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Research article

Diferencias en la fertilidad del suelo en cuatro plantaciones forestales comerciales de pino en Amanalco, Estado de México

Differences in soil fertility in four commercial pine forest plantations in *Amanalco*, State of Mexico

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Abstract

In the *Amanalco-Valle de Bravo* basin, Mexico, most plantations are established on plots with an agricultural past and histories of soil management, which determined different initial situations of nutrient supply for the trees. The aim of the present study was to evaluate the fertility and organic carbon storage in the soil of four commercial pine forest plantations: (1) *Rincón de Guadalupe* (*Pinus ayacahuite*), (2) *Loma del Rincón de Guadalupe* (*Pinus pseudostrobus*), (3) *San Miguel Tenextepec* (*Pinus patula*) and (4) *El Potrero* (*Pinus patula*). In September 2022, soil sampling was carried out and the following variables were analyzed: pH, OM, SOC, N and P. The pH of the soil, in the *Loma del Rincón de Guadalupe* plantation, was neutral and in the others, moderately acidic. The plantations showed a low level of OM, except in *El Potrero* where a medium level was observed. The N concentration was higher in the plantations of *El Potrero* and *Loma del Rincón de Guadalupe* and lower in *San Miguel Tenextepec* and *Rincón de Guadalupe*. The P content was the following: *El Potrero* (11.9 %), *Loma del Rincón de Guadalupe* (8.2 %), *San Miguel Tenextepec* (1.4 %) and *Rincón de Guadalupe* (0.3 %). The SOC storage was highest in *El Potrero* plantation, followed by *San Miguel Tenextepec*, *Loma del Rincón de Guadalupe* and *Rincón de Guadalupe.* In conclusion, the forest plantations analyzed presented differences in soil fertility and C storage.

Key words: Chemical analysis of soil, soil quality, soil organic carbon, nutritional diagnosis, forest plantations, forest soils.

Resumen

En la cuenca Amanalco-Valle de Bravo, México, la mayoría de las plantaciones se establecen en parcelas con pasado agrícola e historias de manejo del suelo que determinaron diferentes situaciones iniciales de suministro de nutrientes para los árboles. El objetivo del presente estudio fue evaluar la fertilidad y almacenamiento de carbono orgánico en el suelo de cuatro plantaciones forestales comerciales de pino: (1) Rincón de Guadalupe

(*Pinus ayacahuite*), (2) Loma del Rincón de Guadalupe (*Pinus pseudostrobus*), (3) San Miguel Tenextepec (*Pinus patula*) y (4) El Potrero (*Pinus patula*). En septiembre de 2022 se realizó un muestreo de suelo y se analizaron las siguientes variables: pH, MO, COS, N y P. El pH del suelo, en la plantación de Loma del Rincón de Guadalupe fue neutro y en las otras, moderadamente ácido. Las plantaciones mostraron un nivel bajo de *MO*, excepto en El Potrero donde se observó un nivel medio. La concentración de N fue mayor en las plantaciones de El Potrero y Loma del Rincón de Guadalupe y menor en San Miguel Tenextepec y Rincón de Guadalupe. El contenido de P fue el siguiente: El Potrero (11.9 %), Loma del Rincón de Guadalupe (8.2 %), San Miguel Tenextepec (1.4 %) y Rincón de Guadalupe (0.3 %). El almacenamiento de COS fue mayor en la plantación de El Potrero, seguido de San Miguel Tenextepec, Loma del Rincón de Guadalupe y Rincón de Guadalupe. Se concluye que las plantaciones forestales analizadas presentaron diferencias en la fertilidad y almacenamiento de C del suelo.

Palabras clave: Análisis químico de suelo, calidad del suelo, carbono orgánico del suelo, diagnóstico nutrimental, plantaciones forestales, suelos forestales.

Introduction

Commercial forest plantations are defined as those established on lands with previous agricultural use or that have lost their natural forest vegetation (Conafor, 2017). These productive systems provide goods and services (Zhang and Stanturf, 2008) such as wood, non-timber products, clean water and air, soil erosion control, biodiversity, aesthetics, carbon sequestration and climate control. For the establishment and management of the plantations, site preparation, planting, replanting, weed control, fertilization, pest control, pruning, fire prevention and harvesting activities are carried out (García *et al.*, 2011).

The establishment and subsequent development of vegetation in a forest plantation is influenced by the conditions of the environment and, in particular, by those of the soil. In this sense, soil fertility is one of the components of site quality. Fertile soil provides essential chemical elements in the quantities and proportions necessary for tree growth (McGrath *et al.*, 2014). Many forest plantations are established on abandoned agricultural plots. In this case, it is possible that previous management causes the enrichment of soil fertility linked to its past use, which may result in an increase in forest productivity compared to natural soil fertility. However, it is possible that the production of successive forest generations will decrease because the supply of nutrients to the trees will return the soil to its original fertility level (Ranger, 2018).

The determination of the composition and properties of the soil, such as pH, texture, electrical conductivity and organic matter, provides basic information to know the productive potential of the soil, since such properties define the physicochemical processes related to the availability of nutrients (Azcón-Bieto and Talón, 2008). The mineral and organic particles of the solid phase of the soil function as reservoirs of K, P, Ca, Mg and Fe, and the organic components contain N, P and S (Taiz *et al.*, 2015), which after being mineralized can be acquired by plants.

The interaction of numerous physical, chemical and biological properties of the soil control the availability of nutrients for plants and the concentration of N, S, P and some micronutrients is related to soil microbial activity (Havlin *et al.*, 2014). Soil organic matter (*SOM*) performs physical functions, including improving aggregation, aeration and water movement, and reducing evaporation and thermal conductivity; as well as chemicals, such as improving ionic exchange, buffering, pedochemical weathering, chelation and translocation of substances within the soil (Osman, 2013). *SOM* plays a critical role in the global carbon budget, which largely controls global climate change (Weil and Brady, 2017). SOM decomposes continuously and forms humus, a compound that contributes to increasing the quality of the soil. However, poor human management interrupts the cycle of return of plant or animal waste to the soil, altering (or reducing) the beneficial effects (Franzmeier *et al.*, 2016). Organic carbon, which depends on SOM, is the largest store of C on earth (Doetterl *et al.*, 2016) next to the soil inorganic C reserve (Lal, 2016).

The objective of the present study was to evaluate soil fertility and estimate the amount of organic carbon stored in the soil of four commercial forest plantations (CFP) established within the *Amanalco-Valle de Bravo* basin, State of Mexico. Previous studies on the state of soil fertility in forest plantations are scarce in the region and there are no known antecedents in key variables such as pH, OM, C, N and P. Additionally, there is no information in the literature about the storage of soil organic carbon (SOC) of commercial forest plantations, within the basin, which allows valuing the environmental services provided by these productive systems. The hypothesis that was raised was that C storage and fertility in the soil differs between plantations due to the history of land use and the characteristics of each plantation (age, species and management).

Materials and Methods

Study area

The work was carried out in the *Amanalco-Valle de Bravo* hydrological subbasin (392760 E and 2129224 N, Zone 14), South of the State of Mexico and covering a total area of 77 000 ha (Bonfil and Madrid, 2006). The prevailing climate is subhumid temperate, with an average annual temperature of 18.8 °C and precipitation of 1 000 mm per year (Inegi, 2020a). The soil is Andosol type (Inegi, 2020b) derived from volcanic ash (Meza-Pérez and Geissert-Kientz, 2006). In the fine fraction, amorphous materials of the allophane and ferrihydrite type dominate, which have a high phosphate retention capacity (Alcalá de Jesús *et al.*, 2009). The experimental plantations are located in four communities of *Amanalco* (Figure 1), in the following UTM coordinates Zone 14 N: (1) *Rincón de Guadalupe* (395569 E and 2130744 N), (2) *Loma del Rincón de Guadalupe* (395670 E and 2132770 N), (3) *San Miguel Tenextepec* (389992 E and 2133174 N) and (4) *El Potrero* (395422 E and 2135813 N). The average altitude in the area is 2 609 m.

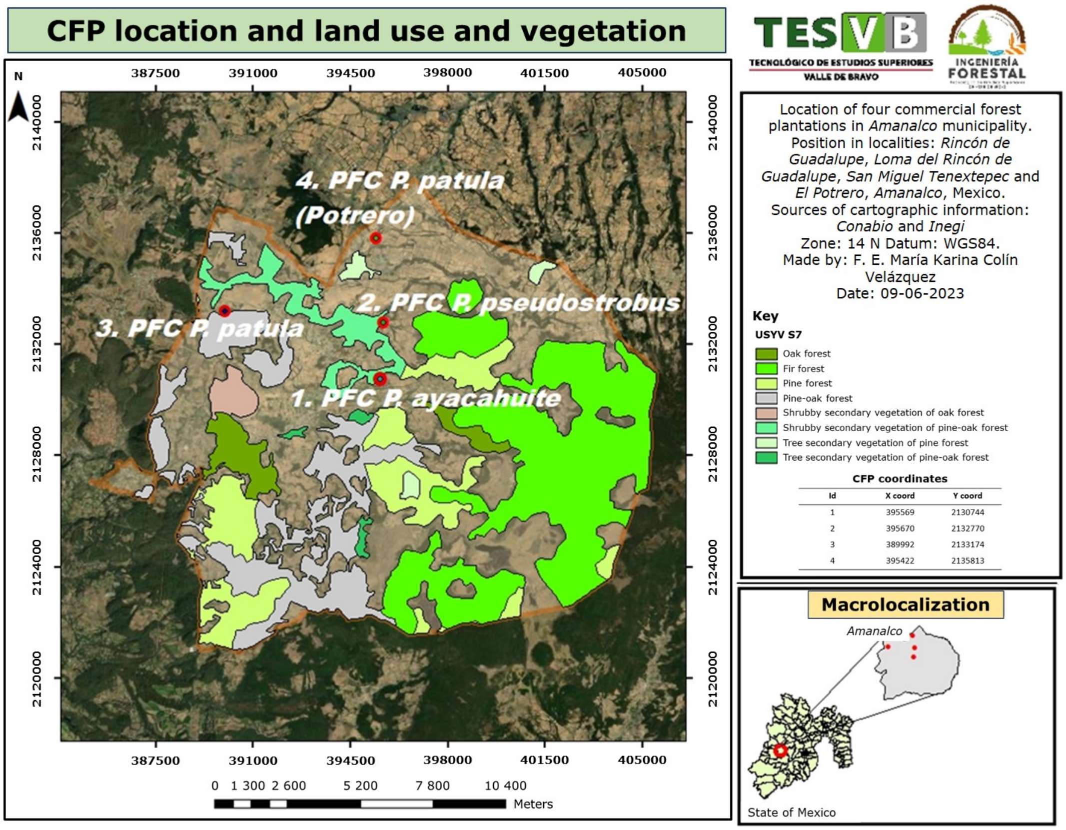

Figure 1. Location of commercial forest plantations in the *Amanalco-Valle de Bravo* basin, State of Mexico.

Commercial forest plantations

Four commercial forest plantations of different ages were studied (Table 1).

Table 1. General characteristics of four plantations of pine species evaluated in the *Amanalco-Valle de Bravo* basin, State of Mexico.

Locality	Species	Age (years)	Density in 2022 (trees ha^{-1})	Area (ha^{-1})	Manegement before the plantation
Rincón de Guadalupe	*P. ayacahuite* C. Ehrenb. *ex* Schltdl.	20	719	1	Corn cultivation with application of diammonium phosphate fertilizer
Loma del Rincón de Guadalupe	*P. pseudostrobus* Lindl.	8	980	4.2	Cultivation of beans and corn and application of sheep manure compost
San Miguel Tenextepec	*P. patula* Schltdl. & Cham.	19	625	0.5	Forest land use
El Potrero	*P. patula* Schltdl. & Cham.	6	1 000	1	Cultivation of corn and oats with application of urea and sheep bovine manure compost

Characterization of trees

In each plantation, 10 circular sites of 250 m^2 were randomly established and, in each one, the characteristics of the trees present were measured, based on the methods reported by West (2015). The normal diameter (cm), with a Mantax Blue Haglöf® caliper and the height, with a Vertex Laser Geo Haglöf® hypsometer.

Soil sampling

To characterize fertility, soil sampling was carried out in September 2022. In each plantation, 10 samples were extracted at a depth of 0 to 30 cm, in the same places where the trees were measured, with a stainless steel auger (model HA 6510 SPECTRUM®) of 2 cm in diameter (Acosta-Mireles *et al.*, 2009). The simple samples from each plantation were mixed to form a composite sample, which was placed in plastic bags and transported to the Soil Fertility and Environmental Chemistry Laboratory of the Postgraduate Studies College, *Montecillo* Campus, for analysis. The soil was dried in the shade, at room temperature and subsequently ground in a porcelain mortar until passing the 2 mm sieve. Finally, they were stored in paper envelopes until the time of chemical analysis.

Soil chemical analysis

pH was measured in a water-soil suspension, ratio 2:1 (Weil and Brady, 2017), with a model GroLine Combo Hanna® portable potentiometer. SOM and SOC were quantified with the Walkley-Black method (Sleutel *et al.*, 2007). N was determined with the semimicro-Kjeldahl technique (Saéz-Plaza *et al.*, 2013) and P with the method of Olsen *et al.* (1954).

Bulk density of the 0 to 30 cm soil depth was determined by relating the mass of the dry soil (dried in an 18 L ICB® oven, at 105 °C for 24 hours) and the volume of the auger with which the sample was extracted (Osman, 2013). The average value of bulk density was 1.1 Mg m^{-3}. This information was used to calculate soil C storage.

The results of the previously described determinations were compared with the reference values of NOM-021-RECNAT-2000 (Semarnat, 2002) and data from the scientific literature (Binkley and Fisher, 2013; Osman, 2013; Havlin *et al.*, 2014; Weil and Brady, 2017; Porta *et al.*, 2019).

Soil carbon storage was calculated with the following formula (Acosta-Mireles *et al.*, 2009):

$$Carbon\ (Mg\ ha^{-1}) = A \times PS \times DA \times COS$$

Where:

A = Land area (10 000 m^2)

PS = Sampling depth (0.3 m)

DA = Soil bulk density (1.1 Mg m^{-3})

SOC = Organic Carbon concentration in the soil $\left(\frac{Mg\ of\ C}{100\ Mg\ of\ soil}\right)$

Statistical analysis

To identify differences between the plantations, the diameter and height data of the trees were subjected to an analysis of variance, which is a method of testing the equality of three or more population means, through the analysis of sample variances (Triola, 2018) and means comparison tests with the Tukey method ($p \leq 0.05$), using the SAS version 9.4® statistical program (SAS, 2013). The soil chemical fertility data were not analyzed statistically because only one value was obtained from the compound sample of forest plantations.

Results and Discussion

The diameter and height of the trees showed differences depending on the species and the age of the plantation (Table 2). *Pinus ayacahuite* C. Ehrenb. *ex* Schltdl. (*Rincón de Guadalupe*) and *Pinus patula* Schltdl. & Cham. (*San Miguel Tenextepec*) recorded the highest values in diameter and height, due to being older (Table 1); however, the latter were 5.7 m taller than *P. ayacahuite* trees. Individuals of *P. patula* (*El Potrero*) were more than 70 cm taller than those of *Pinus pseudostrobus* Lindl. (*Loma del Rincón de Guadalupe*), despite being, the former, younger. This behavior is common in these species (Romo *et al.*, 2014; González *et al.*, 2016).

Table 2. Characteristics of the trees of the four forest plantations in the *Amanalco-Valle de Bravo* basin, State of Mexico.

Locality	Species	Diameter (cm)	Height (m)
Rincón de Guadalupe	*P. ayacahuite* C. Ehrenb. *ex* Schltdl.	18.6±2.8 a	15.9±1.6 b
Loma del Rincón de Guadalupe	*P. pseudostrobus* Lindl.	9.1±2.3 b	5.4±2.3 d
San Miguel Tenextepec	*P. patula* Schltdl. & Cham.	19.0±3.6 a	21.6±1.4 a
El Potrero	*P. patula* Schltdl. &	8.3±3.3 b	6.1±2.4 c

Cham.

Means with the same letter in each column are statistically equal Tukey ($p \leq 0.05$).

Soil chemical variables

The results of the soil fertility variables are shown in Table 3.

Table 3. Soil chemical analysis of the four forest plantations in the *Amanalco-Valle de Bravo* basin, State of Mexico.

Locality	Species	pH	N (%)	P (mg kg^{-1})	*OM* (%)	*SOC* (%)
Rincón de Guadalupe	*P. ayacahuite* C. Ehrenb. *ex* Schltdl.	6.3	0.01	0.3	4.5	2.6
Loma del Rincón de Guadalupe	*P. pseudostrobus* Lindl.	6.7	0.21	8.2	5.1	3.0
San Miguel Tenextepec	*P. patula* Schltdl. & Cham.	6.2	0.04	1.4	6.0	3.5
El Potrero	*P. patula* Schltdl. & Cham.	6.3	0.30	11.9	6.2	3.6

pH

The soil pH was in the range of 6.2 to 6.7. The data agree with studies carried out in the region in which the soil pH of a temperate forest was 6.2 (Prado *et al.*, 2007) and in an avocado plantation (*Persea americana* Mill.) it was 6.4 (García-Martinez *et al.*, 2021). This variable mainly affects the availability of nutrients for plants. According to the NOM-021-RECNAT-2000 classification (Semarnat, 2002), the pH of the soil in the *Loma del Rincón de Guadalupe* plantation was neutral and in the rest of the plantations it was moderately acid. In general, forest soils have pH values from extremely acid (pH 4.0) to slightly acid (pH 6.5) (Barnes *et al.*, 1998). Elements in soil are available in a pH range of 5.5-6.5 (Porta *et al.*, 2019). Therefore, the results obtained in this research indicate that there are no restrictions for the absorption of macro and micronutrients in the plantations of *Rincón de Guadalupe*, *San Miguel Tenextepec* and *El Potrero*. However, in the *Loma del Rincón de Guadalupe* plantation there may be limitations in the availability of micronutrients, but it is necessary to carry out nutritional diagnostic studies on the trees to confirm this.

Organic Matter and Organic Carbon

The soil of the *El Potrero* plantation presented a medium concentration of OM. This plot was previously used for growing corn and oats with application of manure compost (sheep and cattle) and urea. The low *OM* content in the *Rincón de Guadalupe* and *Lomas del Rincón de Guadalupe* plantations is related to the previous cultivation of corn with the application of mineral fertilizers and the sowing of broad beans and corn with the application of bovine manure compost, respectively. The *San Miguel Tenextepec* property has always had forest use, which means that the OM content has not experienced important changes. In general, the OM content in agricultural soils is approximately 2 %, while in forests values reach up to 5 % (Osman, 2013). OM comes from the deposition of aerial plant biomass or roots and is the substrate needed for the growth and maintenance of soil microbial populations (Barnes *et al.*, 1998).

The percentage of SOC in the experimental sites, ordered from highest to lowest, was as follows: *El Potrero* (3.6 %), *San Miguel Tenextepec* (3.5 %), *Loma del Rincón de Guadalupe* (3.0 %) and *Rincón de Guadalupe* (2.6 %). These values are lower than those recorded by Acosta-Mireles *et al.* (2009) in mixed forests of *Pinus patula* and *Abies religiosa* (Kunth) Schltdl. & Cham. in the state of *Tlaxcala*, Mexico, where SOC concentrations are located at 7.92 % in the 0-20 cm profile and 5.28 % from 20 to 40 cm depth. Prado *et al.* (2007) referred a decrease in *SOC* from 5.5 % in the 0-10 cm profile to 1.3 % in the 15-37 cm layer. Additionally, after Histosols, Andosols accumulate the highest concentrations of C, which is why they have a high potential to sequester C (Galicia *et al.*, 2016) and soil fertility is generally given as a function of *SOC* content (Szalai *et al.,* 2016).

N

N is the mineral nutrient that plants require in the greatest quantity, so, in soils deficient in this element, trees do not develop properly (Taiz *et al.*, 2015). The Kjeldalh-N range in the soils of the experimental plots was from 0.01 to 0.30 %. According to Havlin *et al.* (2014), total N content in mineral soils varies from 0.02 to 0.5 % and is positively correlated with the *OM* content and negatively with depth. In the *Loma del Rincón de Guadalupe* and *El Potrero* plantations, the highest percentage of N was due to the producer applying nitrogen fertilizers in the two years prior to the evaluation. The *Rincón de Guadalupe* and *San Miguel Tenextepec* plantations are older and did not receive fertilizer applications after their establishment.

P

The content of Olsen P in the soil is an approximate indicator of the availability of this element; in the *Rincón de Guadalupe* and *San Miguel Tenextepec* plantations it was low (0.3 and 1.4 mg kg^{-1}, respectively), but medium in *Loma del Rincón de Guadalupe* (8.2 mg kg^{-1}) and high in *El Potrero* (11.9 mg kg^{-1}). In the latter, phosphate fertilizers were applied to the soil in the first four years, which explains the high Olsen P values. In the soils of humid and tropical regions, the extractable P content is lower, compared to that of arid and semi-arid areas; to ensure the availability of this element to plants, it is advisable to apply mineral or organic fertilizers (Havlin *et al.*, 2014). In the present case, in which the soils are Andosols, the availability of P is expected to be relatively low, but, although it was not measured, the roots of the pines are expected to have associations with mycorrhizal fungi, such as those reported by Garibay-Orijel *et al.* (2013) in a study carried out in the Trans-Mexican Volcanic Belt.

Soil Carbon Storage

The C storage represented by soil is important in climate change mitigation. Soil has the capacity to store more C than aboveground biomass, but for C accumulation in the soil to occur, there must be a constant supply of plant material (Ontl and Schulte, 2012). The *SOC* stores of the soils are shown in Figure 2. The soil of the *El Potrero* plantation stored 38.5 % more C than *Rincón de Guadalupe*, 15.4 % more than in *Loma del Rincón de Guadalupe* and 3 % more than *San Miguel Tenextepec*. The lower amount of C stored in the *Rincón de Guadalupe* and *Loma del Rincón de Guadalupe* plantations is due to their previous initial agricultural vocation. In the *El Potrero* plantation, although the plot was intended for agriculture, in the management of the plantation contributions of organic fertilizers (manure) were made, which explains the greater carbon storage. Finally, in *San Miguel Tenextepec*, the land preserved its forest vocation, thereby maintaining a high level of C in the soil.

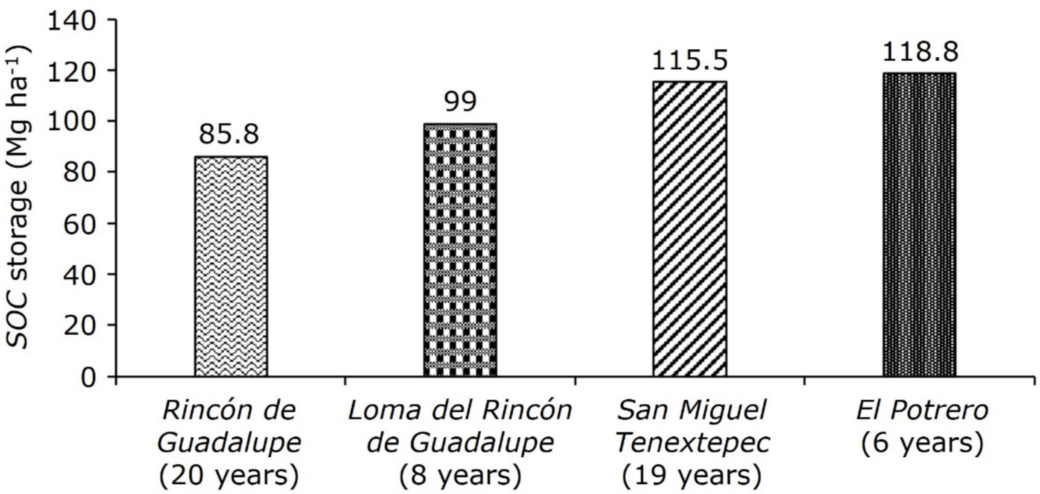

Figure 2. Soil carbon storage (0-30 cm) in four commercial forest plantations in the *Amanalco-Valle de Bravo* basin, State of Mexico.

Pérez-Ramírez *et al.* (2013) described that the average *SOC* in conserved pine-oak forests is 103 Mg ha^{-1}, while harvested and disturbed forests have 39 and 13 Mg ha^{-1}. In the *El Faro* protected natural area in *Tlalmanalco*, State of Mexico, Cano-Flores *et al.* (2020) measured SOC storage in *Pinus*-*Quercus* and *Quercus*-*Pinus* forests, which was found to be 59.8 Mg ha^{-1} and 98.3 Mg ha^{-1}, respectively. In general, the amount of C accumulated depends on the degree of soil erosion (Li *et al.*, 2019).

Conclusions

C storage and soil fertility are different between the forest plantations evaluated due to the background and characteristics of each one (age, species and management). The differences in fertility and in the concentrations of *OM*, N and P in the studied soils are related to the application of mineral and organic fertilizers as part of the management prior to establishment. The results of this work provide information on the soil characteristics of these productive systems and support the design of programs for fertility management in forest plantations in the region, since there are gaps in knowledge about soil management prior to forest plantation installation.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

René García-Martínez: planning of field work, review of field data, chemical analysis of the soil and interpretation of results and writing of the manuscript; Felipe Neri Hernández Soto: review of field data and manuscript; Jacqueline Emeterio Moreno: development of the research, interpretation of results and writing of the manuscript; María Karina Colín Velázquez: development of the research, interpretation of results and writing of the manuscript.

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