

Carbon sequestration potential of Tamanu (*Calophyllum inophyllum*) in Gunung Kidul, Yogyakarta

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Abstract. Indigenous tree species play an important yet underestimated role in tropical ecosystems' carbon sequestration, mitigating global climate change. Tamanu (*Calophyllum inophyllum*), an indigenous tree species, is studied for its carbon sequestration capacity in Gunung Kidul, Yogyakarta, Indonesia, an environmentally diverse location. Our comprehensive investigation included aboveground and belowground biomass, soil carbon concentration, and understory carbon content. The study found that tamanu stands can store carbon in their biomass, understorey, and soil, i.e., 54.2, 0.5, and 64 tons/ha, respectively. It was also shown that soil stores the most carbon because the Tamanu planted in this study area is still relatively young and has a relatively large space. This study also revealed the understory plants' often overlooked role, increasing these ecosystems' carbon sequestration capability. The need for comprehensive conservation programs considering carbon storage above and below ground is highlighted. The above discoveries contribute to creating efficient local climate mitigation policies and the global effort to combat climate change.

1 Introduction

The urgent issue of global climate change has highlighted the crucial requirement for efficient measures to control the rise in atmospheric carbon dioxide levels [1]. The method of carbon sequestration, which involves the capture and storage of carbon dioxide from the atmosphere, is of paramount importance in these endeavors as it aids in mitigating persistent carbon emissions. Trees and plants have a crucial role in the process of mitigating climate change as they serve as natural carbon sinks. Therefore, they are considered vital elements of any comprehensive strategy aimed at addressing climate change [1,2].

Tamanu (*Calophyllum inophyllum*), also referred to as the Alexandrian laurel or beach mahogany, is a type of tropical evergreen tree that is highly regarded for its many ecological

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and economic characteristics [3]. Tamanu, a plant species found in abundant numbers along coastal parts of tropical areas, has garnered significant interest due to its various noteworthy attributes [4]. These include its valuable timber [5], medicinal capabilities [6,7], biodiesel potential [8,9], and its capacity to trap considerable quantities of carbon [10,11]. The forestry sector has various mitigation alternatives at its disposal, including the extension of carbon retention in harvested wood products, product substitution, and the production of biomass for bio-energy [12]. Tamanu has the opportunity to sequester and store carbon in its tree biomass and produce fruits for bioenergy production, which can be one of the activities to mitigate climate change. The use of various techniques such as natural regeneration, afforestation, reforestation, agroforestation, and climate-wise agriculture in Indonesia offers a potential avenue for restoring degraded lands [13].

Within the local environment of the Gunung Kidul region in Yogyakarta, Indonesia, the species Tamanu has a noteworthy ecological significance. The peculiar environmental circumstances found in Gunung Kidul, which include an arid climate and unique geological formations, offer a remarkable opportunity to investigate the carbon sequestration capabilities of this particular species [13]. Notwithstanding its apparent importance, there is a dearth of empirical studies examining the carbon sequestration capability of Tamanu in this particular geographical area.

The primary objective of this study is to address the existing knowledge gap by examining the carbon sequestration capacity of Tamanu in the Gunung Kidul district of Yogyakarta. By doing extensive field surveys, collecting data, and afterward analyzing it, our objective is to quantitatively assess the role of this particular species in carbon sequestration and gain a deeper understanding of its ecological ramifications. This work provides useful insights into the carbon sequestration ability of Tamanu in a specific environment, hence contributing to local conservation initiatives and broader measures for mitigating climate change.

This study aims to enhance the comprehension of the involvement of Tamanu in carbon sequestration endeavors, specifically within the distinctive setting of Gunung Kidul, Yogyakarta. The primary objective of this study is to present significant data that might assist decision-making processes concerning the preservation and administration of Tamanu populations. Additionally, this research aims to contribute to the broader academic discussion surrounding the possible role of tropical tree species in addressing the challenges posed by climate change. This research highlights the significance of conducting localized ecosystem-specific studies in order to develop effective solutions for mitigating climate change. It aims to address the information gap pertaining to the carbon sequestration capability of Tamanu in the Gunung Kidul region. In addition, this study adds to the existing pool of knowledge regarding the role of trees in worldwide attempts to sequester carbon, emphasizing the ecological importance of this particular species amongst the current environmental issues. In the next sections of this paper, we will examine the pertinent literature, describe the methodology utilized in this study, report the outcomes of our field investigations, and engage in a thorough discussion regarding the implications and importance of our results.

2 Literature review

The significance of trees and plants in the process of carbon sequestration has garnered much attention as a crucial approach to addressing climate change and diminishing levels of atmospheric carbon dioxide. Trees play a significant role as natural carbon sinks, aiding in the extraction and subsequent long-term sequestration of carbon from the Earth's atmosphere [14]. Numerous scholarly investigations have underscored the significance of comprehending the carbon sequestration capability exhibited by various tree species, specifically in relation to their development rates, biomass accumulation, and capacity for carbon storage [14-16].

Trees fulfill a double function in the process of carbon sequestration, as they engage in the absorption of atmospheric carbon dioxide via photosynthesis and subsequently store carbon within their biomass, encompassing various components such as leaves, stems, branches, and roots [17]. The carbon sequestration process in trees is subject to a range of parameters, such as tree type, age, environmental conditions, and management practices [12]. On a global scale, forests play a significant role in the sequestration of substantial quantities of carbon inside their woody biomass and soil. In a hypothetical scenario wherein a forest achieves a state of pseudo equilibrium with its surrounding environment, the growth of biomass will be counterbalanced by turnover. Additionally, the inputs of litter resulting from biomass turnover will be offset by heterotrophic respiration. Consequently, over an extended period and across the expanse of a forest landscape, the quantity of carbon stored within the ecosystem will exhibit a relatively stable pattern [15].

Tropical tree species possess notable potential for carbon sequestration, mostly attributed to their accelerated growth rates and substantial biomass accumulation [18]. The net annual rates of carbon sequestration were seen in different types of plantations and forests. In their study in India, Kaul, Mohren and Dadhwal [18] found that fast-growing short-rotation poplar attained a rate of 8 tonC/ha/year, while Eucalyptus plantations achieved a rate of 6 tonC/ha/year. Moderate-growing teak forests exhibited a rate of 2 tonC/ha/year, while slow-growing long rotation sal woods had a rate of 1 tonC/ha/year.

Tamanu, an exemplary specimen, has attracted attention not only due to its economic significance but also due to its ability to sequester carbon. Research findings indicate that tropical tree species have the capacity to effectively capture and store carbon, thereby rendering them significant resources in the global efforts to mitigate climate change. Tamanu, which is indigenous to coastal areas in tropical countries, is renowned for its capacity to thrive in many environmental circumstances and its versatile range of applications. The species has traits that render it appealing for diverse purposes, including its function as a carbon sink. The capacity of the species to amass biomass and retain carbon in both its aboveground and belowground components establishes it as a potentially noteworthy participant in endeavors aimed at carbon sequestration.

Although there is a general interest in investigating the carbon sequestration capability of tropical tree species, there is a lack of comprehensive research on the specific role of Tamanu in carbon storage within the Gunung Kidul region of Yogyakarta. The growth and carbon sequestration dynamics of the species may be influenced by the distinctive geological and climatic circumstances present in this area. As far as current information is concerned, there is a lack of a comprehensive study that has quantitatively assessed the degree of carbon sequestration facilitated by Tamanu within this particular setting.

The literature review emphasizes the significant contribution of trees, particularly tropical species such as Tamanu, in the mitigation of climate change by sequestering carbon. Nevertheless, the current lack of research on the carbon sequestration capacity of Tamanu in the Gunung Kidul region highlights the necessity of conducting this study. Through the examination of the development patterns, biomass accumulation, and carbon sequestration capacity of Tamanu within this distinctive ecological setting, our research seeks to further the collective understanding of the contribution of tropical tree species towards the mitigation of climate change.

3 Methodology

3.1 Location and time of study

The research was conducted in Playen, Gunung Kidul regency, located in Yogyakarta, Indonesia (Figure 1), in July 2023. The study area of the study is 25 ha of Tamanu stand. However, in some plots, there are other species, e.g., teak and mango. The area encompasses diverse topography, including limestone hills and coastal plains, and experiences a tropical monsoon climate characterized by distinct wet and dry seasons. The average annual rainfall is 2,066 mm. During the 12 years of observation, there were five years with below-average rainfall. This phenomenon illustrates that the rainfall in this region is classified as erratic and has high variability.



Fig. 1. Location of the study.

3.2 Data collection and analysis

Carbon stock measurements in this study used the RaCSA/Rapid Carbon Stock Appraisal procedure [19]. Biomass measurements were made on five carbon pools, namely tree biomass, understory biomass, woody necromass, non-woody necromass (debris), and soil organic matter. The measurement plots consisted of a 20 m x 20 m main plot of 20 plots and five subplots measuring 50 cm x 50 cm within each main plot of 10 plots (half of the total main plot) (see Figure 2).



Fig. 2. Plot design in the study area.

Tree biomass measurements were conducted in the main plot for trees with diameter at breast height (DBH). Each tree in the measurement plot was recorded for species and measured for DBH. Aboveground biomass per tree was calculated using the allometric equation developed by Basuki, Leksono, Baral, Andini, Wahyuni, Artati, Choi, Shin, Kim, Yang, Samsudin and Windyarini [11] for Tamanu species, i.e.:

$$AGB = \exp -0.972 + 2.078 \ln D \quad (1)$$

Meanwhile, the weight of belowground biomass was calculated using the allometric equation [10]:

$$BGB = \exp -3.559 + 2.359 \ln D \quad (2)$$

The allometric equation to estimate the amount of carbon stored in teak is the equation developed by Aminudin [20], i.e.:

$$AGB = 0.37D^{2.125} \quad (3)$$

The allometric equation for mango used is the allometric equation developed by Dao, Bationo, Traoré, Bognounou and Thiombiano [21], i.e.:

$$AGB = -101.87 + 10.02D \quad (4)$$

The root biomass of teak and mango was estimated by an allometric equation developed by Cairns, Brown, Helmer and Baumgardner [21], i.e.:

$$RGB = -1.085 + 0.9256AGB \quad (5)$$

Soil samples were collected from the root zones of selected Tamanu trees at each site. Soil properties, including texture, organic carbon content, and nutrient levels, were analyzed following standard laboratory protocols. Carbon content in both tree biomass and soil was estimated using established conversion factors for tropical ecosystems, i.e., 0.47 [22]. The

carbon stored in aboveground biomass, belowground biomass, and soil was calculated for each sampled tree and aggregated for the entire site.

4 Results and discussions

4.1 Carbon stored in tree biomass

Tamanu stands at the research site were planted in 2017 with a spacing of 3.5 x 3.5 meters. The area of Tamanu stands in the research location is 25 ha. Tamanu trees have quite a lot of branching so that one tree can have more than two main trunks. The number of trees in each plot varies between 12 - 30 trees with variations in DBH and height. Since no necromass was found during data collection, the necromass carbon pool is not reported in this paper.

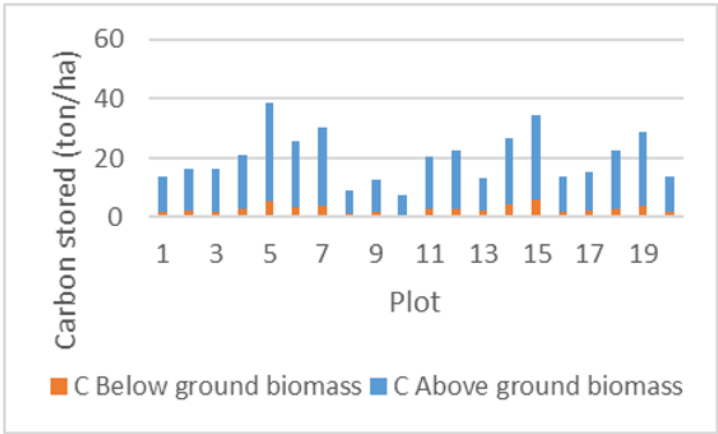


Fig. 3. Carbon stored in tree biomass of Tamanu in Playen, Gunung Kidul.

The data exhibits substantial heterogeneity in the carbon content of both aboveground and belowground biomass across the various plots. The carbon content of the aboveground biomass exhibits a range of approximately 6.7 to 33.5 tons, whereas the carbon content of the belowground biomass displays a range of around 1.0 to 6.0 tons (Figure 3). In the majority of plots, the carbon content of aboveground biomass is typically greater than that of belowground biomass. This outcome is anticipated, given the aboveground biomass encompasses various constituents, including stems, branches, leaves, and fruits, all of which possess substantial carbon content as measured by Kumar, Tewari, Singh, Kumar, Kumar, Bisht, Devi and Kaushal [23] stands in India. In contrast, the belowground biomass encompasses the roots and various subterranean structures.

The data presented illustrates the distribution of carbon among various biomass constituents. The comprehension of carbon distribution inside the tree and its implications for carbon sequestration and storage is contingent upon a thorough grasp of this allocation pattern. The observed differences in carbon content among the plots can be attributed to the inherent variability of the research area and the diverse growing conditions experienced by the trees. Trees that possess greater amounts of biomass both above and below the ground make a more substantial contribution to the potential of the ecosystem to sequester carbon.

Plant diversity also strongly influences ecosystem functions and services, such as soil carbon storage [24,25]. In warm and arid regions, there are considerable correlations between plant diversity and soil carbon levels, as well as between plant diversity and the quality of soil organic matter, specifically the carbon-to-nitrogen ratio. Plant diversity affects soil

carbon storage by the quality of organic matter rather than the quantity of plant biomass inputs [25].

The data offers valuable insights into the respective contributions of aboveground and belowground biomass to the overall carbon storage of the trees. The acquisition of this knowledge is of paramount importance in comprehending the function of various constituents of trees in the process of carbon cycling and their potential for long-term carbon sequestration. Trees that possess a greater amount of aboveground biomass have the capacity to offer a wider range of ecosystem services, including but not limited to shading, supply of habitat, and storage of carbon. Furthermore, it is crucial to take into account the carbon content of belowground biomass in order to comprehensively assess the overall capacity of trees and the surrounding soil to sequester carbon.

4.2 Carbon stored in understory

There is observed variability in the biomass of the understory throughout the plots, with recorded values ranging from approximately 0.64 tons per hectare to 1.46 tons per hectare (Table 1). The observed variance can be attributed to various factors, including the unique microclimate present in the area, the distinctive attributes of the soil, and the makeup of the plant species. It is crucial to recognize that the existence of the understory, encompassing smaller vegetation such as plants, herbs, and shrubs, also exerts a substantial influence on the comprehensive carbon storage within the ecosystem.

Table 1. Carbon stored in the understory under Tamanu stand.

Plot	Understorey biomass (ton/ha)	C stored in understorey (ton/ha)
Plot 1	1.15	0.54
Plot 3	1.37	0.64
Plot 5	1.05	0.49
Plot 7	0.64	0.30
Plot 9	1.16	0.54
Plot 11	0.81	0.38
Plot 13	1.37	0.65
Plot 15	1.46	0.69
Plot 17	0.90	0.42
Plot 19	1.09	0.51
Average	1.10	0.52

The carbon content present in the understory vegetation exhibits a similar trend to that of the understory biomass, including a range of approximately 0.30 to 0.69 tons per hectare. The carbon concentration of the understory vegetation is a pivotal factor in determining the overall carbon sequestration capacity of the ecosystem. The estimated average biomass of the understory is around 1.10 metric tons per hectare, whereas the average carbon content within the understory vegetation is approximately 0.52 metric tons per hectare. The presence of an understory within Tamanu stands plays a crucial role in augmenting the carbon storage capacity of the ecosystem in its entirety. While the quantity of carbon present in the understory is comparatively smaller than that found in the aboveground biomass, it still constitutes a noteworthy element of the overall capacity for carbon sequestration. The results highlight the interconnectedness of various layers of vegetation in their role in providing

ecosystem services, such as carbon sequestration. Contrasting results regarding the contribution of understorey plants in carbon absorption can be seen in research on the role of various understorey diversity, which is very significant compared to abandoned soil. The results highlight the interconnectedness of different vegetation layers in their role in providing ecosystem services, such as carbon sequestration [26].

4.3 Carbon stored in soil

Bulk density (BV) is a metric used to quantify the mass of soil relative to its volume, providing valuable information about soil compaction. The term "organic carbon content," referred to as Organic C, represents the proportionate quantity of organic carbon present within the soil. The aforementioned parameter holds substantial importance in the assessment of soil fertility and its potential for carbon sequestration. There is observed variability in the soil carbon concentration among the plots, with recorded values spanning from approximately 1.41 tons per hectare to 2.10 tons per hectare. The observed variation is likely influenced by other factors, such as vegetation cover, land use history, and soil management practices. The analysis of soil carbon concentration at different depths (0-10 cm, 10-20 cm, 20-30 cm) provides significant insights into the spatial distribution of carbon within the soil profile. Based on the principles of natural decomposition, a common observation is that the concentration of carbon tends to decline with increasing soil depth. The computation of mean values: The computed average values for soil bulk density, organic carbon percentage, total soil carbon content, and soil carbon content at different depths have been derived from the provided dataset. The amount of carbon stored in soil is presented in Table 2.

Table 2. Carbon stored in soil under Tamanu stand.

Plot	BV (gr/cm3)	Organic C (%)			Soil carbon content (ton/ha)			Soil carbon content 0-30 cm depth (ton/ha)
		0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm	
Plot 1	1.10	1.70	1.58	1.59	19	17	17	54
Plot 3	0.93	3.51	3.01	1.74	33	28	16	77
Plot 5	1.04	2.03	1.95	2.10	21	20	22	63
Plot 7	1.22	2.09	2.00	1.91	25	24	23	73
Plot 9	1.13	1.54	1.49	1.41	17	17	16	50
Plot 11	1.05	1.66	1.69	1.69	17	18	18	53
Plot 13	1.18	1.94	1.87	2.00	23	22	24	69
Plot 15	1.25	2.11	2.03	1.78	26	25	22	74
Plot 17	1.05	1.60	2.22	1.61	17	23	17	57
Plot 19	1.05	3.08	1.88	1.65	32	20	17	69
Ave	1.10	2.13	1.97	1.75	23	22	19	64

The results suggest that the soil in the specified research site demonstrates an average bulk density of 1.10 g/cm³ and an average organic carbon content of 2.13%. The average soil carbon content in soil depths of 0-10 cm, 10-20 cm, and 20-30 cm across all plots are 2.13, 1.97, and 1.75 tons/ha, respectively. Therefore, the soil carbon content in 0-30 cm is 64 tons/ha, which is slightly greater than the carbon content in tree biomass. The aforementioned numerical values indicate the soil's ability to store carbon, which is a critical determinant in reducing atmospheric carbon dioxide concentrations. The historical influence of land management practices such as fertilization at the research location, which incidentally is

former agroforestry land, is thought to support high soil carbon uptake [27,28] The soil carbon sequestration method involves utilizing soils as substantial repositories for the retention of organic carbon, hence assuming a pivotal function in the amelioration of carbon emissions. The results emphasize the importance of conserving and improving soil organic carbon levels, as it plays a critical role in raising soil fertility and increasing the capacity for carbon sequestration.

5 Conclusion

This study examines Tamanu's carbon sequestration potential in Yogyakarta's Gunung Kidul region. Our study quantified aboveground, belowground, soil, and understory carbon levels across various plots in the study region. This study shed light on Tamanu's involvement in tropical carbon storage and climate change mitigation. Our study shows Tamanu's carbon sequestration potential. Due to their aboveground and belowground biomass, these trees sequester carbon. The large variance in carbon content among plots emphasizes the importance of considering local environmental conditions and management methods when carbon accounting. It was shown that Tamanu's aboveground biomass has more carbon than its belowground biomass. This crucial information is needed to understand tree carbon distribution and its effects on ecosystem services and carbon cycling. The carbon content of the soil in Tamanu stands shows its role as a carbon sink. The soil in the study region stored carbon, with differences between depths and plots. Our study also considered the often overlooked understory vegetation, which sequesters carbon in the ecosystem. The presence of carbon in understory vegetation shows how different vegetation layers sequester carbon. The conservation and management of Tamanu populations in Gunung Kidul and other areas are affected by this study. Mature tree protection and appropriate land management can boost carbon sequestration and climate change mitigation. This study provides valuable insights, but further research is needed to determine how tree age, species mix, and land use history affect carbon sequestration. Long-term monitoring and experiments can help us understand Tamanu's role in carbon cycling. In conclusion, Tamanu in Gunung Kidul, Yogyakarta, is an important carbon sink. Their aboveground and belowground biomass, soil, and understory plants retain a lot of carbon. The identification and use of this carbon sequestration capacity can help regional climate change mitigation and sustainable land management programs. This research emphasizes the need to conserve these ecosystems and examine their impact on the global carbon cycle.

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