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Research article

Effects of forest management on the carbon-nitrogen ratio of litter in temperate forests

Efectos del manejo forestal en la relación carbono-nitrógeno del mantillo en bosques templados

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Abstract

In temperate forests, carbon storage is distributed among biomass, mineral soil, and litter. The latter acts as both a carbon source and a carbon sink, as it accumulates plant debris that, through microbial decomposition, promotes the formation of stable organic matter in the soil and controls the gradual release of labile organic compounds. This study assessed the impact of various silvicultural treatments on the carbon-nitrogen ratio in the litter of managed *Pinus patula* forests in the *Emiliano Zapata ejido*, *Chignahuapan*, state of *Puebla*, Mexico. Circular sampling plots of 1 000 m^2 were established, 18 of them distributed across stands treated with Regeneration cutting (*RGC*), Release cutting (*RC*), Thinning 2 (*T2*), and Thinning 3 (*T3*), and five in stands with Selective logging (*SL*). The basal area of the tree stand was estimated, and the litter was sampled in two layers (LL: leaf litter and FE: fermentation); the soil variables of temperature, moisture, and *pH* were measured. In the laboratory, organic carbon (*OC*) and total nitrogen (*TN*) were determined, and the *C:N* ratio was calculated for both layers using general linear models with a gamma distribution and effects modeled using a Structural partial equation model. The *C:N* ratio was found to differ between LL and FE; the treatment with the most open canopy (*RGC*) had the greatest influence on the forest floor microclimate. Therefore, silvicultural treatments modulate soil and climate conditions, affecting the decomposition of organic matter and carbon sequestration in the litter layer.

Keywords: Temperate forests, organic carbon, litter, total nitrogen, *C:N* ratio, silvicultural treatments.

Resumen

En los bosques templados, el almacenamiento de carbono se distribuye entre la biomasa, el suelo mineral y el mantillo. Este último actúa como fuente y sumidero de carbono, ya que acumula detritos vegetales que, mediante procesos de descomposición microbiana, promueven la formación de materia orgánica estable en el suelo y controlan la liberación gradual de compuestos orgánicos lábiles. En la presente investigación, se evaluó el impacto de diversos tratamientos silvícolas en la relación carbono-nitrógeno en el mantillo de bosques bajo manejo de *Pinus patula*, del ejido Emiliano Zapata, Chignahuapan, Puebla, México. Se establecieron unidades de muestreo circulares de 1 000 m^2, 18 distribuidas en rodales con tratamientos de Corta de Regeneración (*CR*), Corta de liberación (*CL*), Aclareo 2 (*A2*), y Aclareo 3 (*A3*); además de cinco en Corta de selección (*CS*). Se estimó el área basal de la masa arbórea y se muestreó el mantillo en dos capas (HO: hojarasca y FE: Fermentación); se midieron las variables edáficas de temperatura, humedad y *pH*. En laboratorio se determinaron el carbono orgánico (*CO*), nitrógeno total (*NT*) y la relación *C:N* se calculó para ambas capas, mediante modelos lineales generales con distribución gamma y los efectos con un modelo estructural de ecuaciones parciales. Se determinó que la relación *C:N* difiere entre HO y FE; el tratamiento con más apertura del dosel (*CR*) tuvo mayor influencia en el microclima del piso forestal. Por lo tanto, los tratamientos silvícolas modulan las condiciones edafoclimáticas, impactando la descomposición de la materia orgánica y el secuestro de carbono en el mantillo.

Palabras clave: Bosques templados, carbono orgánico, mantillo, nitrógeno total, relación *C:N*, tratamientos silvícolas.

Introduction

Temperate forests store carbon primarily in three compartments: soil, biomass, and litter (Galicia et al., 2016). The latter refers to the topsoil (horizon 0), which consists of organic matter in various stages of decomposition and accumulates significant amounts of carbon; as a result, it is considered an important reservoir of this element. Litter plays a key role in regulating essential ecosystem processes, such as protecting the soil from water erosion, and helps water infiltrate the soil profile. Furthermore, it serves as the primary source of nutrients for plant species and is the basic component for the formation of humic substances, forms of recalcitrant carbon, and nitrogen in the soil (Galicia et al., 2016).

The soil recycling cycle is influenced by the interaction between carbon and other chemical elements, a process that varies depending on specific ecological factors such as climatic conditions, altitude, and soil properties (Paz-Pellat et al., 2015). Within this context, the role of litter in regulating nutrient quality and availability within the soil profile has been highlighted in various studies on carbon dynamics in temperate forests, which demonstrate how changes in temperature and moisture affect the decomposition dynamics and mineralization of this organic soil layer (Pérez-Vázquez et al., 2021).

Carbon (*C*) and nitrogen (*N*) are key indicators of organic matter quality, as they influence soil structure, nutrient availability, water retention, and microbial activity. Soil carbon plays a role in the global carbon cycle, while nitrogen availability is a major limiting factor for plant productivity because it regulates plant growth. The amount of nitrogen in the soil is influenced by environmental conditions, topography, management practices, and vegetation type, which in turn determine the quality of the organic matter.

In the temperate forests of Latin America, particularly in ecosystems dominated by pine and pine-fir, recent research suggests that management practices can reduce the volatility of the *C:N* ratio by promoting the input of high-quality organic matter and soil conditions conducive to the stability of non-mineralizable organic carbon (Getino-Álvarez et al., 2023). However, results vary depending on the design of the intervention (intensity and frequency of cutting) and regional soil and climate conditions, revealing a knowledge gap in regard to the causal effects of forest management. In this sense, while approaches such as Piecewise structural equation modeling (Lefcheck, 2016) have made it possible to gain insight into these complex relationships, their application remains limited in capturing spatial and temporal variability and the nonlinear effects associated with managed forest systems. Therefore, strengthening these approaches by incorporating this variability offers a key opportunity to improve causal inference and advance a more robust understanding of the processes linking forest management to soil dynamics (Lefcheck, 2016).

In this context, assessing the *C:N* ratio in the litter layer can help monitor the impact of management practices and inform strategies to ensure the sustainability of forest ecosystems (Fernández-Getino-García, 2024). Therefore, the objective of this study was to evaluate the effects of treatments on stands managed using two different methods—the Silvicultural Development Method (SDM) and the Mexican Method for the Management of Irregular Forests (MMOBI, for its acronym in Spanish)—on the *C:N* ratio in the litter layer. According to the hypothesis, the *C:N* ratio in litter shows a significant negative correlation with soil temperature and moisture, and a positive correlation with soil *pH*; consequently, increases in temperature and moisture would reduce the *C:N* ratio, while higher *pH* values would increase it, depending on the silvicultural treatments applied. The study aims to contribute to our understanding of how silvicultural practices influence carbon and nitrogen cycles, which are fundamental to the sustainability of forest ecosystems.

Materials and Methods

The study site is located in the *Emiliano Zapata ejido*, in *Chignahuapan* municipality, *Puebla*, Mexico, between parallels 19°39'42" and 19°58'48" North and the meridians 97°57'18" and 98°18'06" West, where a temperate subhumid climate with summer rainfall (Cw) prevails (García, 2004), with an average annual temperature of 13.4 °C and an average annual relative moisture of 85 %. The vegetation consists of a pine forest dominated by *Pinus patula* Schiede ex Schltdl. & Cham. and, to a lesser extent, *Pinus ayacahuite* Ehrenb. *ex* Schltdl.; at the higher altitudes (2 919 masl), *Abies religiosa* (Kunth) Schltdl. & Cham. predominates (Velasco-Bautista et al., 2025).

A quasi-systematic sampling design was developed based on the *ejido*'s Timber Forest Management Program (TFMP), in which two methods are applied: the Mexican Method for the Management of Irregular Forests (MMOBI, in Spanish) and the Silvicultural Development Method (SDM). The first involves selective tree logging, resulting in stands with an uneven age distribution, *i. e.*, mixed-age stands. This method may require frequent, labor-intensive silvicultural practices and interventions. SDM is a method for managing even-aged stands; its objective is to maximize the soil's productive potential through the application of appropriate silvicultural techniques tailored to each forest condition (Ramírez-Maldonado, 2017).

Sampling units (SU) were established using a grid of points spaced 100 m apart, generated from Landsat 8 images (OLI sensor). Twenty-three circular sampling plots of 1 000 m^2 (Figure 1) were delineated based on the frequency of silvicultural treatments: three in *RGC*-Regeneration cutting, five in *RC*-Release cutting, 10 in Thinnings (*T2* and *T3*) under the Silvicultural Development Method (SDM), with an altitudinal range of 2 757-2 855 m, and five in *SL*-Selective logging, corresponding to the Mexican Method of Irregular Forest Management (MMOBI), at an altitude of 2 877 to 2 919 m.

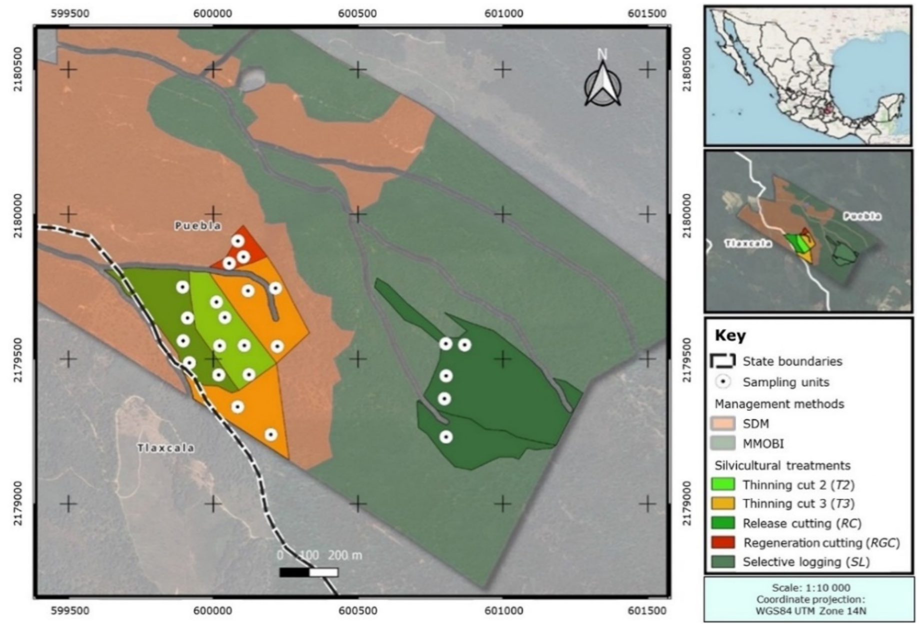


Figure 1. Study area, *Emiliano Zapata ejido*, *Chignahuapan*, *Puebla*, Mexico.

In each SU, the following dendrometric variables were recorded for trees with a diameter of ≥7 cm: age (Pressler-Haglöf® borer, inner diameter of 5.15 mm), height (Suunto® Clinometer % and 0 to 90°), normal diameter (Mantax blue *Haglöf*® 95 cm aluminum caliper), canopy cover (50-m Truper® measuring tape); in addition, the physical condition of the trees was recorded (Comisión Nacional Forestal [Conafor], 2017).

Litter sampling was conducted according to the methodology of the National Forest and Soil Inventory (Conafor, 2017) in four 0.25 m^2 subplots per sampling unit (one in each cardinal direction/quadrant). The forest floor was divided into the leaf litter (LL) and fermentation (FE) layers (92 samples per layer). The total forest floor layer (*Tot*) was obtained by adding the LL and FE layers. The data collection took place during the wet season (September 2023) and the dry season (May 2024). In the experimental plots, soil data on temperature (°C; model TE VA-100 AVALY® analog or penetration-type needle thermometer), moisture content (%), and *pH* (Keway Soil Tester, Kel Instruments Co. Inc.®, Japan) were recorded. Measurements were taken weekly (between 10:00 and 11:00 a. m., at a depth of 20 cm) over a period of five months.

The analysis of the LL and FE layers' samples was conducted at the National Laboratory of Soil Fertility and Plant Nutrition of the *Instituto Nacional de Investigaciones Forestales*, *Agrícolas y Pecuarias* (National Institute of Forestry, Agricultural and Livestock Research), located at the *Bajío* Experimental Site in *Celaya*, *Guanajuato*, Mexico. The leaf litter was dried at 70 °C for 72 hours in a forced-air oven (model FE-292AD FELISA®); it was then weighed on an electronic balance accurate to the nearest hundredth of a gram (model PA3202 OHAUS®) and ground with a mill (Willey-Arthur Thomas H. Co. Scientific Apparatus®). The carbon content (*CO %*) was determined using the dry digestion method at 900 °C; the total nitrogen content (*NT %*) was determined using the Kjeldahl method, with a model UDK159Velp Scientifica® distillation-titration unit (Mamani et al., 2020). The carbon content was calculated by multiplying the *C* concentration by the biomass (total weight) of each sample. The organic carbon was estimated using the Van Bemmelen index, assuming that organic matter contains 58 % carbon (López-Merlín et al., 2015; Pérez-Vázquez et al., 2021).

The *C:N* ratio was calculated based on the percentages of carbon and nitrogen in both layers (LL and FE) of the mulch (Equation 1); this ratio provides an estimate of the degree of decomposition of the soil organic matter (Kirkby et al., 2011). A high *C:N* ratio indicates low relative *N* availability (in some cases, *N* immobilization), while a low *C:N* ratio tends to increase *N* availability:

$$C{:}N\ ratio = \frac{OC}{TN} \qquad (1)$$

Where:

OC = Organic carbon (%)

TN = Total nitrogen (%)

The basimetric area was estimated from the diameter at breast height (*DBH*) measurements (Equation 2).

$$BA_i = \frac{\pi \cdot DBH_i^2}{4} \qquad (2)$$

Where:

BA_i = Individual basimetric area of tree *i* (m^2)

DBH_i = Diameter at breast height of tree *i* (m)

π = Constant (3.1416)

The basimetric area per sampling unit was calculated by adding up the individual basimetric areas of all recorded trees and was expressed in m^2 ha^{-1}, using the scaling factor corresponding to the size of the sampling unit (1 000 m^2).

Generalized Linear Models (GLM)

A database was constructed containing 384 estimates of the *C:N* ratio. The normality of the data was assessed using the Shapiro-Wilk test (W=0.95964; p=1.597×10^{-8}) (Zar, 2010), and the homogeneity of variances was assessed using Levene's test (p=9.278×10^{-9}), which revealed a non-Gaussian distribution. Nonparametric tests were applied: the Kruskal-Wallis test for differences in the *C:N* ratio between the LL and FE layers, and the Wilcoxon-Holm test (Holm, 1979) for comparisons between forestry treatments.

For the interannual variations, the change delta was estimated as the difference between the 2024 and 2023 averages. Multicollinearity was assessed using Spearman's correlations with the 'cor' function from the 'stats' package in R version 4.5.2 (R Core Team, 2024). The variables remained below a correlation threshold of 0.70 (Table 1).

Table 1. Variables used in the linear models (only variables with a correlation of less than 0.7 are shown).

Acronym	Set of variables	
Temp	Maximum temperature July	Minimum temperature September
	Maximum temperature August	Minimum temperature October
	Maximum temperature September	Temperature range August
	Maximum temperature October	Temperature range September
	Minimum temperature July	Annual temperature delta
	Minimum temperature August	
pH	Maximum *pH* July	Minimum *pH* August
	Maximum *pH* August	Minimum *pH* September
	Maximum *pH* September	Minimum *pH* October
	Maximum *pH* October	*pH* range July
	Minimum *pH* July	*pH* range September
		Annual *pH* delta
M	Maximum moisture July	Minimum moisture July
	Maximum moisture August	Minimum moisture August
	Maximum moisture September	Minimum moisture September
	Maximum moisture October	Minimum moisture October
		Annual moisture delta
Silvicultural	Release cutting (*RC*)	Thinning cut 3 (*T3*)
	Thinning cut 2 (*T2*)	Selective logging (*SL*)
	Regeneration cutting (*RGC*)	
Substratum_ type	Fermentation layer (FE)	Litter layer (LL)
Mensuration	*Abies religiosa* (Kunth) Schltdl. & Cham. basimetric area	*Pinus greggii Engelm. ex* Parl. basimetric area
	Alnus acuminata Kunth basimetric area	*Pinus teocote* Schied. *ex* Schltdl. & Cham. basimetric area
	Arbutus xalapensis Kunth basimetric area	*Quercus crassifolia* Bonpl. basimetric area
	Pinus ayacahuite Ehrenb. *ex* Schltdl. basimetric area	*Quercus rugosa* Née basimetric area
Period	Data sampled in 2023	Data sampled in 2024

Temp = Soil temperature (maximum and minimum); *pH* = Soil *pH*; M = Soil moisture; Silvicultural = Silvicultural treatment (*RGC*-Regeneration cutting, *RC*-Release cutting, *T2*-Thinning 2; *T3*-Thinning 3, and *SL*-Selective logging); Substratum_Type = % of *C* (Carbon), and % of *N* (Nitrogen) in litter (Fermentation layer [FE] and Leaf litter layer [LL]); Period = Variable registration date (2023 and 2024).

The *C:N* ratio in the LL and FE layers was analyzed using Generalized linear models (GLMs) with a Gamma (log) distribution, since the response variable is continuous, positive, and asymmetric. To assess the significant effects on the *C:N* ratio, a comprehensive model was fitted that included all the variables in Table 1, and separate models were fitted for LL and FE. This approach made it possible to assess the predictive power and stability of the ratios across years.

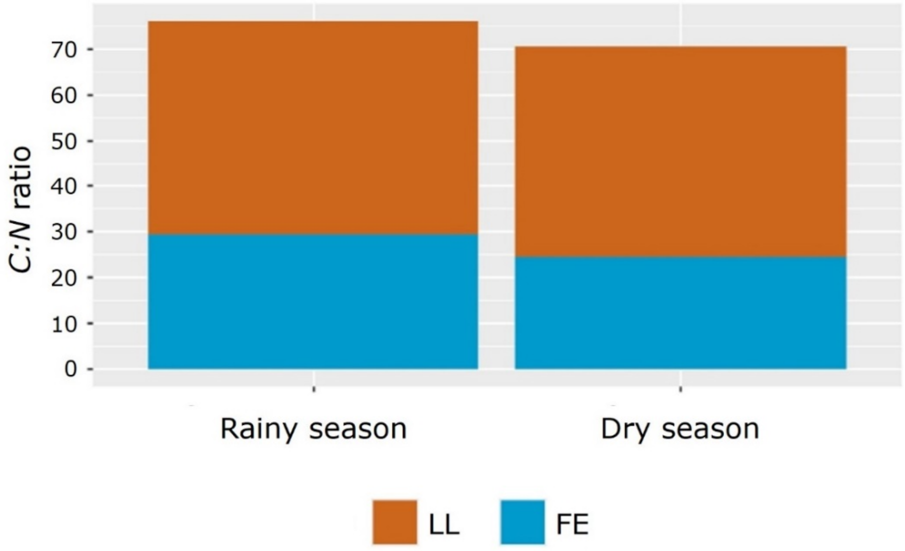
The variables were selected by minimizing the Akaike Information Criterion (*AIC*), using the 'step' function (with the 'both' option) of the 'stats' package. Because the traditional R^2 is not applicable to GLM, Nagelkerke's pseudo-R^2 was used, estimated with the 'bruceR' package. The metric ranged from 0 to 1, which facilitated a comparative assessment of the fit between models and the individual contribution of each predictor or variable (Bao, 2023).

Piecewise structural equation modeling (PSEM)

The direct and indirect relationships between treatments and soil microenvironmental variables were determined using a Piecewise structural equation model (PSEM) in the R software, version 4.5.2 (R Core Team, 2024). Silvicultural treatments served as predictor variables, while response variables included variations in temperature (*Temp_delta*), moisture (*M_delta*) and soil *pH* (*pH_delta*). The independence of the model was assessed using Fisher's test (Zar, 2010).

Results and Discussion

The *C:N* ratio of the litter showed a distinct seasonal response, particularly in the fermentation fraction (FE), while that of the leaf litter (LL) remained relatively constant across seasons (Figure 2). This behavior suggests that seasonal changes modulate transformation/mineralization processes and, consequently, the availability or retention of nitrogen within advanced decomposition fractions, while the functional contribution of the LL layer remains more stable (Davidson & Janssens, 2006). Thus, the seasonal variation in the *C:N* ratio can be interpreted as the result of changes in biological activity and decomposition dynamics in the FE fraction, with a lesser influence on LL (Manzoni et al., 2012).



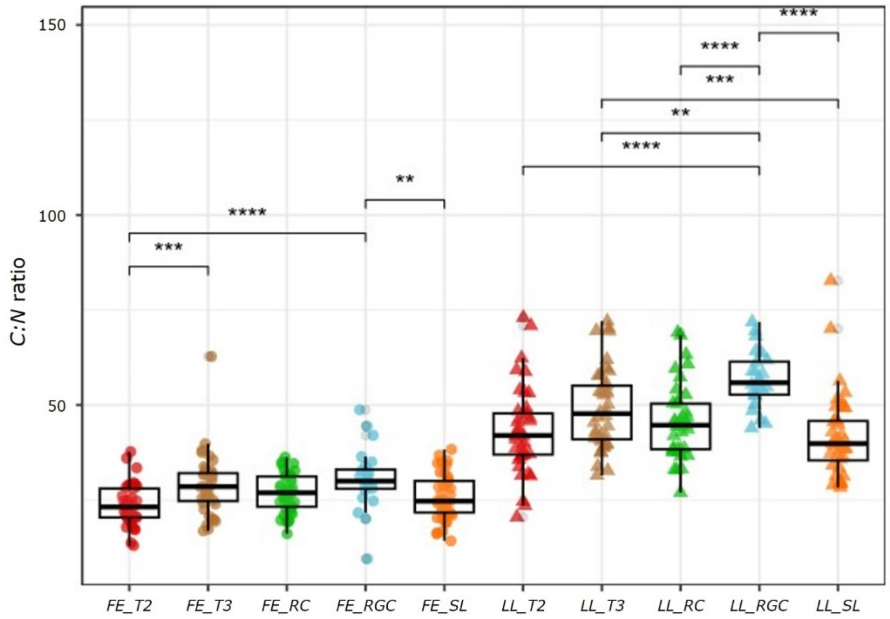
LL = Leaf litter; FE = Fermented litter.

Figure 2. Seasonal effects on the *C:N* ratio on litter in areas under forest management.

The Kruskal-Wallis test was significant ($p<0.001$), suggesting differences in the *C:N* ratio between the leaf litter layer (LL) and the fermentation layer (FE). This pattern was consistent with the generalized linear models (GLM), which revealed different dynamics in the responses and effects of the *C:N* ratio with both litter layers. This is associated with the ongoing mineralization of organic matter in the presence of moisture (60-70 %) and high temperatures (~30 °C) (Spohn & Stendahl, 2024).

Effect of silvicultural treatments on the *C:N* ratio on litter

In the LL layer, the Kruskal-Wallis test revealed significant differences between the silvicultural treatments (X^2=22.35, *df*=4, *p*<0.001). The Wilcoxon test identified five significantly different pairs, indicating variability between treatments in the accumulation of *C* and *N*. The Regeneration cutting (*RGC*) showed significantly higher *C* and *N* values in the LL, while Selective logging (*SL*) and Thinning 2 (*T2*) had the lowest values (Figure 3). The fermentation layer (FE) showed low values across treatments. Similarly, the Kruskal-Wallis test was significant (X^2= 22.29, *df*=4, *p*<0.001) for the treatment groups (*T2*, *T3*, *RC*, and *SL*) at the FE layer level (*p*<0.001) according to the Wilcoxon-Holm test (Holm, 1979).



FE_T2 = Fermentation layer in the silvicultural treatment Thinning 2; *FE_T3* = Fermentation layer in the silvicultural treatment Thinning 3; *FE_RC* = Fermentation layer in the Release cutting silvicultural treatment; *FE_RGC* = Fermentation layer in the Regeneration cutting silvicultural treatment; *FE_SL* = Fermentation layer with the silvicultural treatment known as Selective logging. *LL_T2* = Litter layer with the Thinning 2 silvicultural treatment; *LL_T3* = Litter layer with the Thinning 3 silvicultural treatment; *LL_RC* = Litter layer with the silvicultural treatment known as Release cutting; *LL_RGC* = Litter layer with the silvicultural treatment known as Regeneration cutting; *LL_SL* = Litter layer with the silvicultural treatment known as Selective logging. $^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$.

Figure 3. Box-and-whisker plot of the *C:N* ratio in managed temperate forests, at the silvicultural treatment and litter type levels (litter [LL] and fermented litter [FE]).

These findings support the hypothesis that the *RGC* had a positive effect by promoting carbon accumulation in the FE layer. The silvicultural practices of *SL* and *T2* showed contrasting patterns for *N* (Figure 3), with *T2* exhibiting lower values than Selective logging. These differences are associated with changes in the soil microenvironment resulting from the type of silvicultural treatment. The higher accumulation of *C* in the

RGC indicates less decomposition of the litter and a decrease in the relative availability of *N*; these results are consistent with those reported in the literature (Getino-Álvarez et al., 2023; Kuśmierz et al., 2023).

The *C:N* ratio is an indicator of the mineralization of nitrogen available to plants and of the quality of organic matter (Prévost-Bouré et al., 2010). In this study, the LL layer ranged from 41.8 to 48.7, and the FE layer, from 21.3 to 28.5, depending on the silvicultural treatments; these figures are similar to those recorded in managed forest soils (Dai et al., 2001). The increase in *N* is attributed to the microbial decomposition of organic matter (Alhamd et al., 2004).

Interactions between layers and mechanisms

The variability observed between the LL and FE layers can be explained by their different responses to the various silvicultural practices and microclimatic variations. Although both layers respond to changes caused by forest management, the magnitude and direction of their responses differ (Table 2), highlighting the need to evaluate them separately (Cano-Flores et al., 2020).

Table 2. A global model of the substrate variable, as well as models for the litter (LL) and fermentation (FE) layers.

Model	*AIC*	Nagelkerke's R^2	Variables	Estimator	*P* value
Global	2 566.388	0.655	*Min_temp_Oct*	-0.146	<0.001
			Annual_temp delta	0.178	<0.001
			Max_pH_Jul	-0.141	<0.001
			Min_pH_Jul	0.146	<0.001
			Max_pH_Oct	0.083	<0.001
			Max_M_Jul	0.165	<0.001
			Min_M_Sep	0.071	<0.001
			Substratum type	0.547	<0.001
			Period	0.099	<0.001
Interannual variability		0.705	*Max_temp_Sep*	-0.035	<0.001
			Temp_range_Sep	0.046	<0.001
			Substratum type	0.457	<0.001
			RC	0.145	<0.001
			T3	0.178	<0.001
			RGC	0.131	<0.001

Min_temp_Oct = Minimum temperature in October; *Annual_Temp_delta* = Variations in annual temperature; *Max_pH_Jul* = Maximum *pH* in July; *Min_pH_Jul* = Minimum *pH* in July; *Max_pH_Jul* = Maximum *pH* in July; *Min_pH_Oct* = Minimum *pH* in October; *Max_M_Jul* = Maximum moisture in July; *Min_M_Sep* = Minimum moisture in September; *Type of substratum* = Litter layer (LL: Leaf litter layer, FE: Fermentation layer); *Period* = Years 2023 and 2024; *Max_Temp_Sep* = Maximum temperature in September, *Temp_range_Sep* = Temperature range in September; *RC* = Release cutting; *T3* = Thinning 3; *RGC* = Regeneration cutting (Silvicultural treatments).

The FE layer had a lower *C:N* ratio than that determined in the LL layer, where the moisture content and the degree of decomposition are higher. The former ranged between 8.6 and 12.3 Mg ha^{-1}, while the latter ranged from 32.2 to 61.1 Mg ha^{-1} (Figure 3). The higher *C:N* ratio observed in the LL is consistent with the presence of recently incorporated residues that are less decomposed, while the lower values in the FE reflect material that is further along in its biogeochemical transformation process. The organic matter present on the soil surface exhibited high heterogeneity, both in terms of quantity and distribution; however, it constitutes the primary source of carbon for the soil system and plays a significant role in carbon accumulation and sequestration processes in forest soils (Cano-Flores et al., 2020).

The carbon stock in the LL of the silvicultural treatments ranged from 3.7 to 5.7 Mg ha^{-1} (Figure 3), while in the FE it ranged between 11.6 and 16.5 Mg ha^{-1}. The higher accumulation of carbon in the fermentation layer (FE), along with lower *C:N* ratios, is consistent with advanced decomposition processes and a higher relative proportion of nitrogen in this layer. These results are consistent with estimates of carbon stocks in litter from other forest types (Pérez-Vázquez et al., 2021), indicating that the decomposition/transformation process does not occur evenly along the LL→FE pathway; rather, the shift toward FE is associated with a decrease in the *C:N* ratio. In this regard, it has become clear that assessing the mineralization dynamics of litter under field conditions is complex due to its heterogeneous composition, comprising residues from trees, shrubs, and herbaceous plants with varying chemical and structural characteristics (De Frenne et al., 2021). The decomposition of these materials is essential to the functioning of ecosystems, as it controls the rates of recycling of essential nutrients and the dynamics of carbon in soils (Valladares-Samperio & Galicia-Sarmiento, 2021)

Environmental variables and seasonality

The *C:N* ratio showed high sensitivity to intra-annual environmental variations, particularly during periods of extreme temperature or moisture (Table 2). However, the interannual temperature variability also plays an important role in the dynamics of the *C:N* ratio, as decomposition and mineralization rates may vary from year to year, even under similar short-term climatic conditions (Gregorich et al., 2017).

Recent studies have highlighted that temporal trends in decomposition and mineralization are linked to interannual climate variability (Althuizen et al., 2018). This supports the idea that future climate scenarios could alter the correlations between *C* and *N* in surface layers, with implications for long-term carbon pool estimates.

Prediction of the *C:N* ratio and silvicultural treatments

The models showed a good fit when estimating the *C:N* ratio for 2024 based on the variables recorded in 2023 (Nagelkerke R^2=0.74), indicating a high explanatory power of the set of predictors considered. This result suggests that the silvicultural treatments and associated microenvironmental conditions contribute to the interannual variation in the *C:N* ratio in the litter (Leyva-Pablo et al., 2021). Temperature was a key variable in explaining the interannual dynamics of the *C:N* ratio; this is consistent with literature, which indicates that temperature variation is a determining factor in predicting carbon or nitrogen accumulation in the fermentation layer (Latterini et al., 2023).

Silvicultural treatments and the *C:N* ratio

The *T2* treatment was the only one to show a significant effect; this suggests that certain types of silvicultural interventions alter the *C:N* ratio in a detectable way when their interaction with the temperature is taken into account (Table 2). *T2* had the lowest *C:N* values compared to the *RGC*, indicating greater *N* availability and a higher degree of litter decomposition. In the case of *T2*, canopy opening resulting from thinning alters the soil microenvironment, suggesting that reduced disturbance of the forest floor could lead to a different dynamic in the relative uptake of *N versus C* during litter decomposition. This promotes microbial activity and accelerates decomposition processes, leading to greater nitrogen availability and, consequently, lower *C:N* ratios. In this sense, the harvesting intensity acts as a modulator of the soil microclimate, which controls the decomposition/transformation of litter (LL→FE) through changes in the chemical structure represented by the *C:N* ratio; thus, low-intensity forest management practices (*T2* and *SL*) can promote the incorporation of higher-quality organic matter and improve the soil conditions that sustain the stability of non-mineralizable organic carbon (Spohn & Stendahl, 2024).

The *C:N* ratio of the litter also depends on the degree of decomposition of the LL and FE layers, which is influenced by three main factors: climate, litter quality, and the abundance of decomposing organisms (Rocha-Loredo & Ramírez-Marcial, 2009). In this study, the differences are reflected in the lower *C:N* ratios in the fermentation layer (FE), indicative of a higher degree of decomposition compared to the leaf litter layer (LL). Furthermore, the variation observed among treatments, particularly in *T2*, suggests that management-induced changes in the soil microenvironment (temperature and moisture) regulate microbial activity and decomposition rates. In addition, decomposition involves physical and chemical processes that transform organic matter into more stable forms (Rocha-Loredo & Ramírez-Marcial, 2009).

Layer-by-layer dynamics: LL and FE

In regard to the prediction and influence of the silvicultural treatments, most of the variation was significant for the *C:N* ratio (Table 2), which is associated with interactions between management practices and temperature. It should be noted that only the *RGC* showed a significant effect ($p<0.026$) on the LL layer when linear models were applied (Table 3). This suggests that *RGC* influences carbon and nitrogen accumulation in the short term, especially when combined with temperature fluctuations or interannual changes in *pH* that modulate decomposition and mineralization. Within this context, MMOBI and SDM have potential positive effects by diversifying nutrient availability and maintaining cover continuity, which can result in greater incorporation of high-quality organic carbon and a lower decomposition rate of the non-mineralizable fraction (Leyva-Pablo et al., 2021).

Table 3. Generalized linear models for determining the dynamics associated with the silvicultural treatments and the *C:N* ratio at the litter layer level.

Model	Type	Nagelkerke's R^2	Variables	Estimator	*P* value
General	LL	0.213	*Max_pH_Jul*	-0.051	0.035
			RGC	0.190	0.026
	FE	0.364	*Max_temp_Jul*	0.345	<0.001
			Max_temp_Oct	0.230	<0.001
			Min_temp_Aug	0.275	<0.001
			Min_temp_Sep	-0.744	<0.001
			Max_pH_Jul	-0.250	<0.001
			Max_pH_Aug	-0.428	<0.001
			Max_pH_Oct	-0.648	<0.001
			Min_pH_Sep	0.160	<0.001
			Annual_pH_delta	-0.255	<0.001
			Max_M_Aug	0.332	<0.001
			Min_M_Sep	-0.686	<0.001
			Period	0.204	<0.001

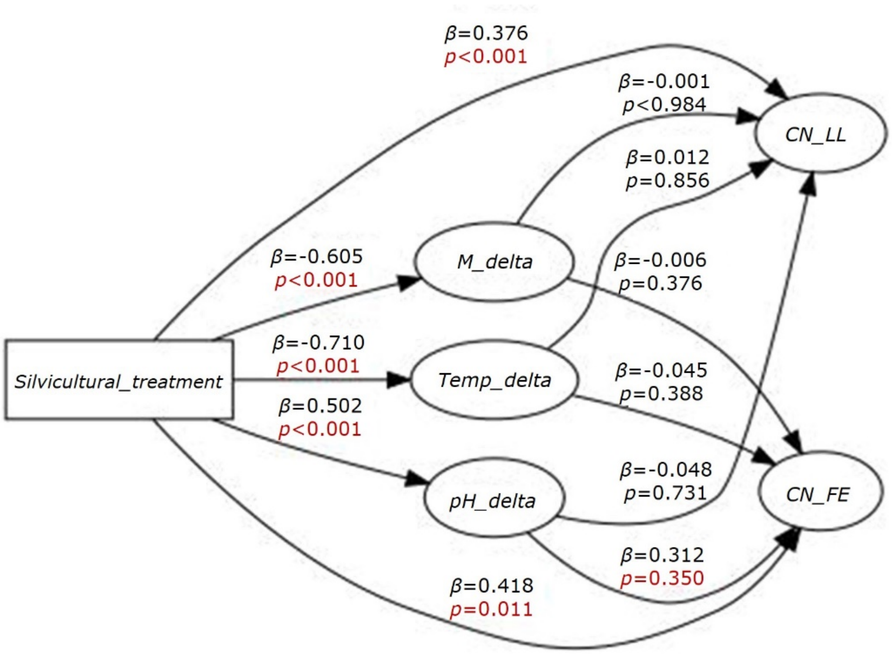
Max_pH_Jul = Maximum *pH* in July; *RGC* = Regeneration cutting; *Max_temp_Jul* = Maximum temperature in July; *Max_temp_Oct* = Maximum temperature in October; *Min_temp_Aug* = Minimum temperature in August; *Min_temp_Sep* = Minimum temperature in September; *Max_pH_Jul* = Maximum *pH* in July; *Max_pH_Aug* = Maximum *pH* in August; *Max_pH_Oct* = Maximum *pH* in October; *Min_pH_Sep* = Minimum *pH* in September; *Annual_pH_delta* = Variations in the annual *pH*; *Max_M_Aug* = Maximum moisture in August; *Min_M_Sep* = Minimum moisture in September; *Period* = Years 2023 and 2024.

Carbon and nitrogen accumulations exhibit interannual variability, supporting the idea that both monthly patterns and interannual variations influence the dynamics of the *C:N* ratio in the surface layer (Althuizen et al., 2018; Zhang et al., 2015). In FE, the *C:N* ratio may have accounted for interannual variations in *pH*, while, in the LL, the maximum *pH* value in July proved to be a significant variable (Table 2). Among the soil variables, the maximum *pH* in July stood out as a significant variable (p<0.005), consistent with evidence identifying interannual *pH* as a significant predictor of decomposition and mineralization in the surface soil layers (Kuśmierz et al., 2023; Spohn & Stendahl, 2024).

Treatment-environment interactions

GLMs had a significant effect on the *C:N* ratio in the *RGC* silvicultural treatment for the LL layer (Table 2), particularly in their interactions with interannual variations in temperature and *pH* (Figure 2). There are two possible explanations for the limited importance of silvicultural treatments in the models used: (I) The treatments significantly alter *C:N* ratio patterns so that a linear model cannot capture them; and (II) Environmental variables, including basimetric area per species, may be overrepresented, leading to overfitting (Table 2 and 3).

The structural equation model revealed significant direct effects of silvicultural practices and soil variables. In particular, significant direct effects were observed on temperature change (*Temp_delta*, β=-0.710, p<0.001), as well as on soil moisture (*M_delta*, β=-0.605, p<0.001) and *pH* (*pH_delta*, β=0.502, p<0.001) (Figure 4). These results suggest that the alteration of surface soil conditions caused by low-intensity cutting (*T2* and *SL*) leads to a decrease in temperature and an increase in *pH*, thereby modifying the processes associated with the decomposition and mineralization of organic matter (Gilliam et al., 2004; Kuśmierz et al., 2023).



CN_FE = Carbon:Nitrogen ratio (*C:N*) in the fermentation layer (FE); *CN_LL* = Carbon:Nitrogen ratio (*C:N*) in the leaf litter layer (LL); Silvicultural_treatment = Silvicultural treatment; *M_delta* = Moisture; *Temp_delta* = Temperature; *pH_delta* = *pH*. Standardized coefficients (*β*) and *p*-values. Significant ratios are shown in red (*p*<0.05).

Figure 4. A structural model that determines the effect of silvicultural treatments on microenvironmental variables (temperature and moisture) at the soil level.

In this regard, it has been documented that the opening of the forest canopy—whether due to thinning or some other disturbance—reduces canopy density and allows direct sunlight to reach the forest floor, resulting in increased solar radiation and heat gain in that area (Paul et al., 2022). This increase tends to raise the temperature of the lower layer of the atmosphere directly above the canopy, especially under conditions of low relative moisture, when evaporation and transpiration do not offset the heat flux (Tong et al., 2024).

In this study, the magnitude of the effect of the temperature on the LL layer suggests that, under drier conditions, the interaction between surface warming, evaporation (in the litter layer), and transpiration dynamics was likely intensified at sites with greater canopy openness (Tong et al., 2024; Zhang et al., 2024).

On the other hand, changes in *pH* showed a significant association with the *C:N* ratio in both LL (β=0.376, *p*<0.001) and FE (β=0.418, *p*=0.011) layers, indicating variations in *pH* indirectly induced by silvicultural treatments. Such changes may be regulated by nutrient availability and microbial activity and thus influence carbon and nitrogen dynamics, being indicative of an indirect effect of the microenvironmental conditions (temperature and moisture) at the soil level on the carbon dynamics (Kuśmierz et al., 2023); *i. e.*, changes in *pH* alter the *C:N* ratios in the leaf litter and fermentation layers. For this reason, this variable and its interannual variation can be utilized in forest management to explain and predict soil *C* and *N* reserves (Spohn & Stendahl, 2024).

Conclusions

The silvicultural treatments evaluated, particularly Thinning cut 2 (*T2*), alter the surface soil conditions (temperature, moisture, and *pH*), which is reflected in indirect changes in litter decomposition and in the dynamics of carbon and nitrogen (*C:N*) in the litter and fermentation layers. These effects suggest that forest management alters key microenvironmental processes with implications for ecosystem resilience; however, the effects depend on the specific design of the intervention (intensity, type of cutting, regeneration scheme) and on the regional soil and climate conditions. Therefore, management practices require local adaptation and monitoring to mitigate negative impacts on the *C:N* ratio.

A significant difference in the *C:N* ratio between LL and FE has been confirmed, which justifies a layer-by-layer analysis and highlights the need to include both layers in the assessment of the impact of management practices on the *C:N* ratio.

The results suggest that the interaction between silvicultural practices and soil microenvironmental conditions plays a key role in litter dynamics, as well as in regulating the carbon accumulation and transformation processes in forest ecosystems.

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Conflict of interest

The authors declare that they have no conflict of interest. Dr. Bertha Patricia Zamora Morales, Dr. Leticia Bonilla Valencia, and M.Sc. Marisela Cristina Zamora Martínez declare that they had no involvement in the editorial process of this manuscript.

Contribution by author

Bertha Patricia Zamora-Morales: design, implementation, and monitoring of field activities, analysis and processing of field and laboratory data, and drafting of the original manuscript; Aurelio Báez-Pérez: field monitoring, sample analysis and processing, contribution to the drafting of the manuscript; Marisela Cristina Zamora-Martínez: drafting of the manuscript, technical review and editing; Leticia Bonilla Valencia: data analysis and drafting of the manuscript; Arian Correa-Díaz: information revieew of and contribution to the drafting of the manuscript; Omar Santiago-Clemente: data analysis and drafting of the manuscript; Ismael Fernando Chávez-Díaz: revision of the manuscript.

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