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Carbon storage in total biomass and soil in a teak (*Tectona grandis* L.f.) plantation

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ABSTRACT

Objective: To estimate carbon storage in young teak plantations (*Tectona grandis* L.f.) in total biomass, dry litter, and soil due to the effects of chemical fertilizers and green manure (GM).

Methodology: A completely randomized block experimental design was used. At two years of age, chemical fertilizer (CF) (NPK) treatments were applied: control 0-0-0, 60-60-60, 90-60-60, and 120-60-60 kg ha^{-1}. At three and four years of age, treatments 0-0-0, 120-60-60, 150-60-60, and 180-60-60 kg ha^{-1} were used. *Crotalaria juncea* was used as green manure (GM).

Results: Significant differences were observed in the interactions between CF and AV on total biomass at both ages, 3.2 and 4.7 years. The highest values were recorded in the control without AV and in the 180-60-60 kg ha^{-1} treatment with AV. No significant differences were detected in litterfall. At 3.2 years of age, the plot without AV receiving the 90-60-60 kg ha^{-1} dose exhibited the greatest increase in carbon storage, whereas at 4.7 years, the highest increase occurred in the control with AV. Significant differences were also observed in soil carbon storage (SOC), with an increase of 166.32 t C ha^{-1} under the 150-60-60 kg ha^{-1} treatment.

Conclusion: Total biomass at 3.2 years of age can store 35.05 t C ha^{-1}. Carbon in litter increases with the dose of chemical fertilization. Overall, a greater amount of carbon is stored in the soil than in above-ground and below-ground biomass and litter.

Keywords: allometric model, fertilization, green manure, litter, soil.

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INTRODUCTION

Carbon (C) stored in humid tropical forests results from the long-term balance between C assimilated during photosynthesis and its loss through respiration and tree mortality (Brando *et al.*, 2019).

Climate change is driven by increased CO_2 resulting from the disruption of the carbon cycle, highlighting the need for public policies aimed at mitigating these gases, implementing appropriate technologies, and adopting rational measures that both reduce emissions and maintain carbon balance in forests and commercial forest plantations (Correa-Guaicha & Romero-Hidalgo, 2016; Ávila *et al.*, 2001). The use of fossil fuels is a major source of greenhouse gases (GHGs), which contribute to global warming (Becerril-Piña *et al.*, 2007). Commercial forest plantations help mitigate GHG emissions caused by motor vehicles and industries, which act as the main pathways through which these pollutants are released (Erakhrumen & Inaede, 2018). Commercial forest plantations function as carbon sinks because they sequester large amounts of CO_2, primarily in their above-ground and below-ground biomass (Dhillon & Von Wuehlisch, 2013).

Importantly, forests and commercial forest plantations are significant carbon reservoirs, absorbing approximately 30% of annual CO_2 emissions (Pan *et al.*, 2011), making them strategic tools for atmospheric CO_2 sequestration. In the case of commercial forest plantations, wood serves as a short- to medium-term carbon sink when used to produce furniture and housing, while 30-40% of the total biomass remains stored in the soil due to litter incorporation and the below-ground biomass of trees (Gerardo-López *et al.*, 2018).

Teak (*Tectona grandis* L.f.) is a deciduous species during the dry season, which allows it to withstand severe droughts for up to five months of the year. It adapts well to humid sites and grows successfully in areas with year-round rainfall and no distinct dry season. Teak plantations have the potential to produce 26.7 t C ha^{-1} $year^{-1}$ (González-Martínez *et al.*, 2014), although researchers such as Gerardo-López *et al.* (2018) report values of up to 151.37 t C ha^{-1} $year^{-1}$. Due to the importance of carbon storage in commercial forest plantations and its relevance to climate change, carbon storage was estimated in total biomass, dry litter, and soil in young teak plantations (*Tectona grandis* L.f.) treated with chemical fertilizer and green manure (GM).

MATERIALS AND METHODS

Study area and experimental design

The study was conducted at a commercial site of the company Agropecuaria Santa Genoveva (ASGv) (17° 50' 47.64" N, 91° 12' 6.37" W), covering an area of 2.2 ha, located in the municipality of Balancán, Tabasco, Mexico. The climate of the site is warm subhumid with summer rainfall (Aw2(x)), an average annual precipitation of 1,500 mm, and a mean temperature of 26.5-27 °C (Aceves-Navarro & Rivera-Hernández, 2019). The site is situated at an altitude of 42 m above sea level.

At the start of the experiment, a preliminary soil fertility study was conducted. According to NOM-021-RECNAT-2000, the soil is sandy clay loam with a pH of 7.5 (moderately alkaline) and a medium organic matter content (SOM, 3.5%). The cation exchange capacity (CEC, 22.85 $cmol_{(c)}$ kg^{-1}) is medium. Total nitrogen (Nt) content is medium (0.14%), and phosphorus (P, 7.65 mg kg^{-1}) is also at medium levels. Exchangeable bases show high calcium (Ca, 12.33 $cmol_{(c)}$ kg^{-1}), low magnesium (Mg, 0.62 $cmol_{(c)}$ kg^{-1}), and very low potassium (K, 0.15 $cmol_{(c)}$ kg^{-1}) content.

The established teak plants were clones produced by Agropecuaria Santa Genoveva (ASGv). At the start of the experiment, they were two years old and planted in a square spacing of 3.5×3.5 m. Nitrogen (N), phosphorus (P), and potassium (K) fertilizer treatments were applied at doses of 0-0-0, 60-60-60, 90-60-60, and 120-60-60 kg ha^{-1} when the plantations were two years old, increasing to 0-0-0, 120-60-60, 150-60-60, and 180-60-60 kg ha^{-1} at ages three and four.

The fertilizer sources used were urea (46-00-00), diammonium phosphate (18-46-00), and potassium chloride (00-00-60). Fertilizers were applied using a handspike to a depth of 20 cm in two holes located to the north and south within the drip zone of each tree. The experimental design was a randomized block design with a split-plot arrangement. The factor tested was green manure (GM), *Crotalaria juncea*, sown at a density of 20 kg ha^{-1} by broadcasting in the plantation alleys. After 60 days, it was incorporated into the soil to a depth of 15 cm using mechanized equipment.

Calculation of Carbon in Total Biomass and Dry Litter

Following the application of fertilizer and green manure treatments, the diameter at breast height (DBH, 1.30 m) was measured using a vernier caliper when the trees were two years old, and with a forest caliper once they were over three years old. Total height (H) was measured on five trees per plot using a Haglöf hypsometer (±0.1 cm). To estimate the above-ground biomass of teak trees, a general allometric model developed by Kenso *et al.* (2020) was used:

$$AGB = 0.0649 \times DBH^{2.5702}$$

where: *AGB*: Above-ground biomass of the tree (kg dry weight); *DBH*: Diameter at breast height (DBH, 1.3 m).

The below-ground biomass of teak trees was calculated using the following allometric model (Kenso *et al.*, 2020):

$$BGB = 0.0460 \times DAP^{2.1763}$$

where: *BGB*: Below-ground biomass of the tree roots (kg dry weight); *DAP*: Diameter at breast height (DBH, 1.30 m).

To determine carbon in dry litter, biological traps made of fine plastic mesh, measuring 1.5×1.5 m, were randomly placed and secured to stakes to prevent contact with the soil surface and avoid contamination or mineralization effects (Pulido & Díaz, 2005). Vegetative material was collected after treatment application and placed in perforated paper bags, labeled with site and treatment information. Litter samples were taken to the laboratory and dried at 65 °C in a forced-air oven until constant weight was achieved (Murtinah *et al.*, 2016).

The values of dry litter, above-ground biomass, and below-ground biomass were multiplied by a factor of 0.52 to calculate carbon, as estimated by Kumar-Jha (2005) for teak. The results of the two biomasses were then summed to obtain total biomass. The carbon conversion factor corresponds to the percentage of carbon in the tree mass: carbon 50%, oxygen 41%, hydrogen 6%, nitrogen 1%, and ash 2%. In other words, the amount of carbon per ton of dry matter is approximately 500 kg (50%).

Calculation of Soil Organic Carbon

Soil sampling was conducted at the end of the experiment, when the teak trees were 4.7 years old, for each of the treatments. Samples were taken at a depth of 30 cm using a stainless-steel auger, placed in labeled plastic bags, and transported to the laboratory. The samples were air-dried, ground, and sieved (2 mm). Organic carbon was determined using the Walkley-Black method (1934), which is based on oxidation with a potassium dichromate solution and the heat generated by reaction with concentrated sulfuric acid.

From the laboratory results, soil organic carbon (SOC) content was calculated using the equation proposed by Rojas *et al.* (2009),

$$SOC = OC\left(Bd\right)Sd$$

where: SOC=Soil organic carbon (t ha^{-1}); OC=Organic carbon (%); Bd=Bulk density (g cm^{-3}) Sd=Soil depth (cm).

Statistical Analysis

Data on carbon storage in total biomass, litter, and soil were analyzed using the statistical software Infostat 2020, through analysis of variance and mean comparisons using Tukey's test ($p<0.05$).

RESULTS AND DISCUSSION

Carbon Storage in Total Biomass

At 3.2 years of age, statistical analysis of the interaction between chemical fertilization and green manure (GM) showed significant differences ($p<0.05$, Figure 1). The control treatment in the plot without GM and the 60-60-60 kg ha^{-1} fertilization treatment * GM showed the highest carbon storage (35.05 t C ha^{-1}), which gradually decreased as the fertilization dose increased. The opposite trend was observed in the plot with GM and 60-60-60 kg ha^{-1} fertilization, where carbon in total biomass increased.

At 4.7 years of age (Figure 1), the interaction between chemical fertilization * GM again showed significant differences ($p<0.05$). Increases in carbon were observed when chemical fertilization was combined with GM, compared to fertilization without GM. In the latter, carbon storage was highest in the control treatment and decreased as nitrogen fertilization increased up to 150-60-60 kg ha^{-1}, before increasing again in the subsequent treatment.

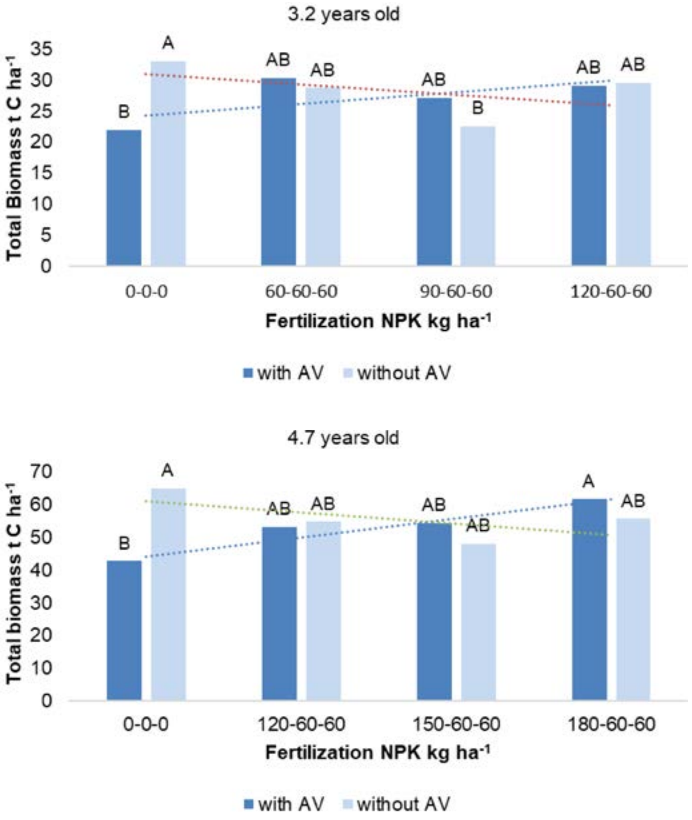

Figure 1. Interactions between fertilization * GM on carbon content in total biomass in teak.

Teak plantations, considering biomass quantity, have the potential to produce 26.7 t C ha^{-1} $year^{-1}$ (González-Martínez *et al.*, 2014). In adult plantations, total above-ground biomass can range from 151.37 to 214.7 t C ha^{-1}, with 16.6% stored in roots (Gerardo-López *et al.*, 2018; N'Guessa-N'Gbala *et al.*, 2017). Differences in reported carbon storage between these studies and the present work are likely due to vegetation type and seed propagation. In this experiment, the higher carbon storage can be attributed to the use of highly productive clones (ASGv) at early ages.

Other species under five years old, such as *Gmelina arborea* Roxb. ex Sm., can store 15.8 t C ha^{-1} in above-ground biomass and 2.37 t C ha^{-1} in below-ground biomass (Tamang *et al.*, 2021), while *Hevea brasiliensis* Muell. Arg. can store 26.28 t C ha^{-1} in above-ground biomass (López-Reyes *et al.*, 2016). In other vegetation systems, Pompa-García & Sigala-Rodríguez (2017) found that protected natural areas have higher above-ground carbon storage (135.3 t C ha^{-1}) than primary forests and managed forests (105.1 and 115.4 t C ha^{-1}, respectively), with the lowest carbon storage rates observed in secondary forests (51.2 t C ha^{-1}), followed by reforested areas, commercial plantations, and agroforestry systems with 45.6, 62.8, and 35.8 t C ha^{-1}, respectively.

Carbon storage in total biomass (above-ground and roots) in teak plantations in this study was higher compared to other studies (Figure 1). Kumar-Jha (2015), in young teak plantations, reported 1.6, 15.8, 35.5, 39.0, 61.5, and 73.2 t C ha^{-1} at ages of 1, 5, 11, 18, 24, and 30 years, respectively. Sreejesh *et al.* (2013) reported 21 t C ha^{-1} at five years of age. In these studies, carbon values were obtained from plantations established from seeds, and differences in site index and soil fertility likely explain variations in above-ground and total biomass carbon among studies. Other experiments on carbon storage in teak total biomass in Nuevo Urecho, Michoacán, Mexico, found 77 t C ha^{-1} at 11 years of age (Jiménez-Pérez *et al.*, 2020).

Carbon storage in litter

At 3.2 years of age, no significant differences were found among treatments ($p<0.05$, Figure 2). The 90-60-60 kg ha^{-1} dose without GM showed the highest increase, with 0.6 t C ha^{-1}. Although increases with GM were lower compared to treatments without GM, the highest dose (120-60-60 kg ha^{-1}) showed the largest increase with 0.5 t C ha^{-1}. When the teak plantations reached 4.7 years of age (Figure 2), no significant differences were observed ($p>0.05$). The greatest increase was found in the control with GM, with 0.56 t C ha^{-1}. Among treatments without GM, the highest increases were observed in the 60-60-60 and 90-60-60 kg ha^{-1} doses, with 0.53 and 0.52 t C ha^{-1}, respectively.

Carbon stored through dead litter is generally more labile and contributes significantly to the increase of soil fertility in forest systems. Kraencel *et al.* (2003) reported that 20-year-old teak plantations can store between 2.6 and 3.4 t C ha^{-1} in litter. Average carbon contributions from litter in teak plantations and secondary forests are 4.7 and 2.3

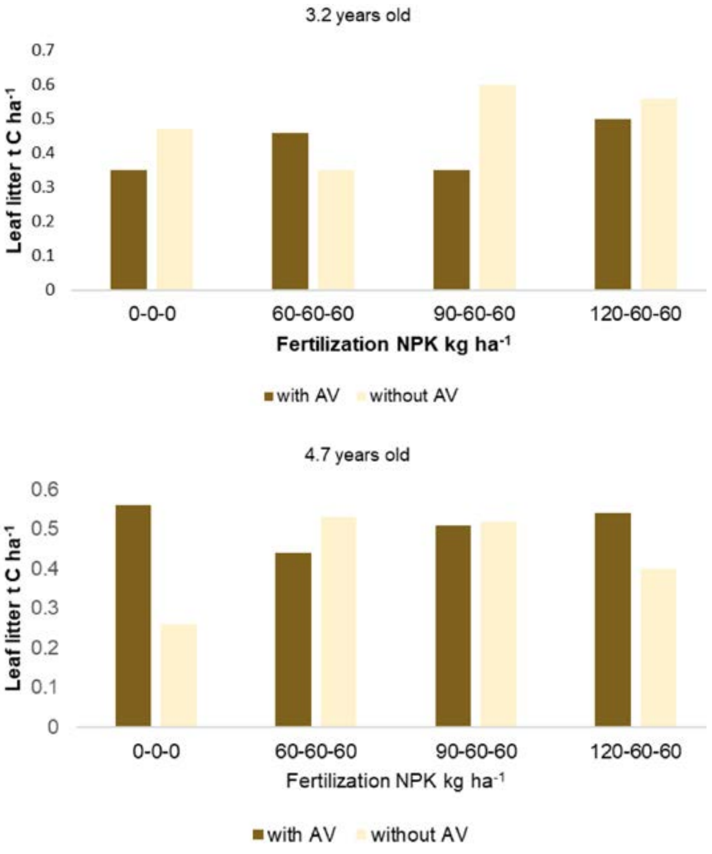

Figure 2. Interactions between fertilization * GM on carbon storage in teak litter.

t C ha^{-1}, respectively (N'Guessa-N'Gbala *et al.*, 2017). A large proportion of carbon in teak plantations comes primarily from litter and roots (Hansen *et al.*, 2013).

The amount of carbon stored in litter depends on the tree species. For example, in Sichuan Province, China, within the Wanglang National Nature Reserve, three forest types were compared: coniferous forests (*Picea purpurea* Mast.) stored the most carbon, followed by mixed forests (*Picea purpurea* Mast., *Abies faxoniana* Rehd. & E.H. Wilson, *Betula albosinensis* Burkill), and broadleaf forests (*Tilia tuan* Szysz., *Padus racemosa* L., *Salix paraplesi* C.K. Schneid), with 0.4, 0.36, and 0.14 t C ha^{-1}, respectively (Chen *et al.*, 2021). These values are lower than those found in the present study.

Carbon storage in soil

In soil carbon, interactions between chemical fertilization * green manure GM were observed (Figure 3), showing significant differences ($p<0.05$). In the plot with GM, the 150-60-60 kg ha^{-1} treatment recorded the highest carbon storage, with 166.32 t C ha^{-1}, while in the plot without GM, the same treatment resulted in lower carbon storage, with 150.52 t C ha^{-1}.

Under different management practices in five-year-old teak plantations, soil carbon storage can range from 39.55 to 45.84 t C ha^{-1}, which is lower than the values found in the present study. These differences may be related to soil fertility (Agyei-Kumi *et al.*, 2021).

The green manure *C. juncea* helps increase soil fertility by reducing degradation and water runoff, decreasing bulk density, and increasing soil organic carbon (SOC) and nutrient availability (Ma *et al.*, 2021). When green manure is established together with chemical fertilization, there is an increase in mineralizable and hydrolysable carbon, which improves microbial activity and promotes rapid decomposition of the green manure (Almagro & Martínez, 2014). In a study by Song-Juan *et al.* (2018) on rice cultivation in Hunan Province, China, the application of green manure resulted in dissolved organic carbon (DOC) storage of 711.10 mg kg^{-1}, which was significantly higher compared to the application of chemical fertilizers alone (428.50 mg kg^{-1}).

Similarly, agroforestry systems, such as teak plantations combined with *C. juncea*, absorb more CO_2 as soil organic carbon (SOC). De Stefano and Jacobson (2017) reported that

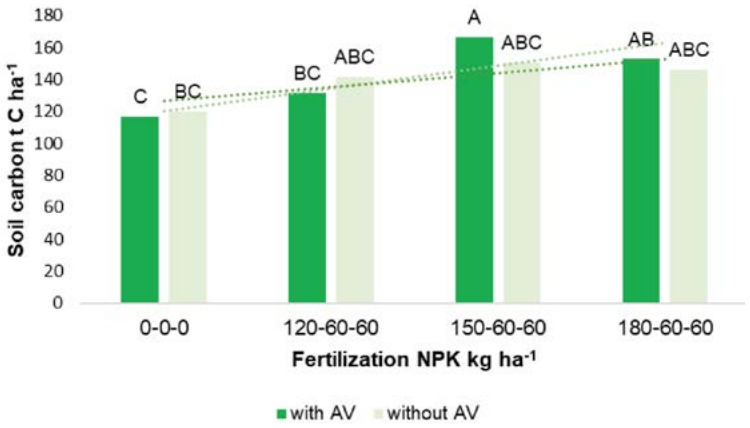

Figure 3. Interaction between chemical fertilization * GM on soil carbon storage in a teak plantation.

these systems can store between 12 and 228 t C ha^{-1}, a much higher amount than that stored in conventional agricultural crops.

Other studies, such as Tangsinmankong *et al.* (2007), recorded carbon storage in soils of deciduous mixed forests and teak plantations, finding that soil organic carbon at all sites generally decreased with increasing depth from the soil surface to the lower layer. In teak plantations of different ages, at 6, 24, and 15 years, and in the deciduous mixed forest (157.03, 105.67, 78.78, and 70.96 t C ha^{-1}, respectively), this difference in carbon storage may be due to forest fires, forest management, and topography. In teak plantations aged 12 to 20 years, Meunpong *et al.* (2010) reported soil carbon storage of 40 t C ha^{-1} in Thailand. Soil organic carbon influences many physicochemical processes and biological properties (Smith *et al.*, 2013), playing a key role in soil productivity and quality (Lal, 2016). Forest type also affects soil carbon storage, along with characteristics such as tree species, litter quality, and primary productivity (Bai *et al.*, 2019).

CONCLUSIONS

Total biomass (root and above-ground biomass) at 3.2 years of age can store 35.05 t C ha^{-1} in the control treatment without GM. At 4.7 years of age, carbon storage reaches 67.17 t C ha^{-1} under chemical fertilization combined with GM. Carbon storage in litter increases with higher doses of chemical fertilization; however, the control plot with GM showed the highest litter carbon storage.

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