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Carbon storage potential of *Eucalyptus urophylla* at several density levels and forest management types in dry land ecosystems

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Abstract. *Marimpan LS, Purwanto RH, Wardhana W, Sumardi. 2022. Carbon storage potential of* Eucalyptus urophylla *at several density levels and forest management types in dry land ecosystems. Biodiversitas 23: 2830-2837.* Tropical forests can store high amounts of carbon because they have suitable environmental factors. Furthermore, they are different from others that grow in dry areas, which tend to experience limited rainfall. Ampupu (*Eucalyptus urophylla*) is an endemic tree in East Nusa Tenggara, Indonesia which is continuously damaged. This is caused by various anthropogenic activities, which increase along with the population around the forest. Therefore, this study aims to estimate the carbon content stored in natural forest areas of *E. urophylla* at different density levels and land use types. Field inventory was carried out in the study location using the stratified sampling method, after which the density levels were divided into three groups, viz. high, medium, and low. Sampling was then carried out in 3 different land-use areas, including production, protection, and conservation forests. Furthermore, a total of 90 plots were used, where each land-use type consists of 30 plots with a size of 25 m × 40 m. The results showed that the carbon content at the low, medium and high-density levels were 108.20, 185.24, and 291.33 $MgCha^{-1}$, respectively. Values of 211.91, 214.69, and 221.14 $MgCha^{-1}$ were also obtained from the production, protection, and conservation forests, respectively. Based on the results, the natural forests of *E. urophylla* have a significant effect on carbon sequestration in East Nusa Tenggara.

Keywords: Allometric equation, carbon stock, Myrtaceae, Timor, vegetation densities

INTRODUCTION

Forests provide various direct and indirect benefits to humans (Pasaribu et al. 2021). The direct benefits include providing a wood source for building materials and fuel, as well as food and clean water. Meanwhile, the indirect benefits include the provision of ecosystem services, such as storing large amounts of carbon, which makes the forests a natural reservoir (Chu et al. 2019; Purwanto et al. 2021). Land cover plays an essential role in controlling carbon dioxide (CO_2) emissions as well as its storage in forest stands (Olorunfemi et al. 2019). The ongoing destruction of ecosystems reduces their ability to absorb carbon (McNicol et al. 2018; Chen et al. 2019; Liu et al. 2021). Forest encroachment, timber theft, fire outbreak, livestock release, and shifting cultivation are factors that can also trigger an increase in CO_2 emissions. This is caused by uncontrolled human activities, which often lead to enormous climate changes (Dako et al. 2019; Liu et al. 2021). Furthermore, this phenomenon is characterized by increasingly uncontrolled global warming (Palacios Peñaranda et al. 2019; Olorunfemi et al. 2019). The role of humans, especially the control of the local community over forest carbon needs to be properly monitored (Benjaminsen and Kaarhus 2018; Etemesi et al. 2018; Gu et al. 2022). The concentration of CO_2 in the atmosphere has a very significant contribution to the occurrence of various global environmental problems (Rajashekar et al. 2018; Yin et al. 2019).

Vegetation canopy density is a physiognomy description of forests as well as a measure of their health condition (Hartoyo et al. 2019). It is also a factor that helps in increasing and maintaining the carbon content in an area. Decreasing vegetation density can cause a 56% decrease in the amount of carbon (Pandey et al. 2020; Purnomo et al. 2022). This is in line with a previous study that its reduction in lowland land areas led to a loss of 269.1-46.3 $MgCha^{-1}$ (Astiani et al. 2017). Furthermore, canopy change is an important factor that needs to be considered because it is closely related to land cover change (Skole et al. 2021), and has an impact on carbon storage (Puspanti et al. 2021). Conservation and protected forests have a lower risk of CO_2 emissions due to reduced human activities (Nogueira et al. 2018). Production forests are expected to produce various products, including meeting the demand for carpentry wood and firewood (President of Indonesia 2021). However, its carbon content also plays a role in reducing CO_2 emissions when it is properly managed.

The natural forests of *Eucalyptus urophylla* S.T. Blake; Myrtaceae (locally called Ampupu) is an endemic plant to Timor Island and its dominance in the Mutis Timau area needs to be considered in terms of its carbon content

(Marimpan and Purwanto 2010). Their presence is also expected to help in the control of microclimate in the surrounding area. The quality of environmental services in the form of honey and clean water sources is important in meeting the needs of South Central Timor, North Central Timor, and Kupang Districts (Nature Conservation Agency 2018; Njurumana et al. 2021). There are few studies on the potential for carbon storage in the natural forests of *E. urophylla* in dryland areas. Therefore, this study aims to estimate the carbon storage of *E. urophylla* in the production, protection, and conservation of forests at various vegetation densities.

MATERIALS AND METHODS

Research area

This study was carried out specifically on the natural forests of *E. urophylla* located in 3 management types, viz. production, protection, and conservation areas in Kupang, South Central Timor, as well as South and North Central Timor Districts, respectively, East Nusa Tenggara Province, Indonesia. The production forest is located in the Lelogama Sub-district, which is geographically located between 123°58'-123°59' E and 9º45'-9º46' S, as shown in Figure 1. This area is located at an altitude of 1200-1300 m above sea level and is 75 km east of the capital city of Kupang District. The annual rainfall is in the range of 179-559 mm/year (Central Agency on Statistics of East Nusa Tenggara 2021). Its topographic conditions range from flat to steep with an average slope of 20%. The types of soil found in the area are Mediterranean, grumosol, and latosol. Meanwhile, the conservation and protected forest are geographically located at 124°10'-124°20' east longitude and 9°30'-9°40 latitude, as shown in Figure 1. They are located at an altitude of 2500 m above sea level with a landscape ranging from hilly to mountain. Their topographic conditions range from flat to very steep with an average slope of 60%. The area is dominated by Mediterranean soil, and the rainfall ranges from 2000-3000 mm with temperatures between 14-29°C (BKSDA 2018).

Inventory of *Eucalyptus urophylla*

The forest inventory was carried out in the stand cover area of *E. urophylla,* which was delineated from the Landsat 8 OLI Surface Reflectance image (patch/row: 110/65) dated 31 August 2020 for the production forest research area, while for the Protection forest and conservation forest area (patch/row: 110/67) dated 30 July 2020 and verified based on field observations. The tools used were phiband, roll meter, stake, paint, raffia rope, brush, handheld Abney level, and Global Positioning System (GPS). The study was performed because the focus of the study was the natural forest of the plant species. Based on the delineation results, measurements were then taken to produce an inventory of the carbon stock, which represents the current state of the forest (Hoover 2008). Furthermore, the cluster sampling method was used to determine the stand density level and then continued with stratified random sampling (Sugiyono 2020; Bentsi-Enchill et al. 2022) for random selection of the population with a proportional placement. The number of samples taken at high, medium and low densities was determined based on the representativeness of the area. The wider the density, the more samples that were collected (Sugiyono 2020). This method was used because *E. urophylla* had a different land cover, and they were collected from each plot. Nurgiyantoro et al. (2009), stated that to achieve a normal distribution in a population, a minimum of 30 samples are needed. In table 1, 30 samples have the same relative value as an infinite population. The three forest areas had a total of 90 plots, and Figure 2 shows their distribution at the study site.

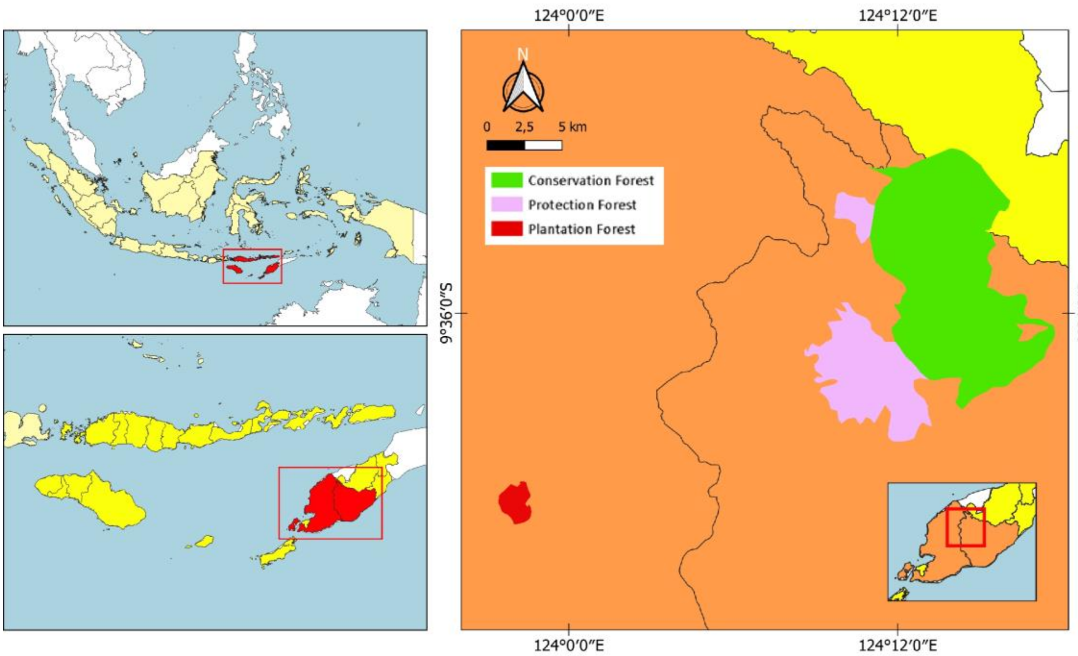


Figure 1. Research locations in Kupang District and TTS District, East Nusa Tenggara Province, Indonesia

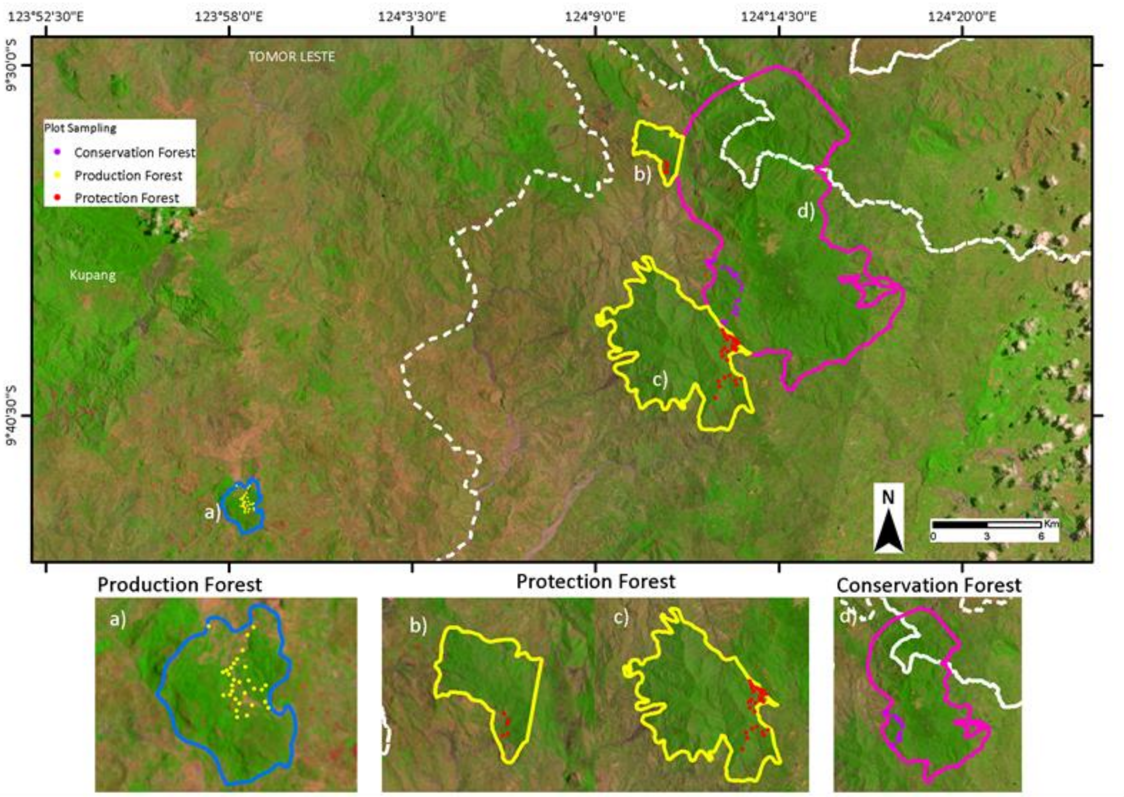


Figure 2. Map of the plot distribution at the research site

The total area of the research site was 17,376.55 ha, where the production, protected and conservation forest areas were 430.37 ha, 4,630.92 ha, and 12,315.26 ha, respectively, as shown in Figure 1. Furthermore, the data collection method is similar to that of Pham et al. (2019), where the area of the sample plot used was 25 × 40 m (0.1 ha). Measurements were then carried out on *E. urophylla* vegetation, which contained trees, poles, saplings, and seedlings in 25 m × 40 m, 10 m × 10 m, 5 m × 5 m, and 2 m × 2 m plots, respectively. The areas were made in the field by pulling the rope 25 meters to the north and 40 meters to the east and the points were tied rectangularly to a stake (Hairiah et al. 2001). The formation of the measuring plots was based on the type of object being examined (Makinano-Santillan et al. 2019).

Trees on the outer boundary were used in the measuring plots when > 50% of their trunk diameter was included in the plot. Furthermore, all trees in the study location were numbered with yellow paint, while the belt at diameter at breast height (1.3 m) was painted in red for easy measurement when needed. The measuring plots were rectangular, where the center had a larger portion than the edges. The form of this measuring plot is very useful in avoiding the border effect because the edges were located on the boundary between the plot and the road (Hairiah et al. 2001; Marsono 2007).

Carbon estimation

Measurement was carried out in the field to estimate the carbon content in the natural forest of *E. urophylla* using an allometric equation, as shown below: (Marimpan and Purwanto 2010)

$K_{Root} = 0.008\ D^{2,478}$ with $R^2 = 0.990$

$K_{Stem} = 0.021\ D^{2,604}$ with $R^2 = 0.992$

$K_{Branch} = 0.011\ D^{2,380}$ with $R^2 = 0.984$

$K_{Leaf} = 0.008\ D^{2,012}$ with $R^2 = 0.972$

$K_{Total} = 0.042\ D^{2,532}$ with $R^2 = 0.992$

Description: D = diameter, R^2 = coefficient of determination

This allometric equation was obtained from the results of previous studies carried out at forest locations (Marimpan and Purwanto 2010). Subsequently, carbon stock was measured in the roots, stems, branches, and leaves. Various parameters were also measured, including the number of trees in each plot, average diameter, average height, and total carbon as an indicator of the vegetation structure (Bentsi-enchill et al. 2022). These measurements were carried out at the high, medium, and low-density levels. It was also performed at 3 different types of forest management, viz. conservation, protection, and production forest. The value of carbon stock at the density levels and management type per hectare was calculated in $MgCha^{-1}$.

Data analysis

The data obtained were analyzed quantitatively by calculating the mean value and standard error to ensure the characteristics were well distributed (Sadono et al. 2020). The result was presented in the form of a histogram for ease of viewing the carbon stock at each density and type of forest management (Table 1). Subsequently, One-way analysis (ANOVA) was used to examine the relationship between carbon content with density and forest management type (Zhang et al. 2012; Wirabuana and Pratiwi 2021).

RESULTS AND DISCUSSION

Results

Measurements were carried out on three types of forest with a total of 30 plots each. The stand density of *E. urophylla* was classified into three groups, viz. high, medium and low. The results showed that the distribution of the sample trees was in the normal range, as shown in Figure 3. This finding indicates that the selection of the trees represents the current state of the observed forest. The diameter was also measured to estimate the amount of carbon stored at the research site. It may be due to a very strong relationship with tree height, volume, canopy cover, annual rainfall, and vegetation structure (Simon 2007; Karyati et al. 2019; Balima et al. 2021). Furthermore, its measurement in the field is more practical. Hence, it can reduce the error factor during the process.

Based on the results, the carbon content varied in each tree part, as shown in Table 1. The highest value of 65.59% was obtained from the stems, while 16.19%, 15.29%, and 2.93 were recorded in the roots, branches, and leaves, respectively. This is in line with a previous study, which stated that the largest carbon content was obtained in the stems, branches, and leaves (Sadono et al. 2021). The high storage in the stem and branches was due to its large biomass accumulation. A previous study revealed that the majority of water and nutrients obtained from the photosynthesis process are stored in the stem through translocation (Wirabuana et al. 2020). However, this finding is inconsistent with this study, where the carbon content in the roots was higher than in the branches. This was caused by firewood theft, which often occurs throughout the year in the area. The woods are collected from the branches to reduce the accumulation of carbon in the organs. Other causal factors include natural disasters, such as lightning strikes during the rainy season and the breaking of twigs and branches caused by wind. The community's dependence on *E. urophylla* forests is inevitable due to the lack of alternative energy sources (Pandey et al. 2020). Anthropogenic pressure also affects the accumulation of carbon in a forest ecosystem (Eddy et al. 2021; Liu et al. 2021). Disturbances, including clearing of agricultural and plantation land as well as illegal logging and mining activities, contribute to the decrease in the population of trees. The damage caused by these activities leads to the opening of the land. Consequently, the activities of microorganisms are reduced, which indicates that the nutrient cycle is disrupted as the ability of the forest to store carbon is reduced (Liu et al. 2021; Bentsi-Enchill et al. 2022; Gu et al. 2022).

Carbon storage at density

The carbon stock obtained in the production forest at low, medium, and high-density levels were 26.30, 150.76, and 331.15 $MgCha^{-1}$, respectively. Meanwhile, values of 142.74, 206.84, and 255.72 $MgCha^{-1}$, were recorded in the protected forest at the three levels, respectively. The total carbon in the conservation forests was 149.65, 194.27, and 283.73 $MgCha^{-1}$, respectively, as shown in Figure 3. Figure 4B shows that the highest content value was obtained at the high-density level, followed by the medium and low levels. The carbon stocks value at the low, medium, and high densities levels were 108.20, 185.24, and 291.33 $MgCha^{-1}$, respectively.

A study by Zhao et al. (2019) has shown that the density of the forest stands was increased with 20% increase in canopy cover. Consequently, the carbon content was raised from 38.18 $MgCha^{-1}$ to 44.52 $MgCha^{-1}$. Dangwal et al. (2022) said that the density of trees in the ecosystem also affects the carbon stock. In his research, an arboretum with a tree density of 332.6 ha-1 was able to store carbon 49.5 $MgCha^{-1}$, while in a natural forest with a tree density of 184 ha^{-1} it was only able to store 30.8 MgCha-1 of carbon.

The 36.29% increase in land cover of plantation forests from 2009 to 2018 caused an increase in carbon sequestration from 23.49 to 68.88 $MgCha^{-1}$ (Zhang et al. 2020). A previous study in the Atlantic forests of South Brazil revealed that regeneration causes an increase in the value of the stock. Furthermore, the old forest had the largest carbon content where values of 231 ± 43 $MgCha^{-1}$, 141 ± 33 $MgCha^{-1}$, and 42 ± 24 $MgCha^{-1}$ were obtained at the age of ≥ 80 years, 35-55 years, and 7-17 years, respectively (Capellesso et al. 2021). The increase in carbon by 2.6% per year in community-based managed forests is different from areas that are not managed by communities, where an increase of 0.18% occurred per year (Wood et al. 2019). Stand density is positively correlated with carbon content (Bentsi-Enchill et al. 2022)

This study's results showed that the stand density of *E. urophylla* affects their carbon storage. Hence, increasing its value (increase in the number of trees in the unit area) causes an increase in the stock of the forest ecosystem. An increase in the diameter and height also correlates with an increase in the canopy area, branches, twigs, and roots. However, this approach tends to change in an abnormal forest, which is limited by climate, weather, temperature, and altitude factors. The carbon content of the area is determined by the local environmental conditions.

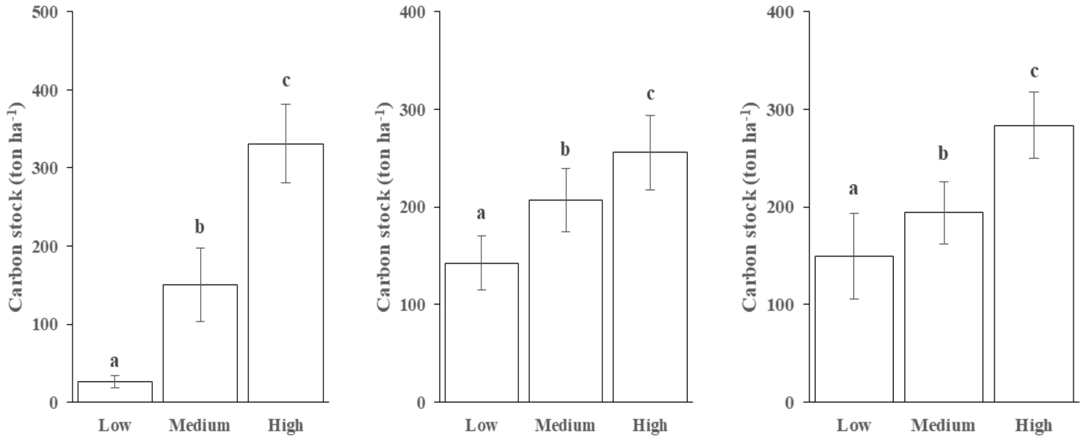
Carbon storage in forest management type

The carbon storage in the natural forests of *E. urophylla* varied at each plot observed. The lowest value obtained was 26.30 $MgCha^{-1}$, while the highest was 331.15 $MgCha^{-1}$, as shown in Figure 3. The highest carbon storage was recorded in the production forests due to silvicultural treatment, which causes the optimal growth of the trees in terms of obtaining growing space and nutrients. In the conservation and protected forests, the storage was relatively low due to environmental factors as well as anthropogenic pressure. However, the results showed that they had the highest total accumulation. The carbon and biomass content of a forest ecosystem is strongly influenced by the physiological process, i.e. photosynthesis

(Lukito and Rohmatiah 2013). The sequestration is influenced by biophysical factors, such as climatic conditions (Yin et al. 2022). Forest ecosystems that grow in high topography serve as landslide protection, but they have low temperatures, which causes shortness as well as low diameter in the plants (Fischer et al. 2019; Pach et al. 2022). Dry climates in areas, such as Timor Island in East Nusa Tenggara also have an impact on carbon storage.

Table 1. Carbon content in various components of *E. urophylla* in tree density and land use type

Components	Units	Type of forest			Vegetation density		
		Production	Protected	Conservation	High	Medium	Low
Roots	N	30	30	30	42	22	26
	Mean	31.29	32.08	33.02	43.30	27.56	16.19
	SE	5.26	3.26	3.38	3.51	3.05	3.16
Stem	N	30	30	30	42	22	26
	Mean	148.96	148.53	153.13	202.97	128.87	74.70
	SE	25.82	15.73	16.37	17.42	15.00	15.10
Branches	N	30	30	30	42	22	26
	Mean	27.15	28.43	29.23	38.03	24.26	14.38
	SE	4.45	2.80	2.90	2.95	2.59	2.73
Foliage	N	30	30	30	42	22	26
	Mean	3.75	4.05	4.15	5.34	3.42	2.07
	SE	0.56	0.36	0.37	0.35	0.32	0.35



(a) Production forest **(b) Protected forest** **(c) Conservation forest**

Figure 3. Carbon storage distribution in every vegetation density at each type of forest ecosystem

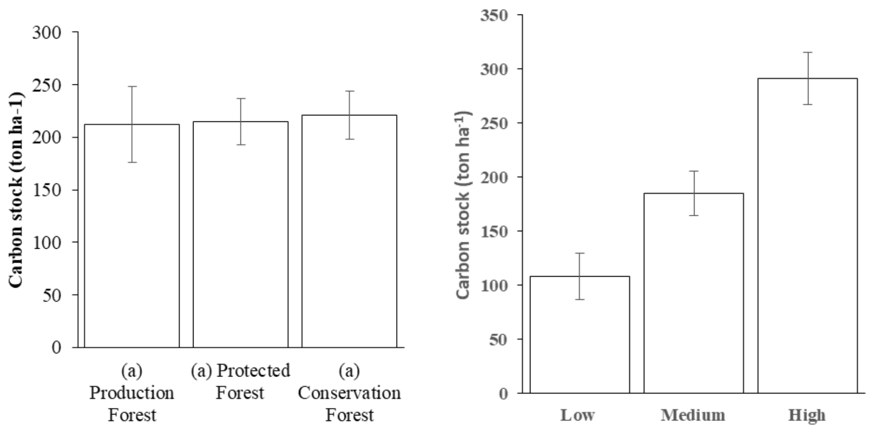


Figure 4. Comparison of carbon storage in the research site based on (a) type of forest and (b) vegetation density

The highest carbon content was obtained from the conservation forest, followed by protection and production forests, as shown in Figure 4A. The storage values in the three areas were 221.14, 214.69, and 211.91 $MgCha^{-1}$ respectively. These results are in line with a previous study on *E. urophylla* plantations in the Pearl River Delta, South China and *Acacia* forest, where carbon storage of 207.45 $MgCha^{-1}$ and 189.35 $MgCha^{-1}$ were obtained (Zhang et al. 2012). Meanwhile, a value of 200 ± 500 MgCha was recorded in the conservation forests in the Malaysian State of Sabah, which was significantly different from that of areas experiencing deforestation, i.e. 60 ± 140 $MgCha^{-1}$ (Asner et al. 2018). Values of 181 ± 298 $MgCha^{-1}$, 68.10 ± 20.92 $MgCha^{-1}$, and 10.81 ± 0.005 $MgCha^{-1}$ were obtained in the mangrove forests of Sagara Anakan Lagoon, Nusa Lembongan Bali, and Pangarengan Cirebon, as well as *Avicennia*, stands, respectively (Kusumaningtyas et al. 2019; Pricillia et al. 2021; Purwanto et al. 2021).

Research on damaged protected forests in North Mexico obtained a carbon stock of 68.81 $MgCha^{-1}$ (Orta-Salazar et al. 2021). Other studies stated that the storage in lowland, upland and evergreen forests were 121.7, 116.2, and 105.2 $MgCha^{-1}$ respectively (Yi et al. 2014). Furthermore, a study on protected forests in the Himalayas obtained a value of 164 ± 8 $MgCha^{-1}$, which was greater than the value recorded in unprotected areas, i.e. 114 ± 5 $MgCha^{-1}$ (Måren and Sharma 2021). Based on a previous study in Burkina Faso, West Africa, the carbon storage ranged from 47.82 ± 67.95 $MgCha^{-1}$ in protected areas (Balima et al. 2021).

A study on the production forest with plantation type in Lishui, South China, revealed that the Pine and Fir have relative carbon storage of 223.36 and 232.04 $MgCha^{-1}$, respectively (Diao et al. 2022). A similar study, which was also carried out in Chilas, Gilgit District, Baltistan, Pakistan recorded a stock value of 19.41 $MgCha^{-1}$ (Raqeeb et al. 2021). In the *Eucalyptus* forests, located on the north of Heyfield forest in West Gippsland, low carbon storage of 134 ± 8.4 $MgCha^{-1}$ was obtained due to frequent fires (Fairman et al. 2022). A value of 130.78 MgCha-1 was recorded in the semi-deciduous forest in the Rio Doce Basin, Atlantic *Eucalyptus* species, where there was no damage. Meanwhile, the carbon storage in damaged areas decreased to 7.08 $MgCha^{-1}$ and 18.20 $MgCha^{-1}$ at the age of 5 and 30 years, respectively (Coelho et al. 2022). Several studies revealed that the storage of *E. urophylla* in production forests managed by the Forest Management Unit of South Center Timor was 171.76 ± 52.25 $MgCha^{-1}$ (Sadono et al. 2020). A previous study in Jilin China obtained high carbon storage of 2165.0 $MgChm^{-2}$ because the area was supported by environmental factors (Yin et al. 2022). Carbon sequestration is influenced by biophysical factors, including climatic conditions (Yin et al. 2022; Yuan et al. 2022).

E. urophylla is a natural forest that is dominantly found on the mainland of Timor Island, especially in the Mutis Timau area (BKSDA 2018). People in East Nusa Tenggara are aware that the region is a water catchment area, as well as a source of honey and firewood for communities around the buffer zone (Njurumana et al. 2021). Furthermore, the high wood density of 0.93 $grcm^3$ and durability make the trees attractive to the public as a source of firewood (Marimpan and Purwanto 2010). Apart from the high carbon storage in these three forest areas, they are still affected by a very low regeneration. This is caused by the high rate of livestock farming, where the seedlings of trees are trampled upon by grazing animals. At the state level, threats are also posed by thieves that often cut down trees as a source of firewood. Previous studies stated that regeneration must be considered in forests as an alternative way of increasing carbon storage and conserving plants (Capellesso et al. 2021). Therefore, several policies need to be implemented to prevent the extinction of forests.

The results showed that the conservation, protection and production forests of *E. urophylla* can store a large amount of carbon. The amount of mineral conserved depends on the density of the area. The existence of the three forest areas provides a clean source of oxygen and water that flows throughout the year. They also serve as a source of hygienic forest honey, which increases the income of the surrounding community. Therefore, rehabilitation needs to be carried out in forest areas with medium and low density to improve environmental services. Future studies are also expected to examine the storage in necromass and soil so that the information related to the carbon content in natural forests of *E. urophylla* could be further detailed.

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