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Research article

**Characterization of forest fuels in a pine-oak forest
under forest management in the *Sierra Tarahumara*,
Chihuahua, Mexico**

**Modelos Acoplados en México Caracterización de
combustibles forestales en un bosque de pino-encino
bajo manejo forestal en la Sierra Tarahumara,
Chihuahua**

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Abstract

Over time, forest fires have shaped the form and structure of forest ecosystems; one essential element for their occurrence is forest fuels, which can be altered to influence fire behavior. The objective of this research was to assess the load of dead forest fuels in two areas with timber harvesting and a diverse vegetation cover in the years 2013 and 2021. The planar intersection technique was used to estimate woody fuels; leaf litter and the fermentation layer were collected and dehydrated to determine their weights. The averages for the years 2013 and 2021 were 43.21 Mg ha⁻¹ and 55.22 Mg ha⁻¹, respectively. The results showed that the woody fuel load was higher in 2013, but the organic layer was larger in 2021. The light (leaf litter and fermentation) materials accumulated the highest total amount of fuel in both years, with 61.46 and 76.53 %, respectively. The high proportion of fuel in the organic layer implies the need to develop strategies for its management, as it is considered key to the ignition of a fire; if the effects of climate change are taken into account, fires are expected to increase in frequency.

Keywords: Load fuel, soil fermentation layer, leaf litter, fire, management, planar intersection.

Resumen

A lo largo del tiempo, los incendios forestales han modelado la forma y estructura de los ecosistemas forestales; uno de los elementos esenciales para su ocurrencia son los combustibles forestales, que pueden ser alterados para incidir en el comportamiento del fuego. El objetivo de esta investigación fue evaluar la carga de combustibles forestales muertos en dos áreas con aprovechamiento maderable y diferente cobertura vegetal (anualidades 2013 y 2021). Para la estimación de combustibles leñosos se utilizó la técnica de intersecciones planares; la hojarasca y la capa de fermentación fueron recolectadas y deshidratadas para el cálculo del peso. Los promedios para las anualidades 2013 y 2021 fueron de 43.21 Mg ha⁻¹ y 55.22 Mg ha⁻¹, respectivamente. Los resultados mostraron que la carga de combustibles leñosos fue superior en la anualidad 2013, pero la capa orgánica fue mayor en la anualidad 2021. El material liviano (hojarasca y fermentación), acumuló la mayor cantidad de combustible total en ambas anualidades con 61.46 y 76.53 %, respectivamente. La alta proporción de combustible en la capa orgánica implica el desarrollo de estrategias para su manejo, ya que se considera clave para el inicio de un incendio; si se consideran los efectos del cambio climático, se espera que los incendios aumenten su frecuencia.

Palabras clave: Carga de combustible, capa de fermentación, hojarasca, incendio forestal, manejo forestal, intersecciones planares.

Introduction

Climate change has increased the frequency of forest fires, especially in highly sensitive regions (forests, jungles) (Sparks et al., 2018). Fires can occur naturally or be caused by human activities, and are one of the most significant disturbances in forest ecosystems (González-Tagle et al., 2020, 2023). As a disturbance, fires affect the structure and composition of forests (Ávila-Flores et al., 2014; Elia et al., 2020; Huang et al., 2019). According to *Comisión Nacional Forestal* (Conafor, 2024), in the last 50 years, almost 400 000 forest fires have been recorded in Mexico, of which 32 000 occurred in the state of *Chihuahua*, and 570, in the *Guachochi* region in the last decade. Forest fuel assessment studies are essential, as they enable fuel management, the identification of risk areas, and the modeling of fire's behavior (Ortiz-Mendoza et al., 2024), as well as the estimation of carbon storage and the quantification of pollutant gas emissions (Harris et al., 2019; Rodríguez-Trejo et al., 2020).

The natural load of forest fuels (branches, twigs, fruits, logs, roots) depends on the cover of different types of vegetation, which generates differences in the density,

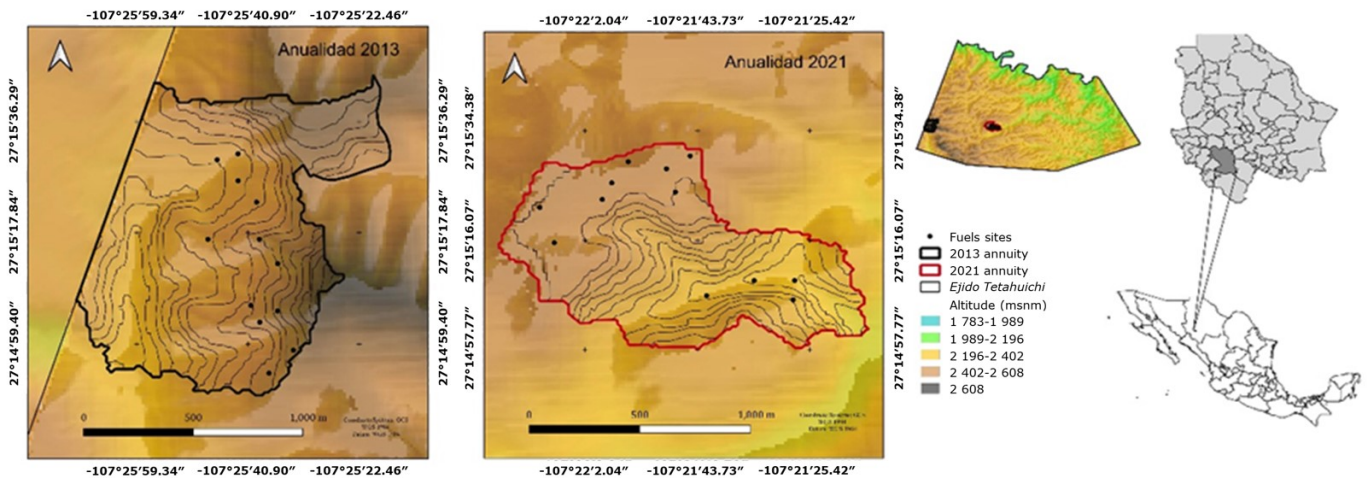
quantity, and quality of combustible material, all factors that determine fire's behavior (Torero, 2013; Xelhuantzi-Carmona *et al.*, 2011). However, such practices as illegal logging, phytosanitary control, and forest harvesting activities also contribute to increasing the amount of wood waste (Franco *et al.*, 2009; Rentería-Anima *et al.*, 2005). Therefore, the technical management of a forest requires quantifying fuel accumulation (Caballero-Cruz *et al.*, 2018). One of the most widely used techniques for evaluating dead fuel *in situ* is planar intersection (Brown, 1974).

In Mexico, fuels have been studied in different ecosystems and regions by Rentería-Anima *et al.* (2005) in *Durango*, Rodríguez-Trejo *et al.* (2011) in *Yucatán*, Chávez-Durán *et al.* (2021) in forests of *Jalisco*, and Ruíz-Corzo *et al.* (2022) in *Chiapas*, among others. Within this context, the objective of this study was to determine the dead fuel load in two areas under forestry use (2013 and 2021) in a temperate mixed forest, under different vegetation covers. To this end, two hypotheses were proposed: (a) The accumulation of forest fuels increases in areas where more time has elapsed since harvesting, and (b) The forest fuel load varies significantly depending on the vegetation cover, being higher in sites with high cover and lower in those with low cover.

Materials and Methods

Study area

This study was conducted in a temperate forest in the *Sierra Tarahumara*, part of the *Sierra Madre Occidental* (SMO), in the *ejido Tetahuichi* of the municipality of *Guachochi*, in *Chihuahua*, Mexico. In two areas corresponding to the 2013 and 2021 forest harvesting annuities (Figure 1). The first area, corresponding to the 2013 annuity, is located at the extreme coordinates 27°14'50" to 27°15'45" North latitude and -107°25'16" to -107°26'10" West longitude, and the second (2021), between 27°14'57" and 27°15'33" North latitude, and -107°21'11" and -107°22'16" West longitude, at an altitude of 2 300 to 2 440 meters above sea level.



Anualidad 2013 = 2013 annuity; *Anualidad 2021* = 2021 annuity

Figure 1. Geographic location of the study areas: *ejido Tetahuichi*, *Guachochi* municipality, in the state of *Chihuahua*, Mexico.

According to García and *Comisión Nacional para el Conocimiento y Uso de la Biodiversidad* (García & Conabio, 1998), the climate in the *ejido* is Cb'(w₂)x' —i. e., semi-cold subhumid temperate subhumid—, with an average annual rainfall of 800 mm; the main soil types are Luvisol and Regosol (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2007). Extreme temperatures range from -13 to 31.5 °C, with an average annual temperature of 10.6 °C (Balderrama-Castañeda et al., 2011). The mix of species is made up of the pine-oak forest (BPQ), composed of *Pinus arizonica* Engelm., *P. durangensis* Martínez, *P. leiophylla* Schiede ex Schltdl. & Cham. var. *chihuahuana* (Engelm.) Shaw, *P. strobiformis* Engelm., and, to a lesser extent, *P. lumholtzii* B. L. Rob. & Fernald, as well as *Quercus sideroxyla* Bonpl., *Q. rugosa* Née, *Juniperus deppeana* Steud., and *Arbutus xalapensis* Kunth.

The Mexican Method for Irregular Forest Management (MMOBI, Spanish acronym) is applied in the *ejido*, using selection and thinning treatments, with a cutting intensity of 30 % and a cutting cycle of 15 years (Beltrán-Bustamante, 2012).

Selection of the sampling areas

The delimitation of the communal land area into micro-basins made it possible to select two work areas, namely, the 2013 and 2021 forest exploitation annuities of the current forest management program (FMP). At the time of measurement (2023), the areas had accumulated fuel during ten and two years, respectively. The selection was based on similarity criteria related to their pine-oak forest vegetation, the applied silvicultural treatments, their altitude, and the fact that they have the same type of climate. Table 1 shows the characteristics evaluated at the sampling sites that reflect the variability of the terrain in the area.

Table 1. Summary of slopes and exposures recorded in the forest-fuel sampling transects in pine-oak forests.

Annuity	Transects	Minimum slope (%)	Maximum slope (%)	Medium slope (%)	Exposures
2013	36	8	48	21.77	NW, S, SE, and W
2021	36	4	38	15.44	N, NE, NW, E, S, SE, and SW

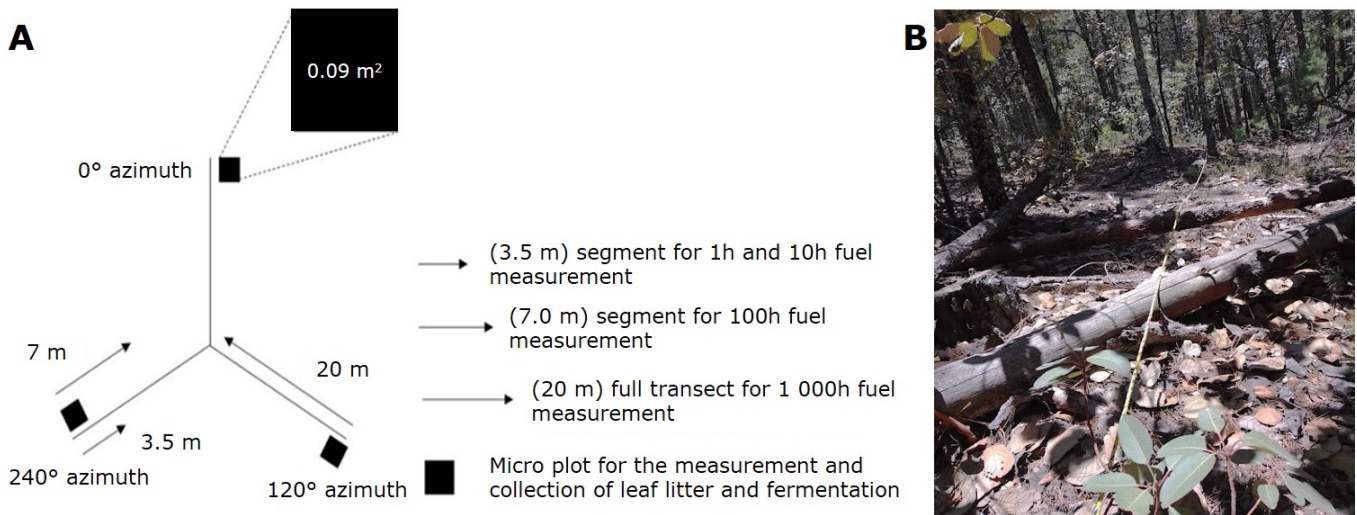
The vegetation cover was determined using high-resolution satellite images (Microsoft, 2023) from the SAS Planet software version 230909.10403 Stable (SAS.Planet, 2023), which allows collecting satellite images and cartographic data from various online servers. Once the scenes corresponding to each micro-basin had been defined, the supervised classification method was applied (Jensen, 2015). Using this procedure and the texture of each image, the vegetation cover was defined and classified as high cover (HC), medium cover (MC), and low cover (LC).

The method developed by Castañeda-Rojas et al. (2015) was adapted and modified for use with a 100×100 m grid over the digital layer of these covers, in order to determine the cover percentages per hectare and distribute the sampling sites accordingly. Twelve sampling sites per annuity, *i. e.*, 24 sites total, were randomly distributed using QGis v 3.28 (QGis Development Team, 2022).

Fieldwork

The measurement was carried out in July and October 2023, using the planar intersection method (Brown, 1974) adapted by Morfin-Ríos et al. (2012). Each site was georeferenced with a model eTrex 20 Garmin® GPS. Three 20-meter transects were drawn from the center, using a model F-5010 Brunton® compass to determine

their orientation. Thirty-six litter samples and 36 samples from the fermentation layer were collected each year from a 0.09 m² microplot located at the end of each transect (Figure 2A). These were weighed (model NV422 Navigator Ohaus® precision scale) and dehydrated (model H-41 Riossa® drying oven) in the laboratory of the Faculty of Agricultural and Forestry Sciences at the Autonomous University of Chihuahua, in Ciudad Delicias, Chihuahua.



A = Array used to record the fuel load and structure present at the site; B = Field view showing the distribution of fine and coarse combustible material.

Figure 2. Schematic for quantifying and surface disposition of forest fuels.

The litter samples analyzed were a mixture of pine and oak species, among which *Pinus durangensis*, *P. leiophylla* var. *chihuahuana*, *Quercus rugosa*, and *Q. sideroxyla* predominate (Figure 2B).

In both annuities, 2 500 m² vegetation sampling plots were established, and their main attributes were recorded (Table 2).

Table 2. Tree characteristics of the pine-oak sampling areas.

Annuity	No. of species	Trees ha⁻¹	Mean diameter (cm)	Basal area (m² ha⁻¹)	Average height (m)
2013	8	828	18.06	28.24	12.57
2021	9	708	17.26	20.72	8.84

Laboratory work and fuel weight estimation

The classification of wood fuel, measured and quantified, was carried out based on the diameter of each piece, in accordance with the criteria established by Fosberg et al. (1970). The leaf litter and fermentation samples were dehydrated during 72 hours at a constant temperature of 70 °C in a model H-41 Riossa® drying oven in the laboratory. Before and after they were placed in the oven, they were weighed on a model NV422 Navigator Ohaus® scale to calculate the weight or load of the materials and the difference between their weights.

Fuel loads were estimated using the equations described by Morfín-Ríos et al. (2012) (Table 3). The specific gravity estimation method (SG) consists of immersing dry pieces of forest fuel in liquid paraffin to make them waterproof and subsequently immersing them in water to determine their displacement and thus calculate the SG (Nalder et al., 2000). The fine fuel load per hectare was estimated by extrapolating the data obtained from the 0.09 m² microplot. Statistical analyses were performed using R v. 4.4.1 (R Core Team, 2024).

Table 3. Equations used to calculate forest fuels.

Combustibles de 1, 10 y 100 h	Combustible de 1 000 h
$C = \frac{(k) SG (MSD) (f) (c)}{L}$	$C = \frac{(k) SG \Sigma (SD) (c)}{L}$

C = Fuel load (Mg ha^{-1}); $k = 1.234$; SG = Specific gravity; MSD = Mean square diameter for fuels; SD = 1 000h fuel square diameter; diameter range of fuels 1h (0-0.5 cm), 10h (0.6-2.5 cm), 100h (2.6-7.5 cm), and 1 000h (>7.5 cm); f = Number of pieces' frequency; c = Slope correction; L = Length of the transect.

Statistical analysis

Based on field information regarding the different types of fuels, the woody material was integrated as having a delay of 1, 10, 100 and 1 000 hours (C-1h, C-10h, C-100h, and C-1 000h), and leaf litter and fermentation material (C-lit and C-fe). Six comparison groups were formed, differentiated by high, medium, and low coverage, followed by the corresponding annuity (HC-2013, MC-2013, LC-2013, HC-2021, MC-2021, and LC-2021) (Table 4). The normality and homogeneity of the variances of the fuel load data across the different groups were verified using the Shapiro-Wilk and Levene's tests, respectively. The statistical differences were determined using an analysis of variance (ANOVA) with a 95 % confidence level, and the Tukey *post hoc* test ($\alpha=0.05$), or utilizing the nonparametric Kruskal-Wallis test of rank means, and applying Dunn's test to calculate the differences between groups (Hood et al., 2018).

Table 4. Average fuel load, by combustive agent class and group, considering the type of cover and annuity, including the Shapiro-Wilk normality tests and Levene homoscedasticity tests.

Grupo	n	Average values of dead biomass expressed in Mg ha ⁻¹						
		C-1h	C-10h	C-100h	C-1 000h	C-lit	C-fe	Total
AC-2013	12	0.38 _a	2.78 _a	4.40 _a	11.37 _a	14.66 _{ab}	17.28 _{ab}	50.87 _a
AC-2021	12	0.31 _{ab}	1.86 _{ab}	3.40 _a	7.97 _a	14.97 _{ab}	30.76 _a	59.26 _a
MC-2013	12	0.37 _a	2.26 _{ab}	4.85 _a	12.48 _a	14.31 _{ab}	14.35 _b	48.64 _{ab}
MC-2021	12	0.27 _{ab}	2.12 _{ab}	3.17 _a	10.45 _a	18.41 _a	26.93 _a	61.34 _a
BC-2013	12	0.30 _{ab}	2.13 _{ab}	3.10 _a	5.56 _a	10.71 _b	8.37 _b	30.16 _b
BC-2021	12	0.21 _b	1.51 _b	2.67 _a	4.92 _a	16.91 _{ab}	18.84 _a	45.06 _{ab}
2013	36	0.35	2.39	4.11	9.8	13.23	13.33	43.21
2021	36	0.26	1.83	3.08	7.78	16.76	25.5	55.22
Shapiro-Wilk		W=0.87 p<0.001	W=0.96 p=0.06	W=0.95 p=0.012	W=0.78 p<0.001	W=0.91 p<0.001	W=0.96 p=0.06	W=0.98 p=0.35
Levene		F=0.17 p>0.97	F=0.75 p=0.58	F=0.89 p=0.48	F=0.90 p=0.48	F=1.83 p=0.11	F=2.55 p=0.03	F=0.87 p=0.50

Statistical differences by group in each fuel class are indicated by different letters.

HC = High cover; MC = Medium cover; LC = Low cover; n = Number of samples;

C-lit = Litter; C-fe = Fermentation.

Results and Discussion

The average fuel load for 2013 was 43.21 Mg ha⁻¹, and 55.22 Mg ha⁻¹ for 2021. The statistical test showed a difference between the total loads ($F_{1, 70}=8.61$, $p=0.004$); however, the first hypothesis was rejected because the time elapsed since harvesting did not influence fuel accumulation.

In terms of load by cover type, the 2013 annual yield was 50.87 Mg ha⁻¹ in closed covers (HC), 48.64 Mg ha⁻¹ in medium covers (MC), and 30.16 Mg ha⁻¹ in open areas

(LC). The estimates for 2021 showed an increase in load (HC=59.26; MC=61.34, and LC=45.06 Mg ha⁻¹). The corresponding covers showed differences of 8.39, 12.7, and 14.9 Mg ha⁻¹, respectively. Once the assumptions of normality for the coverage load ($W=0.98$, $p=0.35$) had been verified, an ANOVA was applied, which revealed differences between the coverages ($F_{5, 66}=5.44$, $p<0.001$); the Tukey test showed differences between the HC-2013, HC-2021, and MC-2021 coverages with respect to the LC-2013 coverage. Therefore, the variation in total load on the roofs of both annuities supports the second hypothesis, as it shows that roofs with high coverage registered a larger accumulation of flammable material (Figure 3 and Table 4).

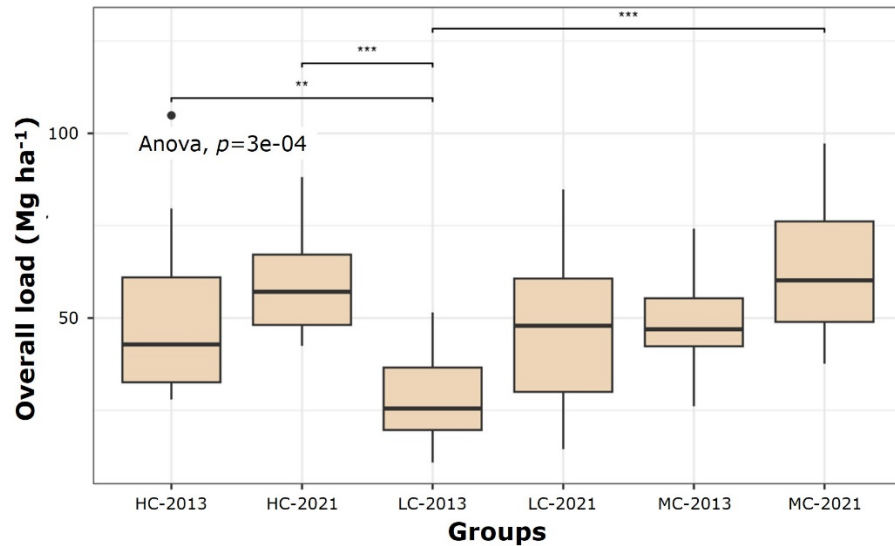


Figure 3. Statistical test of fuel load by type of vegetation cover for the 2013 and 2021 annuities.

The estimated average loads for both annuities are considered high (43.21 and 55.22 Mg ha⁻¹, respectively) compared to the 17.9 Mg ha⁻¹ of temperate forest (Xelhuantzi-Carmona *et al.*, 2011), and they exceed 7.09 Mg ha⁻¹ in burned forest and 31.72 Mg ha⁻¹ in unburned areas (Bonilla-Padilla *et al.*, 2013). However, similar values have been documented in low and high tree densities, with loads of 50.51 and 46.79 Mg ha⁻¹, respectively, in a temperate forest of Oaxaca (Caballero-Cruz *et al.*, 2018). This shows that fuel accumulation responds to forest structure conditions and forest

management practices that generate residues, which in this case were chipped and spread for soil protection purposes (Beltrán-Bustamante, 2012).

Together, the layers of leaf litter and fermentation accounted for 61.46 % of total fuel in 2013, while in 2021 they accounted for 76.53 %; both values are lower than those cited by Chávez-Durán et al. (2021) in protected forests in *Jalisco*, who mention that loads above 100 Mg ha⁻¹ have the highest risk in conflagrations. The high load values in the organic profile of this study are due mainly to the composition and structure of the forest, as well as to silvicultural management; therefore, the risk of ignition will depend primarily on the greater amount of flammable fuel in these surface layers.

One-hour fuels (C-1h) had the lowest loads in both years; the average was 0.35 Mg ha⁻¹ for 2013 and 0.26 Mg ha⁻¹ for 2021. This type of fuel accounts for less than one percent of the total in each year.

This fuel category had statistical differences ($X^2=21.48$, *d. f.*=5, $p<0.001$). According to Dunn's test, differences were observed between the high and medium cover groups in 2013, compared to low cover groups in 2021, with respective means of 0.38, 0.37, and 0.21 Mg ha⁻¹ (Table 4). The loads are similar to those reported by Castañeda-Rojas et al. (2015) in *Pinus hartwegii* Lindl. forests of central Mexico. Meanwhile, in grasslands and savannas, they differ by amounts less than 0.17 Mg ha⁻¹ (Rodríguez-Trejo et al., 2020). This suggests that fuel accumulation is influenced by the type of cover, which favors the accumulation of combustibles; moreover, these materials are rapidly decomposed by microorganisms and environmental factors, becoming part of the organic layer (Tapia-Coronado et al., 2022). However, even in small quantities, it still poses a risk, as it promotes the rapid spread of fire.

C-10h fuels accumulated an average of 2.39 and 1.83 Mg ha⁻¹ during the 2013 and 2021 annuities —values that represent 5.53 and 3.31 % of the fuel contribution in each year. The statistical analysis showed a discrepancy ($F_{5, 66}=2.99$, $p=0.017$). The Tukey multiple comparison test showed differences between high and low cover in the HC-2013 and LC-2021 groups, with averages of 2.78 and 1.51 Mg ha⁻¹, respectively (Table 4). These results are similar to those observed by Hoffman et al.

(2007), whose values ranged from 1.79 to 2.35 Mg ha⁻¹. However, they differ from those of Rubio-Camacho *et al.* (2016) and Castañeda-Rojas *et al.* (2015), who recorded higher amounts in forests with different densities and in areas with and without evidence of fire, respectively.

According to Xelhuantzi-Carmona *et al.* (2011), when tree density is high, the material load tends to be greater; thus, differences in biomass load are a consequence of variations in tree density and coverage. Therefore, the accumulation of smaller combustible material in high cover allows the fire to spread quickly and continuously to higher categories of woody material.

The average fuel load for C-100h was 4.11 and 3.08 Mg ha⁻¹, equivalent to 9.51 and 5.58 % of the contribution of this class of combustibles for the years 2013 and 2021. The statistical test showed no differences between the groups ($X^2=7.82$, *d. f.*=5, $p=0.16$), and Dunn's multiple comparison test confirmed this. Even though numerical differences were observed in the extreme means of the MC-2013 and LC-2021 groups (4.85 to 2.67 Mg ha⁻¹, respectively). Internal variability was high, as verified by the Coefficient of variation, a factor that explains the absence of statistical differences between the groups.

The average C-100h fuel load is similar to that reported by Hoffman *et al.* (2007) in areas slightly affected by parasites, and contrasts with that described by Barrios-Calderón *et al.* (2024), with higher values. On the other hand, lower loads of this type of fuel have been documented in grasslands, ranging between 0.23 to 0.37 Mg ha⁻¹ (Rodríguez-Trejo *et al.*, 2020). The differences in fuel load between forests and grasslands are due to greater biomass and vegetation cover density in temperate ecosystems.

C-1 000h fuels accumulated average amounts of 9.8 Mg ha⁻¹ (22.67 %) and 7.78 Mg ha⁻¹ (14.09 %) for 2013 and 2021, respectively. The Kruskal-Wallis test showed no differences between groups ($X^2=3.65$, *d. f.*=5, $p=0.6$). Although the average fuel fluctuated from a minimum of 4.92 to a maximum of 12.48 Mg ha⁻¹ in the LC-2021 and MC-2013 groups (Table 4); the Coefficient of variation showed high internal dispersion, indicating a strongly heterogeneous distribution, which limited the Dunn test to detecting statistical differences. These loads were lower than those cited by

Castañeda-Rojas et al. (2015) and Barrios-Calderón et al. (2024) in forests in the Center and South of the country.

The C-1 000h and C-100h fuel class groups showed no statistical differences due to high internal variability. However, the highest volumes were found at sites with a broad cover. By nature, these types of fuels are incorporated into the forest floor gradually and steadily, increasing as a result of extreme weather events and human activities. Rentería-Anima et al. (2005) point out that they are decisive factors due to the intensity and duration of incineration and the difficulty of controlling them.

Leaf litter (C-lit) was the second largest source of fuel in both annuities, with average values of 13.23 and 16.76 Mg ha⁻¹, equivalent to 30.61 and 30.35 % of the total fuel in 2013 and 2021, respectively. The statistical analysis revealed differences ($X^2=14.49$, $d. f.=5$, $p=0.012$). The Dunn multiple comparison test showed a difference between the LC-2013 group and the medium cover group for the 2021 annuity (Table 4). The results showed moderate variability.

The rate of leaf litter decomposition is related to environmental factors such as temperature and humidity (Bonilla-Padilla et al., 2013). Decomposition occurs slowly in temperate ecosystems (Ibarra et al., 2011). Some studies, like those by Moreno-Valdez et al. (2018) and Rodríguez-Balboa et al. (2019), have shown that the 99 % decomposition rate of leaf litter can be prolonged from 10.8 to 29 years in temperate forests. For their part, Fry et al. (2018) indicate that the needles accumulated in *Pinus jeffreyi* Balf. forests decay very slowly, at a rate of 7 to 11 % per year.

The amount of litter recorded in this study was higher than that observed by Xelhuantzi-Carmona et al. (2011) and Rubio-Camacho et al. (2016). Fry et al. (2018) note that annual litterfall in *Pinus jeffreyi* forests is variable. This type of oxidizer increases the risk of ignition and increases the speed at which fire propagates (Scott et al., 2014).

The fermentation layer (C-fe) was the most abundant fuel in both annuities; the average values were 13.33 and 25.51 Mg ha⁻¹ for 2013 and 2021, respectively, equivalent to 30.84 and 46.18 % of the total fuel in each area. The nonparametric Kruskal-Wallis test revealed differences between the groups ($X^2=27.16$, $d. f.=5$,

$p < 0.0001$). According to Dunn's comparison test, differences were found between high and medium cover for the 2021 annuity, compared to medium and low coverage for the 2013 annuity (Table 4).

Various factors, such as slopes, exposure, cover, humidity, and temperature, among others, may have had different effects on each area evaluated, which affected the biological activity of microorganisms in terms of decaying organic matter (Bonilla-Padilla *et al.*, 2013; Martínez-Atencia, 2013); this led to fermentation and increased the load, unlike in less humid areas, which slow down the decomposition process and increase the organic layer.

The results coincide with those obtained by Rubio-Camacho *et al.* (2016), who note that the fermentation layer was the fuel with the highest contribution in temperate forests. Similarly, Rodríguez-Trejo *et al.* (2011) registered 13.14 Mg ha⁻¹ of fermentation in areas highly affected by natural disturbance.

Conclusions

This study contributes to the understanding of fuel load distribution in different pine-oak forest cover types. The characterization carried out is a fundamental technical element that supports the design and implementation of short-, medium-, and long-term planning and control strategies aimed at mitigating forest fires in the region.

The accumulation of fuel in the 2013 annuity did not show an increase in the total load in relation to the time elapsed since the exploitation. Although the woody material accumulated a greater amount of fuel compared to 2021, the first hypothesis was not fulfilled. The variation in fuel by type of cover in both annuities led to accept the second hypothesis.

Differences in fuel loads by type of cover and age are mainly due to forest composition and structure, environmental conditions, and forest management; the organic profile load is a priority concern due to the risk it poses in terms of fire ignition and spread. In the future, it will be necessary to expand the sampling network to characterize fuel loads at the regional level, taking into account the nature and dynamics of materials in areas with and without forest exploitation. This will enable the prediction of fire's behavior based on factors such as species composition, structure, and forest cover, thereby identifying priority areas for forest fire prevention, response, and control.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Aldo Saúl Mojica Guerrero: field sampling, laboratory work on the samples, data analysis, and drafting of the document; Marco Aurelio González Tagle: sampling design, revision of the document; Luis Ubaldo Castruita Esparza: field sampling, provision of laboratory facilities for the sample analysis, revision of the document; Wibke Himmelsbach: revision of the document; Óscar Alberto Aguirre Calderón: revision of the document; Israel Yerena Yamallel: revision of the document.

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