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Original article

Nutrients in the forest floor and roots in a *Pinus stand pseudostrobus* ***under thinning***

Nutrientes en el piso forestal y raíces en rodal de ***Pinus pseudostrobus*** *bajo aclareo*

Nutrientes no solo e nas raízes da floresta em um povoamento desbastado de ***Pinus pseudostrobus***

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ABSTRACT

The forest stores nutrients in the biomass of its compartments, which can be favorably modified through silvicultural treatments. The objective was to analyze the effect of thinning in response to silvicultural treatments in a young stand of *Pinus pseudostrobus* In San Pedro el Alto, Oaxaca, Mexico, a destructive sampling of herbaceous and shrubby plants, necromass, leaf litter, humus, and roots was conducted in 2021 to quantify biomass, carbon (C), and nitrogen (N). A completely randomized design (CRD) was used for biomass nutrient analysis, and a factorial CRD was used for root analysis. Analysis of variance and Duncan 's multiple range test were performed for mean comparisons. The IA_BA treatment, corresponding to a high thinning intensity (IA = 75%) and high basal area (BA >14 m^{2} ha^{-1}), with a density of 2083 trees per hectare, showed significant differences compared to other treatments, specifically in the amount of N in the leaf litter and in necromass biomass. The total carbon (C) in treatment IB_BA, which exhibited low thinning intensity, was 11.80 t ha^{-1}, distributed among litter (35.76%), necromass (14.40%), and humus (49.83%). The highest root weight recorded was 9.6 g m^{-2}, while root C content reached 5.1 t ha^{-1} in treatment IA_BA. Furthermore, thinning intensity, soil depth, and root thickness had significant effects on the root system, with a density of 17.6 fine roots per square meter under low thinning intensity (50%) and high basal area, compared to the control, which showed 9.6 fine roots per square meter at a depth of 15 cm. Biomass and nutrients were affected by thinning intensity as well as site conditions.

Keywords: biomass, carbon, humus, thinning intensity, necromass , nitrogen.

RESUMEN

El bosque almacena nutrientes en la biomasa de sus compartimientos, mismos que pueden modificarse favorablemente por medio de tratamientos silvícolas. El objetivo fue analizar el efecto del aclareo en respuesta a tratamientos silvícolas en un rodal joven de *Pinus pseudostrobus* en San Pedro el Alto, Oaxaca, México. En 2021 se realizó un muestreo destructivo de plantas herbáceas y arbustivas, necromasa, hojarasca, humus y raíces para cuantificar biomasa, carbono (C) y nitrógeno (N). Se utilizó un diseño complemente aleatorizado (DCA) para los nutrientes en la biomasa y un DCA con arreglo factorial para el análisis de raíces. Se realizó un análisis de varianza y prueba de Duncan para la comparación de medias. El tratamiento IA_BA, que corresponde a una intensidad de aclareo alta (IA = 75 %) y área basal alta (BA >14 m^2 ha^{-1}), con una densidad de 2083 árboles por hectárea, mostró diferenciales significativas en comparación con otros tratamientos, específicamente en la cantidad de N en la hojarasca y en la biomasa de necromasa. El total de C fue en el tratamiento IB_BA, que presenta una intensidad de aclareo baja, fue de 11,80 t ha^{-1}, distribuyéndose en hojarasca (35,76 %), necromasa (14,40 %) y humus (49,83 %). El peso más alto de raíces registrado fue de 9,6 g m^{-2}, mientras que el contenido C en raíces alcanzó las 5,1 t ha^{-1} en el tratamiento IA_BA. Además, el aclareo, la profundidad del suelo y el grosor de las raíces tienen efectos significativos en el sistema radical, con una densidad de 17,6 raíces finas por metro cuadrado en condiciones de intensidad de aclareo baja (50 %) y área basal alta, en comparación con el testigo, que presentó 9,6 raíces finas por metro cuadrado a una profundidad de 15 cm. La biomasa y nutrientes se ven afectados por la intensidad de aclareos al igual que las condiciones de los sitios.

Palabras clave: biomasa, carbono, humus, intensidad de aclareo, necromasa, nitrógeno.

RESUMO

As florestas armazenam nutrientes na biomassa de seus compartimentos, que podem ser modificados favoravelmente por meio de tratamentos silviculturais. O objetivo deste estudo foi analisar o efeito do desbaste em resposta a tratamentos silviculturais em um povoamento jovem de Pinus pseudostrobus em San Pedro el Alto, Oaxaca, México. Em 2021, foi realizada amostragem destrutiva de plantas herbáceas e arbustivas, necromassa, serapilheira, húmus e raízes para quantificar biomassa, carbono (C) e nitrogênio (N). Um delineamento inteiramente casualizado (DIC) foi utilizado para a análise de nutrientes na biomassa, e um DIC fatorial foi utilizado para a análise das raízes. Análises de variância e o teste de Duncan foram realizados para comparação de médias. O tratamento IA_BA, correspondente a uma alta intensidade de desbaste (IA = 75%) e alta área basal (AB > 14 m^2 ha^{-1}), com densidade de 2083 árvores por hectare, apresentou diferenças significativas em comparação aos demais tratamentos, especificamente na quantidade de nitrogênio na serapilheira e na biomassa da necromassa. O carbono total no tratamento IB_BA, que apresenta baixa intensidade de desbaste, foi de 11,80 t ha^{-1}, distribuído entre serapilheira (35,76%), necromassa (14,40%) e húmus (49,83%). O maior peso radicular registrado foi de 9,6 g m^{-2}, enquanto o teor de carbono radicular atingiu 5,1 t ha^{-1} no tratamento IA_BA. Além disso, o desbaste, a profundidade do solo e a espessura das raízes têm efeitos significativos no sistema radicular, com uma densidade de 17,6 raízes finas por metro quadrado em condições de baixa intensidade de desbaste (50%) e alta área basal, em comparação com o controle, que apresentou 9,6 raízes finas por metro quadrado a uma profundidade de 15 cm. A biomassa e os nutrientes são afetados tanto pela intensidade do desbaste quanto pelas condições do local.

Palavras-chave: biomassa, carbono, húmus, intensidade de desbaste, necromassa, nitrogênio.

INTRODUCTION

Climate change is usually considered to be solely related to what happens in the atmosphere; however, the soil and its forests are the second most important carbon (C) sink, where, irrationally, logging is the most significant disturbance, both in extent and in C removal (Oswalt *et al*, 2019).

Forest ecosystems store more carbon per unit area than any other land use. This is because forest soils contain between 60% and 85% of the total carbon in temperate forests (Domke. *et al*., 2021). This capacity to accumulate carbon makes forests fundamental in mitigating climate change.

Given the economic importance of sustainable forest management in forest ecosystems, studies of forest nutrients and carbon sequestration are receiving increased attention. These aspects allow for an understanding of primary production and energy flow in ecosystems. For this reason, they tend to have the highest prices in the economic and ecological valuation of ecosystem services, especially those directly related to carbon capture (Ontl). *et al*., 2020).

Many researchers and forestry service providers question whether silvicultural practices alter nutrient levels and reduce soil fertility, particularly when whole trees are felled (Mayer *et al.*, 2020). The current carbon stock in the world's forests is estimated at 861 ± 66 Pg C, with 42% in live biomass (above and below ground), 8% in dead wood, and 44% in mineral soil (Galicia *et al.*, 2016).

Disturbances in forests, whether intentional or not, have a very significant effect on terrestrial C reserves, both in the forest floor and in the mineral soil (Cao *et al.* , 2019). Research conducted on forests has found that the extraction of forest matter reduces soil C by 8 to 11% depending on the type of ecosystem and up to 36% if it is the first layer of soil (James and Harrison 2016).

Therefore, it is essential to evaluate changes over time, applying silvicultural practices such as thinning to restore and maintain the soil's carbon sequestration potential (Mayer *et al.*, 2020). Furthermore, in the long term, it is highly beneficial, primarily in terms of volumetric timber stocks and carbon within the ecosystem structure (Zhang *et al.*, 2018). However, the harvesting of underground biomass has been understudied due to a lack of robust experimental data, as the direct method employed (felling the tree and extracting roots) is destructive to the forest (Quintero-Gradilla *et al.*, 2022).

However, accurately estimating belowground biomass is essential to understanding the changes that occur after thinning. Roots, for example, represent a significant fraction of a tree's total biomass (15–45%) and play a crucial role in forest nutrient dynamics, performing important functions in biogeochemical cycles and nutrient flows (Fan *et al.*, 2017). Soil contains the largest amount of carbon interacting with the atmosphere, estimated at around 1,500 P g C at 1 m depth and approximately 2,456 P g C at 2 m, indicating an increase in the sequestration of other nutrients such as nitrogen (Deng *et al.*, 2016).

Therefore, the present study aims to analyze the effect of thinning intensities on C and N content in the forest floor and roots of a young stand of *Pinus pseudostrobus* Lindl. of San Pedro el Alto, Oaxaca, Mexico.

MATERIALS AND METHODS

Study area

The experimental area was established in a stand of *Pinus Pseudostrobus* in La Cofradía, belonging to San Pedro el Alto, Zimatlán, Oaxaca, within the area called "La Pobreza," where a fire occurred in 2008, resulting in high density (approximately 1,100 trees per hectare) and homogeneity in size. The sites were established in 2018 and are located at an altitude of 2,800 m, 16°80′83.33″ N and -097°05′33.3″ W. It is an 18-hectare area where plots of trees in the lamella stage of development were established, with heights between 7 and 13 m. Thinning was carried out to optimize the diametral growth of remaining trees (Pérez- Alavez. *et al.*, 2023).

Experimental designs are

The work was carried out in 2018 in an area under forest management. Within the study area, 15 circular sampling sites of 400 m^2 were established to develop two trials. 1) Trial 1: used 12 sites that were subjected to thinning intensities (I) of high IA = 75% and low IB = 50%, applied under conditions of high basal area (B) (BA > 14.2 m^2 ha^{-1}) and low basal area (BB < 12.8 m^2 ha^{-1}); from this, four treatments (IA_BA, IB_BA, IA_BB, and IB_BB) were established with three replicates, in a completely randomized experimental design (CRD). Based on this design, the C and N content in the aboveground structural and compartmental biomass (litter, humus, herbaceous, shrubby, and necromass) was quantified.

Trial 2: Three control sites (without thinning) were added to the 12 sites of the first trial. A completely randomized design with a 5×3×3 factorial arrangement was used, with thinning intensity, soil depth (15, 30, and 50 cm), and root thickness (coarse, medium, and fine) with three replications (Pérez- Alavez. *et al*., 2023). Under this test, root weight, dimensions, volume, density per unit area, apparent density and C content were studied.

The variables recorded in the field to perform the estimates of aboveground biomass and root density are indicated in Table 1.

Table 1. *- Variables recorded in the Pinus field pseudostrobus Lindl. under thinning*

Design 1	**Variables recorded in the field**
	Place
	Tree number
	Normal diameter (cm)
	Total height (m)
	Sample number. Biomass in compartments and structures
Design 2	**Variables recorded in the field**
	Place
	Weight and volume of root
	Root length and diameter (mm)
	Soil depth, root density, and bulk density

Sampling on the forest floor

Samples of necromass (components of dead plants) were collected from the surface, including leaf litter, fallen trunks and branches, stumps, and dead roots (Pearson *et al.*, 2005). In this study, thick and thin branches, fallen trunks, and cones were considered necromass.

Additionally, samples of live herbaceous plants were collected from 3×3 m plots within each site and weighed on a Torrey® EQB/EQM series scale in Houston, TX, USA (*fresh* sample weight, kg). From these samples, approximately 700 g was taken to the Agroecosystems Laboratory of the National Technological Institute of Mexico/Technological Institute of the Valley of Oaxaca, where biomass conversion factors (BCF) per site were obtained $FCB = \frac{PSM}{PFM}$. Where, PSM = dry sample weight (kg), PFM = fresh sample weight (kg); these were used to estimate branch biomass per tree using the product $FCB \times PFR$.

For humus collection, a 1 m² area was delimited within each of the 12 sites (g, defined here as organic matter in its final stage of decomposition by soil microorganisms), obtaining three replicates per site, and then weighing the samples. The subsamples were placed in a drying oven (Beschickung/Loading-modell 100-800 Memmert) at 72 °C to obtain their dry weights (g). The determination of the *biomass conversion factor (BCF)* per compartment was carried out using the methodology of Rodríguez-Ortiz *et al.* (2019), where biomass was calculated with the biomass conversion factor B = (DW/FW) / 1000. Where, B = biomass (kg), DW = dry weight, and FW = fresh weight.

Walkey and *Black method* (NOM-021-RECNAT-2000) was used to determine organic carbon (C) through organic matter content. 0.5 g of each sample was weighed into a 500 mL Erlenmeyer flask, to which 10 mL of 1.00 N $K_2Cr_2O_7$ were added. To the resulting solution, 20 mL of H_2SO_4 were added and the mixture was allowed to stand for 30 min. After this time, 200 mL of distilled water, 5 mL of H_3PO_4, and five drops of diphenylamine were added. The titration was then performed to calculate the percentage of organic matter, which was multiplied by 0.58 for its conversion to organic carbon. For the determination of nitrogen, the *Kjendahl* method was used, which consisted of the wet oxidation of organic matter with hot sulfuric acid (López-Choque *et al.*, 2023).

Destructive sampling of underground biomass

In the center of each site, a 50×50 cm area was carefully marked out to remove leaf litter and humus. The mineral soil was then excavated with a shovel and crowbar to a depth of 15 cm. This first layer of soil was sieved through a 3 mm mesh. The total weight of the roots was then recorded, and a representative sample of each size was obtained. This procedure was repeated until a depth of 30 cm was reached, and finally, a depth of 50 cm. Three replicates were collected per site. The roots were measured with a caliper to classify them according to thickness: fine roots (≤1 mm), medium roots (1.1–3.0 mm), and coarse roots (>3.0 mm). The root samples were sent to the Central University Laboratory of Chapingo, where they were analyzed to obtain the C content by the calcination method (Izquierdo-Bautista and Arévalo-Hernández, 2021).

To determine the specific gravity of the roots and the soil, the following equation (1) was used:

$$GE = \frac{P}{VOL} (1)$$

Where:

GE = specific gravity (g cm $^{-3}$);

P = dry weight (g);

VOL (cm $^{-3}$) = volume, in roots and soil.

The organic carbon (OC) and N contained in the root sample was inferred per unit area (kg ha $^{-1}$) and the total weight of the root sample (g) and the proportion of C and N obtained in the laboratory analysis were obtained as a product.

Statistical analysis

The assumptions of normality and homogeneity of variances were verified in the data using the respective *Shapiro - Wilk* and *Bartlett tests* (*a* = 0.05) (Rodríguez-Vásquez *et al*., 2024); previously, the original data of some variables were transformed to the square root of x+1, because they presented probability distributions different from the normal distribution (Gutiérrez-Pulido and De la Vara-Salazar, 2012). Analysis of variance and Duncan 's tests ($p \leq 0.05$) were performed for the comparison of means, using the Statistical statistical software Analysis System (SAS) version 9.4 (SAS Institute University Version®, 2018).

RESULTS

Residual trees

The initial density (2,083 trees), as well as all the biomass contents evaluated, differed between treatments ($p \leq 0.05$); the C contents in necromass, humus, and shrubs differed between thinning levels ($p \leq 0.05$), which did not occur in the leaf litter and herbaceous compartments ($p > 0.05$). The N content in leaf litter showed high significant differences ($p = 0.01$), which did not occur with the other variables (p > *0.05)*, where the thinning intensities did not differ. On the other hand, N and biomass in necromass were the variables with the greatest heterogeneity (CV = 179%), unlike the initial density and biomass in leaf litter, which showed greater homogeneity (CV ≤ 14.8%) between treatments (Table 2).

Table 2. *- Summary of the analysis of variance of carbon (C) and nitrogen (N) content in biomass in a Pinus stand pseudostrobus Lindl. under thinning*

Feature	Silvicultural treatment	Mistake	Total	Coefficient of variation (%)	Root mean square error
Degrees of freedom	3	8	11		
Initial density $^{\pi}$	76.70 *	31.70		14.80	5.60
Biomass in leaf litter $^{\pi}$	0.30 *	0.08		10:30	0.30
Biomass in necromass $^{\pi\pi}$	1.30 **	0.15		179.70	0.39
Biomass in humus $^{\pi\pi\pi}$	6.40 *	3.20		52.20	1.80
Herbaceous biomass	0.03 *	0.12		97.60	0.34
Biomass in shrubs $^{\pi\pi\pi}$	18.50 *	20.90		62.30	4.50
C in leaf litter $^{\pi\pi\pi}$	26.40 ns	30.90		22.40	0.90
C in necromass †	0.22 *	0.09		104.70	0.30
C in humus $^{\pi\pi\pi}$	10.90*	5.00		54.10	2.20
C in herbaceous $^{\pi\pi\pi}$	0.00 ns	0.00		135.50	0.07
C in bushes $^{\pi\pi\pi}$	0.00 *	0.00		62.80	0.03
N leaf litter $^{\pi\pi}$	0.00**	0.00		21.10	0.03
N necromass $^{\pi\pi\pi}$	0.07 ns	0.08		179.00	0.29
N in humus $^{\pi\pi\pi}$	0.10 ns	0.08		65.60	0.29
N in herbaceous $^{\pi\pi\pi}$	0.00 ns	0.00		119.00	0.00
N in bushes $^{\pi\pi\pi}$	0.00 ns	0.00		64.50	0.00

*ns = not significant ($p > 0.05$); * Significant ($p \leq 0.05$); ** Highly significant ($p \leq 0.01$). Variables with transformation $^{\pi, \pi\pi}$ sine(x), $^{\pi\pi\pi}$ tangent(x), † cosine(x) ($\sqrt{X+1}$).*

The highest biomass content was found in the necromass (98.76 t ha^{-1}) and litter (9.03 t ha^{-1}) compartments where an *AI* = 75% was applied, with *a basal area (BA)* > 14 m^2 ha^{-1}. This resulted in respective differential increases of 588.7% and 83.5% compared to the treatment with *an AI* = 50% in sites with less basal area. Humus biomass also stood out in the treatments with *an AI* = 50% compared to the sites with *an AI = 75%*, regardless of basal area (Table 3). Humus biomass reached 6.3 t C ha^{-1} in treatment 4 (*IB* = 50%, *BB* ≤ 14 m^2 ha^{-1}), which generated a differential increase of 70.7% (2.6 t ha^{-1}) more than the average of the other treatments; while in necromass The highest carbon content (4.85 t ha^{-1}) was found in treatment IA_BA (*IA* = 75%, *BA* >14 m^2 ha^{-1}), *generating a differential increase of 286.9% more than the average of the other three treatments. The case of N was similar, as* the highest humus content was 0.58 t ha^{-1} in treatment IB_BB. It should be noted that only the litter variable showed a better response to the treatments ($p < 0.01$) than the variables necromass, humus, herbaceous and shrub, which did not generate significant changes ($p > 0.05$) (Table 3).

Table 3. *- Carbon (C) and nitrogen (N) content (t ha $^{-1}$) in Pinus biomass pseudostrobus Lindl. under thinning*

Variable	Treatment 1	Treatment 2	Treatment 3	Treatment 4
	IA (75 %) _ *BA* (>14 m ^{2} ha $^{-1}$)	*IB* (50 %) _ *BA* (>14 m ^{2} ha $^{-1}$)	*IA* (75 %) _ *BB* (≤14 m ^{2} ha $^{-1}$)	*IB* (50 %) _ *BB* (≤14 m ^{2} ha $^{-1}$)
Initial density (trees ha $^{-1}$)	2083±449 ^{a}	1 425±232 ^{ab}	1 217±123 ^{ab}	1 167±145 ^{b}
Biomass in leaf litter	9.03± 1.30 ^{a}	7.44±1.00 ^{ab}	5.48±0.80 ^{b}	4.92±0.10 ^{b}
Biomass in necromass	98.76±82.00 ^{a}	30.50±14.80 ^{b}	17.36±3.90 ^{b}	14.34±3.20 ^{c}
Biomass in humus	34.30±8.30 ^{b}	45.00± 11.70 ^{a}	35.0±12.60 ^{b}	50.71± 15.80 ^{a}
Herbaceous biomass	0.40±0.10 ^{b}	0.30±0.10 ^{b}	0.39±0.10 ^{b}	1.23± 0.80 ^{a}
Biomass in shrubs	0.36±0.20 ^{b}	0.96±0.06 ^{a}	0.5±0.10 ^{b}	0.77±0.30 ^{ab}
C in leaf litter	3.82± 0.30 ^{a}	4.22± 0.70 ^{a}	4.92± 0.40 ^{a}	3.96± 0.60 ^{a}
C in necromass	4.85±4.00 ^{a}	1.70±0.80 ^{b}	0.65±0.10 ^{b}	1.41±0.30 ^{b}
C in humus	3.04±0.70 ^{b}	5.88± 1.50 ^{a}	2.15±0.70 ^{b}	6.30± 1.90 ^{a}
C in herbaceous	0.04±0.01 ^{a}	0.03±0.01 ^{a}	0.04±0.01 ^{a}	0.13±0.08 ^{a}
C in shrubs	0.03±0.01 ^{b}	0.08±0.00 ^{a}	0.04±0.01 ^{b}	0.07±0.03 ^{a}
N leaf litter	0.15±0.01 ^{b}	0.14±0.02 ^{b}	0.22±0.01 ^{a}	0.15±0.02 ^{b}
N necromass	0.31± 0.20 ^{a}	0.08±0.04 ^{a}	0.06±0.01 ^{a}	0.05±0.01 ^{a}
N in humus	0.26±0.06 ^{a}	0.41± 0.10 ^{a}	0.34±0.00 ^{a}	0.58± 0.10 ^{a}
N in herbaceous	0.003±0.00 ^{a}	0.002±0.00 ^{a}	0.004± 149.40 ^{a}	0.009±0.00 ^{a}
N in shrubs	0.006±0.00 ^{a}	0.005±0.00 ^{a}	37.00±0.00 ^{a}	0.009±0.00 ^{a}

Means with different letters in rows are statistically different (Duncan, $p \leq 0.05$); mean ± standard error; $I_{A,B}$ = thinning intensity (%) high and low; $B_{A,B}$ = residual basal area high and low

Destructive root sampling

The thinning factor had significant effects on all variables ($p < 0.05$); the highest number of roots was found in response to treatment *IB_BA (T2)* with 17.6 roots m $^{-2}$, at a depth of 15 cm (17.9 roots m $^{-2}$) and a higher proportion of fine roots (16.8 roots m $^{-2}$). The same occurred with root diameter, as the highest value was presented in treatment IB_BA *with* 3.3 mm.

, the longest roots were found at a depth of 15 cm, and the root thickness was medium to fine. Treatment *IA_BA* resulted in statistically superior root dry weight at 9.6 g/ $m^{2,}$ but this differed from treatment *IA_BB* (4.2 g/m^2), which was lower. Regarding its relationship with soil depth, there were no significant differences at any of the three depths, but there were differences ($p \leq 0.01$) in root thickness, with thick roots showing the greatest statistical variability (16.1 g). m^{-2}).

Finally, the highest concentration of carbon in roots (5.1 t C ha^{-1}) was found in treatment *IA _ BA* which was different from treatment *IA _ BB* (2.2 t C ha^{-1}); and in this case, root thickness significantly affected the C content in the three thickness types, where thick roots generated a higher carbon content (8.3 t ha^{-1}), it should be noted that although there were no significant differences between the treatments and the control, the volume variable showed the most notable contents compared to the other variables (Table 4).

Table 4. *- Characteristics of Pinus roots pseudostrobus Lindl. under thinning at different soil depths*

Treatment	**Dry weight (gm $^{-2}$)**	**Volume (cm ^{3} m $^{-2}$)**	**Carbon (t ha $^{-1}$)**	**Quantity (roots m $^{-2}$)**	**Diameter (mm)**	**Length (mm)**
Lightening treatment						
$I_B\_B_A$	7.50±1.50 ab	15.80± 3.70 a	4.00±0.80 ab	17.60± 3.30 a	3.30± 0.70 a	238.50± 38.10 a
$I_A\_B_A$	9.60± 2.30 a	23.40± 6.50 a	5.10± 1.20 a	8.10±1.60 b	3.00±0.50 ab	178.30±22.70 bc
Witness	7.90±1.90 ab	20.50± 7.70 a	4.30±1.00 ab	9.60±2.00 b	2.80±0.50 ab	162.10±20.80 c
$I_B\_B_B$	6.80±1.50 ab	20.60± 6.70 a	3.70±0.80 ab	12.70±1.20 b	2.70±0.40 ab	220.60±29.70 ab
$I_A\_B_B$	4.20±0.80 b	8.90± 2.20 a	2.20±0.40 b	10.10±0.90 b	2.10±0.30 b	164.20±33.20 c
Soil depth (cm)						
15	7.30± 0.95 a	17.60± 3.80 a	3.90± 0.50 a	17.90± 2.30 a	2.90± 0.40 a	310.50± 29.10 a
30	8.40± 1.71 a	21.50± 5.70 a	4.50± 0.90 a	9.70±0.80 b	2.80± 0.30 a	169.20±13.20 bc
50	5.80± 1.19 a	14.50± 3.60 a	3.20± 0.60 a	7.20±0.80 b	2.60± 0.30 a	98.50±8.30 c
Root thickness (mm)						
Gross	16.10± 1.53 a	45.90± 5.80 a	8.30± 0.80 a	4.40±2.10 c	3.00± 0.30 a	95.70±6.30 b
Average	4.50±0.37 b	6.50±0.50 b	2.70±0.20 b	13.60±1.20 b	1.70±0.00 b	242.60±19.00 a
Fine	0.90±0.12 c	0.80±0.10 b	0.60±0.00 c	16.80± 0.30 a	0.60±0.00 c	239.90±30.00 a

Means with different letters in columns and by factor are statistically different (Duncan, $p \leq 0.05$); mean ± standard deviation. $I_{A, B}$ = High and low thinning intensity (%); $B_{A,B}$ = High and low residual basal area (m^2).

Furthermore, the highest significant effects on root bulk density (Figure 1) were generated in treatment *IA_BA* (high intensity and high basal area) with a density of *4.0298 g* cm^3, which was statistically different from treatment IA_BB. It is worth noting that the highest root bulk density (*BD*) was found at depths of 30 and 50 cm (3.4503 g cm^3), and the lowest at 15 cm (2.0338 g cm^3). Thicker roots had significantly higher effects on root bulk density (6.8548 g cm^3); that is, greater root thickness resulted in higher bulk density.

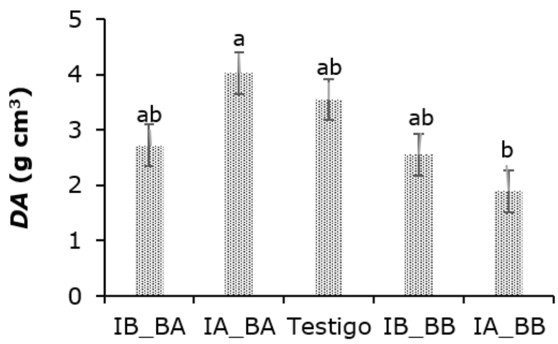

Figure 1. *- Apparent root density (AD) in a Pinus stand pseudostrobus Lindl. under thinning*

Note: *$I_{A, B}$ = high and low thinning intensity (%); $B_{A,B}$ = high and low residual basal area (m^2). Different letters indicate statistically significant differences (Duncan, $p \leq 0.05$). Vertical lines above columns represent standard error.*

DISCUSSION

Thinning

It was generally observed that applying thinning at these two intensities has a variable effect on nutrient content due to the removal of large amounts of biomass. In this context, *IA_BA* generates greater differences in N content in litter and biomass in necromass, which could be due to the young age of the trees and the high thinning intensity applied, resulting in the release of large amounts of litter. In this regard, in forest stands subjected to silvicultural treatments in Pueblo Nuevo, Durango, Solís-Hernández *et al*. (2014) found that litter represents 71% of the total biomass contribution, necromass 23%, and herbaceous and shrubby vegetation 2% and 7% of the total biomass, respectively. On the other hand, Retana-Chinchilla *et al*. (2019) estimated in a primary forest in Costa Rica, where they analyzed several components: necromass, herbaceous vegetation, leaf litter, saplings, stems and soil, that the latter two have the highest total carbon (46.35% and 50.79%, respectively).

Necromass was the component with the highest biomass content (98.76 t ha^{-1}), which can be explained by the amount of residual biomass generated after thinning. This amount falls within the range reported by Galicia *et al.* (2015), who analyzed the consequences of forest extraction on biomass and necromass in a temperate forest of the Sierra Norte of Oaxaca and concluded that necromass ranged from 63 to 177 t ha^{-1}, mostly due to coarse woody residues. The second compartment with the highest biomass content was humus (50.7 t ha^{-1}), a figure that exceeds that reported by Chávez-Pascual *et al.* (2017) in an estimate of aboveground biomass, forest floor and understory in stands of *P. oaxacana* under management in Ixtlán, Oaxaca, where the humus compartment generated only a total of 20.53 t ha^{-1} and there was no statistical difference between the four treatments applied.

It was observed that silvicultural treatments influence C fixation (Rodríguez-Ortiz *et al.*, 2019); based on the analysis, humus and necromass generated the highest amounts of carbon (6.3 and 4.85 t ha^{-1}) in treatments T4 and T1 respectively, values lower than those reported by Espinoza-Zúñiga *et al*. (2023) who found that silvicultural treatments generate a greater amount of C compared to sites where no management is applied; when comparing the C stored in forests with management (San Pedro el Alto) and without management (San Juan Atepec) in Oaxaca.

However, these authors found that humus content was 233.7% higher in the uncertified community than in the managed one (9.2 t C ha^{-1}). This is attributed to the fact that no human intervention takes place in the Atepec community, as silvicultural treatments can alter nutrient concentrations. Meanwhile, necromass carbon content was higher in San Pedro el Alto (13.4 t C ha^{-1}), due to the size of the fallen dead material, the decomposition time, and the thinning residues used as fertilizer for the stands (Leyva-Pablo *et al*., 2021).

On the other hand, the sites evaluated in this study are rich in organic matter due to the edaphic and physiographic characteristics of the place. In this sense, it can be mentioned that, although leaf litter is the main input of nutrients to the soil, and due to the close relationship, it has with humus, this was the compartment where the greatest amount of N was found (0.58 t ha^{-1}). followed by necromass (0.31 t N ha^{-1}). These values are similar to those found by Torres-Duque *et al.* (2022), who in *Pinus* forests *hartwegii* Lindl. in Texcoco, Mexico, found 0.36 t N ha^{-1} in mulch, 3.27 t N ha^{-1} in soil and 0.11 t N ha^{-1} in annual leaf litter.

Root density

In this study, the highest number of roots was found in response to *IB _ BA*, and in greater proportion fine roots (16.8 roots m $^{-2)}$, which means that applying low intensity thinning with high *AB* can be beneficial for the root system. This result was similar to that of Pavón *et al*. (2012) who evaluated the root biomass of pines (*Pinus teocote* Schltdl. & Cham., *P. montezumae* Lamb. and *P. patula* Schltdl. & Cham.) in a managed temperate forest in Hidalgo, Mexico; where fine roots made up the largest percentage, at 66.8% of the total between coarse and fine roots. Therefore, Medrano-Meraz *et al.* (2021) mention that root biomass in conifers generates significant percentages of biomass, with values ranging between 12.1 and 22% of the total tree biomass.

Considering the depth within the site is very important to know more specific data: the greatest number of roots are located in the first 15 cm and decrease as depth increases (Gómez *et al.*, 2021), that is, at a certain soil depth, the root anchorage capacity and nutrient absorption in the upper soil horizon increase. As mentioned by Galicia *et al.* (2015), who in a study carried out in temperate forests with and without management in the Sierra Norte of Oaxaca, found that forest harvesting had significant effects on root biomass (2.2 Mg ha $^{-1)}$ only at a depth of 0-10 cm, while the unmanaged forest showed no difference between treatments.

The thickness of the root varied irregularly between diameter and length, as reported by Germon *et al*. (2020) who mention that the root system can vary due to its genetics and plasticity, since the roots elongate towards where they can develop best according to the soil condition (Lwila *et al*., 2021). On the other hand, the root dry weight and C content variables showed significant results at T1, which was possibly due to the good water retention of the sites (Luna, 2019).

In this study, the highest total C content was found in *IA_BA* (5.1 t ha^{-1}); however, C also decreases as biomass decreases. The results indicate that the highest C content in *Pinus roots Pseudostrobus* are found in the first 30 cm of soil. When sampling at greater depths, this nutrient decreases. This is because the greater nutrient activity of the roots favors microbial activity, which generally occurs in the first few centimeters of soil due to the high concentration of organic matter (Galicia *et al*., 2016). This result surpasses that reported by Quintero-Gradilla *et al*. (2022) in the Sierra de Manantlán, Mexico, who quantified C in root biomass in a temperate *Pinus forest. Douglasian* Martínez found that in the first 30 cm of soil, the roots store 3.51 t ha^{-1}, within which 46% of the C is present in the fine roots while 54% was found in the thick roots, as happened with the result of this study.

Treatment *IA - BA* had the greatest influence on root *bulk density (DB),* reaching 4.0298 g cm^{-3} at a depth of 30–50 cm. thicker roots exhibited higher *DB* compared to thinner roots. Root biomass alone is not a reliable indicator of nutrient uptake capacity; root density is a better indicator, as it relates root length to a unit volume of soil. However, it is clear that fine roots are responsible for acquiring the necessary resources for the tree; the greater the root biomass, the greater the uptake capacity (McCormack and Guo 2014).

CONCLUSIONS

The biomass and nutrient contents of the different compartments evaluated in the *Pinus stand The pseudostrobus trees* of San Pedro el Alto, Oaxaca, are affected by thinning at intensities of 50% and 75% of the residual basal area at low and high levels. After thinning, a better response of the trees to the site conditions is observed, since the reduction in tree density allows for greater spacing between them. This decreases competition for water, nutrients, and light, facilitating increased biomass and nutrient accumulation in all compartments. The application of high-intensity thinning (75%) in sites with high basal area (>14 m^2 ha^{-1}) generates the greatest variations in C and N content in the structural biomass and in the different compartments.

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Conflicts of interest:

The authors declare no conflicts of interest.

Authors' contribution:

The authors have participated in the writing of the work and analysis of the documents.