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Research article

Changes in soil carbon quantity and quality due to forest harvesting

Cambios en la cantidad y calidad del carbono del suelo por efecto del aprovechamiento forestal

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Abstract

Soil is the main carbon reservoir in forest ecosystems. Forest harvesting may alter both the quantity and quality of soil organic carbon (*SOC*) and its respiration potential; however, few studies have addressed these effects. This study aimed to quantify organic carbon mass to 80 cm depth, the *C/N* ratio, and estimate the potential CO_2 respiration of surface soil (0-15 cm) in *Abies religiosa* stands with (CA) and without (SA) timber harvesting. The study was conducted in *Atlautla*, State of Mexico, where three harvested stands (three years after logging) and three unharvested stands were selected. Comparisons between sites were made using the Mann-Whitney test (p>0.05). No significant differences were found in bulk density, *SOC* content, or potential respiration between CA and SA stands. The *C/N* ratio was significantly lower at 45 cm depth in SA stands, indicating more labile carbon. Respired carbon represented 4.6 and 6.3 % of total *SOC* for CA and SA stands, respectively. Although this result was contrary to expectations, since soil disturbance from logging could enhance carbon oxidation, it was consistent with the trend of lower *C/N* ratio, suggesting higher labile soil carbon in SA sites. Due to the short post-harvest period (three years), low harvesting intensity, and high natural soil variability, detecting changes in soil carbon mass and quality caused by forest harvesting is difficult.

Key words: Soil organic carbon, forest management, *C/N* ratio, carbon reservoir, soil respiration, forest soils.

Resumen

El suelo es el principal reservorio de carbono en los bosques. El aprovechamiento forestal puede afectar la cantidad y calidad de carbono orgánico del suelo, así como su potencial de respiración; sin embargo, hay pocos estudios al respecto. Por lo que se propuso determinar la masa de carbono orgánico hasta 80 cm de profundidad del suelo, conocer la relación *C/N* y determinar el potencial de respiración de CO_2 del suelo superficial (0-15 cm), en rodales de oyamel con (CA) y sin (SA) aprovechamiento maderable, ubicados en el municipio Atlautla, Estado de México. Se seleccionaron tres rodales aprovechados tres años antes y tres sin aprovechamiento. La comparación entre sitios se hizo mediante la prueba de *Mann-Whitney* (p>0.05). No se obtuvieron diferencias significativas en densidad aparente, carbono del suelo o respiración potencial entre sitios CA y SA. La relación *C/N* solo fue estadísticamente menor en la profundidad de 45 cm en los rodales SA, indicando carbono de fácil descomposición. El carbono respirado correspondió a 4.6 y 6.3 % del carbono edáfico para rodales CA y SA, respectivamente. Este resultado es contrario a lo esperado, dado que la remoción del suelo por aprovechamiento maderable podría estimular la oxidación del carbono; pero consistente con la tendencia de menor relación *C/N*, que sugiere más carbono lábil en sitios SA. El plazo corto (tres años), intensidades de corta bajas y la alta variabilidad de los suelos forestales dificultan detectar cambios en masa y calidad de carbono edáfico por efecto del aprovechamiento forestal.

Palabras clave: Carbono orgánico del suelo, manejo forestal, relación *C/N*, reservorio de carbono, respiración del suelo, suelos forestales.

Introduction

Temperate forests promote the provision of ecosystem services, such as water and climate regulation, in addition to supporting biodiversity (Castillo-Argüero et al., 2016). The increase in CO_2 emissions is largely explained by the use of fossil fuels and deforestation (Hansen et al., 2013). The increase in atmospheric CO_2 influences the rise in temperature and climate variation, as indicated in the reports of the Intergovernmental Panel on Climate Change (IPCC) (Anderegg et al., 2015; Lee et al., 2023).

In Mexico, climate variability is reflected in drought records (Servicio Meteorológico Nacional [SMN], 2025), which also warn of future negative effects on forest functionality and the ecosystem services they provide.

Given this scenario, soil, as one of the main carbon reservoirs, is important as a regulator of natural CO_2 emissions. The role of soil is highlighted primarily by its supporting services and its capacity to retain stabilized carbon in the long term (Seidl et al., 2017).

Forest soils represent up to three times the aboveground carbon mass in a forest (Schlesinger & Bernhardt, 2020); however, inadequate ecosystem management can turn them into significant CO_2 emitters (Lal, 2005).

Studies of soil carbon in managed forest ecosystems are still scarce, and further research is needed to propose best forest management practices (Clarke et al., 2015; Gómez-Guerrero & Doane, 2018). These studies aim to determine strategies that allow for the preservation or enhancement of soil carbon reservoirs while maintaining sustainable forest management (Cortés-Pérez et al., 2021).

Determining total organic carbon (*TOC*) content is useful for understanding the carbon cycle in different forests and under different management intensities. If carbon inputs are offset by losses due to respiration, deforestation, erosion, fire, or other degradation processes, the soil carbon reservoir remains stable and its contribution to the greenhouse effect is not intensified (Pan et al., 2024). In addition to net carbon amounts, carbon dynamics are important and can be quantified using soil respiration potential (Zinke & Stangenberger, 2000).

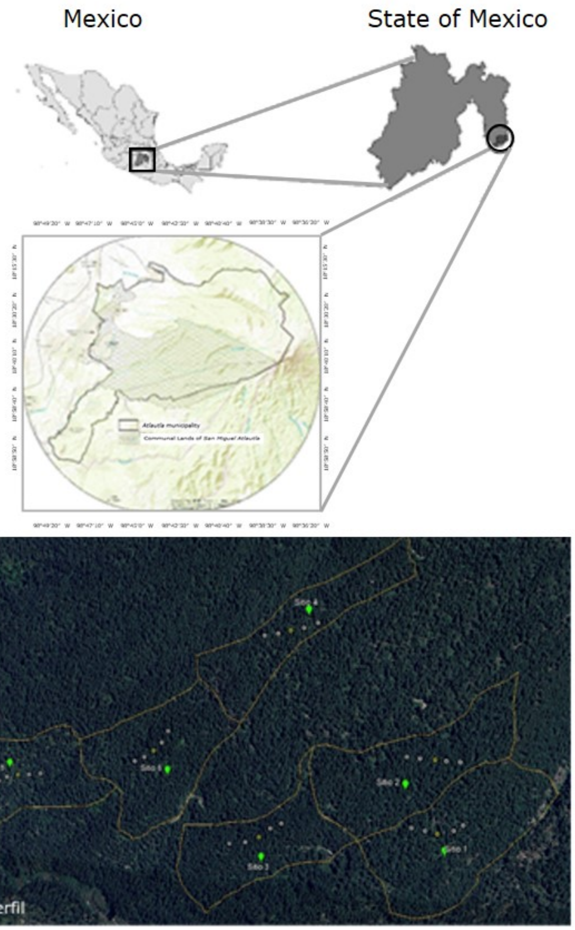
Since logging alters the physical properties of the surface soil, it is expected to promote higher rates of CO_2 respiration (Achat et al., 2015). However, the effects of logging on carbon reservoirs depend on the resilience of each soil type; for example, Ultisols and Spodsols are less resilient than Andisols (James & Harrison, 2016).

Therefore, the objectives of this study were: (a) To determine the mass of stored soil carbon and its distribution at different soil depths; (b) To determine carbon quality using the *C/N* ratio; and (c) To determine the respiration potential of the surface soil (0-15 cm) in harvested (CA) and unharvested (SA) stands. The null hypothesis was that regardless of the harvesting history, the soils of all the studied stands contain similar total carbon mass stored at a depth of 0.8 m, as well as similar soil *C/N* ratios and surface soil respiration potential (0-15 cm).

Materials and Methods

Study Area

The study area was located between the extreme coordinates 19°04’58.04”-18°59’26.67” N and 98°37’46.25”-98°48’45.38” W (Figure 1), which consist of forest lands of the Communal Lands of *San Miguel Atlautla*, *Atlautla* municipality, State of Mexico. The climate is C(E)(w_2)(w)b(i)g semi-cold, sub-humid, with summer rains, with winter precipitation less than 5 %, average annual temperature between 5 and 12 °C, with average annual precipitation of 800 to 1 300 mm. The soils present, according to the 1988 FAO-UNESCO classification, are eutric Regosol and vitric Andosol with a coarse texture (Instituto de Información e Investigación Geográfica, Estadística y Catastral del Estado de México [Igecem], 2019). According to Series VII-Land Use and Vegetation of the National Institute of Statistics and Geography (Instituto Nacional de Estadística y Geografía [Inegi], 2018), the vegetation consists of fir forest [*Abies religiosa* (Kunth) Schltdl. & Cham.].



1, 2, and 3 = Sites designated for timber harvesting (CA); 4, 5, and 6 = Sites designated for non-timber harvesting (SA). Yellow circles indicate soil profiles, and white circles indicate supplementary sampling for bulk density and soil respiration.

Figure 1. Location of the sampling sites in the *San Miguel Atlautla* Communal Lands, *Atlautla*, State of Mexico.

Site establishment and sampling

Sites were established based on their timber harvesting history. Three stands that had been harvested three years prior and three unharvested stands were selected (Figure 1). The management of the studied forests is carried out using the Mexican Method for the Management of Irregular Forests (*MMOBI*, for its acronym in Spanish), which aims to achieve a diameter category distribution close to an inverted J-shaped distribution by harvesting overmature trees (Leyva-Pablo et al., 2021).

Study sites were selected to be similar in: (a) Altitude (2 900 to 3 300 m); (b) Vegetation type (*Abies religiosa* forests); and (c) Year of intervention (for harvested stands). Once identified, a simple random sampling was conducted, resulting in a total of six sites. Soil sampling was conducted between May and July 2024. At each site, a soil profile was taken out at 0.8 m deep. These sites are indicated with a green symbol in Figure 1. Eight samples were taken from each soil profile at 10 cm depths and placed in labeled plastic bags. These samples were used to determine total soil organic carbon (*TOC*) and total nitrogen (*TN*). A total of 48 samples were collected for *TOC* and *TN*.

For bulk density (*BD*) estimation, four undisturbed soil samples were collected at 15 cm depth intervals (15-30 cm, 30-45 cm, 45-60 cm, and 60-75 cm). This depth was chosen due to the homogeneous condition of the vitric Andosols in the study forests. Additionally, a transect with five points spaced 50 m apart was established, indicated as white circles in Figure 1. At each point along the transect, undisturbed soil samples were collected using a metal cylindrical sampler with a diameter of 5 cm and a height of 15 cm (model 400 Soil Bulk Density Sampler AMS®) as supplementary estimates of surface *BD*. The total number of samples collected from the profiles and supplementary samples for *BD* estimation was 48.

The samples used to determine surface soil respiration potential were also obtained along the aforementioned transect and near the points where the supplementary surface *BD* samples were collected. In this case, the total number of samples was 24.

Determination of soil organic carbon and total nitrogen

Total organic carbon (*TOC*) was determined using an automatic carbon analyzer (model TOC SSM 5050A Shimadzu®). The organic carbon content *(% TOC*), bulk density, and sampling horizon thicknesses were used to calculate carbon mass. Since the soil is volcanic, acidic, and non-reactive to HCl, no correction estimates were made for inorganic carbon (carbonates). The amount of carbon in tons or megagrams (Mg) per hectare was estimated using the following formula, which implicitly includes a unit adjustment factor:

$$C(Mg\ ha^{-1}) = (\%\,TOC)(Dep)(BD) \qquad (1)$$

Where:

C = Carbon mass in Mg ha^{-1}

% TOC = Carbon content in percentage

Dep = Horizon depth in cm

BD = Bulk density in Mg m^{-3}

For the determination of *NT*, the micro Kjeldahl method was used, which consists of a digestion process with concentrated H_2SO_4, steam distillation, and distillation (Bremmer, 1965). The *NT* percentage was obtained with the following formula:

$$N\ (\%) = \frac{(V_{sample} - V_{control})\ N\ acid \times 14}{sample \times 10} \qquad (2)$$

Where:

V_{sample} = Volume of sulfuric acid used to titrate the sample

$V_{control}$ = Volume of sulfuric acid used to titrate the blank

N = Exact normality of the sulfuric acid

14 = Milliequivalent weight of N (mg)

Sample = Weight in grams

10 = Factor to convert to percentage $\left(\frac{1\,000}{100}\right)$

The analysis and determination of *TOC* and *TN* were carried out in the Soil Fertility and Environmental Chemistry Laboratory of the Graduate Studies School, *Montecillo* Campus, *Texcoco*, State of Mexico.

Determination of respiration potential

Soil respiration potential was measured using laboratory incubations, adapting the methodology of Rowell (1994). This involved incubating soil and sand samples (the latter used as a control). The samples were placed in a 250 mL Erlenmeyer flask, and 10 mL of 0.3 M sodium hydroxide (NaOH) was added to a vial. This vial was placed in the flask's cap, sealed, and the samples were stored in a dark place at room temperature for 17 days.

At the end of the incubation period, the vials containing each sample, including the controls, were removed, and the remaining NaOH solution was transferred to a 125 mL flask. To this flask, the following were added: 10 mL of distilled water, 10 mL of 1 M barium chloride ($BaCl_2$), and 6 drops of phenolphthalein. Next, the solution was titrated with hydrochloric acid (0.1 M HCl) until the color changed from pink to colorless. The volume of HCl used was recorded to determine the amount of CO_2.

The estimated respiration rates were then converted to field respiration rates using the bulk density and soil depth data.

A standardization process was also performed to determine the exact concentrations of the NaOH (0.3 M) and HCl (0.1 M) solutions. It was ensured that they met the values specified by the methodology used, through an acid-base titration with a primary standard.

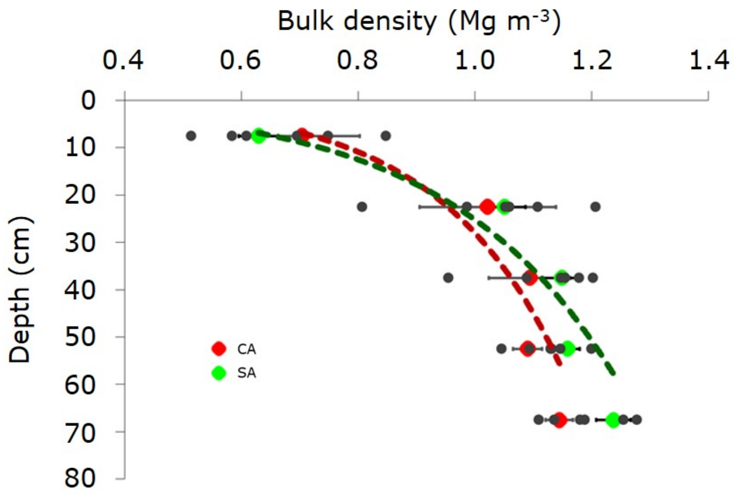
Statistical Analysis

Given the small number of samples per horizon (between three and eight), the non-parametric Mann-Whitney test was used to determine statistical differences between CA and SA stands, with a significance level of 5 %. Statistical analysis was performed using R software 4.4.1 (R Core Team, 2024). The response variables were: percentage of carbon, carbon mass, bulk density, *C/N* ratio and respiration potential.

Results and Discussion

Bulk Density

Although there were no statistically significant differences due to the harvesting effect, the results indicated a trend toward greater variation in bulk density in the topsoil of CA stands. This may be due to the degree of topsoil disturbance caused by forest operations. Log dragging and tree fall could have increased this variation in topsoil bulk density (Figure 2).



There were no statistically significant differences due to harvesting. The dotted lines are only shown to describe the trend.

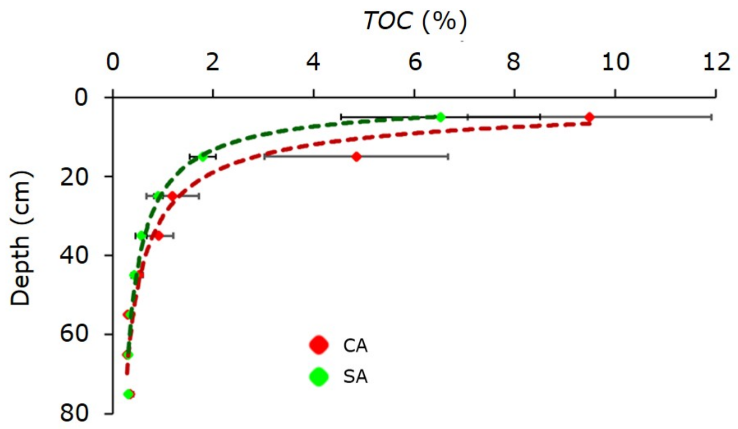
Figure 2. Bulk density in stands with (CA) and without (SA) timber forestry.

Bulk density ranged from 0.51 to 1.21 Mg m^{-3} in the CA stands and from 0.58 to 1.28 Mg m^{-3} in the SA stands. These low bulk density values, especially in the topsoil, are explained by the nature of the Andisols and by low impacts on compaction resulting from logging (Binkley & Fisher, 2020). Furthermore, these bulk density values indirectly indicate soils with good physical condition, good drainage, good aeration, and that allow for adequate root development (Toivio et al., 2017).

Carbon concentration and mass

No statistically significant differences in total organic carbon (*TOC*) percentage were found between CA and SA stands. *TOC* values decreased exponentially with increasing soil depth. This trend is explained by the effect of litter decomposition in the surface layer, as well as the greater contribution of fine roots with short residence times and organic compounds that are mobilized to deeper layers (Binkley & Fisher, 2020; Schlesinger & Bernhardt, 2020).

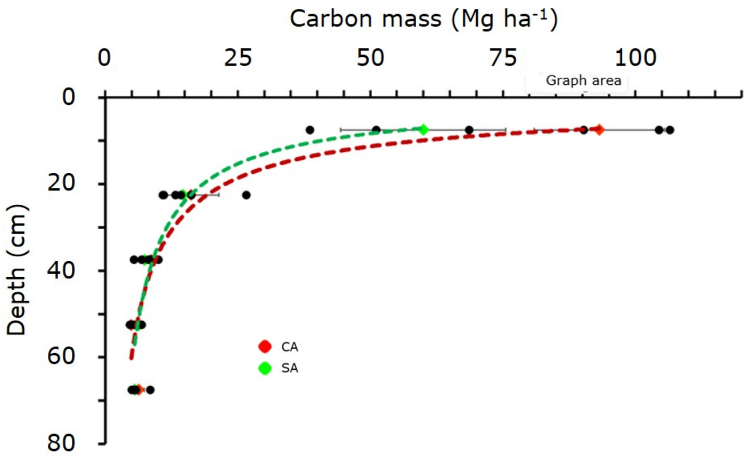
The CA sites showed a trend toward greater variability in *TOC* percentage, possibly also influenced by harvesting practices that impact the surface soil (Figure 3).



There were no statistically significant differences due to harvesting. The dotted lines are shown only to illustrate the trend.

Figure 3. Total organic carbon (*TOC*) in stands with (CA) and without (SA) timber harvesting.

Regarding carbon mass, SA stands showed a trend toward greater carbon mass in the surface soil. However, at depths greater than 40 cm, this trend disappears, and the carbon mass in stands with and without harvesting was similar (Figure 4). The estimated soil carbon mass at 80 cm depth was 129.1 and 93.9 Mg ha^{-1} for CA and SA stands, respectively.



There were no statistically significant differences due to harvesting. The dotted lines are shown only to illustrate the trend.

Figure 4. Carbon mass in stands with (CA) and without (SA) timber harvesting.

The carbon mass values in this study are lower than those reported by other authors for *Abies religiosa* forests, who obtained values of 163.09±53.8 Mg ha^{-1} of *TOC* in the first 30 cm deep (Cruz-Sánchez et al., 2021). Other studies have reported 153±41 Mg ha^{-1} of carbon for conserved stands and 95±47 Mg ha^{-1} for harvested stands (Pérez-Ramírez et al., 2013). The lower *TOC* recorded in this study is likely due to the recent formation of the soils in the area. Carbon accumulation is slower in sandy textures compared to finer textures (Binkley & Fisher, 2020).

Some studies indicate that forest harvesting decreases total soil carbon, but the most significant losses are observed in organic horizons (Mäkipää et al., 2023). Organic horizons were not evaluated in this study. Furthermore, it has been noted that the removal of forest vegetation does not significantly affect the amount of carbon in mineral soils (Zhang et al., 2018).

The carbon mass trends are contrary to expectations. The SA sites showed a trend toward higher carbon mass in topsoil (0-10 cm) (Figure 4). This result may reflect the spatial variation inherent in the soils of the studied forests; that is, the natural variation of the terrain is so high that a larger sample of stands is required. It is also possible that the method applied was not sufficiently effective in detecting the impacts of harvesting.

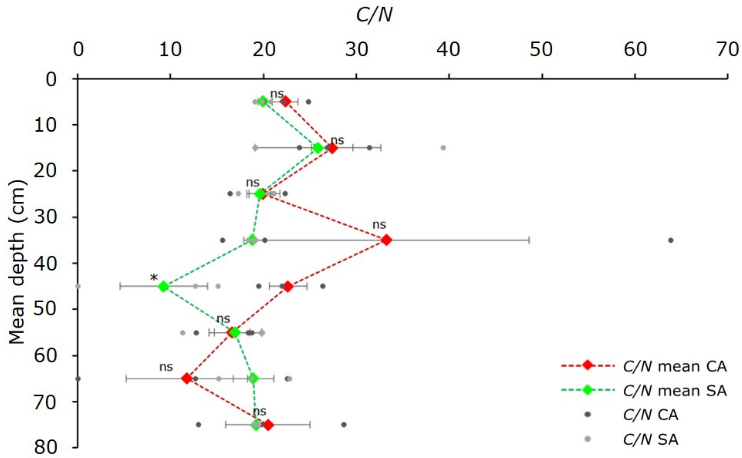
On the other hand, the effect of mixing organic and mineral horizons in stands subject to timber harvesting likely influenced the trend toward higher carbon in CA stands. Another factor is the low harvesting intensities, less than 35 %, used in forest management methods for irregular forests (Leyva-Pablo et al., 2021), as it happens in the study area.

Results also indicate that the three-year timeframe is not enough to demonstrate the effect of forest management on the quantity and quality of soil carbon, particularly when evaluating harvesting systems with low cutting intensities.

C/N Ratio

Except for the depth of 45 cm, no statistically significant differences were found between CA and SA stands with respect to the *C/N* ratio. In general, there is a trend toward a higher *C/N* ratio in CA stands.

Since the *C/N* ratio is an indicator of the ease of decomposition of organic matter, the results indicate the presence of more readily decomposable carbon at 45 cm in SA stands (Figure 5).



CA = Harvested stands; SA = Unharvested stands; ns = Indicates no significant differences (p>0.05) at the same depth; * = Indicates significant differences at the same depth.

Figure 5. Average *C/N* ratio at the study sites.

Most sites exhibit a *C/N* ratio of less than 30, indicating that the carbon in all stands is readily decomposed. Values below 30 are favorable for the decomposition of organic matter (Ostrowska & Porębska, 2015).

Soil Respiration

No statistically significant differences in respiration potential were found between CA and SA stands. Results only indicate a trend toward higher soil respiration potential in CA stands, which is similar to the findings of Moktan et al. (2025). Table 1 shows that CA stands reached values of up to 20.22 Mg CO_2 ha^{-1} yr^{-1}, while in SA stands the maximum values were 16.16 Mg CO_2 ha^{-1} yr^{-1}.

Table 1. Average respiration rate for the six study sites at a soil depth of 0 to 15 cm and according to their harvesting condition.

Stand condition	**Respiration Rate (Mg CO_2 ha^{-1} yr^{-1})**	***S. D.***	***S. E.***
CA	14.02	4.37	2.18
CA	13.03	3.2	1.6
CA	20.22	5.31	2.65
SA	16.16	6.46	3.23
SA	12.57	3.47	1.74
SA	12.84	1.81	0.91

CA = With timber harvesting; SA = Without timber harvesting; *S. D.* = Standard deviation; *S. E.* = Standard Error.

Some studies have documented that, for mixed fir and pine forests, soil respiration across the four seasons fluctuates between 9.08 and 29.51 g m^{-2} day^{-1}, with an annual average of 52.67 Mg CO_2 ha^{-1} $year^{-1}$ (Cruz-Sánchez et al., 2021). These figures are higher than the respiration rate estimated in the present study, given that in CA stands it was estimated at 15.76±5.17 Mg CO_2 ha^{-1} $year^{-1}$, while for SA stands it was estimated at 13.85±4.30 Mg CO_2 ha^{-1} $year^{-1}$. Converting these data to net carbon mass, they correspond to 4.29 Mg C ha^{-1} $year^{-1}$ in CA stands and 3.77 Mg C ha^{-1} $year^{-1}$ in SA stands.

When global estimates of surface soil respiration potential were made, based on calculations for net carbon mass, it was observed that for CA stands the carbon respiration potential was 4.6 % $\left(\frac{4.26}{93.18} \times 100\right)$, while for SA sites the potential rate was 6.3 % $\left(\frac{3.77}{59.97} \times 100\right)$. Although these values were determined in the laboratory, they were close to those estimated for temperate forests (Schlesinger & Bernhardt, 2020; Wang et al., 2006). It is noteworthy that the rate of respired carbon loss is higher in SA stands, but this is consistent with the *C/N* ratio trends, which indicate a greater ease of organic matter decomposition in the top 40 cm of soil (Figure 5).

Conclusions

The lack of significant effects after three years of logging suggests that selective forest management has not, to date, significantly impacted soil carbon stocks, their quality, or respiration potential. Therefore, it is difficult to estimate soil carbon gains in natural forests managed to maintain an irregular structure.

The greater soil carbon mass in harvested areas also reflects the spatial variability of this variable in the study area and not solely the effect of harvesting. However, the trend of greater variability in both bulk density and organic carbon content in the topsoil is consistent with the recent impact of harvesting.

The trend of higher respiration rates in stands without timber harvesting is consistent with the *C/N* trend observed in the soil profile, which could suggest more labile carbon in these sites.

Results highlight the importance of taking longer timeframes (10 years or more), as well as considering that the management of forests with low cutting intensity, combined with the natural variability of the soil, makes it difficult to definitively identify the effects of timber harvesting on carbon dynamics.

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Conflict of interest

The authors declare no conflict of interest.

Contribution by author

Ana Laura Martínez-Campos: establishment of fieldwork and laboratory work, data collection and writing of the first draft; Armando Gómez-Guerrero: planning of experiments, interpretation of results and writing of manuscript versions; Gregorio Ángeles-Pérez: advising and planning of fieldwork, interpretation of results and writing of the manuscript; Juliana Padilla-Cuevas: advising and conducting the laboratory experiment, analysis and review of laboratory results and writing of the manuscript.

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