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# Changes in Carbon Stocks and the Economic Value of Forest Carbon in a Secondary Forest of Mt. Nacolod, Silago, Southern Leyte, Philippines

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**ABSTRACT**

Tropical forests play a critical role in climate mitigation, yet long-term data on their carbon dynamics remain scarce, particularly in the Philippines. This study examines forest structure and carbon sequestration in a 1-hectare permanent plot established in a secondary forest on Mt. Nacolod, Southern Leyte, Philippines using 2012, 2016, and 2024 tree inventory data. The study aimed to (1) assess biomass and carbon storage trends, and (2) estimate the economic value of carbon. The secondary forest stored 202.4 Mg C/ha, comparable to reported values of old-growth forests in the Philippines. Its sequestration rate of 2.53 Mg C/ha/year is approximately nine times faster than old-growth forests and exceeds regional dipterocarp regrowth rates. Although sequestration slowed post-2016, the site remained a robust carbon sink. The estimated economic value of the stand's carbon stock increased from USD 4,798 in 2012 to USD 7,220 in 2024, while carbon sequestered over the 12 years was valued at USD 1,076 under prevailing carbon credit prices. Key findings underscore the dominance of Dipterocarpaceae and the site's high carbon sequestration capacity, emphasizing its critical role in regional climate mitigation strategies. Continuous monitoring reinforces its value as a long-term carbon sink, providing a benchmark for conservation and climate policy for tropical forests in the region.

**HIGHLIGHTS**

The permanent plot stored 202.4 Mg C/ha which is comparable to reported old-growth forest carbon stock-values. Its sequestration rate was approximately nine times higher than reported old-growth uptake. Dipterocarp stands maintained strong carbon stocks after 2016. Stored carbon represents substantial climate-mitigation and economic value. The site serves as a vital carbon sink and model for tropical forest management.

## 1. INTRODUCTION

Climate change has led to significant negative consequences, affecting environmental, social, political, and economic systems (Abbass et al., 2022; IPCC, 2023). Forests are essential for climate regulation, carbon sequestration, and biodiversity, playing a central role in climate change mitigation strategies (Bonan, 2008; Kaarakka et al., 2021; Millar and Stephenson, 2015; Mori et al., 2021; Pan et al., 2011; Whitehead, 2011). However, forests face threats from anthropogenic and natural disturbances (Elkin et al., 2013; Kurz et al., 2008; Reyer et al., 2014; Reyer et al., 2017). While natural disturbances are common, increased frequency and intensity may exceed the forests' adaptive capacity, degrading ecosystem services crucial for climate mitigation (Dale et al., 2000; Marcos-Martinez et al., 2019; Trumbore et al., 2015).

Climate change will substantially influence forests and may alter their composition and structure (Dale and Rauscher, 1994). Recent studies show that climate change will exacerbate forest disturbance impacts, with potentially far-reaching ecological and socioeconomic consequences (Huo et al., 2019; Seidl et al., 2017). Tropical forests have already exhibited such changes (Condit, 1998; Phillips et al., 2004;

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Phillips and Gentry, 1994). Under certain climate scenarios, existing carbon stocks in tropical forests may become significant carbon sources, even without further deforestation (Cox et al., 2000; Cramer et al., 2001). Furthermore, remnant forests face degradation and fragmentation from climate change and other pressures, with extinction risk for species unable to rapidly adapt (Deb et al., 2016).

Long-term forest dynamics, crucial for conservation and management, can be studied through permanent plots (Baithalu et al., 2013; Brearley et al., 2019). These plots enable the study of long-term changes in tree communities under human pressure and climate change (Chazdon et al., 2005; Murthy et al., 2016). Research on tropical forest biomass and carbon stocks is crucial for assessing atmospheric $CO_2$ removal, estimating net carbon gains, and improving conservation and management strategies (Heriansyah et al., 2007; Siregar and Heriyanto, 2010; Subiandono et al., 2013). Biomass data also provide insights into ecosystem productivity (Nelson et al., 1999).

Beyond ecological roles, forests provide measurable economic value through carbon markets and climate finance. Carbon credits, representing one metric ton of $CO_2$ equivalent sequestered or avoided, have become central to global climate policy under frameworks such as REDD+ (Fuss et al., 2021; UN-REDD Programme, 2023). Protecting and enhancing tropical forest carbon stocks can generate billions in potential cost savings for climate stabilization (Scheinkman, 2024). In the Philippines, legislative initiatives aim to establish a domestic carbon crediting system aligned with the Paris Agreement, highlighting the growing relevance of forest carbon valuation (Enviliance ASIA, 2023).

Permanent plots are particularly valuable as they provide long-term, verifiable data on biomass and carbon dynamics, essential for credible carbon accounting and valuation (PennState Extension, 2023; Phillips, 2023). By linking ecological monitoring with economic valuation, permanent plots serve as reference sites demonstrating the potential of secondary forests to contribute to biodiversity conservation and climate finance opportunities. This is especially relevant for Eastern Visayas, Philippines, where extensive upland and mangrove forests store substantial carbon stocks, highlighting both ecological resilience and potential for carbon markets (Asilo and Yap-Dejeto, 2025; Meniano, 2024).

Given climate change's global impact, long-term forest monitoring is crucial for understanding forest structure, dynamics, and ecosystem functions. This study investigated current carbon storage and sequestration changes within a one-ha permanent plot measured in 2012, 2016 and 2024 in a Long-Term Ecological Research (LTER) site established in Barangay Catmon, Silago, Southern Leyte in 2012. Specifically, it aimed to: (1) assess current biomass, carbon storage and sequestration trends over time; and (2) estimate the economic value of stored and sequestered carbon.

## 2. METHODOLOGY

### 2.1 Site description

The study was conducted in a one-hectare subplot within the 50-hectare permanent ecological research plot in Mt. Nacolod, Barangay Catmon, Silago, Southern Leyte (10°5'45"N, 125°09'30"E) (Figure 1). This area, known as Silago Biodiversity Research Station or SilBioRS, was established for long-term ecological research on forest structure, dynamics, and processes (Philippine Tropical Forest Conservation Foundation, 2013).

The province of Southern Leyte is characterized by a type IV climate featuring evenly distributed rainfall throughout the year, averaging 2,565.4 mm annually. Based on the Köppen-Geiger climate classification at 1-km resolution (Beck et al., 2018), the province falls under the Af (tropical rainforest) category, characterized by consistently high rainfall and absence of a pronounced dry season. Elevation in the study area ranges from 577-582 meters above sea level (Jarvis et al., 2008). Southern Leyte's mountainous areas consist primarily of Ultisols (Barrera et al., 1954), characterized by their acidic nature, clayey texture, and low nutrient levels (Piamonte et al., 2014).

Approximately two-thirds of Silago's forests lie within the Mt. Nacolod Forest Reserve (14,000 ha), recognized as a Key Biodiversity Area (Mallari et al., 2014; NewCAPP, 2014). In October 2012, following the stakeholder presentation of assessment results, the Provincial Board of Southern Leyte approved Ordinance No. 2012-43, designating Mt. Nacolod as a Forest Conservation Area (NewCAPP, 2014).

Mt. Nacolod features diverse vegetation, including tropical lowland forests, secondary forests, and mossy forests (Cabras et al., 2023). The study site was formerly dominated by lowland dipterocarp forests; however commercial logging from the 1950s until 1989, altered the site into a regenerating logged forest or secondary forest (Carandang et al., 2013;

Fernando et al., 2008; Langenberger and Belonias, 2011; Veridiano et al., 2020). At present, the site is under conservation management, although stand dynamics may still be influenced by natural mortality, recruitment, tree competition, and localized human disturbances such as access trails or nearby land-use activities.

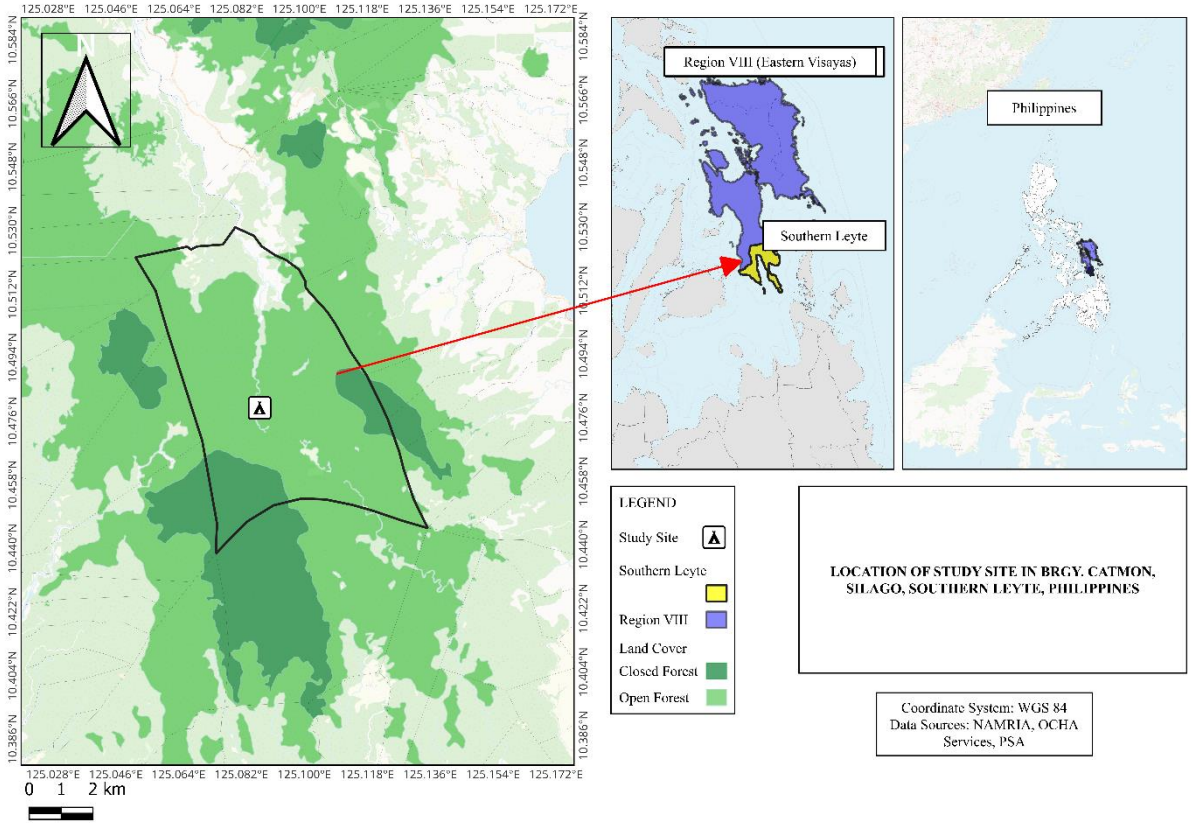



**Figure 1.** Location map of the study site

## 2.2 Research design

*2.2.1 Plot establishment*

This study used secondary data from tree inventories conducted in the one-hectare plot in 2012 and 2016. All calculations and analyses, including 2024 measurements, used the same formulas for biomass and carbon content estimation. The one-hectare plot was used because it forms part of the long-term ecological monitoring design of the Silago Biodiversity Research Station and contains tagged trees with repeated measurements from 2012, 2016, and 2024. The plot location was selected during the original establishment of the permanent ecological research site to represent the regenerating lowland dipterocarp-secondary forest condition of Mt. Nacolod and to allow repeated measurement of the same individuals through time. The analysis is based on a single one-hectare subplot, therefore the results should be interpreted as plot-level evidence of forest recovery and carbon accumulation rather than as a direct estimate for the entire 50-ha research plot or the whole Mt. Nacolod landscape.

The initial 2012 inventory established twenty-five 20 m × 20 m subplots, identified and tagged trees with a diameter at breast height (DBH) ≥10 cm for future remeasurement (Philippine Tropical Forest Conservation Foundation, 2013). In 2016, Veridiano et al. remeasured tagged trees and recorded new recruits that met the DBH criterion (Veridiano et al., 2020). Trees recorded in earlier censuses but no longer alive during remeasurement were treated as mortality and were excluded from live aboveground biomass estimates for the corresponding census year. Newly recruited individuals that reached the ≥10 cm DBH threshold were included in the census year in which they first met the measurement criterion. Thus, net biomass change reflects the combined effects of survivor growth, mortality losses, and recruitment gains. Remeasurement was conducted in 2024 for this study.

*2.2.2 Aboveground biomass and carbon content*

Height and diameter of trees ≥10 cm DBH were measured and recorded. Aboveground biomass was calculated using the allometric equation (1) developed by Chave et al. (2014) for tropical trees:

$$Y = 0.0673 \times (\rho D^2 H_t)^{0.976} \quad (1)$$

Where; Y=aboveground biomass (kg); ρ=wood density (g/cm$^3$); D=DBH (cm); $H_t$=total height (m).

Veridiano et al. (2020) used Chave et al.'s (2014) pantropical allometric equation because country-specific allometric equations for Philippine secondary-growth dipterocarp forests remain limited (Lasco and Pulhin, 2009). The present study applied the same equation to maintain comparability with the 2012 and 2016 secondary data. While the equation is suitable for broad tropical forest applications—incorporating DBH, tree height, and wood density—it may introduce uncertainty when applied to this specific Philippine secondary forest due to local variation in tree architecture, wood density, disturbance history, and stand structure. Tree carbon content was computed as 50% of aboveground biomass, a default value used in studies (Brown and Lugo, 1992; Malhi et al., 2004; Roy et al., 2001). This study focused only on live aboveground tree biomass and therefore provides a conservative estimate of total forest carbon stock. Other major forest carbon pools, including belowground biomass, deadwood, litter, and soil organic carbon, were not included because comparable measurements were unavailable across the census periods. Forest carbon pools include living aboveground and belowground biomass, dead organic matter, and soil organic matter, therefore the actual total carbon stock and potential economic value of the site are likely higher than reported here.

*2.2.3 Carbon accounting*

This study used the inventory approach to estimate carbon-stock change and sequestration between inventory periods (2012, 2016, and 2024). The formula, Equation (2), adapted from UNDP Forest Carbon Accounting: Overview & Principles (UNDP, 2015) is:

$$\Delta C = \sum \frac{(C_{t2} - C_{t1})}{(T_2 - T_1)} \quad (2)$$

Where; ΔC=carbon stock change (Mg C/year); $C_{t1}$=carbon stock (Mg C) at time $t_1$; $C_{t2}$=carbon stock (Mg C) at time $t_2$.

*2.2.4 Economic value of carbon*

Several studies have used international or national carbon market price averages to estimate the economic value of forest carbon storage (Danardono et al., 2019; Hussainzad and Mohd Yusof, 2020; Pache et al., 2020; Raihan et al., 2021; Rumahorbo et al., 2019). This study used the average forest carbon credit price for each inventory year, from reports published by Forest Trends' Ecosystem Marketplace (Hamrick and Gallant, 2017; Peters-Stanley et al., 2013; Procton, 2024). Recorded prices were used to estimate the economic value of forest carbon storage within the one-hectare plot during inventory years.

This study also compared the site's economic value of aboveground carbon across 2012, 2016, and 2024. To ensure a fair comparison, estimated economic values of carbon stock in 2012 and 2016 were converted to equivalent 2024 U.S. dollar values using the Consumer Price Index (CPI). This adjustment accounts for inflation, allowing a more accurate representation of the economic value of carbon stock. The CPI-based adjustment follows the formula shown in Equation (3):

$$\text{Adjusted Value}_{2024} = \text{Value}_t \times \frac{\text{CPI}_{2024}}{\text{CPI}_t} \quad (3)$$

Where; t represents the year of interest (2012 or 2016). This approach ensures that all values are expressed consistently, reflecting their real economic significance in 2024.

The monetary value of carbon sequestration was determined using established $CO_2e$ pricing as outlined by Gallant et al. (2020). Furthermore, carbon credits are generally issued based on net carbon gains within a project area rather than gross gains from only the highest-performing sections; therefore, the valuation of sequestration should account for the net change in carbon stock across the monitoring period (American Forest Foundation, 2025).

To estimate the economic value of carbon sequestration from 2012 to 2024, this study multiplied net carbon sequestered by the 2023 average carbon credit price of USD 9.72/t$CO_2$ in forestry and land use. The United Nations Environment Programme (UNEP), through the UN-REDD Programme, indicates that high-quality forest carbon emission reductions are cost-effective but not cheap, with the average cost of forest carbon estimated at approximately USD 30-50/t$CO_2$. These values should not be interpreted as the market price of the carbon stored in the one-hectare plot alone. Rather, they

reflect the estimated cost of generating high-integrity forest carbon emission reductions, including REDD+ implementation, monitoring, accounting, and opportunity costs. Thus, the present valuation remains conservative because it covers only aboveground carbon sequestration and excludes broader ecosystem services, biodiversity, watershed protection, cultural values, and non-use values (UN-REDD, 2023).

## 3. RESULTS AND DISCUSSION

### 3.1 Stand dynamics and aboveground biomass

Across the three census periods, the plot contained 721, 853, and 832 trees with DBH ≥10 cm in 2012, 2016, and 2024, respectively. These recorded trees represented 26 families in 2012 and 2016, and 24 families in 2024, and identified species richness remained stable at 48 species. In 2024, the five most dominant species based on Importance Value Index were *Shorea palosapis* (IVI=39.28), *Pinanga* spp. (IVI=35.52), *Shorea negrosensis* (IVI=34.37), *Shorea almon* (IVI=27.43), and *Lithocarpus celebicus* (IVI=20.34). These results indicate that the stand was structurally dominated by dipterocarps, with increasing ecological importance of palms and declining contribution of Fagaceae. In 2024, the plot was dominated by medium-sized trees, with 673 individuals or 80.9% of all trees falling within the 10-30 cm DBH class. Large trees with DBH >30 cm represented 159 individuals or 19.1% of the stand. Tree height ranged from 2.3 to 62.0 m, with most individuals measuring between 10.1 and 20.0 m tall. This structure indicates that although medium-sized trees were more abundant, larger trees remained important contributors to aboveground biomass and carbon storage.

Total aboveground biomass (AGB) in the one-hectare plot increased steadily across all inventory periods, reflecting ongoing forest growth and carbon accumulation (Table 1). AGB increased from 344.07 Mg/ha in 2012 to 372.82 Mg/ha in 2016, then 404.79 Mg/ha by 2024. Growth slowed over time, with annual gains averaging 7.19 Mg/ha between 2012-2016 and 3.99 Mg/ha from 2016-2024.

**Table 1.** Aboveground biomass in the site

| Year | Biomass (Mg/ha) | Total increment (Mg/ha) | Annual increment (Mg/ha) |
|---|---|---|---|
| 2012 | 344.07 | - | - |
| 2016 | 372.82 | 28.75 | 7.19 |
| 2024 | 404.79 | 31.97 | 3.99 |

Dipterocarpaceae consistently represented the largest share of aboveground biomass across all inventory years (Figure 2). In 2012, the family accounted for 195.46 Mg/ha, equivalent to 56.81% of total biomass. This increased to 215.41 Mg/ha, or 57.78%, in 2016 and further to 252.78 Mg/ha or 62.44% in 2024. This sustained increase indicates that biomass accumulation in the plot was largely driven by dipterocarp species, particularly large and mature individuals that persisted across the monitoring period. In 2024, the leading species contributors were *Shorea palosapis* (63.35 Mg/ha), *S. falciferoides* (55.01 Mg/ha), *S. polysperma* (44.86 Mg/ha), *S. almon* (37.19 Mg/ha), *S. negrosensis* (26.58 Mg/ha), and *S. astylosa* (17.75 Mg/ha). Together, these Dipterocarpaceae species confirm the family's central role in maintaining forest structure, biomass retention, and aboveground carbon storage in the secondary forest.

The dominance of Dipterocarpaceae in aboveground biomass reflects the stand structure, where large trees contribute disproportionately despite being fewer than medium-sized trees. Large trees with DBH >30 cm accounted for most of the biomass, contributing 77.81%, 76.29%, and 81.69% of total biomass in 2012, 2016, and 2024, respectively. Although the total number of Dipterocarpaceae individuals slightly declined from 306 in 2016 to 285 in 2024, their relative biomass share increased, highlighting the growth advantage and persistence of surviving large dipterocarps. In contrast, Fagaceae declined from 51.13 Mg/ha (14.86%) in 2012 to 38.13 Mg/ha (9.93%) in 2024, accompanied by a reduction in individual numbers from 96 to 55 and mortality events during the study period. These patterns suggest structural and successional shifts in this regenerating secondary forest, where biomass and carbon storage are increasingly concentrated in large, carbon-dense dipterocarp trees. This interpretation is consistent with recent studies showing that biomass accumulation during secondary succession is influenced by stand maturation, demographic shifts, mortality, and recruitment dynamics (Tian et al., 2023; Ordoñez et

al., 2024). The observed trend may therefore reflect density-dependent competition, shade-driven suppression of smaller stems, and the differential survival and growth of large remnant trees, rather than an increase in overall species diversity.

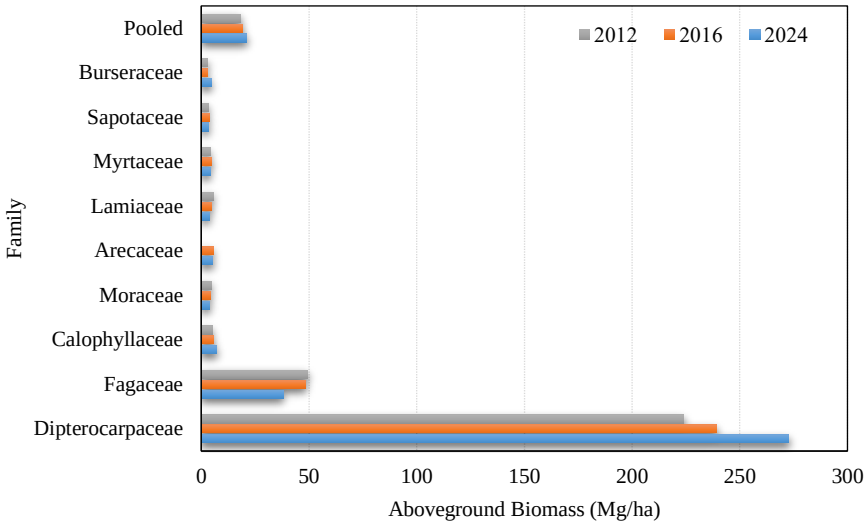



**Figure 2.** Total aboveground biomass of trees according to family (Note: Pooled refers to the aggregate biomass of the remaining minor tree families at the site)

*3.1.2 Comparison of aboveground biomass*

Aboveground biomass at the site aligns with published values for various forest types, particularly dipterocarp forests (Table 2). However, as a secondary forest, the site exhibits relatively lower biomass compared to a secondary forest in Mt. Makiling, Philippines.

Araza et al. (2022) compiled a global reference dataset from National Forest Inventories and research networks, encompassing more than 100,000 plots across all major biomes. These plots (0.02 to 25 ha) provided standardized AGB estimates (Mg/ha) for global carbon stock assessments. The study site's AGB is relatively higher than reported average AGB values for tropical forest plots in the global dataset. Within the Asian tropical forest plots compiled by Araza et al. (2022), where AGB values averaged 139.3 Mg/ha and ranged from 25.9 to 703.3 Mg/ha, the study site's AGB falls in the upper portion of this distribution.

**Table 2.** Aboveground biomass of various sites and forests using various allometric equations

| Forest type and location | Aboveground biomass (Mg/ha) | Source |
|---|---|---|
| Secondary forest (Mt. Nacolod) (2024) | 404.79 | This study |
| Tropical forest plots AGB | | |
| Africa | 234.1 | Araza et al. (2022) |
| Asia | 139.3 | Araza et al. (2022) |
| Australia | 70.4 | Araza et al. (2022) |
| C. America | 125.8 | Araza et al. (2022) |
| S. America | 326.5 | Araza et al. (2022) |
| Sri Lanka | | |
| Old-growth mixed dipterocarp forest | 430.11 | Ediriweera et al. (2024) |
| Philippines | | |
| Secondary forest (Mt. Makiling) | 538.05 | Lasco et al. (2004) |
| Selectively logged dipterocarp forest (Surigao del Sur) | 399.00 | Lasco et al. (2004) |
| Natural forest (Aurora Province) | 131.30 | Raga-as (2004) |
| Plantation forest (Aurora Province) | 72.20 | Raga-as (2004) |
| Samar | 401.07 | Abino et al. (2014) |

Differences in AGB among Mt. Nacolod, Mt. Makiling, Samar Island, and other secondary forests may reflect variation in stand age, disturbance history, species composition, soil conditions, rainfall, and the abundance of large trees (Becknell and Powers, 2014; Poorter et al., 2016; Oberleitner et al., 2021). In Mt. Nacolod, the relatively high AGB appears to be associated with the continued dominance of large Dipterocarpaceae individuals.

*3.1.3 Aboveground biomass according to DBH classes*

The distribution of aboveground biomass (AGB) across tree size classes offers valuable insight into the forest's structural composition and successional stage. Following Li et al.'s (2023) classification, trees were grouped into two main DBH classes: Medium (10-30 cm), representing growing individuals, and Large (>30 cm), representing mature trees. AGB distribution reveals a clear structural pattern: while smaller trees are more numerous, biomass is disproportionately concentrated in larger individuals (Figure 3). In 2012, large trees held most of the biomass, accounting for 77.81% of the total biomass (267.73 Mg/ha), while more abundant medium-sized trees contributed 22.19% (76.33 Mg/ha). This pattern persisted in 2016 and 2024, with large trees maintaining dominance at 76.29% and 81.69% of total biomass, respectively (Table 3).

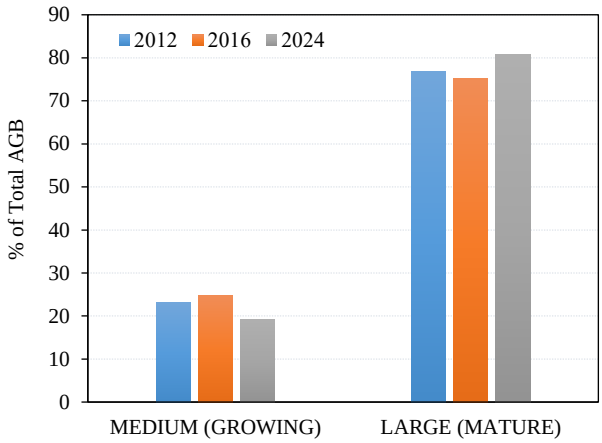



**Figure 3.** Percentage of total aboveground biomass by DBH class of trees within the one-hectare permanent plot

**Table 3.** Aboveground biomass growth by DBH class of trees

| DBH classification | 2016 Biomass (Mg/ha) | 2024 Biomass (Mg/ha) | Biomass growth (Mg/ha) |
|---|---|---|---|
| Medium (10-30 cm) | 87.02 | 72.78 | -14.24 |
| Large (>30 cm) | 266.28 | 328.89 | 46.18 |

Stephenson et al. (2014) challenged the assumption that tree growth slows as size increases. Their findings show that across most species, large, old trees continue to actively sequester substantial amounts of carbon—often at rates exceeding those of smaller trees. In extreme cases, a single large tree can fix as much carbon in a year as an entire mid-sized tree contains in its biomass. The results of our study show the same pattern—large trees contribute disproportionately to biomass growth within the stand. Applying Li et al.'s DBH classification and excluding new recruits confirms that large trees account for the most substantial biomass increase.

## 3.2 Carbon accounting

*3.2.1 Carbon stocks*

The 1-hectare permanent plot consistently accumulated aboveground carbon stocks over the 12-year period, reinforcing its role as a sustained carbon sink (Table 4). Carbon stocks increased from 172.03 Mg C/ha in 2012 to 202.40 Mg C/ha in 2024, reflecting a net gain of 30.37 Mg C/ha. While the mean annual increment of carbon stocks slowed from 3.40 Mg C/ha (2012-2016) to 2.00 Mg C/ha (2016-2024), the overall trend confirms continued sequestration. The decline in mean annual carbon increment may be associated with stand maturation and structural change. As the stand accumulated biomass, the proportional rate of biomass gains likely slowed because larger trees increasingly dominated total carbon stock, while mortality, recruitment limitation, and competition may have reduced net gains during the longer 2016-2024 interval. The longer second measurement period may also smooth short-term growth pulses, making the annualized increment appear lower. Similar patterns have been observed in tropical secondary forests, where AGB accumulation rates can decline as biomass increases during succession, and where mortality and recruitment are important determinants of forest structural processes and biomass turnover (Tian et al., 2023; Ordoñez et al., 2024).

**Table 4.** Aboveground carbon stock across inventory periods

| Year | Carbon (Mg C/ha) | Increase from previous inventory |
|---|---|---|
| 2012 | 172.03 | - |
| 2016 | 186.41 | 14.38 Mg C/ha (6.51%) |
| 2024 | 202.40 | 15.99 Mg C/ha (8.58%) |

According to Pan et al. (2024), a carbon sink is a system where carbon gains from growth and recruitment exceed losses from mortality or disturbance. The observed net increase observed in the plot aligns with this definition and places the site within broader discussions on the contribution of tropical forests to global carbon uptake.

The study site, a secondary forest, exhibits a carbon stock of 202.4 Mg C/ha, placing it within the range reported for old-growth forests in the Philippines (Table 5). Lasco and Pulhin (2009) documented that old-growth forests in the country typically store around 201 Mg C/ha, indicating the carbon storage capacity is comparable to these mature forests. Furthermore, the site's carbon stock exceeds other natural forest types in the Philippines, including mossy (189 Mg C/ha), mangrove (184 Mg C/ha), and pine (191 Mg C/ha).

The carbon stock can be further evaluated against the findings of Peters et al. (2023), who examined aboveground carbon across various Philippine Forest types under different disturbance levels, interpreted through the forest transition theory. This model explains that regions move through stages: an initial stage with largely intact forests and low deforestation, an intermediate stage with accelerated forest loss, and a later stage where forest cover stabilizes and may increase. Peters et al. (2023), described several forest categories under different disturbance histories, including reference forests (least disturbed), logged forests (previously subjected to timber extraction), and plantation forests (planted stands, often monocultures). Against this backdrop, the Silago secondary-growth forest (202.4 Mg C/ha) stored less carbon than Eastern Visayas reference forests (260.27±80.31 Mg C/ha) but more than logged (99.6±52.09 Mg C/ha) and plantation forests (59.85±29.43 Mg C/ha) in the same region. It also exceeded both reference (131.68±80.31 Mg C/ha) and logged forests (56.51±30.38 Mg C/ha) in Cagayan Valley, Philippines, which Peters et al. (2023) considered to be in the initial transition stage.

**Table 5.** Comparison of carbon stocks in forests from published studies

| Forest type and location | Carbon stock (Mg C/ha) | | Source |
|---|---|---|---|
| | Average | Range | |
| Study site | 202.4 | | This study |
| Natural Forests in the Philippines | | | |
| - Old-growth | 201 | | Lasco and Pulhin (2009) |
| - Mossy | 189 | | Lasco and Pulhin (2009) |
| - Mangrove | 184 | | Lasco and Pulhin (2009) |
| - Pine | 191 | | Lasco and Pulhin (2009) |
| Forests in Eastern Visayas, Philippines (Intermediate disturbance) | | | |
| - Reference | 260.27 | 123-397 | Peters et al. (2023) |
| - Logged | 99.6 | 48-152 | Peters et al. (2023) |
| - Plantations | 59.85 | 30-89 | Peters et al. (2023) |
| Forests in Cagayan Valley, Philippines (Low disturbance) | | | |
| - Reference | 131.68 | 51-212 | Peters et al. (2023) |
| - Logged | 56.51 | 26-86 | Peters et al. (2023) |
| Dipterocarp forests | | | |
| - Philippines | | 93-193 | Lasco and Pulhin (2009) |
| - Philippines (Plantation) | 221 | | Lasco and Pulhin (2009) |
| - Malaysia (Moderate to Superior) | | 190-260 | Lasco and Pulhin (2009) |
| Regenerating secondary forest stands in Panama (40-120 years old) | | | |
| - 40 | 61.35 | | Jones et al. (2019) |
| - 60 | 75.11 | | Jones et al. (2019) |

**Table 5.** Comparison of carbon stocks in forests from published studies (cont.)

| Forest type and location | Carbon stock (Mg C/ha) | | Source |
|---|---|---|---|
| | Average | Range | |
| - 90 | 96.25 | | Jones et al. (2019) |
| - 120 | 96.86 | | Jones et al. (2019) |
| Bukit Timah Nature Reserve in Singapore | | | |
| - Primary Forest | 167.5 | | Ngo et al. (2013) |
| - Secondary Forest | 104.5 | | Ngo et al. (2013) |

When compared with dipterocarp forests in Malaysia, the study site's carbon stock falls between the moderate condition (190 Mg C/ha) and superior condition categories (220 Mg C/ha) suggesting it is in a relatively advanced recovery state and functioning effectively as a carbon-storage system. Furthermore, the carbon stock in the study site was comparably higher than secondary forests in Panama and Singapore (Table 5). These carbon-stock patterns provide the basis for evaluating the site's annual carbon sequestration rate across the monitoring period.

*3.2.2 Carbon sequestration*

The study site exhibited a carbon sequestration rate of 2.53 Mg C/ha/year from 2012 to 2024. This rate declined over time, averaging 3.60 Mg C/ha/year from 2012 to 2016 and 2.00 Mg C/ha/year from 2016 to 2024 (Table 6).

**Table 6.** Overall sequestration rate (2012-2024)

| Carbon stock (Mg/ha) | Total increment | Sequestration rate | Year |
|---|---|---|---|
| 202.40 | 30.37 Mg/ha | 2.53 | 2012-2024 |

When compared with similar forests, this rate falls within expected ranges for dipterocarp ecosystems and secondary tropical forests (see Table 7). Relative to dipterocarp forests, the study site's sequestration rate exceeds those reported for Philippine dipterocarps (1.33 Mg C/ha/year; 54) and Malaysian dipterocarps (1.2 Mg C/ha/year) (Kayode, 2024); but slightly lower than the rate reported for Java dipterocarp forests (2.89 Mg C/ha/year) (Hairiah and Sitompul, 2000).

Compared to secondary tropical forests, the study site's sequestration rate is slightly below the 3.05 Mg C/ha/year recorded by Poorter et al. (2016), who noted that this rate was 11 times faster than carbon uptake of old-growth forests. In comparison, the study site's sequestration rate of 2.53 Mg C/ha/year was approximately 9.13 times higher than old-growth uptake, indicating substantial carbon accumulation in the regenerating stand. Compared to fast-growing species, the study site's sequestration rate was moderate. While reforestation projects in Leyte and Nueva Ecija recorded higher rates (Table 7), the site's steady carbon accumulation highlights the value of long-term storage in naturally regenerating secondary forests.

**Table 7.** Carbon sequestration rates of different forest types

| Forest type and location | Carbon sequestration (Mg C/ha/year) | Source |
|---|---|---|
| Study Site | 2.53 | This study |
| Dipterocarps | | |
| Java | 2.89 | Hairiah and Sitompul (2000) |
| Philippines | 1.33 | Lasco and Pulhin (2009) |
| Malaysia | 1.2 | Kayode (2024) |
| Mt. Makiling (Reforestation) | | |
| Mahogany and Dipterocarp | 2.8 | Racelis et al. (2019) |
| Fast-growing species (Reforestation) | | |
| Nueva Ecija | 0.30-3.73 | Racelis et al. (2019) |

**Table 7.** Carbon sequestration rates of different forest types (cont.)

| Forest type and location | Carbon sequestration (Mg C/ha/year) | Source |
|---|---|---|
| Leyte | 0.7-9.0 | Racelis et al. (2019) |
| Natural forests (Philippines) | >1 | Lasco and Pulhin (2003) |
| Secondary Tropical Forests | 3.05 | Poorter et al. (2016) |

However, because this study is based on a single one-hectare subplot within a larger 50-ha research area, its estimates should not be directly extrapolated to the entire Mt. Nacolod landscape without additional spatial replication. The plot provides valuable long-term evidence of carbon accumulation under a specific secondary-forest condition, but broader estimates of regional carbon mitigation potential and economic value require additional plots across different disturbance histories, elevations, soil conditions, and stand structures.

### 3.3 Economic value of carbon

*3.3.1 Carbon stock*

The economic value of the stand's carbon stock increased between 2012 and 2024, primarily due to two factors: (1) carbon stock accumulation and (2) carbon credit price appreciation. Without adjusting for inflation, total economic value rose by 51.97%, increasing from USD 4,798.34 in 2012 to USD 7,219.94 in 2024—an average annual increase of approximately USD 200 (Table 8).

**Table 8.** Economic valuation of carbon stock

| Year | Carbon stock (tons) | $CO_2e$ (tons) | Price per $tCO_2e$ (USD) | Economic value (USD) | Inflation adjusted value (USD) |
|---|---|---|---|---|---|
| 2012 | 172.03 | 631.36 | 7.60 | 4,798.35 | 6,553.53 |
| 2016 | 186.41 | 684.13 | 5.10 | 3,489.04 | 4,563.12 |
| 2024 | 202.40 | 742.79 | 9.72 | 7,219.94 | - |

Note: Carbon credit prices were sourced from annual reports by Forest Trends' Ecosystem Marketplace

*3.3.2 Carbon sequestration*

If the total carbon sequestered at the site over 12 years were converted into carbon credits in 2024, the $CO_2$ equivalent of 110.70 tons would be valued at USD 1,076.00, or an average of USD 89.67 per year (see Table 9). Under the same assumptions, stakeholders in the Philippines engaged in carbon trading would need to monitor approximately 18-19 hectares of the same forest stand to generate USD 20,000 in revenue over 12 years.

**Table 9.** Value generated from carbon sequestration (2012-2024)

| Carbon sequestered (ton) | $CO_2$ equivalent (ton) | Value generated (USD) | Annual increment (USD) |
|---|---|---|---|
| 30.37 | 110.70 | 1,076.00 | 89.67 |

However, these figures capture only one component of the forest's total economic value: the carbon sequestered in a single hectare. For instance, the total economic valuation of ecosystem services (Direct Use Value, Indirect Use Value, and Non-use Value) of Malaysian tropical forests was estimated at USD 3 billion, (Emerton and Aung, 2014).

As mentioned previously, the United Nations Environment Programme recommends increasing carbon credit prices in Forestry and Land-use to USD 20-50 per ton of $CO_2$ to align with Paris Agreement targets and USD 30-50 per ton to incentivize meaningful climate action. However, with USD 9.72 as the baseline price, the disparity between current carbon credit values and levels necessary to effectively combat climate change is evident (see Table 10). Bridging this gap is crucial for ensuring carbon markets provide sufficient financial incentives for climate mitigation. For example, at UNEP's recommended carbon credit prices of USD 20, USD 30, and USD 50 per ton of $CO_2$, stakeholders would only need approximately nine, six, or three hectares, respectively, to generate USD 20,000 in revenue, compared to 18 to 19 hectares at the baseline price (Table 10).

**Table 10.** Value of carbon sequestration using UNEP recommended prices

| Price of carbon credit | Value generated per ha (USD) | Value Ggenerated per ha (Philippine Peso) |
|---|---|---|
| USD 9.72* | 1,076.00 | 59,578.34 |
| USD 20 | 2,124.00 | 122,589.20 |
| USD 30 | 3,321.00 | 183,883.80 |
| USD 50 | 5,535.00 | 306,473.00 |

## 4. CONCLUSION

Over decades of regeneration, Mt. Nacolod's secondary forest has emerged as a significant carbon sink, with aboveground biomass and carbon stocks now rivaling those of old-growth forests. This recovery—driven by sustained biomass accumulation and enduring dominance of carbon-rich Dipterocarpaceae—demonstrates the critical role of regenerating tropical forests in climate mitigation. Long-term monitoring proved indispensable, revealing gradual but ecologically meaningful trends that short-term studies might overlook.

Economically, growing carbon stocks in Mt. Nacolod reflect an underutilized opportunity. While the financial value of stored carbon has increased over time, current market prices for credits remain far below the thresholds needed to incentivize large-scale conservation. This gap between ecological potential and economic recognition underscores the urgency of policy reforms and market mechanisms that properly value tropical forests as climate assets.

By bridging ecological data with economic analysis, this study reinforces the dual potential of secondary forests: as robust carbon sinks and as strategic investments in climate resilience. Protecting these forests demands not only scientific validation but also financial frameworks that translate carbon storage into tangible returns, including stronger carbon pricing, payments for ecosystem services, blended public-private finance, and local conservation incentives that reward communities and managers for maintaining regenerating secondary forests.

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## AUTHOR CONTRIBUTIONS

Conceptualization, Come R, Martinez CA; Methodology, Come R, Martinez CA, Peque D, Seriño MN; Formal Analysis, Martinez CA; Investigation, Come R, Martinez CA; Data Curation, Come R and Martinez CA; Writing-Original Draft Preparation, Martinez CA; Writing-Review and Editing, Martinez CA, Come R, Peque D, Lippe M, Seriño MN; Visualization, Martinez CA; Validation, Come R, Peque D, Lippe M, Seriño MN; Supervision, Come R, Lippe M; Project Administration, Come R, Lippe M; Funding Acquisition, Come R, Lippe M.

## DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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