient light availability for photosynthesis.

Understorey Biomass

Plot 1 has the highest understorey biomass, reaching 13.79 tons/ha, while Plot 10 has the lowest value, 0.44 tons/ha (Table 6). This high value in Plot 1 was due to the reasonably open nature of the area with fewer individual trees, leading to optimal understorey growth and the absence of competition for sunlight. Additionally, survival ability significantly influences understorey vegetation characteristics in the forest ecosystem (Passal et al. 2019). The relatively dense vegetation in Plot 10 caused the low understorey biomass. Hence, tall trees with lush crowns blocked sunlight penetration into the canopy. Unexposed understory to direct sunlight experienced obstacles in photosynthesis, leading to smaller biomass, carbon storage, and absorption compared to trees (Darlina et al. 2023). The trees contributed around 61.99% of the total biomass in 12 measurement Plots, which was relatively high compared to poles, saplings, litter, and understorey (Figure 4). Understorey and litter biomass played similar roles in carbon absorption and storage but at low rates.

Table 5. Litter biomass

Plot	Total wet weight (g)	Wet weight of sample (g)	Dry weight of the sample (g)	Biomass (g/0.75 m²)	Biomass (g/ha)	Biomass (tons/ha)
1	865	200	137	592.525	7900333.33	7.90
2	789	200	148	583.86	7784800	7.78
3	853	200	145	618.425	8245666.67	8.25
4	812	200	130	527.8	7037333.33	7.04
5	742	200	141	523.11	6974800	6.97
6	608	200	107	325.28	4337066.67	4.34
7	467	200	134	312.89	4171866.67	4.17
8	711	200	126	447.93	5972400	5.97
9	643	200	133	427.595	5701266.67	5.70
10	1198	200	134	802.66	10702133.3	10.70
11	578	200	135	390.15	5202000	5.20
12	590	200	93	274.35	3658000	3.66
		Total			77687666.7	77.69
		Average			6473972.22	6.47

Table 6. Understorey biomass

Plot	Total wet weight (g)	Wet weight of sample (g)	Dry weight of the sample (g)	Biomass (g/0.75 m²)	Biomass (g/ha)	Biomass (tons/ha)
1	6270	200	33	1034.55	13794000	13.79
2	388	200	83	161.02	2146933.33	2.15
3	131	131	38	38	506666.667	0.51
4	501	200	85	212.925	2839000	2.84
5	388	200	45	87.3	1164000	1.16
6	361	200	37	66.785	890466.667	0.89
7	410	200	59	120.95	1612666.67	1.61
8	242	200	53	64.13	855066.667	0.86
9	262	200	61	79.91	1065466.67	1.07
10	169	169	33	33	440000	0.44
11	352	200	62	109.12	1454933.33	1.45
12	400	200	43	86	1146666.67	1.15
		Total			27915866.7	27.92
		Average			2326322.22	2.33

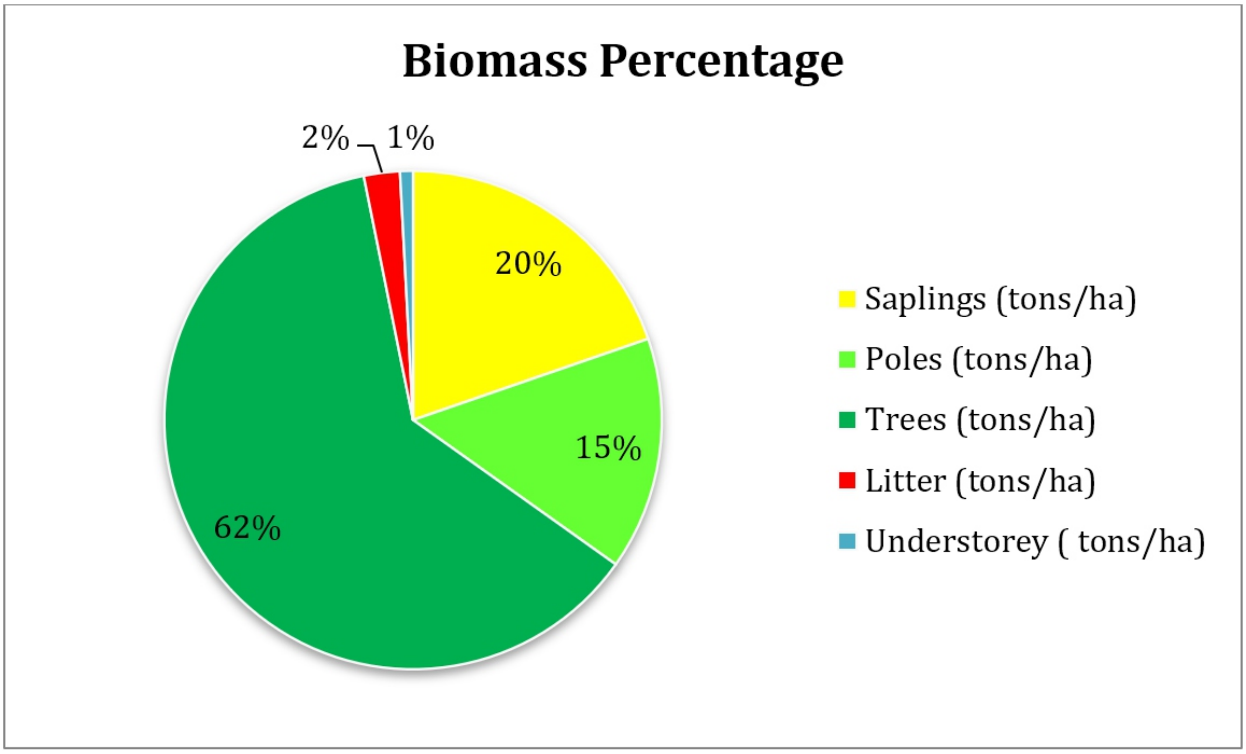

Figure 3. Biomass percentage of trees, poles, saplings, litter, and understory in 12 measurement plots.

Conclusion

In conclusion, this research identified 77 plant species comprising 554 individuals in the Trans Palopo-Toraja Highways. The highest and lowest carbon absorption potentials reached 790.39 tons/ha and 199.63 tons/ha in Plots 4 and 1, respectively. The average carbon storage in the 12 measurement Plots was 461.75 tons/ha. Trees had the most significant carbon absorption value due to their excellent CO_2 absorbing capacity compared to saplings and poles.

Acknowledgments

The authors are grateful to the Ministry of Education, Culture, Research, and Technology for the support rendered through the PDP scheme research grant in 2023. The authors are also grateful to the Faculty of Forestry at Andi Djemma University, the research team, and the students for the valuable assistance provided.

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