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# Soil carbon stock in balsa wood after fertilization strategies

**Abstract** – The objective of this work was to evaluate whether balsa wood plantation and its fertilization can improve soil carbon stocks. Total carbon stocks in the soil-biomass system, at 0.0-0.30 m soil depths, were evaluated under three fertilization strategies, after three and seven years, and compared with carbon stocks from native forest and degraded pasture. At the highest fertilization level, balsa wood showed a carbon stock similar to that of the native forest (65.38 Mg ha$^{-1}$) and, after seven years, it increased carbon stock by 18% in the soil, and by 42% in the soil-biomass system.

**Index terms**: *Ochroma pyramidale*, carbon sequestration, clean development mechanism, planted forest.

## Estoque de carbono no solo após manejo nutricional de pau-de-balsa

**Resumo** – O objetivo deste trabalho foi avaliar se o plantio de pau-de-balsa e seu manejo nutricional aumentam os estoques de carbono no solo. Os estoques de carbono total do sistema solo-biomassa à profundidade de 0,0–0,30 m foram avaliados em três níveis de adubação, após três e sete anos, e comparados com mata nativa e pastagem degradada. No nível de maior adubação, o pau-de-balsa apresentou estoque de carbono semelhante ao da mata nativa (65,38 Mg ha$^{-1}$) e, após sete anos, aumentou o estoque de carbono em 18%, no solo, e em 42%, no sistema solo-biomassa.

**Termos para indexação**: *Ochroma pyramidale*, sequestro de carbono, mecanismo de desenvolvimento limpo, floresta plantada.

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The growing commercial importance of balsa wood, mainly due to its lightweight and its insulating properties, has caused the global market to be segmented according to the application of this wood in some areas such as aerospace/defense, renewable energy, marine, road/rail, industry, and others. The value of balsa wood in the global market was estimated at US$ 146.53 million in 2016, with a potential to reach US$ 217.23 million by the end of 2023 because of the increased consumption of this species composites among the aerospace/defense and wind energy segments (Anand et al., 2019).

In the last decade, the state of Mato Grosso, Brazil, has significantly expanded the area of planted forests, which has increased from 69,700 ha, in 2006, to 251,900 ha in 2017. The main driver in this expansion is the *Eucalyptus* plantation, which accounts for 181,400 ha approximately, whilst teak plantation accounts for 66,700 ha (IBÁ, 2019). In this regard, in Mato Grosso, balsa wood is one of the forest species with potential for the rural economic diversification (that is, forest plantation, integrated crop-livestock-forestry systems). Moreover, planted forests contribute to soil protection, ecosystem services, and reduced pressure on natural forests (FAO, 2020), which is paramount for Mato Grosso state.

Studies on balsa wood growth and soil carbon stock changes under different fertilization strategies are still scarce in Brazil. As to the assessment of soil carbon stocks under balsa wood plantation, such studies are virtually nonexistent in Brazil.

The nutritional management of forest species has a direct economic impact on the result and expansion of the crop planting area. As shown by Santin (2018), the application of fertilizers alters the dynamics and the culmination of the increment curve of balsa wood.

The objective of this work was to evaluate whether balsa wood plantation and its fertilization can improve soil carbon stocks, seeking to improve the knowledge on balsa wood species growth, and the soil carbon stock changes under different fertilization strategies.

The experiment was carried out in the municipality of Guarantã do Norte, in the state of Mato Grosso (9°57'S, 54°52'W, at 370 m altitude) in the Instituto Federal de Educação, Ciência e Technologia de Mato Grosso - IFMT. According to the Köppen-Geiger's classification system, the local climate is classified as Aw, with annual averages of 25ºC temperature, 2,000 mm rainfall, and a dry period extending from May to September (Souza et al., 2013).

The soil is classified as a Latossolo Vermelho-Amarelo distrófico, according to the Brazilian soil classification system (Santos et al., 2018), a typic dystrophic Hapludox (Soil Survey Staff, 2014). Soil texture and chemical characteristics at 0–20 cm soil depths, at the beginning of the *Ochroma pyramidale* (Cav. ex Lam.) Urban planting, in the experiment area, are the following ones: 5.4 pH in water (1:2,5); 1.7 mg $dm^{-3}$ $P_{(Mehlich-1)}$; 18 mg $dm^{-3}$ $K_{(Mehlich-1)}$; 1.3 $cmol_c$ $dm^{-3}$ Ca; 0.6 $cmol_c$ $dm^{-3}$ Mg; 0.3 $cmol_c$ $dm^{-3}$ Al. The soil texture was clayey, with 396 g $kg^{-1}$ sand, 100 g $kg^{-1}$ silt and 504 g $kg^{-1}$ clay. The soil organic matter was 23.4 g $dm^{-3}$.

After suppression of natural vegetation in the early 1980s, the land was converted to livestock ranching until 2003, when the experimental area was corrected with dolomitic lime using disk plow, for soybean cultivation in the 2003/2004 growing season. After soybean harvesting, *Urochloa brizantha* 'Marandu' was sowed for extensively dairy cattle production for approximately six years, without any further fertilization.

In January 2011, the experimental area was desiccated with glyphosate, and balsa wood trees were planted using a furrower in the minimum cultivation system, at 0.50 m soil depth. Pest and weed control, when necessary, was performed using chemical and mechanical measures at all stages of tree development.

The balsa wood experiment was established with 1,111 trees $ha^{-1}$ (3×3 m spacing, 9 $m^2$ per tree), in a randomized complete block design with three replicates. The experimental plot was composed of 136 trees (1,224 m²). The useful area (297 m²) of the experimental plot was delimited by the 33 central plants, discarding the triple row-end border.

The reference dose (T1) used to establish the fertilization treatments of balsa wood is based on the recommended fertilization doses for the eucalyptus and teak plantation, since there was no specific recommendation for balsa wood plantation in Brazil. Treatments consisted of 0 (T0), 1 (T1), and 2 (T2) times the reference fertilization doses. The reference dose (T1) was applied as follows: 400 kg $ha^{-1}$ of Gafsa rock phosphate in the tree furrows, at planting; 100 g of $N-P_2O_5-K_2O$ (04-30-16) per tree applied in lateral furrows, at planting; 1,000 kg $ha^{-1}$ of dolomitic lime and 500 kg $ha^{-1}$ of gypsum applied by throwing, at planting; FTE BR 08 Gran (3.8% S, 2.5% B, 1.0% Cu, 10.0% Mn, 0.1% Mo, and 7.0% Zn) applied in the lateral furrows, at planting; 10 g boric acid per tree and 150 g $N-P_2O_5-K_2O$ (20-00-20) per tree applied in lateral furrows, after 60 days of planting.

To determine the soil carbon stocks before the establishment of the balsa wood experiment, soil samples (composed by 20 subsamples) were randomly collected, in December 2010, with a regular soil auger, in each of the blocks, at 0.0-0.10, 0.10-0.20, and 0.20-0.30 m soil depths, totaling 60 subsamples. Moreover, after the establishment of the balsa wood experiment, soil samples (composed by 21 subsamples) were collected in each treatment, at the same mentioned soil depths, to determine soil carbon stocks after three (2014) and seven (2018) years of the experiment establishment, as follows: seven samples in the center of the planting line; and seven in the east and seven in the west sides, at 1.5 m apart from the planting line.

Furthermore, soil carbon stocks were also determined in a deciduous secondary forest (DSF) and in degraded pasture (DP) areas (reference areas) next to the experiment, in the same toposequence and soil class. The DSF area was selectively logged for high timber value species during the 1980s, and the DP area was planted with 'Marandu' palisade grass (*Urochloa brizantha* 'Marandu'), in the late 1980s, and used for extensive livestock production. To determine soil carbon stocks in the DP area, 20 soil subsamples were randomly collected in 2018 at 0.0–0.10, 0.10–0.20, and 0.20–0.30 m soil depths. As to the DSF, data from 2014 collected at 0.0–0.05, 0.05–0.15, and 0.15–0.30 m soil depths were used.

The average soil density was determined according to Teixeira et al. (2017), using 20 undisturbed soil samples (10 samples on the planting line, and 10 points between lines), collected with volumetric rings (0.05 m height and 0.05 m diameter), in each balsa wood treatment at 0.0–0.10 and 0.10–0.20 m soil depths (totaling 120 samples). For the degraded pasture area, samples were randomly collected in 10 additional points. As to the average soil density in the 0.20–0.30 m soil depths, data from 2014 were used, since the short term effect on the soil density is expected to occur only in the superficial soil layer. All soil samples were prepared and stored in a refrigerator (5 to 8°C) for analysis.

Soil samples were air-dried, sieved through a 2 mm sieve, ground in a mill to pass through a 0.106 mm sieve, and analyzed for total C concentrations by dry combustion (Vario Macro, Elementar Analysensysteme, Hanau, Germany).

For each fertilization level, the balsa wood biomass (leaves, branches, and trunk) was rigorously determined with basis on a plot inventory (Smalian's method), by which five trees of varying diameter at breast height (5 classes of DBH) were selected, and their volumes were quantified at the end of the rainy season. After cutting, the tree components were separated (leaves, branches, bark, and wood) and weighed for the determination of fresh matter weight. To estimate the dry matter weight of these components after homogenization, a subsample was removed, dried in a forced-air circulation drying oven at 75ºC, and periodically weighed until constant weight was attained. The total dry matter was estimated based on the relationship between the dry and fresh matter weights of each sample (tree compartment). The litter samples were randomly collected in each experimental plot (eight subsamples to obtain a composite sample) in the planting line and between tree lines, using a 50×50 cm (0.25 m²) metal frame. The dry biomass samples from the aerial part and litter were grounded and subjected to chemical analysis to determine the C levels through a CHNS analyzer (Vario Macro, Elementar Analysensysteme, Hanau, Germany). The C stocks in the biomass of the aerial part and the litter were estimated using their mass and the respective total C contents.

The C stock in each soil layer was assessed according to Batjes (1996), as follows:

$$SCs = (Cc \times Bd \times L) \times 10^{-1},$$

in which:  is the soil carbon stock (Mg ha$^{-1}$); Cc is the soil carbon content (g kg$^{-1}$); Bd is the bulk density (Mg m$^{-3}$); and L is the thickness of the soil layer (cm).

The soil carbon stock at 0.0-0.30 m soil depths was then corrected with basis on the soil mass of the native forest area, according to Sisti et al. (2004), as follows:

$$TSCs = \sum_{i=1}^{n-1} Cti + [Mtn - (\sum_{i=1}^{n} Mti - \sum_{i=1}^{n} Msi)] - Ctn,$$

in which: TSCs is the total soil carbon stock (Mg ha$^{-1}$); $\sum_{i=1}^{n-1}$ Cti is the sum of the total content of carbon present in the evaluated treatment (Mg ha$^{-1}$) from the first layer until the penultimate layer (n − 1); Mtn is the soil mass of the last layer in the estimated treatment (Mg ha$^{-1}$); $\sum_{i=1}^{n}$ Mti is the sum of soil mass from the first to the last layer of the evaluated treatment (Mg ha$^{-1}$); $\sum_{i=1}^{n}$ Msi is the sum of the soil mass from the first to the last layer in the native forest area (Mg ha$^{-1}$); Ctn is the soil C content in the last layer of the evaluated treatment (Mg Mg$^{-1}$).

The data of carbon stocks were tested for normality and homoscedasticity of the residue, and an analysis of variance was performed. The fertilization levels were compared by the Tukey's test, at 5%, probability, whilst soil carbon stocks among balsa wood, DP, and DSF were compared by the t-test, at 5% probability.

The magnitude of soil C stocks observed in the present work (Table 1) is comparable to other results found in the literature for native vegetation and grasslands areas at the same soil depths (0−30 cm). Segnini et al. (2019) found 49.55 Mg ha$^{-1}$ C in a native vegetation ("seasonal semi-deciduous forest") area, 38.9 Mg ha$^{-1}$ C in a degraded pasture of *Urochloa decumbens* under extensive management, and 63.7 Mg ha$^{-1}$ C in a pasture


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of *Urochloa decumbens* with moderate stocking rate. Other studies examining soil carbon stocks in eucalypts plantations, in Brazil, have previously shown increases (Lima et al., 2006; Maquere et al., 2008), no change (Neufeldt et al., 2002; Zinn et al., 2002), and decreases when trees were planted in areas originally covered by savanna or consolidated pastures (Zinn et al., 2002; Cook et al., 2014). Mean soil carbon stocks were reported as 29 Mg $ha^{-1}$ (± 0.70 Mg $ha^{-1}$) at 0-30 cm soil depths, in continuous rotation eucalyptus plantations, in Brazil, (Cook et al., 2016). The aforementioned authors, characterized soil carbon stocks and change over two decades in 306 eucalyptus plantations across a 1200 km gradient, and they also found that soil carbon tends to increase with increasing soil clay content, precipitation, and mean annual temperature. It is worth mentioning that significant changes in soil C stocks are expected to occur at 0-30 cm soil depths, as a result of agricultural management and changes in land use.

The fertilization level T2 increased the initial soil carbon stock keeping it higher after seven years of balsa wood establishment. However, concerning the initial stocks, the fertilization levels T0 and T1 did not alter the soil carbon stock after three and seven years of balsa wood establishment (Table 1). Thus, the nutritional management with increased chemical fertilization in T2 was the factor responsible for the difference in the soil carbon stocks. The total carbon stock in the aboveground and litter biomass, determined at seven years after balsa wood planting, increased as a function of fertilization levels (Figure 1).

These results indicate that the fertilization of balsa wood plays an important role in C stocks in the long-term as it provides conditions for a sustained forest production and litter input to the soil. In a long-term incubation experiment, the nutrient scarcity ($Ca^{2+}$, $Mg^{2+}$ , and P) was shown to lead to a low efficiency for C accumulation in the subsoil (Briedis et al., 2016). The aforementioned authors also noticed that the improvement of nutrient availability at deeper layers is an efficient strategy to preserve the C stocks, providing a high C sequestration potential and, consequently, increasing the productivity in highly weathered soils. Moreover, there is a strong variation of the carbon sequestration potential among different plantation species, regions, and management (Montagnini & Nair, 2004). Besides, management practices such as fertilization can easily increase the carbon sequestration of species such as eucalypts (Noormets et al., 2015). Thus, the fertilization level T2 guaranteed the minimum amount of nutrients needed for the growth of the trees (besides the nutrients immobilized in the tree biomass), also guaranteeing the maintenance of C in the soil.

**Table 1.** Soil carbon stock (SCs) of balsa wood at 0–0.30 m soil depths, under different nutritional management, after three and seven years of establishment.

| Age after planting | Treat-ment | SCs[1] (Mg $ha^{-1}$) | Bes | DP | SDF |
|---|---|---|---|---|---|
| | | | p-value[2] | | |
| 3 (years) | T0 | 59.18a (±3.61) | 0.461 | 0.542 | 0.450 |
| | T1 | 58.97a (±1.23) | 0.311 | 0.196 | 0.099 |
| | T2 | 61.50a (±1.77) | 0.072 | 0.196 | 0.493 |
| 7 (years) | T0 | 60.82b (±4.28) | 0.259 | 0.245 | 0.731 |
| | T1 | 57.69b (±1.44) | 0.630 | 0.216 | 0.158 |
| | T2 | 66.66a (±1.08) | 0.007 | 0.035 | 0.743 |
| Averages (Mg $ha^{-1}$) | | 60.80 (±3.17) | 56.56 (±1.45) | 54.33 | 65.36 |

[1]Means with equal letters, at each age, do not differ from each other by the Tukey's test, at 5% probability. [2]Significance of carbon stock comparison through the t-test between treatments and the reference area. Values in parentheses correspond to standard deviation. T0, without fertilization; T1, reference dose; T2, twice the reference dose; SCs, soil carbon stocks. Bes, before balsa wood establishment; DP, degraded pasture; DSF, deciduous secondary forest.

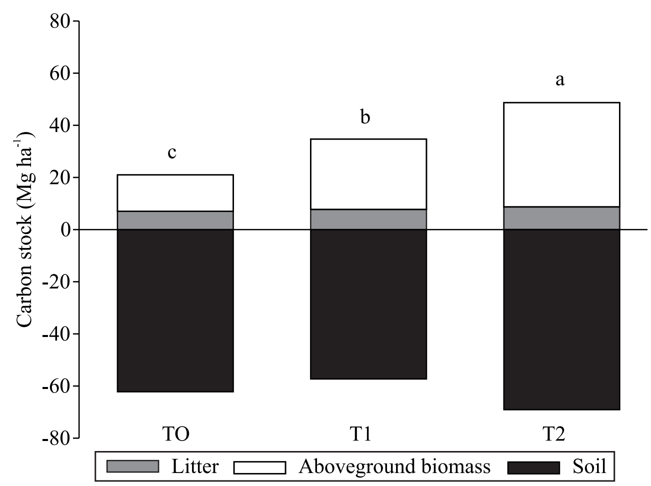


**Figure 1.** Soil carbon stock and total carbon stock of biomass partitioned in aboveground and litter compartment, after seven years of planting of balsa wood for treatments with 0 (T0), 1 (T1), and 2 (T2) times the reference fertilization dose. Different letters above bars indicate difference by the Tukey's test, at 5% probability.

Soil carbon stock was similar in T0 and T1, whilst the accumulated carbon in the biomass (aboveground + litter) in T1 was greater than T0 (Table 1). The greater carbon stock (soil + aboveground + litter) in T1, in comparison to T0, can be explained by the fact that most of the organic carbon is stored in the biomass, where treatments follow the order T2>T1>T0. Before the establishment of the balsa wood experiment, the experimental area was occupied by well-managed, undegraded pasture, with 56.40 Mg $ha^{-1}$ soil carbon stock at 0.0-0.30 m soil depths. In the present study, 'Marandu' palisade grass showed reduced soil C stocks compared to that of the native forest. However, well-managed *Brachiaria* pastures can accumulate more soil C than degraded pastures (Braz et al., 2013; Segnini et al., 2019).

After seven years of balsa wood planting, the soil carbon stock increased by 17.9% at 0.0-0.30 m soil depths, in comparison to soil carbon stock before the experiment establishment. Moreover, the carbon stock (soil + aboveground + litter) in T2 at seven years was 41.6% higher than that of balsa wood without fertilization (T0) (Figure 1). In the current experiment, the average soil carbon storage represented more than 50% of the total C accumulated (aboveground biomass + litter + soil). The balance between the belowground carbon inputs (through both belowground productivity and exudation, as well as aboveground litter inputs) and losses (primarily mineralization) is often expressed via biomass production and C storage efficiencies (Noormets et al., 2015). For instance, the annual input of C to the belowground portion of the eucalyptus plantations varies from 4.3 to 10.0 Mg $ha^{-1}$ per year (Ryan et al., 2010). No difference was observed for soil carbon stock in the treatment T1, after three and seven years of planting, in comparison to the carbon stock before balsa wood establishment. Nonetheless, the total carbon stock (soil + biomass) was higher in T1, with the largest portion allocated to biomass production, which was 10.5% higher than T0 (Figure 1). Forest plantations are expected to increase soil carbon sequestration due to the high aboveground productivity, recalcitrant carbon inputs, and deep rooting systems (Lal, 2005; Laganiére et al., 2010).

In pasture areas, the balsa wood plantation improved the soil carbon stocks; and the fertilized balsa wood plantation, after seven years of establishment, provided a higher total carbon stock in the soil-biomass system than the well-managed pasture. The treatments T0, T1, and T2 showed the same soil carbon stock of the DSF area at 0.0-0.30 m soil depths. However, T2 was the only treatment that differed from T0, T1, and DP, as to the carbon stock at 0.0-0.30 m soil depths. Such response can be explained by the fact that a higher nutrient availability can significantly decrease the plant respiratory costs and allow of a higher carbon storage efficiency (Fernández-Martínez et al., 2014).

A properly fertilized balsa wood plantation can increase the carbon stock by 18% in the soil, and by 42% in the soil-biomass system, after seven years of planting. Such findings for balsa plantations imply that the forest without fertilization will likely have a much larger impact on total C sequestration than any change in soil C storage.

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