Article

Productivity and vertical structure of a temperate forest with incidence of forest fire

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Abstract:

The effects caused by a forest fire, the vertical structure and the association of tree species and their relation to productivity were evaluated through mensuration variables. Field work was performed in two areas, burned and non-burned, in which 36 circular sites of 11.28 m radius and 400 m^2 were established. A classification in three strata was made based upon the Pretzsch index: stratum I (80-100 %), stratum II (50-80 %) and stratum III (0-50 %). Productivity was determined using mensuration data as individual density (ha^{-1}), basal area (m^2 ha^{-1}), crown area (m^2 ha^{-1}) and volume (m^3 ha^{-1}). Productivity for statistical analysis was performed by the r-Studio® program (Ver. 3.1.1), through a comparison of means between independent groups of parameters. Analysis of the vertical structure using the *A* Pretzsch index showed that the burned area was higher with 2.71 against 2.20 A_{max} in the non-burned area. Stratum II concentrated more individuals per hectare in the two areas (50 % and 33 %), with a maximum height of 23.9 and 26 m, respectively. Productivity increased in the burned area, which is explained from the *Pinus pseudostrobus* abundance, while the non-burned area recorded less individuals per hectare, deferred from lower proportionality in volume (m^3 ha^{-1}). It is concluded that there are structural and productivity benefits in a forest with fire incidence.

Key words: Maximum height, burned area, vertical stratification, *A* Pretzsch index, mensuration parameters, forest productivity.

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Introduction

Pine forests in Mexico are the most widely distributed among different types of coniferous forests; they cover about 75 % of their potential distribution, estimated at just over 10 million hectares, although well-preserved forests cover only 5.2 million hectares (Inegi, 2003; Inegi, 2009).

Orographic processes and climatic fluctuations of the past have led to the diversification and speciation of vegetation in Mexico, which is considered the most important center of global pine diversity with 50 % of known species and 33 % of oaks (Nixon, 1993; Styles, 1993; Challenger, 2003; Koleff *et al*., 2004).

The natural productivity of forest ecosystems results in goods and services for society, and it is estimated that the global timber harvest for 2009 in the country was 42.98 million m^3 (Caballero, 2010). *Pinus patula* Schiede ex Schltdl. & Cham and *Pinus pseudostrobus* Lindl. are two of the forest species preferred from their high increases in commercial plantations in several countries (Caballero, 2000).

There is little quantitative research on the relationship between structural complexity and tree diversity with the productivity of temperate forest ecosystems; however, some studies have shown that diversity indexes are reduced with the increase in basal area removed and average productivity tends to increase with increasing removal (Návar and González, 2009).

Agricultural activities are the main cause of the loss of forests and tropical forests, followed by illegal clearing and forest fires (FAO, 2006). The deterioration of forest ecosystems is accentuated by several factors, of which fires are one of the most serious disturbances (González and Rodríguez, 2004). The number of fires has increased over the last thirty years, a trend that seems to be related to the presence and severity of climatic events such as *El Niño*, and to the dead vegetation that accumulates after the hurricanes (Semarnat-Conafor, 2005). These events are discrete over time and modify the structure of an ecosystem, community or population and change the physical environment, substrate or availability of resources (Corral *et al.,* 2002; Caribello, 2003; Fried *et al*., 2004).

The structure of an ecosystem is basically defined by the type, number, spatial ordering and temporal ordering of the constituent elements (Aguirre *et al.*, 2003). In this context, the species structure and the dimensional structure of ecosystems stand out (Thomasius and Schmidt, 1996).

Biological diversity is defined by the complexity of topography, the variety of climates, and the connection of two biogeographic zones (neartic and neotropical) in the Mexican territory, which together form a varied mosaic of environmental conditions (Conabio, 2010).

The vertical structure of the forest is determined by the distribution of different tree species that compose an ecosystem and occupy sites defined in response to microclimatic factors, environmental gradients or to natural or man-made disturbance (Remmert, 1991). Each ecosystem has a unique stratification and spatial heterogeneity, given by the vertical and horizontal structure of the species that comprise it (Dajoz, 2002).

Some synecological studies have detected the environmental factors responsible for the change in the composition and structure of vegetation (Sánchez and López, 2003), and are especially useful for simplifying and ordering large and complex datasets (Rocha *et al*., 2006). The vertical order is characterized by the differentiation of height categories (Zarco-Espinosa *et al.,* 2010). Therefore, the objective of this study was to evaluate the effects of a forest fire and the complexity of the vertical structure, as well as the association of the species, relating productivity through mensuration indicators (abundance, dominance, frequency and the Importance Value Index).

Materials and Methods

The study area is located in the *Cerro Potosí*, between 24°49'08"-24°55'29" N and 100°13'25"-100 °14'05" W, at 3 719 masl in *Galeana* municipality, *Nuevo León* State; it is part of the *Sierra Madre Oriental* and extends over an area of 7 194 ha (Figure 1). The predominant vegetation is represented by coniferous forests, oak forests and mixed forests located at 2 000 masl (García *et al.,* 1999). They have also identified submontane scrub communities, chaparral, oak, in addition to *Quercus* spp., *Pinus pseudostrobus*, *Pinus ayacahuite* Ehrenberg ex Schltdl., *Pseudotsuga menziesii* (Mirb.) Franco, *Pinus hartwegii* Lindl., *Pinus strobiformis* Engelm. and *Pinus culminicola* Andresen & Beaman (Contreras *et al*., 2012). The predominant soil is Litosol combined with Rendzina (García, 1996). It has a C (E) (W_1) x' climate type, subhumid semicold; rains are scarce throughout the year and the total annual rainfall is between 400 and 600 mm, while the average temperature fluctuates between 12 and 18 °C (Arreola *et al*., 2010).

According to national statistics, in the 1998 fire season, about 9 000 fires affected approximately 220 000 ha of temperate, tropical and other vegetation types. For the 2003 season, about 100 000 ha of wooded areas had been burned, and by October 2006 there were 8 657 forest fires impacting around 240 000 ha (Conafor, 2006); in September 2013, about 415 000 ha had been affected and more than 100 000 fires were recorded throughout the country (Conafor, 2013). The phenomenon is associated with global climate change; the frequency and severity of fires increased, causing changes in the structure of the *Sierra Madre Oriental* forests, as occurred in 1998.

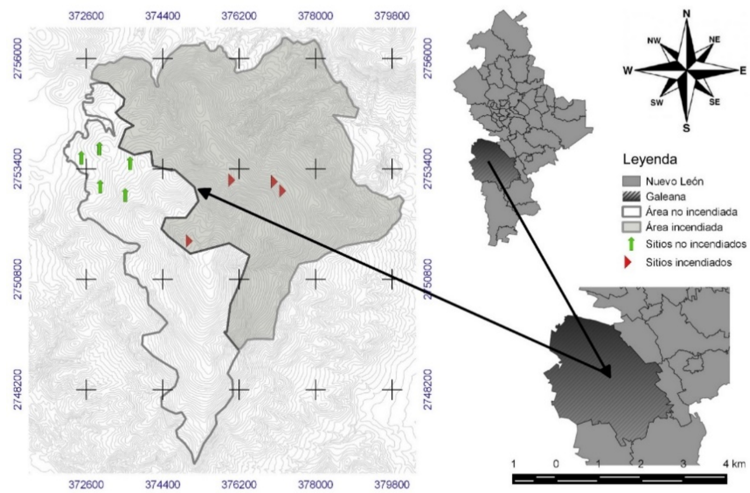


Figure 1. Location of the study area.

Sampling site

Nine sampling clusters were established in *Cerro El Potosí*, which were distributed in the area burned in 1998 and in adjacent areas not burned, in an altitudinal range between 2 800 and 3 600 m, with a slope not greater than 20°.

Each cluster consists of four sampling sites of 400 m^2, which is based on the national forest inventory methodology (Conafor, 2010); in each of them, the genus, species, normal diameter, total height, and two crown diameters (north-south, east-west) were recorded in trees whose normal diameter (DAP) was equal to or greater than 7.5 cm.

For the analysis of the vertical structure of forest species, Pretzsch index *A*, which is a modification of the Shannon index, was used to divide the vertical structure into three strata. This is represented in stratum I (high) corresponding to the interval of 80-100 %, where the tree with greater height represents 100 %; the following strata are classified as follows: II (medium), refers to the range of 50-80 % and III (low), ranges from 0-50 % (Aguirre, 2002; Pretzsch, 2009).

The *A* index comes from the maximum *A* value (A_{max}) provided by the number of species and the height strata; and the relative standardization (A_{rel}) in percentage. This index (*A*) is useful to determine the structural diversity of the vertical structure and is defined as follows:

$$A = \sum_{i=1}^{S} \sum_{j=1}^{Z} P_{ij} * In\ P_{ij} \quad (1)$$

$$A_{max} = ln(S * Z) \quad (2)$$

$$A_{rel} = \frac{A}{ln(S*Z)} * 100 \quad (3)$$

Where:

S = Number of species at the sample area

Z = Number of strata from tree height

P_{ij} = Percentage of species in each zone, which is estimated as follows:

$$P_{ij} = n_{i}{..}_{,j}/N$$

Where:

$n_{i,j}$ = Number of individuals of the same species (*i*) in the zone (*j*).

N = Total number of individuals

The variables to assess the productivity of the areas such as density (N ha^{-1}), basal area (m^2 ha^{-1}), crown cover (m^2 ha^{-1}) and volume (m^3 ha^{-1}), were estimated according to the following equations:

Density was calculated as the following equation describes:

$$D = N_i\left(\frac{Sh}{Se}\right) \qquad (4)$$

Where:

D = Number of individuals per hectare

N_i = Number of individuals per site

Sh = Surface area of each hectare (m^2)

Se = Assessed surface area (m^2)

The basal area was calculated for each area, by the following equation:

$$G = G_i\left(\frac{Sh}{Se}\right) \qquad (5)$$

Where:

G = Basal area per hectare

G_i = Individual basal area per site

Sh = Surface area of a hectare (m^2)

Se = Assessed surface area (m^2)

The crown area was determined for each area by the following equation:

$$Cc = Cc_i\left(\frac{Sh}{Se}\right) \qquad (6)$$

Where:

Cc = Cover per hectare

Cc_i = Individual cover per site

Sh = Surface area of a hectare (m^2)

Se = Assessed surface area (m^2)

Volume for each area was the result of the following equation:

$$V = V_i \left(\frac{Sh}{Se}\right) \quad (7)$$

Where:

V = Volume per hectare

V_i = Individual volume per site (m^3) (height * diameter *morphic coefficient of the species)

Sh = Surface area of a hectare (m^2)

Se = Assessed surface area (m^2)

For the of Importance Value Index (IVI), the relative values of abundance (*Ar*), dominance (*Dr*) and frequency (*Fr*) were used. *Ar* was calculated by dividing the number of individuals of each species (*n*) by the total number of individuals (*N*). For *Dr* the crown area was taken, dividing the surface of each species between the surface occupied by all species. *Fr* was estimated by dividing the frequency of each species (*f*) between the sum of frequencies of all species (*F*). Each indicator was multiplied by 100 to obtain relative values. To determine the IVI of each species, the three relative indicators (Müeller-Dombois and Ellemberg, 1974) were added.

To determine the productivity of the areas, the individual volume was calculated with the height and diameter variables, multiplied by the morphic coefficient, which is expressed in the following equation:

$$V_i = F(Dn * H) \qquad (8)$$

Where:

V_i = Individual volume per site (m^3)

F = Morphic coefficient

Dn = Normal diameter (cm)

H= Total height (m)

Also a production table for *Pinus pseudotrobus* made by Aguirre (1989) was used.

Data were analyzed using a nonparametric test (Shapiro-Wilcoxon) for the density, basal area, crown cover and volume variables, which were analyzed in R© v. 3.1.1 software; the generated routines were created under the software R-Studio© v. 0.99 (Alea *et al*., 2014).

Results

The tree species found in the study areas corresponded to the Pinaceae family; the most representative species based on their density were *Pinus pseudostrobus*, *Pinus strobiformis* and *Pinus hartwegii*; the *Pseudotsuga menziesii* and *Abies vejarii* Martínez were recorded only in the burned area (A1) (Table 1).

Table 1. List of tree species in the study area.

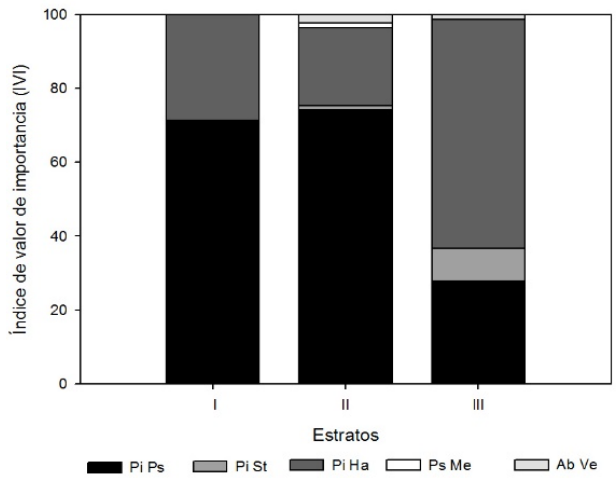
Family	Genus	Species	Area	Density
Pinaceae	*Pinus*	*pseudostrobus* Lindl.	A1	141
Pinaceae	*Pinus*	*strobiformis* Engelm.	A1	12
Pinaceae	*Pinus*	*hartwegii* Lindl.	A1	108
Pinaceae	*Pseudotsuga*	*menziesii* (Mirb.) Franco	A1	2
Pinaceae	*Abies*	*vejarii* Martínez.	A1	4
Pinaceae	*Pinus*	*pseudostrobus* Lindl.	A2	155
Pinaceae	*Pinus*	*strobiformis* Engelm.	A2	5
Pinaceae	*Pinus*	*hartwegii* Lindl.	A2	3

A1 = Burned area; A2 = Non-burned area

Pretzsch Index (A)

Five species of conifers were recorded in the burned area (A1) with a Pretzsch index of 2.26, an A_{max} of 2.71, characteristic of 83.5 % of diversity, suggesting that the distribution of species in the strata is 16.5 % of its maximum dimensional differentiation, *i. e,* that the stand is uniform.

The diversity of heights in the three strata of A1 presented *Pinus pseudostrobus* as the dominant species (72 % in stratum I), with a minimum difference in the trend of its dominance with respect to stratum II (71 %) and stratum III (28 %); *Pinus hartwegii* and *Abies vejarii* increased their importance in strata II and III, with values of 25 % and 2 % of IVI in stratum II, while in III *Pinus hartwegii* and *Pinus strobiformis* recorded 64 % and 7 % of IVI, respectively (Figure 2).



Pi Ps = *Pinus pseudostrobus*; Pi St = *Pinus strobiformis;* Pi Ha = *Pinus hartwegii*; Ps Me = *Pseudotsuga menziesii;* Ab Ve = *Abies vejarii.*

Figure 2. Behavior of the vertical structure of a burned area in *Cerro El Potosí*.

The dendrometric variables in A1, showed average values in diameter for *Pinus hartwegii* of stratum I of 49.5 cm; of layer II of 48.*7* cm and of layer III of 27.4 cm*.* The average diameter of *Pinus pseudostrobus* in stratum I was 46.6 cm*; Pinus strobiformis* in stratum II was 47.5 cm and lastly, *Pinus pseudostrobus* was 25.3 cm in stratum III.

Regarding the heights, in A1 an average of 23.7 m was calculated for *Pinus hartwegii* in stratum I. In II, the dominant species was *Abies vejarii* with 17.3 m of average height, and the co-dominant *Pinus strobiformis* with 16.2 m. In III it was 7.9 m for *Pinus pseudostrobus*, followed by *Pinus hartwegii* and *Pinus strobiformis*, with 7.3 and 5.9 m, respectively (Table 2). The maximum height was 23.9 m and the minimum of 3.3 m, corresponding to *Pinus hartwegii,* in the whole burned area.

Table 2. Importance Value Index (IVI) and mensuration variables (diameter and height) of the burned area (A1).

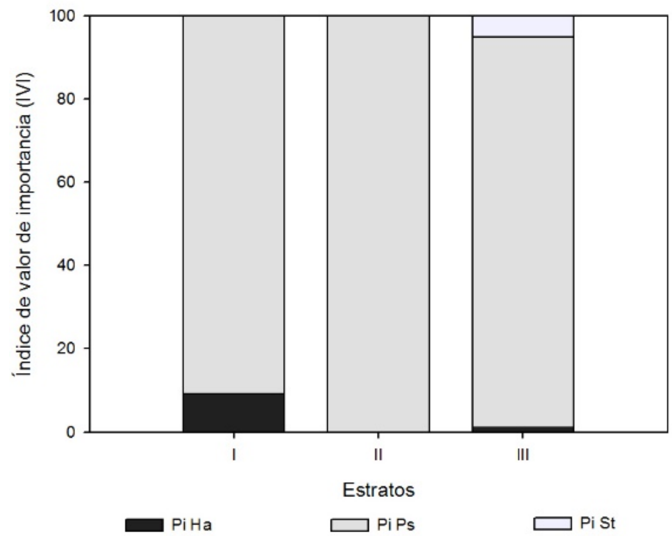
Stratum	Species	Abundance N ha^{-1}	Dominance G(m^2 ha^{-1})	Frecuency N $SubA^{-1}$	IVI	$d_{1.30}$			TH		
						Max	Mean	Min	Max	Mean	Min
I	Pi Ps	8	1.63	2	72	57	46.6	36	22.4	20.9	20
	Pi Ha	3	0.61	2	28	54	49.5	45	23.9	23.7	24
Total		11	2.24	4	100						
II	Ab Ve	3	0.44	2	2	44	42.3	41	18.1	17.3	17
	Pi Ha	28	5.39	4	25	85	48.7	12	18.5	15.2	12
	Pi Ps	98	11.85	12	71	74	42	10	18.1	15.1	12
	Pi St	2	0.28	1	1	48	47.5	48	16.2	16.2	16
	Ps Me	2	0.05	1	1	21	21	21	15	15	15
Total		133	18.01	20	100						
III	Ab Ve	2	0.01	1	1	8.6	8.6	9	4.3	4.3	4.3
	Pi Ha	77	3.04	5	64	50	27.4	5	11.3	7.3	3.3
	Pi Ps	34	1.33	11	28	40	25.3	11	11.8	7.9	4.2
	Pi St	11	0.21	1	7	24	15.9	8	7.8	5.9	4.2
Total		124	4.59	18	100						
Final total		268	25	42	300						

Pi Ps = *Pinus pseudostrobus*; Pi St = *Pinus strobiformis;* Pi Ha = *Pinus hartwegii*; Ps Me = *Pseudotsuga menziesii;* Ab Ve = *Abies vejarii;* SubA = Sub area (400 m^2); IVI = Importance Value Index; $d_{1.30}$ = Diameter at 1.30 m; TH = Total Height.

The non-burned area (A2) is characterized by the presence of three species, with a Pretzsch index of 0.58, A_{max} = 2.20, representing 26.4 % of the species diversity in all strata, of 73.6 %, that is, that the site has variability in the classes of heights for each of the strata.

In this area, *Pinus pseudostrobus* is the dominant species with 63 % in stratum I; for stratum II 100 %; while for stratum III, it was 65 %, followed by *Pinus strobiformis* with 34 %, while the associated species, *Pinus hartwegii,* corresponds to 1 % in stratum III (Figure 3).

In regard to the mensuration variables in A2, the average diameter of *Pinus hartwegii* was 57 cm in stratum I, and in stratum II, *Pinus pseudostrobus*, with 51 cm, while for stratum III it was 42.8 cm for the latter species (Figure 3).



Pi Ps = *Pinus pseudostrobus*; Pi St = *Pinus strobiformis;* Pi Ha = *Pinus hartwegii*; Ps Me = *Pseudotsuga menziesii;* Ab Ve = *Abies vejarii.*

Figure 3. Behavior of the vertical structure of a control area adjacent to the fire in *Cerro El Potosí*.

Pinus pseudostrobus was the representative species for heights in A2; for strata I and II, it measured 23.4 and 16.7 m, respectively. In III, the average height was 11.5 m for *Pinus hartwegii*, followed by *Pinus strobiformis* (8.7 m) and *Pinus pseudostrobus* (8.3 m) (Table 3). The maximum height was 26 and the minimum, 3.8 m, corresponding to *Pinus pseudostrobus* in the whole non- burned area.

Table 3. Importance Value Index (IVI) and mensuration variables (diameter and height) of the non-burned area (A2).

Stratum	Species	Abundance N ha^{-1}	Dominance G(m^2 ha^{-1})	Frequency N $SubA^{-1}$	IVI	$d_{1.30}$			TH		
						Max	Mean	Min	Max	Mean	Min
I	Pi Ps	13	2.32	3	63	56	48	40	26	23.4	21
	Pi Ha	1	0.32	2	37	57	57	57	22	22	22
Total		14	2.64	5	100						
II	Pi Ps	53	8.76	15	100	80	51	22	20.4	16.7	13
Total		53	8.76	15	100						
III	Pi Ha	1	0.02	1	1	15	15	15	11.5	11.5	12
	Pi Ps	90	2.31	9	65	78	42.8	8	12.8	8.3	3.8
	Pi St	5	0.11	4	34	22	16.5	11	10.4	8.7	7
Total		96	2.44	14	100						
Final total		163	13.84	34	300						

Pi Ps = *Pinus pseudostrobus*; Pi St = *Pinus strobiformis;* Pi Ha = *Pinus hartwegii*; Ps Me = *Pseudotsuga menziesii;* Ab Ve = *Abies vejarii;* SubA = Sub area (400 m^2); IVI = Importance Value Index; $d_{1.30}$ = Diameter at 1.30 m; HT = Total Height.

Productivity

The density in A1 was represented by 267 individuals per hectare and A2 by 163; the basal area of A1 was 24.83 m^2 ha^{-1}, greater than that of A2, 13.83 m^2 ha^{-1}, which can be explained by a higher number of individuals found with larger diameters and heights. On the other hand, the crown area of the first zone was 7.35 m^2 ha^{-1}, similarly higher than the second area, of 5 103 m^2 ha^{-1}, which is related to the basal area. The volume calculated in A1 was 238.89 m^3 ha^{-1} also higher than that of A2 (144.24 m^3 ha^{-1}), which is associated with its coverage and basal area (Figure 4).

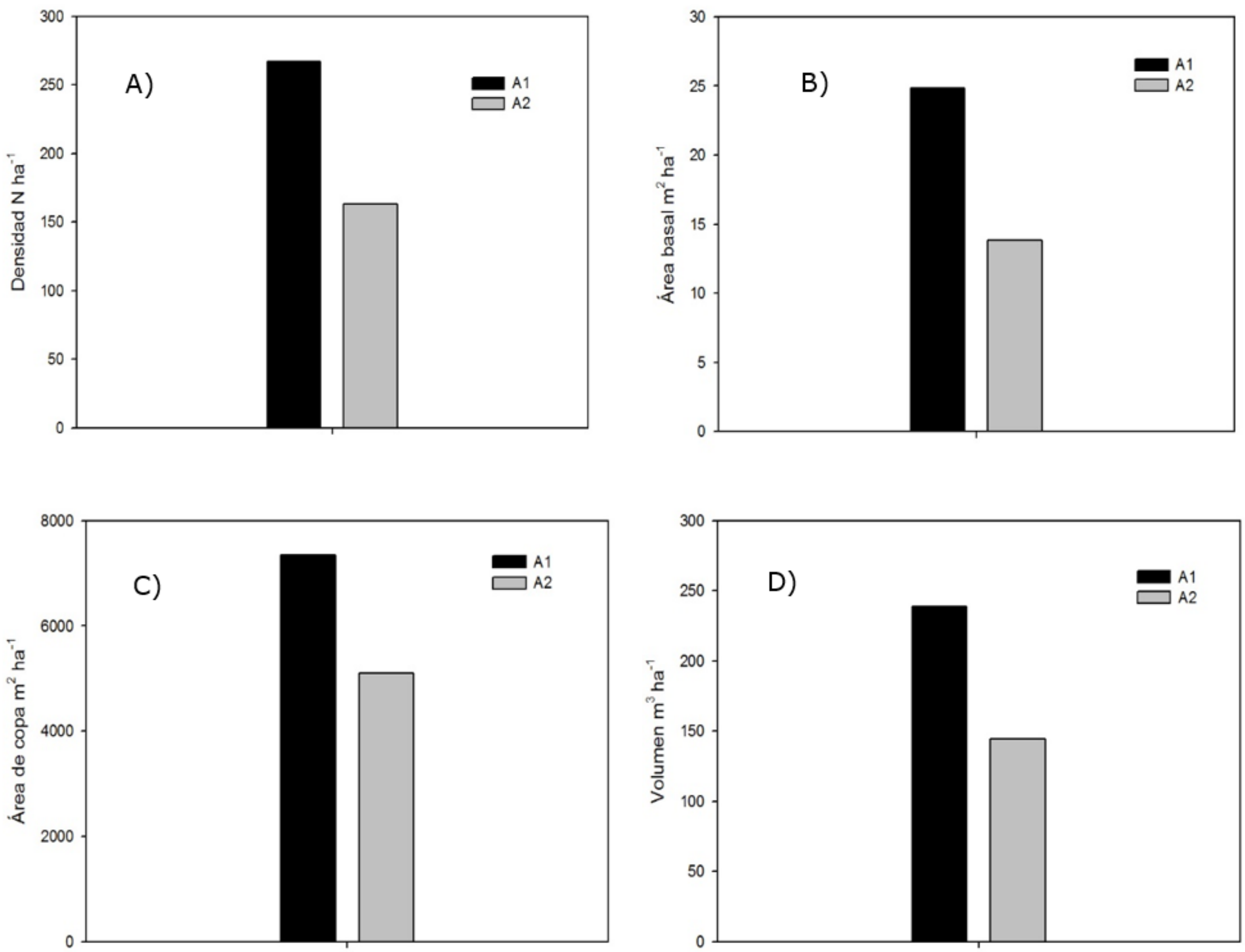


Figure 4. Forest productivity of a burned area (A1) and non- burned area (A2) in *Cerro El Potosí.*

Discussion

The largest species is *Pinus pseudostrobus* with 95.1 % (155 N ha^{-1}) for the burned area and 53.8 % (141 N ha^{-1}) for the non- burned area, lower than those reported by Domínguez *et al.* (2012), with 78 N ha^{-1}, representing 22.1 % of the total trees. *Pinus hartwegii* represents 41.2 % (108 N ha^{-1}) of individuals for the burned area and 1.8 % (3 N ha^{-1}) for the non-burned area, which are also below those recorded by Ávila *et al.* (2012) that were 185 N ha^{-1} for the burned forests. This species is classified as resistant to fire (Rodríguez *et al.,* 2004), which is reflected in the previous figures.

The evaluation of the vertical structure of the coniferous forest studied revealed that *Pinus pseudostrobus* was the most representative in the two compared sites (A1 and A2). The Importance Value Index (IVI) for this species in the burned area (A1) was 72 % in stratum I, 71 % in II and 28 % in III, which are higher than in the fire-free area (A2), which recorded 63 % in stratum I, 100 % in II and 65 % in III. Torres (2006) found similar results, since the main species in all strata was *Pinus pseudostrobus*, 100 % in the upper stratum (I), 85.8 % in the middle (II) and 37 % in the lower stratum (stratum III). As a dominant species, it is in association with *Quercus canbyi* Trel. and *Juniperus flaccida* Schlecht, in a minimal amount in stratum II and in a greater proportion in stratum III.

Vertical stratification, using the Pretzsch index, indicated that the burned area (A1) was better than the non-burned area (A2) by the calculated values: in A1, it was 2.26, A_{max} 2.71 and A_{rel} 83.5 %; These results are similar to those of Rubio *et al.* (2015), who in an area burned calculated an index of 1.86, Amax of 3.30 and A_{rel} of 56 %, indicating that the stand has medium uniformity, in terms of diversity in heights. The A2, recorded a Pretzsch A of 0.58, A_{max} 2.20 and A_{rel} 26.4 %; Rubio *et al.* (2015) in an unburned area calculated an A index of 2.01, with an A_{max} of 3.74 and an A_{rel} of 54 %; which means that the dimensional differentiation of height constitutes 46 %.

The average height and diameter recorded in the upper layer of the burned area (A1) was 20.95 m and 46.6 cm in *Pinus pseudostrobus*. The non-burned area (A2) had an interval of 23.5 m and 48 cm in diameter. Jiménez *et al.* (2001) calculated these dimensions for a pine-oak forest, 12.9 m and 26.1 cm (A1) and 23.5 cm and 13.9 m (A2), respectively.

The productivity of the burned area (A1) was better than that of the non-burned area (A2); there are significant differences in density, basal area, crown area and volume. The latter calculated in A1, for *Pinus hartwegii* and *Pinus pseudostrobus*, was 53.08 and 93.87 m^3 ha^{-1}; while for the fire-free area (A2), it was 3.78 and 111.10 m^3 ha^{-1}; therefore, this ecosystem is of great ecological and economic importance for the region. This agrees with the information of Rodríguez (2001), which describes that the forests of *Pinus hartwegii* increase their width in rings, which is reflected in increase in diameters, and up to 15 % in width of crowns. The basal area is 9.30 m^2 ha^{-1} for pine and 10.67 m^2 ha^{-1} for oak, with 1.38 m^2 ha^{-1}. The total volume for pine was 54.60 m^3 ha^{-1} and for oak 29.04 m^3 ha^{-1}. In comparison with mixed ecosystems, where succession changes diversity, Caspersen and Pacala (2001) and Vilá *et al*. (2007) noted that higher productivity is verified in forests in early successional stages.

Conclusions

Based on the results of this study, the hypothesis was rejected, as it was found that the species of conifers studied were benefited by the fire, since dimensional diversity showed improvements in the burned area, which were manifested in a number of species (83 %) in all strata of A1, compared to 26 % in the non-burned area (A2).

In the vertical structure of the coniferous forest of the *Cerro El Potosí* is present a population composed of dominant, codominant and suppressed forest specimens.

The productivity in the burned area was higher than in the non - burned area, according to the significant differences of density, basal area, crown area, volume and the greater abundance of *Pinus pseudostrobus* in strata II and III. The fire-free area recorded a smaller number of individuals (N ha^{-1}) as a result of lower volume proportionality (m^3 ha^{-1}) and stratum I alone confirmed an abundance of 100 % for *Pinus pseudostrobus.*

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Conflict of interests

The authors declare no conflict of interests.

Contribution by author

Juan Carlos Ramos Reyes: field work, writing of the manuscript; Eduardo Javier Treviño Garza: review and correction of the manuscript; Enrique Buendía Rodríguez: help in field work, review and correction of the manuscript; Oscar Alberto Aguirre Calderón: review and correction of the manuscript; José Israel López Martínez: support in field work and writing of the manuscript and map design.