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Article

Regeneración natural de pino y encino bajo diferentes niveles de perturbación por incendios forestales

Pine and oak natural regeneration under different levels of forest fire disturbance

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Resumen

El comportamiento de los incendios forestales varía por diversos factores, entre los cuales el nivel de severidad condiciona la respuesta que tendrán los ecosistemas ante el fuego, como la capacidad de regeneración natural. En México, poco se ha estudiado al respecto, lo que ha limitado las estrategias de restauración. En este contexto, se realizó un análisis comparativo de la respuesta de la regeneración natural del arbolado en tres intervalos de altura (0–0.30 m, 0.31–1.0 m y 1.1– 3.0 m), con un diseño experimental con dos factores: 1) diferentes condiciones de severidad del incendio (sin incendio, incendio moderado, incendio extremo); y 2) tres regiones de bosques de pino-encino (Sierra de Quila, el Bosque La Primavera y la Sierra de Tapalpa). Para el análisis comparativo se realizaron un ANOVA y una prueba de *Tukey*, con base en un diseño experimental factorial (región y severidad). Los resultados sugieren que existe una diferencia significativa entre las condiciones de severidad de los incendios y entre las regiones, para el intervalo de altura de 0 a 0.30 m, y se observa una mayor regeneración en las áreas con incendios moderados. Esto se confirma en Tapalpa, donde se estiman 160 000 individuos ha^{-1} en promedio. En relación a los otros estratos de regeneración (0.31 –1.0 m y 1.1–3.0 m) no se obtuvieron diferencias significativas entre las condiciones de severidad del fuego, solo en la regeneración de pino. Se concluye que la ocurrencia de un incendio moderado puede propiciar una mayor incidencia de regeneración natural.

Palabras clave: Fuego, perturbación intermedia, régimen del fuego, resiliencia, respuesta de la vegetación, severidad de incendios forestales.

Abstract

The behavior of forest fires varies due to various factors, where the level of severity conditions the response that ecosystems will have to fire, such as the ability of natural regeneration. Not much has been studied in this regard in Mexico, which has limited restoration strategies. Therefore, a comparative analysis of the natural regeneration of trees in three height ranges (0 –0.30 m, 0.31–1.0 m and 1.1–3.0 m) was made, considering an experimental design with two factors: 1) different conditions of severity of the fire (without fire, moderate fire, extreme fire); and 2) three regions of pine-oak forests (*Sierra de Quila, Bosque La Primavera* and *Sierra de Tapalpa*). For the comparative analysis ANOVA and Tukey test were generated, based upon an experimental factorial design (region and severity). Results suggest that there is a significant difference between the conditions of severity of the fires and between the regions, for the height range of 0 to 0.30 m, with a greater regeneration in areas with moderate fires. This is highlighted, in *Tapalpa* where an average 160 000 ha^{-1} individuals are estimated. In regard to the other regeneration strata (0.31 –1.0 m and 1.1–3.0 m) no significant differences were found between the severities of fire conditions, only on the regeneration of pine. It is concluded that the occurrence of a moderate fire can lead to a higher incidence of natural regeneration.

Key words: fire, intermediate disturbance, fire regime, resilience, vegetation response, severity of forest fires.

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Introduction

Fires are disturbance factors to which forest ecosystems are exposed year after year, throughout Mexico. In many cases they affect large areas of the national territory (Jardel *et al.,* 2006; Gómez *et al*., 2013), which causes economic damage, such as loss of timber resources, as well as other of environmental kind (Rodríguez *et al.,* 2012) among which the emissions of various gases stand out.

However, it is important to keep in mind that not all forest fires are the same and that not all ecosystems respond in the same way to this impact. For example, for fire-adapted species such as *Pinus douglasiana* Martínez, *P. durangensis* Martínez, *P. oocarpa* Schiede ex Schlecht. *P. devoniana* Lindl. (Rodríguez-Trejo and Fulé, 2003) and *P. hartwegii* Lindl. (Rodríguez-Trejo, 2001) this element guarantees its permanence (Madrigal *et al*., 2011). From this perspective, fire plays a relevant role in the dynamics of almost all forests and grassland, since it acts as an element that restarts the cycle of ecological succession (Fitch, 2006). However, this dependence is also related to the severity and frequency of fires (Alexander, 1982), which condition the processes and timing of the recovery of biological systems (Varner *et al*., 2009).

Likewise, it should be considered that there is a relationship between severity and the amount of organic matter (fuel) that is consumed, which in turn, can define their recovery capacity (Montorio *et al.,* 2014). For example, high severity is associated with low levels of vegetation recovery and, therefore, with degradation factors such as high rates of erosion and alterations in the hydrological response of the soil (Neris *et al*., 2016).

On the other hand, if the fire is not so severe, it is beneficial for living beings (Juárez-Martínez and Rodríguez-Trejo, 2004), since it influences the biological and reproductive development and the composition and structure of the vegetation within ecosystems adapted to fire (Márquez *et al.,* 2005).

In this way, the presence of fire can have both negative and positive impacts on forests. Within the former, it causes the death of the trees and removes the vegetation cover, which facilitates erosion, specifically during the first year after the disturbance (Bodí *et al*., 2012). On the other hand, among the positive impacts, some species are favored by the opening of the canopy through which sunlight enters, from the death of trees and shrubs, which benefits the growth of shade-intolerant species (Juárez-Martínez and Rodríguez-Trejo, 2004). Another positive aspect of fire is the elimination of organic matter that covers the soil, thus promoting the germination and establishment of seedlings (Márquez *et al*., 2005).

In some species of pines, such as *P. greggii* Engelm. ex Parl., *P. attenuata* Lemmon and *P. patula* Schiede ex Schlecht. & Cham. (Rodríguez-Trejo and Fulé 2003), fire promotes the opening of serotine cones and with it, the release of seeds, which promotes natural regeneration (Vega, 2003). However, this process through seed dispersal is affected by fire and is considered complex, as it depends on a large number of little-studied factors (Vega, 2003). However, there is evidence that fire can favor abundant natural regeneration, specifically in coniferous ecosystems, where it has been observed that in burned areas it is more intense than in non-burned ones (Juárez-Martínez and Rodríguez-Trejo, 2004; Pérez-Gorostiaga *et al.,* 2009; Sánchez *et al*., 2014), although the establishment period can often be long (Shatford *et al*., 2007) or vary according to the characteristics of the forest masses (De las Heras *et al*., 2011).

Based on the above, the aim of this study was to determine if the level of severity of forest fires influences the natural regeneration of the pine-oak woods.

Materials and Methods

Study area

The assessment of the response of natural regeneration by degree of severity was determined in three different ecosystems of pine-oak forest, whose general aspects such as: vegetation, climate, structure, density and species composition were defined. In this way, three different conditions were considered, located in three regions (Figure 1): *Bosque La Primavera* (20°36'34.50" N - 103°35'57.00" W), *Sierra de Quila* (20°17'53.60" N - 104°2'47.24" W) and *Sierra de Tapalpa* (19°57'50.80" N - 103 47'0.70" W), forest regions that have been affected by forest fires of different magnitude.

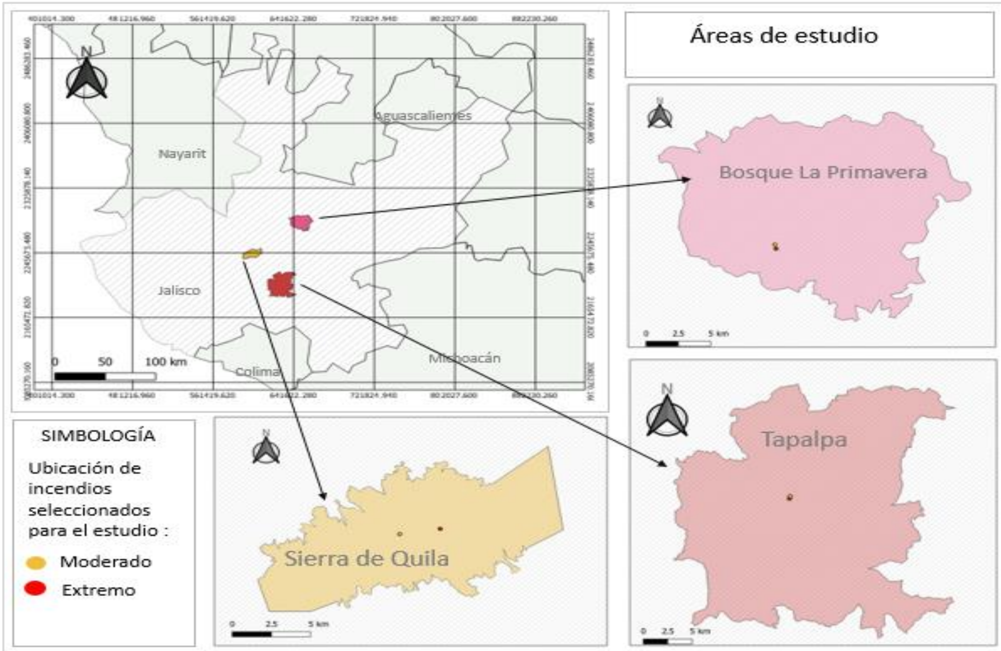


Figure 1. Location of forest regions and fires selected for the study.

In each of these areas, the forest fires that occurred in the last five years were georeferenced, based on information provided, both directly by the personnel of the *La Primavera Flora* and *Fauna* Protection Area and the *Sierra Flora* and *Fauna* Protection Area. *Quila*, as with the forest fire databases of the National Forestry Commission (Conafor, 2020) and the Ministry of the Environment and Territorial Development of the Government of the State of Jalisco (Semadet, 2018).

Severity assessment

After locating the forest fires in each of the regions, the selection of their severity condition was determined through field trips and direct observation of the state of the local vegetation, from which the following areas came out (Figure 2):

Fire-free areas. Sites where no forest fires have been verified or where more than five years have passed since the last event and the structure of the forest has already been re-established.

Area with moderate fire. Forests in which the fire occurred during a rainy season prior to data collection and where the fire did not fully affect the structure of the forest; a foreshortening (height of the fire mark on the stem) is observed below half the total height of the tree and the crown may show partial damage.

Area with extreme fire. Places where the fire was present during a rainy season before data collection and almost completely destroyed the structure and composition of the forest; here the foreshortening exceeds half the total height of the tree and the crown is partially or totally damaged.

A = No fire; B = Moderate fire; C = Extreme fire.

Figure 2. Pine-oak forest ecosystems with the three fire severity conditions.

Experimental design

A factorial experimental design was used, composed of two factors: 1) Regions (*Bosque La Primavera, Sierra de Quila* and *Tapalpa*); and 2) Conditions (no fire, moderate fire and extreme fire), which gave a total of nine treatments, of which three replications (sites) were considered, which were randomly chosen within each of the severity conditions for each region, which resulted in 27 sampling sites.

Site assessment

In each of the 27 sites, a tree inventory was carried out (counting of individuals and taking mensuration data), both of the standing trees and of the regeneration. Thus, a 400 m^2 circular sampling unit was used, in which the following data were taken from the adult specimens (DN $\geq$ 7.5cm): total height, with a Laser hypsometer (Forestry Pro Niko 8381); normal diameter and cup diameter, with a diameter tape (Forestry Suppliers Inc. 283d); burn height, with a tape measure (Urrea 1599LSW); percentage of crown burned, determined with the visually estimated delimitation of the crown area with regressive death, to which a percentage was assigned.

Within each sampling site, smaller circles were also located where the regeneration of the trees was counted and measured in three different height intervals as follows: a) the immediate regeneration after the fire, for which the emergent individuals with heights less than 0.30 m, which were counted and measured in three sub-sites of 5 m^2 oriented at 0°, 120° and 240° and 5.64 m from the center; b) regeneration with a height of 0.31 m to 1.0 m that was measured in a 100 m^2 circle; and c) regeneration with more years of life, with heights of 1.1 m to 3.0 m in an area of 200 m^2 (Figure 3).

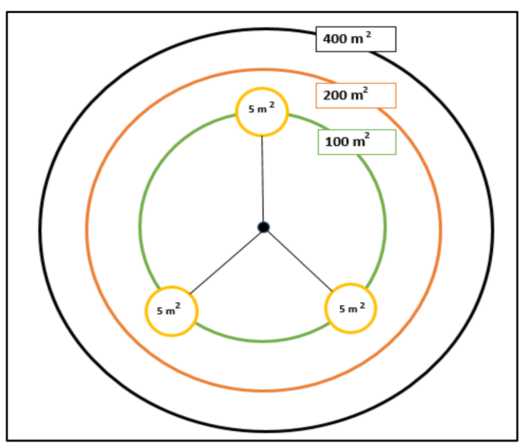


Figure 3. Sampling site form for data collection: a) regeneration from 0 to 0.30 m (5 m^2); b) 0.31 to 1.0 m regeneration (100 m^2); c) 1.1 to 3.0 m regeneration (200 m^2) (Flores *et al.,* 2019).

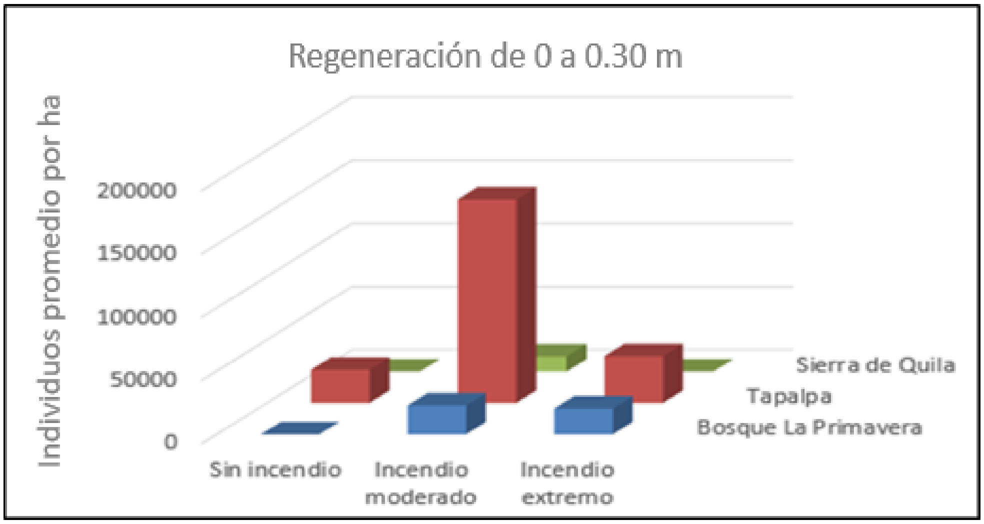
Data analysis

The field information was arranged in a database in an organized and systematic way for its evaluation, and an analysis of variance ($p = 0.05$) was carried out to determine the existence of significant differences between the treatments and a Tukey test ($p = 0.05$). This analysis was done separately for each of the regeneration height intervals, using the statistical program InfoStat (Balzarini *et al*., 2008).

Results

Regeneration from 0 to 0.30 m

The highest number of pine regeneration of height less than 0.30 m was counted in *Tapalpa* region, and the presence of seedlings was recorded in the three evaluated (no fire, moderate and extreme fire), and the highest number of individuals (160 000 seedlings on average per ha^{-1}) in the moderate fire area. In *La Primavera* Forest, 22 806 individuals were calculated on average per ha^{-1} for the moderate fire area and 20 393 for the extreme fire area, and none in the area without fire. Finally, in *Sierra de Quila*, only 12 061 individuals were estimated on average per ha^{-1} in the area of moderate fires (Figure 4).



Sin incendio = No fire; *Incendio moderado* = Moderate fire; *Incendio extremo* = Extreme fire; *Regeneración* = Regeneration; *Individuos promedio por ha* = Average individuals per hectare.

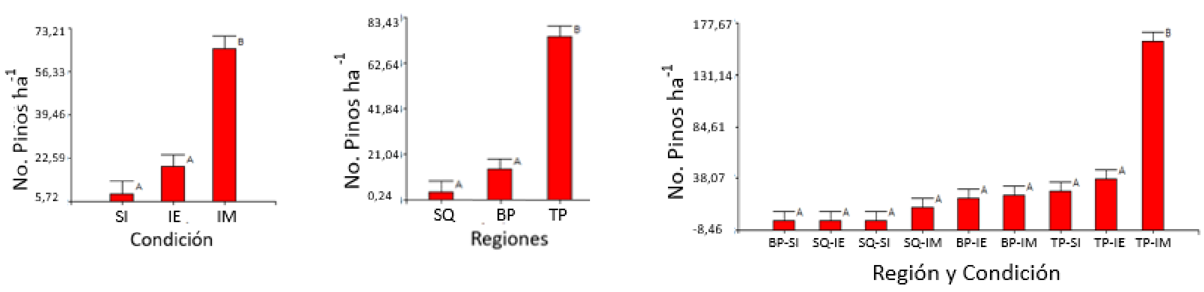
Figure 4. Comparison of the number of pine individuals from 0 to .30 m, by region and by condition.

On the other hand, oak regeneration for this height range, was non-existent. The analysis of variance showed a significant difference, both for the region and for the condition and the interaction region by condition, ($p < 0.05$) which indicates a very low degree of error (Table 1).

Table 1. Analysis of Variance of the factors and their relations with the 0 to 0.30 m pine individuals.

Origin of the variations	Sum of squares	Degrees of freedom	Mean square	F	p-value
Model	183 313.44	8	22 914.18	37.34	<0.0001
Region	78 834.38	2	39 417.19	64.24	<0.0001
Condition	48 848.06	2	24 424.03	39.80	<0.0001
Region*Condition	55 631.00	4	13 907.75	22.67	<0.0001
Error	44 179.59	72	613.61		

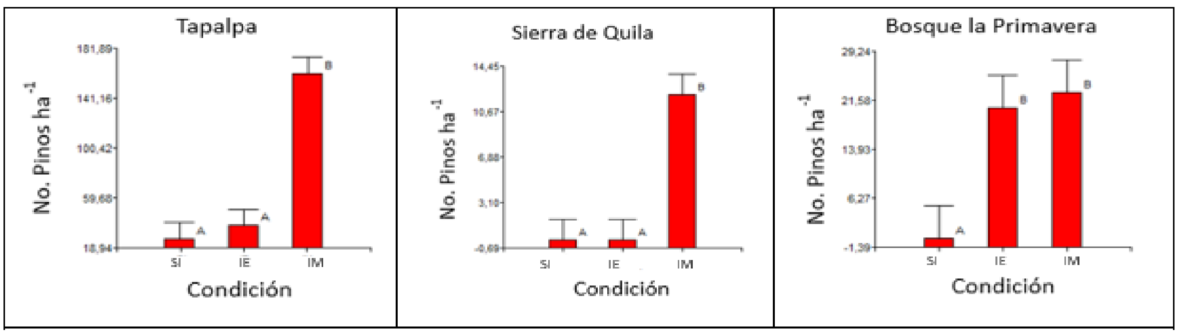
The results of the Tukey test indicate that eight of the nine treatments are not statistically different and that there is only a significant difference between the fire severity conditions and between the sampling regions for the *Tapalpa* region, with the moderate fire condition (Figure 5).



SI = No fire; IE = Extreme fire; IM = Moderate fire; BP = *La Primavera* Forest; SQ = *Sierra de Quila*; TP = *Tapalpa*. Means with different letters are significantly different (p <0.05).

Figure 5. Average pine regeneration ranges with heights from 0 to 0.30 m, in the three different regions and severity conditions.

When analyzing each one of the regions separately, a significant difference ($p < 0.05$) is observed between the number of pine individuals from the areas without fire and extreme fire, compared with the areas with moderate fire, in which the greater number of regenerating individuals. However, for the *La Primavera* Forest, the trend is a little different, since there is no significant difference between the presence of pine trees of small heights between the areas of extreme fire and those of moderate fire; however, a significant difference was confirmed in the areas without fire, where regeneration was less abundant (Figure 6).

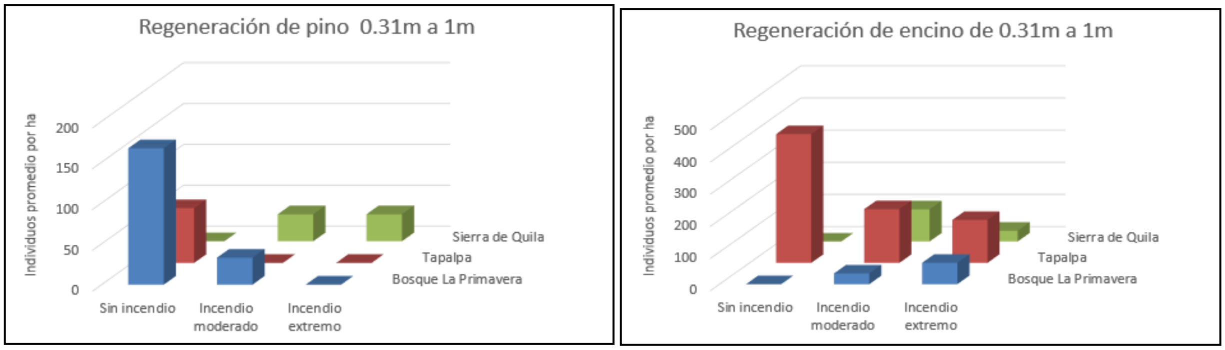


SI = No fire; IE = Extreme fire; IM = Moderate fire. Means with different letters are significantly different ($p < 0.05$).

Figure 6. Mean ranges by region of pine regeneration with heights from 0 to 0.30 m, in the three severity conditions.

Regeneration from 0.31 to 1 m

In this category, regeneration was not as abundant as that of smaller heights; there the maximum average density was 167 individuals per ha^{-1} corresponding to the fire-free area of *La Primavera* Forest, followed by an average of 67 individuals per ha^{-1} for the *Tapalpa* fire-free area. On the other hand, the extreme fire areas of *La Primavera* Forest and *Tapalpa*, the moderate fire area in *Tapalpa* and the area without fire in *Sierra de Quila*, did not record the presence of any pine individual regenerating in this height range (Figure 7).



Sin incendio = No fire; *Incendio moderado* = Moderate fire; *Incendio extremo* = Extreme fire; *Regeneración de pino*= Regeneration of pine; *Regeneración de encino* Regeneration of oak; *Individuos promedio por ha* = Average individuals per hectare.

Figure 7. Comparison of the number of pine and oak individuals from 0.31 to 1 m, by region and condition.

The regeneration of oak in this group was more numerous than that of pine, and in the *Tapalpa* region in the area without fire damage in particular, the highest amount was found, with an average of 400 individuals per ha^{-1}. However, for the *La Primavera* Forest and *Sierra de Quila* in the areas without fire, no individual oak regeneration was recorded (Figure 7).

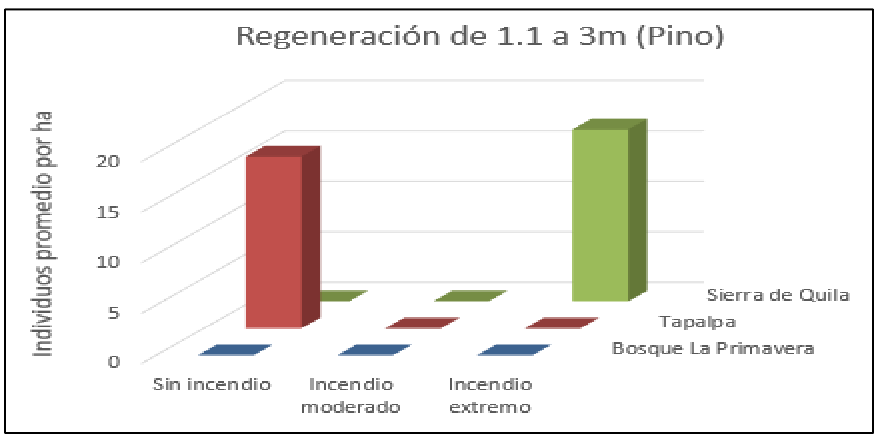
Despite verifying a greater number of regenerating pine individuals with heights from 0.31 m to 1 m, in the areas without fire, both for the *La Primavera* Forest and for *Tapalpa*, the statistical analyzes did not show significant differences between the severity conditions of fire, nor between the study regions, only in regard to pine regeneration. Therefore, statistical analyzes were performed and including thenoak regeneration from the sampling sites. Nor was a significant difference revealed between regeneration and the different conditions affected by fire ($p > 0.05$) (Table 2).

Table 2. Analysis of Variance of the factors and their relation with the 0.31 to 1 m pine and oak individuals.

Origin of the variations	Sum of squares	Degrees of freedom	Mean square	F	p-value
Model	432 556.07	8	54 069.51	0.58	0.7807
Condition	72 133.63	2	36 066.81	0.39	0.6844
Region	183 111.19	2	91 555.59	0.98	0.3933
Region*Condition	177 311.26	4	44 327.81	0.48	0.7528
Error	1 675 868.00	18	93 103.78		

Regeneration from 1.1 to 3.0 m

The regeneration of the tallest pine was the scarcest in all regions and in all conditions, with a maximum of 17 pine individuals on average per hectare, only recorded for the area without fire in *Tapalpa* and extreme fire in *Sierra de Quila* (Figure 8).



Sin incendio = No fire; *Incendio moderado* = Moderate fire; *Incendio extremo* = Extreme fire; *Regeneración de 1.1 a 3 m (Pino)* = Regeneration of 1.1 to 3 m pine individuals; *Individuos promedio por ha* = Average individuals per hectare.

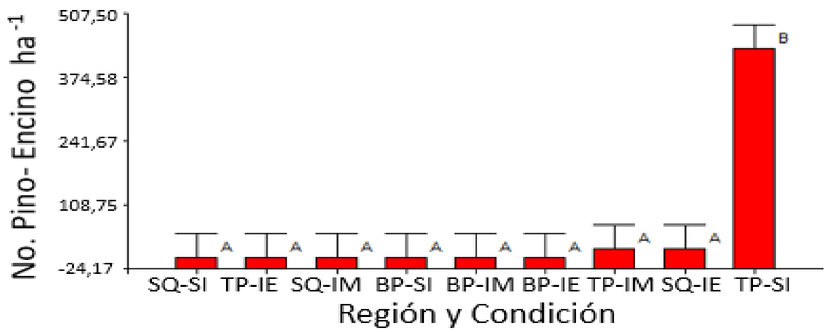
Figure 8. Comparison of the number of 1.1 to 3 m pine individuals by region and condition.

Regarding the statistical analysis related to regeneration with heights of 1.1 to 3 m, no significant differences were found between the fire severity conditions, only referring to the regeneration of pine in all regions. However, when considering both pine and oak regeneration, a significant difference was observed in the presence of young individuals in the 1.1 to 3 m stratum, both for the conditions and for the regions. Showing the value of $p < 0.05$, which indicates an acceptable degree of error (Table 3).

Table 3. Analysis of Variance of the factors and their relationship with pine and oak individuals from 1.1 to 3 m.

Origin of variations	Sum of squares	Degrees of freedom	Mean square	F	p-value
Model	492 407.41	8	61 550.93	8.21	0.0001
Condition	115 740.74	2	57 870.37	7.72	0.0038
Region	130 185.19	2	65 092.59	8.68	0.0023
Region*Condition	246 481.48	4	61 620.37	8.22	0.0006
Error	135 000.00	18	7 500.00		

However, Tukey's test indicates that this difference only corresponds to the *Tapalpa* region and in the area without fire (Figure 9), where 433 individuals ha^{-1} were estimated on average.



SI = No fire; IE = Extreme fire; IM = Moderate fire; BP = *La Primavera* Forest; SQ = *Sierra de Quila*; TP = *Tapalpa*. Means with different letters are significantly different ($p < 0.05$).

Figure 9. Mean ranges by region of pine regeneration with heights from 1.1 m to 3.0 m, in the three severity conditions.

Discussion

In regard to the regeneration of lower height (from 0 to 0.30 m), a high rate of individuals was observed in areas with moderate impact of forest fires, which was also recorded by Juárez-Martínez and Rodríguez-Trejo (2004) who determined in burned areas of the greater *Oaxaca* regeneration of *Pinus oocarpa* Schiede ex Schltdl., than in those not burned. This may be related to the considerable decrease in the layer of litter and accumulated fermentation in the forest floor. Although this aspect was not evaluated in this work, the soil cover was very evident in the *Sierra de Quila* region where the layer of litter and fermentation in the areas not affected by fires exceeded 20 cm in depth in some areas and in where no regenerating individual of any height was recorded. While in the areas where a moderate fire occurred, the litter layer did not exceed 5 cm, which allowed the emerging plants to grow and fixate on the ground (Figure 10), which opens the possibility of continuing the study regarding to the evaluation of the environmental variables affected by the fire that may be influencing the process.

Figure 10. Depth of the soil cover layer in *Sierra de Quila*. At left, the area without fire. To the right, the area with moderate fire, where a young pine shoot can be observed.

The relationship of ground cover (litter layer and fermentation), with the natural regeneration of pine after forest fires has been seen in species such as *Pinus pinaster* Ait. and is related to the initial density and survival of the specimens, together with other factors such as the stony ground and erosion (Madrigal *et al*., 2005). In addition, although forest fuels protect the substrate, it is essential that the layer that covers the forest floor is reduced to allow the seeds to come into direct contact with the soil and the vegetation to develop (Flores and Moreno, 2005; Márquez *et al*., 2005).

On the other hand, this increase in pine regeneration after a moderate fire can be attributed, simply, to the release of seeds, because high temperatures dehydrate the tissues of the cones and favor their release, as it happens with *Pinus halepensis* Mill. (Barbero *et al*, 1987), *P. banksia* Lamb. (Chandler *et al*, 1983) and *P. brutia* Ten. (Lotan, 1975). Likewise, the germination rates of species such as *Pinus sylvestris* L. and *P. pinaster* are not affected by the temperature caused by forest fires (Reyes and Casals, 2000).

On the other hand, the difference between the establishment of the small regeneration (0 to 0.30 m), which was very abundant, compared to that of the larger regeneration (from 0.31 to 1 m and 1.1 to 3 m) is very noticeable. This can be explained by the frequency of fires, since if a fire occurs every two to three years in the same place, it can affect the regeneration already established, and perhaps it favors the emergence of new seedlings, but it eliminates what was already present previously, which does not allow continuity to the forest growth cycle. However, if the frequency of fires is longer, there would be enough time for the establishment of regeneration and its survival. An example of this, in Mexican ecosystems, is the ecological park of *Chipinque* (state *of Nuevo León*), where a canopy coverage of 100 % and an overlapping of canopies have been observed in oak and pine forests after 12 years of a fire (Alanís-Rodríguez *et al*., 2011). On the other hand, in the state of *Jalisco,* specifically in the *La Primavera* Forest, some areas affected by fires after five years show a successful regeneration of *Pinus oocarpa*, a species that shows adaptations to the frequent impact of fire (Sánchez *et al*., 2014).

Therefore, for future work it is important to consider, in addition to the immediate regeneration after a fire, the survival of this regeneration over time and the frequency with which the fires impact the ecosystem.

Conclusions

The occurrence of moderate fires favors a higher incidence of small natural regeneration (0 to 0.30 m) of pine in the three study areas.

The presence of medium (0.31 to 1.0 m) and high (1.1 to 3 m) regeneration was more abundant in areas without fire, for which it is advisable to monitor both the frequency of fires and the survival and adequate density of regeneration with over the years.

The use of fire in a controlled way, through prescribed burns, could emulate the characteristics of a moderate fire and thus be considered as a mitigation measure for the negative impact of forest fires, in such a way that it tends to generate positive effects of fire. in natural regeneration.

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Conflict of interests

The authors declare no conflict of interests.

Contribution by author

Ana Graciela Flores Rodríguez: development of statistical analyzes, interpretation of results, structure and writing of the manuscript; José Germán Flores Garnica: interpretation of results and structure and writing of the manuscript; Diego Raymundo González Eguiarte: development of statistical analyzes and interpretation of results; Agustín Gallegos Rodríguez, Patricia Zarazúa Villaseñor and Salvaador Mena Munguía: information analysis, process and document review; Mónica Edith Lomelí Zavala and Eliceo Ruíz Guzmán: processing of field information.

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