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Sequence of Soil Organic Carbon through the Silvicultural Development Method (MDS) in temperate forests of Durango, Mexico

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The amount of stored organic carbon in the forest soil depends, among other factors, on the quantity of organic litter left after the application of the silvicultural treatments during the different stages of forest growth. Considering the above, the objective of this study was to evaluate the quantity of the soil organic carbon (SOC) stored at two soil depths (0-20 cm and 20-40 cm) as a response to the application of a liberation cutting, four thinning and a seed tree regeneration method applied to different stands, effects that were contrasted against a control 60-year old stand. The results indicate that SOC ranged from 60.0 to 115.6 Mg ha^{-1} for the 0-20 cm soil depth and from 39.5 to 76.5 Mg ha^{-1} to the 20-40 cm soil depth. All the stands stored more SOC than the control, which registered an average accumulated reserve of 99.5 Mg ha^{-1}. The liberation cutting presented the highest reservoir with 192.1 Mg ha^{-1}. Changes in the vegetation cover caused by the cut intensities applied directly influence SOC reserves. In general, the Cambisol soils are good SOC reservoirs where the MDS was applied.

Keywords: Environmental services, cutting intensity, vegetation cover, edaphic system, carbon sequestration.

1. Introduction

Soil organic carbon (SOC) is a key factor in the sustained function of forest ecosystems. It maintains or improves soil health; therefore, forest production. By storing up to 1500 Pg of organic carbon in the soil (doubles and triples what is stored in the atmosphere and terrestrial vegetation, respectively) (Veni et al., 2020, Wang et al., 2021), it becomes a potential contributor in climate change mitigation, considered one of the most important global problems affecting humanity (ElGhamry et al., 2024). However, depending on land use and management it can also become a source of carbon emissions (Shivangi et al., 2024). In particular, temperate forest soils to store on average 120 t C per hectare, making them an important sink (Pan et al., 2011; Luna et al., 2022). Therefore, it is necessary to implement good management practices over time that allow you to increase and/or conserve your carbon reserves significantly (Elbasiouny et al., 2019).

Organic carbon stocks are determined by the decomposition rates of the accumulated organic material which is deposited over the soil after the application of the silvicultural treatments. The quantity of the deposited organic debris depends on the type and intensity of the applied silvicultural treatment to the forest mass. The intensity of the applied silvicultural treatments modifies environmental conditions, affecting local temperature, humidity and soil pH (Aryal et al., 2013; Liu et al., 2016; Jandl et al., 2021).

From the practical point of view, regeneration methods and intermediate treatments are silvicultural strategies widely used in forest management to promote species regeneration and enhance tree growth, respectively. The size of the free spaces must be large enough to promote light, water and nutrient that guarantee the establishment of the new plants and maximize vegetation growth during its growing period (Chase et al., 2016). During the last decade, it has been reported that the modification of the canopy structure has had a direct impact on the soil properties, including the capacity of the carbon reservoir (Zhang et al., 2016; Kurniawan et al., 2018; Luna et al., 2022). Huang et al. (2011), Picchio et al. (2012) and Luna et al. (2021) pointed out that the forest management system (continuous and non-continuous forest systems), the intensity of the applied sylvicultural

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treatment and the harvesting activities directly influence the degree of soil alteration.

Since the beginning of forest management in Durango state, dated approximately from the beginning of the twentieth century (Vargas, 2006), different management methods have been implemented to temperate forest. Between them, the Irregular Forest Management Mexican Method (MMOBI) and Silvicultural Development Method (MDS) are the most widely used (Pérez et al., 2013). Specifically, the MDS, whose objective is to get regular stands maximizing the wood productive potential of the site, contemplates the classification of the forest stands by age classes. The treatments applied (regeneration, liberation first, second, third and four thinning) are related to each each age class. (López et al., 2017; Torres et al., 2018; Pérez et al., 2020).

Although the relationship between forest management and the carbon cycle has been widely evaluated in forest ecosystems, most studies focus on analyzing the effects on the carbon sequestration capacity of biomass, despite the importance and capacity of the soil to capture carbon, contributing to the mitigation of climate change. Based on the above, the objective of this study was to evaluate the relationship between the capacity of the soil organic carbon reservoir and different residual stand densities left after the application of the silvicultural practices considered by the Silvicultural Development Method (MDS) in a Cambisol soil.

2. Materials and methods

2.1. Location of study

The study area is located in the Ejido El Brillante belonging to the municipality of Pueblo Nuevo in Durango, Mexico, within the Sierra Madre Occidental. The main vegetation is composed of Pinus and Quercus species (González et al., 2012). The average altitude is 2580 m and the dominant soil is Cambisol. This type of soil is characterized by being a young little developed soil. The B horizon, in formation from the parent material, consists of sandstones, alluviums, limestones and conglomerates. The precipitation and temperature range of 800-2000 mm and 8-26° C, respectively. (INEGI, 2010) (Fig. 1).

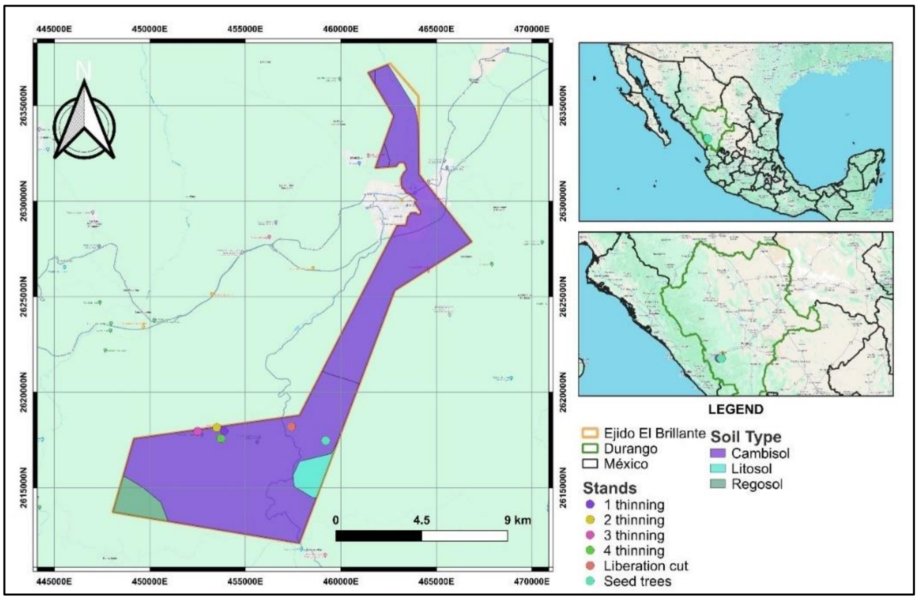

Fig. 1. Location of study.

2.2. Description of the stands evaluated

Seven stands of different ages each one, but with similar species composition and same type of soil, climate and site quality condition, were selected to represent the different forest growth stages developed during the rotation period by each stand (Walker et al., 2010; Pérez et al., 2020). According to the MDS, which is a sylvicultural method applied in México, each stand must receive a silvicultural treatment every ten years during a 60 year rotation period in the following sequence: a) at the end of the rotation age, the regeneration seed tree method, b) after the seedling establishment, a liberation treatment and c) during a 40 year growing period, four sequential thinning called first, second, third and fourth thinning. Every one of six stands received one of the treatments above described to simulate the treatments chrono sequence that must receive every stand during its entire life. One of the stand, close to the rotation age and without treatments, was selected as a control.

2.3. Sampling

In each one of the seven stands, four sites were randomly selected to collect in each site four soil subsamples that were mixed to generate composited samples of approximately 1 kg at two depths, 0-20 cm and 20-40 cm depth, respectively. Before to collect de mineral soil, the leaf litter and humus present over the superficial mineral soil was removed to expose it; then, the mineral soil was removed at each one of the depths mentioned and mixed to homogenize it in order to create composite samples. The soil samples were put in labelled plastic bags to be brought to the laboratory. In the laboratory, the soil samples, before to be stored for further analysis, were dried at room temperature and passed over a 2 mm sieve to classify the soil by particle size (Luna et al., 2021).

2.4. Estimation of organic matter and organic carbon

The organic matter content of the soil samples was determined by the Walkley and Black method. Through this method, the soil samples are digested with sulfuric acid (H_2SO_4) and oxidized with a standardized solution of potassium dichromate ($K_2Cr_2O_7$). The carbon percentage was determined using the Van Bemmelen factor, which assumes that 58% of organic matter is composed of carbon (Woerner, 1989; Cantú and Yáñez, 2018).

2.5. SOC reservoir (Mg ha^{-1})

The estimation of SOC (Mg ha^{-1}) was estimated with the equation described by González et al. (2008):

$$SOC = \%C * BD * \text{D}$$

Where:

SOC = Soil Organic Carbon expressed in Mg ha^{-1}

$\%C$ = Percentage of carbon

BD = Bulk density (g cm^{-3})

D = Sampling depth (cm)

The bulk density of the soil (g cm^{-3}) was determined with the cylinder method, using four undisturbed soil samples for each depth in each evaluated stand (Woerner, 1989):

$$BD = \frac{p2 - p1}{vc}$$

Where:

BD = Bulk density (g cm^{-3})

$p2$= dry weight of the sample with the cylinder (g)

$p1$= weight of the cylinder (g)

vc= Cylinder volume (cm^3)

Finally, the accumulated reservoir of SOC (Mg ha^{-1}) in the 0-40 profile of each of the stands was obtained from the sum of both depths.

2.6.Statistical analysis

Before to realize the statistical analysis, the SOC variable data were tested with Kolmogorov-Smirnov and Levene methods to prove if they met with the normality and homoscedasticity assumptions, respectively. The results of the tests indicated that neither the 0-20 cm nor the 20-40 cm depth data met both assumptions, deciding to apply the non-parametric Kruskal-Wallis test to detect differences between silvicultural treatments at 0.05 significance level. In contrast, the data of the accumulated SOC reservoir variable presented a normal distribution and a homogeneous variance; therefore, one-factor ANOVA was used to detect differences between stands at 0.05 significance level. The multiple comparisons Tukey test (0.05) was applied to test for mean differences in accumulated SOC reservoir between treatments. Data was analysed with the SPSS statistical software version 2.2 (International Business Machines [IBM], 2013).

3. Results

3.1. Percent of soil organic matter, percent of carbon content and soil bulk density

The lowest and highest percentages of soil organic matter occurred in the control stand and in the one that received the liberation of the regeneration from the seed trees cut at the two depths studied, respectively. The percentages of soil organic matter at 0-20 cm soil depth were similar in the stand that received the first, second and third thinning, but it increased abruptly in the stand that was treated with the fourth thinning. The stand where the regeneration seed tree method was applied presented a little more soil organic matter than those that were treated with the first, second and third thinning, but lesser than those reported in the fourth thinning and liberation stands. The stand where the liberation cut was applied presented almost the twice of soil organic matter percent than the stand treated with the first, second and third thinning. Also, it was observed that the amount of organic matter was higher at the 0-20 cm soil depth than in the 20-40 cm soil depth (Table 1). According to the Mexican Official Norm NOM-021-RECNAT-2000 for soil analysis (SEMARNAT, 2002) the values of organic matter determined can be classified as very high.

The percent of soil organic carbon in the 20-40 soil depth was lesser than that reported for the 0-20 cm soil depth in all the treated and control stands. The ratio of the percentages of soil organic content of the 20-40 cm soil depth in relation to the 0-20 cm soil depth also was different in each one of the stand evaluated, ranging from 3.03 to 8.97 %. The lowest change proportion of the percentage of soil organic matter occurred in the seed tree stand (ratio = 99%)

and the highest in the control (ratio = 65.1%) and liberation cut stands (ratio = 65.7%). In relation to percent carbon content, it ranges from 3.47 to 6.67 in the 0-20 cm soil depth and from 2.28 to 5.2 in the 20-40 cm soil depth (Table 1).

Table 1. Mean values of Soil organic matter (SOM) and C content for stands and depths (n=4).

Stands	Soil organic matter (%)		C (%)		Bulk density (g cm^{-3})	
	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm
Control	5.98	3.93	3.47	2.28	0.865	0.865
1st thinning	6.45	4.92	3.74	2.85	0.860	1.014
2nd thinning	6.55	5.49	3.8	3.19	0.953	1.093
3rd thinning	6.48	5.64	3.76	3.27	0.855	0.854
4th thinning	11.48	8.97	6.67	5.2	0.689	0.669
Seed trees	7.76	7.69	4.5	4.46	0.697	0.808
Liberation cut	12.06	7.86	6.99	4.56	0.838	0.833

Although bulk density of the soil varied between stands treatments, this remains quite similar between both soil depths in almost all the stands. The highest difference between both depths was observed in the first thinning (0.154 g cm^{-3}) and seed tree stands (0.116 g cm^{-3}). The bulk density varied from 0.697 to 0.953 g cm^{-3} in the soil depth of 0-20 cm and from 0.669 to 1.093 g cm^{-3} in the soil depth of 20-40 cm. According to Woerner (1989), the bulk density of the soil (<1.20 g cm^{-3}) is classified as very low at both depths.

3.2. SOC reservoir (Mg ha^{-1})

The non-parametric ANOVA of Kruskal Wallis indicated that there are differences in SOC between the stand treatments at both studied depths ($p<0.05$) (Table 2).

The SOC ranged from 60.0 to 115.6 Mg ha^{-1} for the 0-20 cm soil depth, and from 39.5 to 76.5 Mg ha^{-1} in the 20-40 cm range. In particular, the control stand presented the lowest SOC values, in contrast to the liberation stand that showed the highest SOC values at both depths. Considering that the control stand does not provide as much organic materials to the soil as it does the treated stands, it can be inferred that the implementation of the different silvicultural practices leads to an increase in soil carbon stocks in the two depth ranges (Table 3). The ratio of soil organic carbon stored at the upper soil depth in relation to the stored in the lowest soil depth was different between treatment stand. The lowest SOC reservoir was estimated in the control stand; meanwhile, the highest SOC reservoir occurred in the liberation stand.

Table 2. Kruskal Wallis Test Statistics by Depth.

Depth	Statistics	Soil Organic Carbon
0-20 cm	Chi squared	13.448
	Degree of freedom	6
	p value	0.036
20-40 cm	Chi squared	13.947
	degree of freedom	6
	p value	0.030

Table 3. SOC reservoir by soil depth.

Stands	SOC reservoir (Mg ha^{-1})	
	0-20 cm	20-40 cm
Control	60.0	39.5
1st thinning	63.3	57.6
2nd thinning	71.4	69.0
3rd thinning	62.8	55.6
4th thinning	91.4	69.3
Seed trees	65.6	64.4
Liberation cut	115.6	76.5

According to the analysis of variance, the SOC accumulated in the entire profile (0-40 cm) was highly different between stands (p<0.0001). The multiple mean comparison test of Tukey indicated that the SOC content of the control stand, although has the lowest SOC, was only statistically different to the liberation and 4 thinning stands. In this case, the 1, 2 and 3 thinning and seed tree stands had similar SOC. The liberation cut stand, with the highest SOC, was the only reservoir different to all the treatments (Fig. 2).

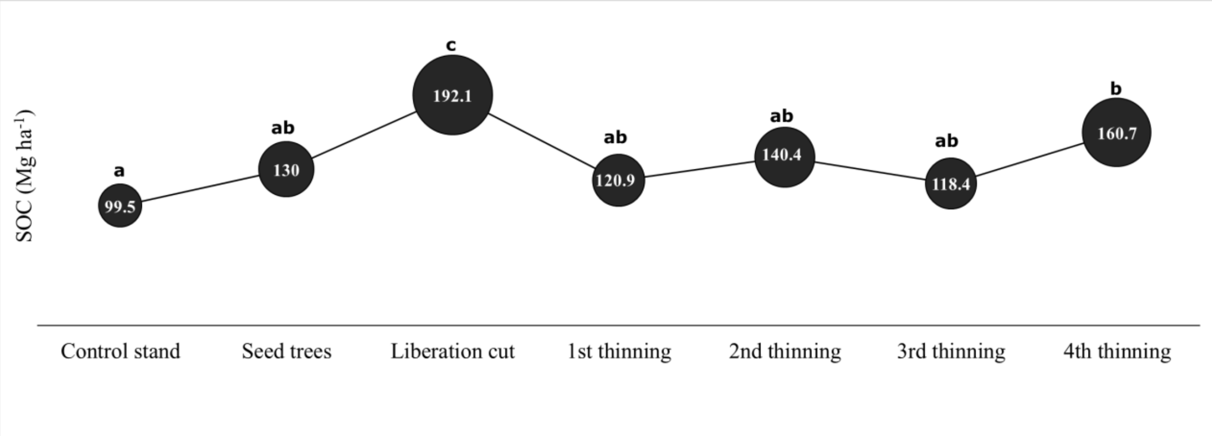

Fig. 2. Successional sequence through the Silvicultural Development Method. Different letters indicate significant differences (P ≤ 0.05).

4. Discussion

Considering that the averages of SOC stored in the Mexican and Durango state soils are 56 and 48 Mg ha^{-1}, respectively (Segura et al., 2005; Vela et al., 2012), it can be inferred that the Cambisol soil evaluated has a high carbon storage capacity. In this study, the average SOC content at 0-40 cm soil depth was 137.48 Mg ha^{-1}. Due to that the Cambisol soil is very predominant in the Sierra Madre Occidental, it takes great importance as a SOC reservoir in that area.

Likewise, the results of the present study are similar to the values reported by Morales et al. (2020), Luna et al., (2022) and Vargas et al. (2023), who determined average SOC reservoirs of 187.06, 144.89 and 170.67 Mg ha^{-1} in forests surrounding the study area, respectively. It should be noted that information on SOC storage in temperate forests is mainly dominated by the assessment of storage in biomass (Galicia et al., 2016). In this sense, Pimienta de la Torre et al. (2007), reported that the average of carbon sequestered by the aerial biomass of the forests of the region of El Salto, Durango is equal to 51.12 Mg ha^{-1}, one third of the amount of SOC reported in this study. The highest SOC stored in the Cambisol emphasizes the importance of this type of soil in the face of climate change.

According to Saynes et al. (2012) and Leyva et al. (2021), the quantity of SOC stored in the soil is influenced by the continuous accumulation of organic material in the soil. The periodic application of the forest management treatments through the MDS has the properties of providing organic materials in the form of cones, leaves, branches, bole parts and roots. Also, the application of the silvicultural treatments entails modifications on the stand density, causing changes in the microclimatic conditions and the activities of the microorganisms of the soil, modifying the mineralization rate of the SOC (Noormets et al., 2012).

Also, according to Albaneci et al. (2003), the amount of organic carbon in the soil depends, in addition to the topographic position and site quality, on anthropogenic activities such as forest harvesting, forest fires and clearing. Selig et al. (2008), Noormets et al. (2012) and Luna et al. (2022) point out that the increase in SOC after logging may be an effect of the accumulation of forest harvesting residues, such as roots that are incorporated as organic matter in the soil, thus contributing to an increase in SOC storage.

Although the stand where the seed tree treatment was applied had an increase of 37% compared to the control stand (99 Mg ha^{-1}), its SOC reservoir was lower than the release cut, which may be related to the intensity of cut applied to seed trees (80%) which usually causes damage to the residual trees. Litter and soil layer derived from felling, dragging and stacking activities (Nájera et al., 2012; Tavankar et al., 2015).

In agreement with Woerner's (1989), whom considered that a bulk density of 1.2 g cm^{-3} is low, the bulk density reported in the present study might be classified as very low. The low bulk density reported in the present study is attributed to the incorporation and decomposition of the organic matter on the soil after the application of the treatments. The soil organic matter softness the soil and reduce soil compactness. According to Ruehlmann and Körchens (2009), the soil organic matter and the SOC concentration is a dominant factor in the change of soil bulk density.

5. Conclusion

In spite of the MDS favors the reservoirs of SOC in the Cambisol soil, it was different between treatments as a response of the changes of the organic matter deposited in the soil that comes from the cutted trees.

The storage of SOC at the depth of 0–20 cm presented the following decreasing order in the stands: Liberation cut > 2nd thinning > 4th thinning >Seed trees> 3rd thinning >1st thinning > control stand. While, at the depth of 20–40 cm the SOC showed the following trend: Liberation cut > 4th thinning > 2nd thinning >Seed trees> 1st thinning > 3rd thinning > control stand.

Considering the analyzed profile of 0-40 cm, the maximum SOC was registered at the end of the release cutting. The Cambisol soil has on average a carbon sequestration capacity of 137.48 Mg ha^{-1}.

List of abbreviations:

C (%): Carbon content

SOC: Soil Organic Carbon

MDS: Silvicultural Development Method

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

Competing interests: The authors declare that they have no conflict of interest.

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Authors' contributions: EOLR responsible for research idea, designing the experiment, and writing the manuscript. ICS Support in experiment design and overall coordination: ICS. FJH Support in data analysis: FJH. SBJP and TGDG general revisions and corrections. All authors read and agree for submission of manuscript to the journal.

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