Carbon and nitrogen sequestration in soils under different tropical legume tree species

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Abstract
This study aimed to investigate the effects of tropical legume tree species on soil C and N storage after pasture conversion. We evaluated soil organic carbon (SOC), soil total nitrogen (STN), and the natural abundance of ^{13}C in the soil profile up to 100 cm beneath *Plathymenia reticulata*, *Hymenaea courbaril*, and *Centrolobium tomentosum* 27-year-old stands. Soil organic carbon was higher for *P. reticulata* up to 1m depth, but STN was similar across species. Most of the SOC originated from the trees rather than the former pasture, except beneath *C. tomentosum*. Specific-species traits mediated effects appear to shape SOC and STN pools and transformations.

Key-words: Soil organic matter, carbon sequestration, soil total nitrogen.

Introduction

The Atlantic Forest biome has been identified as one of the world's hotspots of biodiversity (Myers et al. 2000). Despite its ecological relevance, the biome is one of the most threatened by deforestation on earth where only ~10% of the original vegetation currently exists in small fragments. Given this scenario, forest plantations to recover the biome are urgently needed and, if well managed, recovered degraded sites can also contribute to meet market demand of timber and non-timber products, therefore, reducing illegal logging.

Legume tree species have been prioritized in afforestation programs as they can improve soil fertility and it will be helpful for stand productivity and where more demanding trees can grow (Chaer et al. 2011). Shifting cultivation e.g. pasture to tropical N-fixing species can restore C and N to levels found in the soil under native vegetation in a short period of time (Chaer et al. 2011), since new C and N inputs will occur through above and belowground plant litter (Ngaba et al., 2020). However, C sequestration, as well as N retention in the soil will be mediated by specific functional traits of each species such as litter productivity and chemical composition (Peng et al., 2020).

To better understand the fate of litter C and their transformation and pools in the soil profile after land-use changes, stable isotopic fractionation has been employed as a powerful tool (Paul et al., 2019). The technique is also effective to track land-use changes' effects on soil organic matter (SOM) origin (Vicente et al., 2016).

Apart from soil fertility improvements, soil C storage in the soil profile has a particular contribution for mitigating greenhouse gas fluxes acting as a great sink or source within the climate change context. Its relevance is due to large amounts of organic C stored in the soil globally where deforestation of tropical areas have a significant impact on the global C cycle (Silver et al. 2000).

Thus, our study aimed to quantify soil organic carbon and soil total nitrogen sequestred beneath three tropical legume tree species individually to a layer of 0-30 and down to 100 cm. In addition, we aimed to quantify the contribution of C_3-derived C and C_4-derived C after pasture conversion to each tropical legume tree plantations, 27 years after land use change.

Material and Methods

The study was carried out in the mountain region of Rio de Janeiro, Brazil (22° 04′ 32″ S 42° 03′ 51″ W). The average temperature is between 18 and 24 ºC and annual precipitation of 1100 mm. The site was previously a pasture that had experienced erosion and unplanned fires. In 1992, Atlantic Forest species were planted to recover the area. A total of 49 seedlings of each tree species were planted in single plots and spaced at 3 x 3 m. More details of the plantation can be seen in Barroso et al. (2018). We selected three forest species belonging to the Fabaceae family: *Plathymenia reticulata* Benth, *Hymenaea courbaril* Linneaeus, and *Centrolobium tomentosum* Guillem ex Benth. Yet, a 50-year-old unfertilized pasture composed of *Brachiaria decumbens* and a Secondary Forest (upper canopy logged approximately 35 years ago) were considered as references for C_4 and C_3 vegetation covers, respectively, and used for calculations with soil ^{13}C fractionation data beneath the aforementioned species. These areas are also located in the Atlantic Forest biome and more detailed information can be seen in Vicente et al. (2016).

Mineral soil was sampled in the following layers: 0-10 cm; 10-20 cm; 20-30 cm; 30-40 cm; 40-50 cm; 50-75 cm and 75-100 cm, with four replicates per soil layer under each selected species stand (12 samples per soil layer for each species). We also assessed soil particle size and soil bulk density.

Soil organic carbon (SOC) and soil total nitrogen (STN) contents were determined by dry combustion in an automated elemental analyzer (CHNS/O analyzer). Then, considering soil layer thickness, the soil bulk density at each layer was multiplied by SOC or STN to calculate SOC and STN stocks stored in the soil profile. The natural abundance of ^{13}C was determined using the Isotope Ratio Mass Spectrometer Delta V Advantage (IRMS - Thermo Scientific) along with Organic Elemental Analyzer (Thermo Scientific), and the results were expressed in (‰), calculated using the following equation:

$$\delta^{13}C = (R_{sample} - R_{reference})/R_{reference}$$

Where: R_{sample} = ^{13}C /^{12}C ratio of the sample and $R_{reference}$ = $^{13}C/^{12}C$ of the reference samples

To distinguish the proportion of C derived from the previous pasture (C_4 vegetation) and from the current forest stands (C_3 vegetation) we used the following equation:

$$\%C\text{-}C_4 = [(\delta - \delta_a)-(\delta_p - \delta_a)]*100,$$

Where: δ = natural $\delta^{13}C$ abundance in the samples; δ_a = natural $\delta^{13}C$ abundance in the soil samples without C_4 plant residue (Secondary forest from Vicente et al. (2016) used as reference); δ_p = natural $\delta^{13}C$ abundance of the pasture plant material (-12.65‰). Lastly, the following equation was used to obtain the % of the C_3 carbon:

$$\%C - C_3 = 100 - \%C\text{-}C_4$$

Considering the study site has no statistical design and no fill requirements for parametric analysis, our data was also submitted to descriptive analysis and comparison by Confidence Interval ($P < 0.05$) by Student's T-test. The comparison was based on the overlapping of confidence interval limits (or lack thereof), which allows to differ means with high statistical support.

Results and Discussion

The soil organic carbon (SOC) in the 0-100 cm soil layer was higher for *P. reticulata* (214 Mg ha^{-1}) than *C. tomentosum* (171 Mg ha^{-1}), but no different from each other and between *P. reticulata* and *H. courbaril* (202 Mg ha^{-1}), respectively. Conversely, regarding the 0-30 cm soil layer, an opposite pattern was observed, with SOC showing the lowest value for *P. reticulata* with 84 Mg ha^{-1} and highest for *H. courbaril* with 107 Mg ha^{-1}. The soil total nitrogen (STN) in the 0-100 cm soil layer was similar among species with 44% of the STN accumulated at the top 0-30 cm soil layer (Figure 1). N-fixing tree species enhance soil C stocks when compared to non-N-fixing (Chaer et al. 2011), and greater retention of older C in the soil and higher inputs of new soil C are the main reasons to explain this fact (Resh et al. 2002).

The carbon contribution located deep down the soil profile is unlikely to be on account of the planted N-fixing tree species as changes on soil C are typically distinguishable in the forest floor and top mineral soil layers. Due to the relatively short time after pasture conversion to the N-fixing monospecific stands, the soil C and N in the subsoil are probably derived from the forest vegetation even before the pasture. Therefore, to discuss N-fixing species effects on soil C and N we will limit the evaluated soil layer to 30 cm depth (Garten 2009).

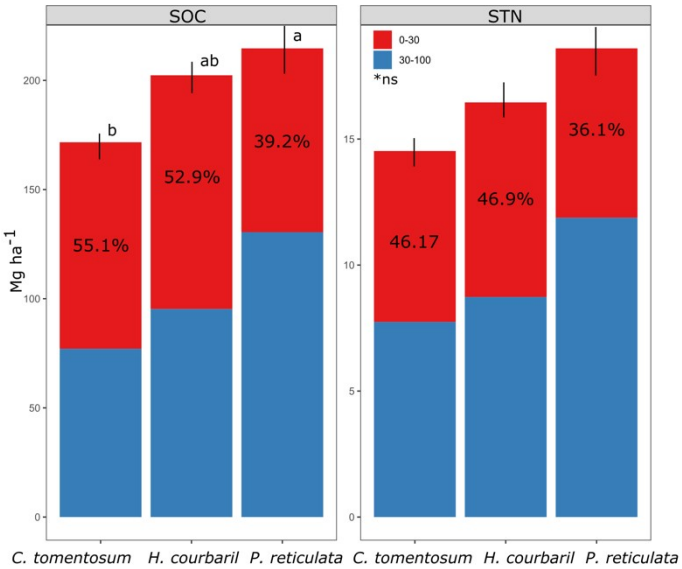

Figure 1. Soil organic carbon (SOC) and soil total nitrogen (STN) stocks in 0-100 cm soil layer beneath N-fixing plantations in the Southeast Brazil. Vertical bars represent ± standard deviation. Means followed by different lowercase letters differed statistically by confidence interval ($P < 0.05$). *ns – not significantly different.

The $\delta^{13}C$ values showed higher contribution of C_4 vegetation under *C. tomentosum* even in the upper soil layers (0-10, 10-20, and 20-30 cm) when compared to *H. courbaril* and *P. reticulata.* Nevertheless, the accumulated C-C_3 at 0-10 cm layer was lower to the Secondary Forest (28.5 Mg ha^{-1}) when compared to the legume tree species where the values ranged from 33.8 Mg ha^{-1} to 46.1 Mg ha^{-1} (Figure 2).

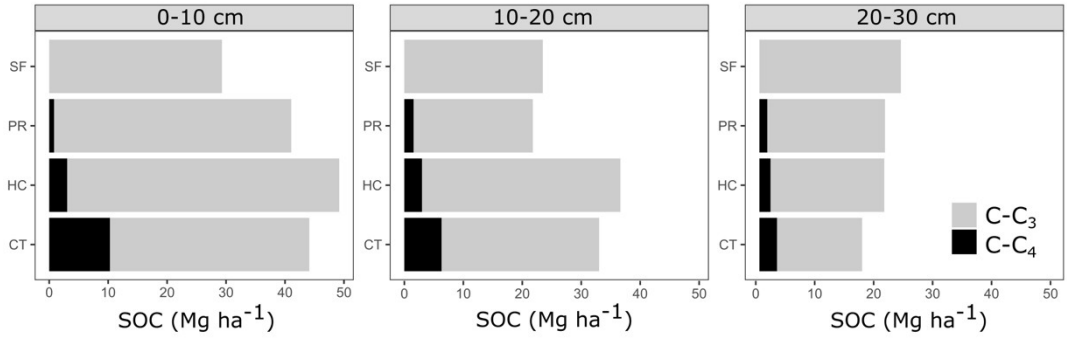

Figure 2. Soil organic carbon divided into C_3 plants (tree)-derived and C_4 plants (pasture)-derived in the 0-30 cm soil layer beneath different tropical N-fixing tree plantations and the Secondary Forest (SF) from Vicente et al., (2016); PR – *Plathymenia reticulata*; HC – *Hymenaea courbaril*; CT – *Centrolobium tomentosum.*

It is frequently reported a relatively rapid shift from C_4-derived C to C_3-derived C in tropical regions mainly due to weather conditions where the warm and humid environment accelerates the organic matter decomposition rates in the upper soil layers (Villela et al. 2012). The soil C_4-derived C losses are decreasing at a slower rate under *C. tomentosum* than *P. reticulata* and *H. courbaril* in the topsoil layers even though the temperature and humidity were similar.

There is high evidence that species-specific traits mediated effects such as litter productivity and chemical composition (Siqueira et al., 2021) and hence microbial community are driving the SOC and STN budgets and organic matter decomposition rates more than weather conditions and/or soil properties (or acting in collaboration), as also observed by du

Preez et al. (2021). Furthermore, the productivity and chemical composition of the litter from understory vegetation might have influenced C and N cycling beneath the N-fixing stands.

Conclusions

Afforestation with tropical 27-year-old legume tree plantations was able to restore soil C and N to similar or even higher levels when compared to the Secondary Forest, but the tree species stored different C budgets up to 30cm depth. Most of the current organic matter is originated from the planted tree species, however, it seems that *C. tomentosum* had a slower decomposition rate of old soil C (higher C_4-derived C left).

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