Abstract: The effect of forest harvesting on the composition and structure of a temperate coniferous forest in Mexico was evaluated after three harvesting periods from 2007–2015. In this forest, we identified seven families and eight tree species. The dominant species is *Pinus pseudostrobus* Lindl. which is also the most important commercial species. Harvesting was oriented towards increasing the abundance of the dominant pine species, resulting in a decrease in forest diversity and favoring a transition to a monospecific forest. The tree canopy structure following harvesting showed a gradual recovery in the number of individuals in each diameter class, but the diameter increment may not necessarily guarantee a sustainable harvest because cutting cycles appear to be too short. The size of harvesting gaps and overall forest cover determine the presence and/or abundance of regeneration (small seedlings, seedlings, saplings, large saplings, and young trees). The establishment of *Pinus pseudostrobus* and *Ilex discolor* Hemsl. differed according to their ecological groups.

Keywords: canopy gaps; forest structure; ecological groups; *Pinus pseudostrobus*

1. Introduction

Sustainable forest management involves decisions and activities about harvesting forest resources according to best management practices integrated with forest conservation and economic development and social needs, both direct (wood products) and indirect (carbon fixation, aesthetics, and soil protection) [1–4]. Sustainable forest management is important in temperate and tropical forests [5,6] to conserve biodiversity and maintain forest composition and structure as well as ecosystem function [7]. Forest harvesting can degrade forest structure [8,9], cause soil erosion [10] and negatively alter forest composition [11,12]. It may also, however, be fundamental for the conservation of forest ecosystems [13,14] by increasing tree growth rates and the recruitment of regeneration through gap dynamics [9,15].

The forest ecosystem structure is described by tree distribution by age and size [16–18]. The vertical forest structure describes the distribution of forest biomass stratified by tree height and is often defined by functional ecological groups [19], while horizontal stratification is determined by the number of individuals by diameter class and spatial arrangement [20].

Forest composition is determined by environmental factors including geographic position, climate, soils, topography and forest dynamics [21,22], as well as the ecological traits of tree species [23]. The goal of forest management is to manage forests for forest products while optimizing forest species composition [1,18,24].

In Mexico, forest ecosystems occupy a large land area (65 million ha) [25], approximately half of which are temperate forests [26]. These forests are characterized by pines [27],...
firs, oaks and other broadleaved species [28], the composition of which is determined by climate and soil type [29–31]. These forests are part of the trans-Mexican volcanic system [32,33].

These forests have long been subjected to a variety of human disturbances, such as logging and fire, causing changes to forest structure and species composition [5,25,34–37]. In addition, forest harvesting under the concept of common property land management (agrarian centers) has been typical, with the main management objective of providing timber and firewood for local communities. Land use practices and natural resource management have been regulated by these agrarian centers under their rules and traditions [38], but this has also led to a reduction of species of economic importance [7,39,40]. Community forest management aims to achieve forest sustainability, ensuring the well-being of the rural population, alongside the conservation of forest systems [41].

In the State of Mexico, one of the most widely used species is *Pinus pseudostrobus* due to the quality of its wood and resin; however, the species has experienced a reduction in its range as a result of climate change [42]. Likewise, the demand for raw materials is reducing the state’s oak forests [43]. Particularly, in Nevado de Toluca, the role of local communities has a direct influence on the conservation of their forests [44].

The objective of this study was to evaluate the effect of timber harvesting on the tree canopy structure and composition of temperate forests in Central Mexico, as well as their capacity for recovery, under the current management system with agrarian centers.

2. Materials and Methods

2.1. Study Site

The Nevado de Toluca (4690 masl) is located in the State of Mexico with multiple human settlements around it, characterized by a temperature of 14 °C and an average annual rainfall of 1212 mm [45]. Andisols are the predominant soil type, covering 90% of this area [46]. Stands include conifer forest species such as *Pinus* spp. and *Abies religiosa* (Kunth) Schltdl. & Cham. and deciduous forest species including *Alnus jorullensis* Kunth and *Quercus laurina* Humb. & Bonpl. [35]. The study area was in the Ejido Palo Seco Municipio of Coatepec Harinas in the state of Mexico covering an area of 578 ha, of which 436 ha is subjected to forest harvesting (Figure 1).

![Study site location](image_url)  
**Figure 1.** Study area—Ejido Palo Seco, Coatepec Harinas in the state of Mexico and map of harvested areas in 2007, 2010 and 2015.
Experimental Design

We compared forest stands at three sites that were similar in site and stand characteristics and where tree harvesting was carried out during three different years: 2007, 2010 and 2015. The three harvest areas serve as a space for time chronosequences to examine the effects of harvesting on forest structure and composition.

At all sites, harvesting was carried out by selecting individual trees in all categories (>7.5 cm DBH) and using directional felling with a chainsaw. The extraction rates were similar: 2007 (2736.3 m$^3$ in 27.02 ha), 2010 (2539.9 m$^3$ in 53.3 ha) and 2015 (2662.7 m$^3$ in 30.39 ha). The focus of harvesting was *Pinus pseudostrobus*, the most important commercial species in these forests.

### 2.2. Sampling Plots

The sampling of the forest composition and tree canopy structure was conducted in a 1 ha plot at each harvested site based on the methodology of Valdez [47] and Lamprecht [48] (Figure 2). The location of the plot was selected using a random walk to select the mooring point for the plot. The average altitude and slope of the plots were 2970 masl and 3$^\circ$, respectively.

![Sampling plots](image)

**Figure 2.** Sampling design with a 1 ha plot with 25 subplots sampled during each harvest year. Tree measurements for height and DBH. Sampling plots were distributed based on tree size classes.

### 2.3. Species Composition and Diversity

An importance value index (IVI) was calculated based on the values of relative abundance, dominance, and frequency for each species [48].

Species diversity was estimated using Simpson, Margalef and Shannon–Wiener indices [17,49]. The Sorensen index of similarity was also used to compare forest communities in different years following harvesting.
2.4. Tree Canopy Structure

Vertical structure was determined using counts of trees of the dominant species for each harvesting year, and a one-way analysis of variance was carried out to test for differences among harvesting years. Horizontal structure was evaluated based on the spatial distribution of trees and the abundance of individuals by diameter class.

3. Results

3.1. Species Composition and Diversity

The sampling plot contained eight species of commercial tree species in seven families: Aquifoliaceae (Ilex discolor), Betulaceae (Alnus jorullensis Kunth), Clethraceae (Clethra mexicana), Cupressaceae (Cupressus lindleyi Klotzsch ex Endl.), Fagaceae (Quercus laurina Bonpl.), Pinaceae (Abies religiosa Flora. and Pinus pseudostrobus) and Salicaceae (Salix sp.). Trees of the Pinaceae species were the most dominant.

*P. pseudostrobus* was the most dominant species and had the highest IVI in each harvest sampling year, with different codominant species in each of the three years: *A. religiosa* (2015), *A. jorullensis* (2010) and *Salix* sp. (2007). In each sampling year, *Q. laurina* only occurred in the understory (Table 1).

| Species           | Ar    | Dr    | Fr    | Ar    | Dr    | Fr    | Ar    | Dr    | Fr    | 2007  | 2010  | 2015  |
|-------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Pinus pseudostrobus| 88.1  | 93.4  | 100   | 76    | 88.5  | 100   | 82    | 93.4  | 100   | 281.5 | 264.5 | 275.4 |
| Abies religiosa   | 5.65  | 2.12  | 52    | 1.1   | 0.28  | 20    | 10    | 4.34  | 64    | 59.77 | 21.38 | 78.34 |
| Alnus jorullensis | 1.54  | 0.85  | 16    | 12    | 6.63  | 80    | 2.6   | 1.17  | 16    | 10.38 | 98.63 | 19.77 |
| Salix sp.         | 4.45  | 1.24  | 52    | 1.1   | 0.15  | 8     | 4.1   | 0.93  | 16    | 57.69 | 9.25  | 21.03 |
| Quercus laurina   | 0.17  | 0.06  | 4     | 0.9   | 0.08  | 4     | 0.7   | 0.15  | 8     | 4.23  | 4.98  | 8.85  |
| Cupressus lindleyi| -     | -     | -     | 8.1   | 4.32  | 8     | -     | -     | -     | 20.42 | -     | -     |

Species diversity estimated using the Simpson index (Table 2) showed that the 2007 harvest area had the lowest diversity. The abundance of *P. pseudostrobus* was higher in the 2007 harvest area compared to the areas harvested in 2010 or 2015.

| Species            | n    | pi^2   | N    | D    | 1-D  |
|--------------------|------|--------|------|------|------|
| A. jorullensis     | 9    | 0.000205 | 593  | 0.78572 | 0.2142849 |
| A. religiosa       | 33   | 0.003008 |      |      |      |
| P. pseudostrobus   | 524  | 0.78065 |      |      |      |
| Q. laurina         | 1    | 0      |      |      |      |
| Salix sp.          | 26   | 0.001852 |      |      |      |

| Species            | n    | pi^2   | N    | D    | 1-D  |
|--------------------|------|--------|------|------|------|
| A. jorullensis     | 59   | 0.015792 | 466  | 0.60867 | 0.3913332 |
| A. religiosa       | 5    | 0.0000923 |      |      |      |
| C. lindleyi        | 37   | 0.0061470 |      |      |      |
| I. discolor        | 2    | 0.0000092 |      |      |      |
Table 2. Cont.

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Figure 4. Horizontal structure characterized by diameter distribution in three years of harvesting (Ejido de Palo Seco, Coatepec Harinas).

Table 3. Harvesting intensity by species and diameter class.

| Diametric Category (cm) | P. pseudostrobus 2007 | P. pseudostrobus 2010 | P. pseudostrobus 2015 | Salix sp. 2010 | Salix sp. 2015 | C. mexicana 2015 | A. jorullensis 2015 | A. religiosa 2015 | C. lindleyi 2010 | C. lindleyi 2015 |
|------------------------|------------------------|------------------------|------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 10                     | 2.68                   | 69.23                  | 9.09                   | 33.33          | 14.29          | 100.00         | 100.00         | 6.67           | 11.11          |
| 15                     | 11.58                  | 54.35                  | 12.50                  | 50.00          | 75.00          | 100.00         | 33.33          | 0.00           | 0.00           |
| 20                     | 26.67                  | 51.09                  | 19.05                  | 0.00           | 0.00           | 100.00         | 95.24          | 0.00           | 0.00           |
| 25                     | 12.20                  | 18.87                  | 12.90                  | -              | 100.00         | -              | 33.33          | -              | 0.00           |
| 30                     | 24.44                  | 25.64                  | 33.33                  | -              | 0.00           | -              | 0.00           | 0.00           | 0.00           |
| 35                     | 31.25                  | 7.69                   | 36.00                  | -              | 33.33          | -              | -              | 0.00           | 0.00           |
| 40                     | 33.33                  | 24.39                  | 50.00                  | -              | 100.00         | -              | -              | 0.00           | 0.00           |
| 45                     | 20.00                  | 10.34                  | 30.00                  | -              | 100.00         | -              | 0.00           | -              | -              |
| 50                     | 28.57                  | 30.77                  | 42.31                  | -              | -              | -              | -              | 0.00           | -              |
| 55                     | 42.86                  | 17.65                  | 47.83                  | -              | -              | -              | -              | 0.00           | -              |
| 60                     | 45.45                  | 41.18                  | 42.86                  | -              | -              | -              | -              | -              | -              |
| 65                     | 18.75                  | 33.33                  | 14.29                  | -              | -              | -              | 100.00         | 0.00           | -              |
3.2.2. Vertical Structure

Harvest years (Figure 5) differed significantly in the lower canopy ($p < 0.05$); data from 2007 and 2015 revealed a dominance of *P. pseudostrobus* ($p < 0.05$), and 2010 showed a codominance ($p > 0.05$) among *P. pseudostrobus*, *A. jorullensis* and *C. lindleyi*, with the 2015 data reflecting reforestation efforts. The abundance of small trees of *A. religiosa* (an intermediate shade-tolerant species) in 2015 decreased as the number of canopy gaps increased.

| Diametric Category (cm) | 2007  | 2010  | 2015  | 2010  | 2015  | 2015  | 2015  | 2010  | Harvesting Per Category (%) |
|-------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-----------------------------|
| 70                      | 31.25 | 87.50 | 42.86 | -     | 100.00| -     | -     | -     | -                           |
| 75                      | 0.00  | 0.00  | 37.50 | -     | -     | -     | -     | -     | 0.00                        |
| 80                      | 33.33 | 75.00 | 0.00  | -     | -     | -     | -     | -     | -                           |
| 85                      | 0.00  | 0.00  | -     | -     | -     | -     | -     | -     | -                           |
| 90                      | 100.00| 100.00| -     | -     | -     | -     | -     | -     | -                           |
| 95                      | 0.00  | 0.00  | -     | -     | -     | -     | -     | -     | -                           |
| 100                     | 0.00  | 0.00  | 100.00| -     | -     | -     | -     | -     | -                           |

Figure 5. Vertical structure following harvesting in three different years; (a) *Abies religiosa*, (b) *Salix* sp., (c) *Pinus pseudostrobus*, (d) stump, (e) *Alnus jorullensis*, (f) *Cupressus lindleyi*. Strata-Un: lower canopy; Mi: intermediate canopy, Up: canopy stratum; mean height and DBH by species, year and stratum; median height by year and stratum.
The intermediate strata also showed significant differences among species \((p < 0.05)\) in the three-harvest year, with a dominance of \(P.\) pseudostrobus in 2010, 2015 and a codominance with \(A.\) religiosa in 2007. The canopy stratum was dominated by \(P.\) pseudostrobus \((p < 0.05)\).

### 3.3. Forest Regeneration

Canopy gaps created by harvesting allowed for the growth of shade-intolerant species, while shade-tolerant species are favored by a closed canopy \([50]\). The establishment patterns of the species in this forest are listed in Table 4. The most abundant species (other than \(P.\) pseudostrobus) were \(Ilex\) discolor, \(Abies\) religiosa, \(Salix\) sp. and \(Alnus\) jorullensis (Table 5). For \(Clethra\) mexicana, its absence is attributable to its establishment being restricted to riverine areas and ravines with slopes greater than 45°.

| Ecological Group | Description | Species |
|------------------|-------------|---------|
| Long-lived shade-intolerant | Shade-intolerant, regenerate in disturbed areas and are long-lived and occupy the canopy. | Aile (\(Alnus\) jorullensis) Cedro blanco (\(Cupressus\) lindleyi) |
| Partial shade-tolerant | Partially tolerant of shade, but depend on gap formation for growth and occupy the canopy. | Oyamel (\(Abies\) religiosa) Cucharillo (\(Clethra\) mexicana) Capulinillo (\(Ilex\) discolor) Encino (\(Quercus\) laurina) Pino (\(Pinus\) pseudostrobus) Guajote (\(Salix\) sp.) |

Table 5. Natural regeneration of tree species (Ejido Palo Seco, Coatepec Harinas, México) in a harvested forest.

| Species          | Small Seedlings | Seedlings | Saplings | Large Saplings | Small Trees |
|------------------|-----------------|-----------|----------|----------------|-------------|
| Relative Abundance (%) |
| \(P.\) pseudostrobus | 94.96 | 78.95 | 72.41 | 38.64 | 47.19 |
| \(I.\) discolor | 4.32 | 21.05 | 3.45 | 13.64 | 5.62 |
| \(A.\) religiosa | 0.72 | - | 13.79 | 4.55 | 15.73 |
| \(Salix\) sp. | - | - | 10.34 | 18.18 | 15.73 |
| \(Q.\) laurina | - | - | - | 13.64 | 6.74 |
| \(A.\) jorullensis | - | - | - | 11.36 | 6.74 |
| \(C.\) mexicana | - | - | - | - | 2.25 |

The type of forest regeneration in harvested forests depends on the canopy gap size and the ecological group \([9,50]\) and tends to promote pioneer species \([52,53]\). Justiniano and Fredericksen \([54]\) highlighted the need to understand the phenology of tree species in order to manage timber cutting with periods of seed dispersal to promote regeneration.

### 4. Discussion

#### 4.1. Species Composition

In this study, indices of species diversity and similarity in composition show a decrease in diversity with forest harvesting, which coincides with the results reported by Endara et al. \([35]\), who affirm that the extraction of individuals of pine trees results in a considerable reduction in their population density. This confirms that harvesting in temperate forests can reduce broadleaved species diversity in genera such as \(Quercus\), \(Alnus\), \(Clethra\) and \(Salix\). The results show that in 2015, compared to 2007 and 2010, trees in smaller diameter categories \((10 \text{ and } 15 \text{ cm})\) had a lower density due to selective extraction because pine species in these forests are shade-intolerant and disturbance-adapted \([27]\) and occupy early successional stages that are eventually replaced by \(Quercus\) species \([55,56]\).
Jiménez et al. [57] noted that management needs to be based on the biological requirements of species, the spatial distribution of trees and their growth and size.

The removal of less valuable species (Alnus jorullensis, Clethra mexicana, Cupressus lindleyi, Ilex discolor, Quercus laurina and Salix sp.) favors the development of high-value species such as Pinus pseudostrobus. The Margalef index (Dmg) showed a low diversity of species with a dominance of P. pseudostrobus. Furthermore, according to the IVI, the P. pseudostrobus forests had different codominant tree species in each year: A. religiosa (2015), A. jorullensis (2010) and Salix sp. (2007). The economic value of P. pseudostrobus is attributed to its rapid growth, straight stem and high wood quality [58–60].

4.2. Tree Canopy Structure

Forest regeneration is associated with the creation of canopy gaps and the degree of shade tolerance among species. In the forests of this study, Alnus jorullensis and Salix sp. are indicators of disturbance because of their response to forest harvesting, corresponding to ecological groups of species that are shade-intolerant and regenerate in areas disturbed by tree harvesting [51,61]. The removal of understory species may have increased the growth of P. pseudostrobus (Figure 5) and less abundant species, such as A. jorullensis, which is used for firewood and fences [62], as well as Salix sp., which is used for handicrafts [63].

Forest harvesting modifies the site conditions for the establishment of many commercial tree species [64], but selective harvesting tends to decrease tree species diversity [39]. Mostacedo et al. [65] note that establishing minimum cutting diameters allows for species to reach the age for seed production before harvesting, which may improve regeneration.

The recommended time for the economic recovery of forests following harvesting is determined by cutting cycles and in Mexico is 10 years; in [66–68], this is noted to be shorter compared to other countries such as Bolivia (20 years) [69,70] and Costa Rica (15 years) [71]. It is notable in this study that, according to the forest structure following harvesting in 2007 and 2015, the cutting cycle is too short to allow for sustainable harvests.

From a study in Bolivia, Dauber et al. [72] found that a cutting cycle of 20–35 years could allow for the recovery of timber stocks in tropical forests, which may be necessary for forests in Mexico, depending on forest type, to improve the sustainability of forest harvesting.

5. Conclusions

The abundance and size-class distribution of Pinus pseudostrobus allows for the selective harvesting of this species across different diameter classes. The tree canopy structure following harvesting displays a trend of gradual recovery, but lengthening the cutting cycle with appropriate minimum diameters can help to increase chances for sustainability. The size of canopy gaps and degree of forest cover determine the growth and abundance of species and the dominance of different ecological groups. Harvesting forests decreased species diversity, stimulating the growth of P. pseudostrobus, which displaces species of the same ecological group, particularly broadleaf species, due to competition.

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