Agrociencia

ECOLOGICAL REHABILITATION INDICATORS FOR ONE EUCALYPTUS REFORESTATION WITH AN OAK FOREST AS REFERENCE

Cristina **Herrera-Ramos**[1], Amador **Rafael-de Jesús**[1], Dante Arturo **Rodríguez-Trejo**[1*], Alejandro **Corona-Ambriz**[1], Reyes **Bonilla-Beas**[1†]

[1] Universidad Autónoma Chapingo. División de Ciencias Forestales. Carretera México-Texcoco km 38.5, Chapingo, Texcoco, Estado de México, México. C. P. 56230.

* Corresponding author: dantearturo@yahoo.com

ABSTRACT

The evaluation of reforestation for ecological restoration purposes in an area requires the comparison of similarity indicators with nearby reference forests. The objective of this study was to compare the vegetal composition, structure, falling debris, and their decomposition in the soil of a reforestation site of *Eucalyptus camaldulensis* Dehnh, planted more than 50 years ago, and a neighbouring forest dominated by *Quercus deserticola* Trel. and *Q. laeta* Liebm (used as reference), in an area of the State of Mexico; and obtain quantitative indicators of the trajectory of rehabilitation through the use of non-native species of Mexico. In reforestation and oak forest, we established 12 sampling sites where the composition, structure and two ecological processes (falling debris and decomposition) were determined. In addition, solar radiation was estimated by taking zenith photos of the canopy, using a hemispherical lens. When data was within normal distribution, we used the Student test, and when it was not, the Wilcoxon test was used to compare the variables studied. The reference forest outperformed reforestation ($p \leq 0.05$) in: richness (68 and 50 species); diversity (Simpson index, 1.6-2.6 and 0.7-2.3); normal diameter (21.3 and 13.7 cm), accumulated leaf litter (18.2 and 9.2 Mg ha^{-1}), detritus fall (0.606 and 0.321 Mg ha^{-1} per month), and litter decomposition (0.443 and 0.251 Mg ha^{-1} per month). Reforestation had a higher total radiation (5384 *vs*. 4376 MJ m^{-2} year^{-1}) and tree height (8.1 *vs*. 7.4 m). The percentage values of importance were 32.8 and 26.9 % for *Quercus deserticola* and *Q. laeta* in the oak forest, and 70 % for *E. camaldulensis* in the reforestation. After 50 years, reforestation still showed statistical differences from forest in composition, structure, and soil processes.

Keywords: oak forest, decomposition, debris, restoration ecology, *Eucalyptus camaldulensis*, *Quercus deserticola*.

INTRODUCTION

Nearly 91% of the forest area of Mexico has some level of deterioration, and a deforestation rate of at least 495 647 ha y^{-1} (CONAFOR, 2019). To counteract this degradation, various activities are carried out for the purpose of ecological restoration, such as reforestation. The Society for Ecological Restoration (SER, 2004) states that ecological restoration is the process of helping to restore a degraded, damaged, or destroyed ecosystem, and involves recovering processes, functions, diversity and, in

Citation: Herrera-Ramos C, Rafael-de-Jesús A, Rodríguez-Trejo DA, Corona-Ambriz A, Bonilla-Beas R. 2022. Ecological rehabilitation indicators for one eucalyptus reforestation with an oak forest as reference. **Agrociencia.** https://doi. org/ 10.47163/agrociencia. v56i3.2803

Editor in Chief:
Dr. Fernando C. Gómez Merino

Received: November 30, 2020.
Approved: April 29, 2022.
Published in Agrociencia:
June 01, 2022.

general, the stability and biological integrity of an original ecosystem. There are other concepts derived from the term: rehabilitation, establishment of artificial ecosystems (Ceccon, 2013), such as reforestation with exotics; each of these terms implies different characteristics.

Restoration ecology and ecological restoration in Mexico are still incipient; there are only 608 research cases registered between 1995 and 2016, with a percentage greater than 70 % in tropical plant communities, and 13 % in temperate-cold forests (López *et al*., 2017; Calva and Pavón, 2018). What is done frequently is reforestation with pines. Between 1967 and 1992, official reforestation programs in Mexico used exotic species such as *Eucalyptus camaldulensis* Dehnh. An example was the Eastern Forest Barrier Program, in the east of the State of Mexico, including El Monte Tlaloc, Texcoco; as part of The Lago de Texcoco Plan Commission which promoted reforestation, soil and water conservation programs to control erosion, reduce dust storms and help to recharge aquifers. The National School of Agriculture (now Autonomous University of Chapingo) participated by establishing reforestation with *E. camaldulensis* and other species in its experimental areas at the foot of Mount Tlaloc (Mario Ávila and Las Cruces), reforestations that are currently more than 50 years old.

In recent years, restoration and research have prevailed (López *et al*., 2017; Calva and Pavón, 2018), but there are still few studies to know the level of success of reforestation with exotics. An example is the contribution of reforestation with exotics in the formation of soil-structure on gravel soils (tepetates) (Ávila *et al*., 2011). Adaptive management, which is modified the more as research is available, is a key in ecological restoration. It can be applied only if reforestation is monitored, and management decisions are informed during the ongoing restoration project (SER, 2004). After a given period, all restorations should be evaluated to determine their level of recovery. In order to do this, there must be a reference ecosystem close to the restored area that represents an advanced point of development, and that allows comparison. Over time, the restored ecosystem is expected to achieve some of the attributes of the reference plant community, regarding composition, structure, and ecological processes (SER, 2004).

The hypothesis of the present study was that reforestation with *Eucalyptus camaldulensis* may show similarities in some attributes with the adjacent oak forest. The objective was to determine the composition, structure, and some ecological processes of a reforestation with *Eucalyptus camaldulensis* and a neighbouring oak forest (with dominant *Quercus deserticola* Trel. and *Q. laeta* Liebm.) as a reference, in an experimental area of the State of Mexico; aimed at obtaining quantitative indicators that help to explain the course for rehabilitation of the reforested area.

MATERIALS AND METHODS

Study area

This study was implemented in a reforestation site of *E. camaldulensis* with more than 50 years of being established, and in a nearby natural oak forest, where *Q. deserticola* and *Q. laeta* prevailed, located in a small ravine, as a reference plant community; both located at the Experimental Forest Station "Las Cruces", Texcoco, State of Mexico. The station belongs to the Autonomous University of Chapingo (Universidad Autónoma Chapingo − UACh), in an area of 325.68 ha.

The reforestation and forest sites studied were located at coordinates 19° 27′ 09″ N, -98° 48′ 59″ W, and 19° 27′ 05″ N, -98° 49′ 00″ W (Figure 1).

The study area with andesitic igneous rocks is in the Trans-Mexican Volcanic Belt. Litosol and Feozem haplic soils prevail, with low moisture retention capacity, moderately rich in organic matter with risk of severe erosion.

The climate is C(W2) (W)bi (the most humid of the temperate, sub-humid, with summer rains) (Ávila *et al*., 2011). Altitude is 2480-2640 m; although the oak forest and reforestation are neighbours, the former is in a ravine with more humidity, and no erosion. While in the adjacent area, erosion occurred before reforestation.

Sampling units in the evaluated areas

Two neighbouring areas were delimited, 3 ha for reforestation and 1 ha for residual forest in good condition, and the respective sampling intensity of the trees was 8 and 24 %; Regarding this, Romahn and Ramírez (2010) referred to up to 1 % sampling intensity in forest inventories.

Plots of 400 m^2 were established, and for the comparison of condition due to coverage effects, three plots were placed under canopies and three between canopies, for a total of six for each condition (oak forest and reforestation).

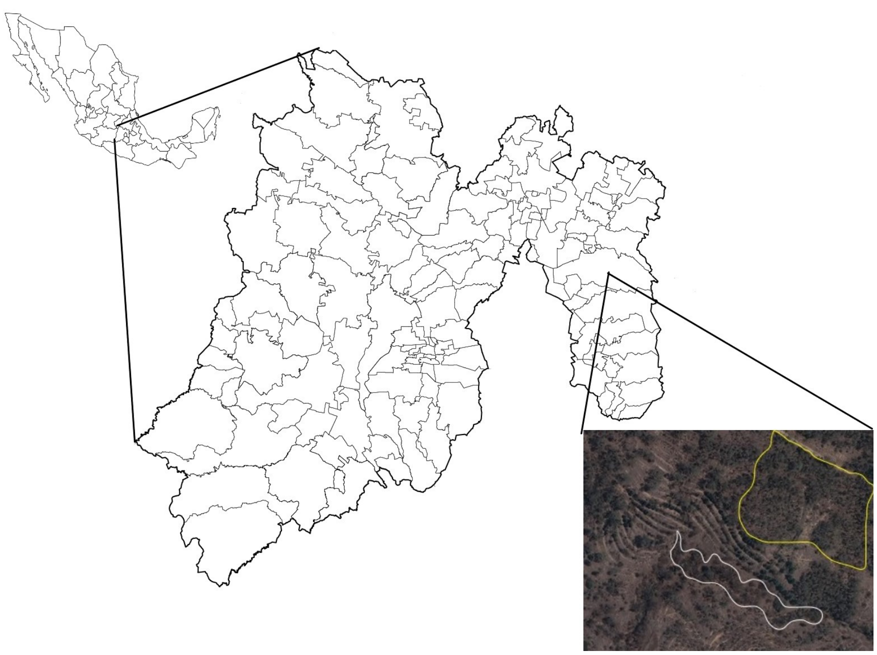

Figure 1. Study areas in the municipality of Texcoco, State of Mexico. The yellow outline indicates reforestation, and the white one the oak forest.

In each plot, the sampling of trees with normal diameters ≥ 5 cm (juveniles and adults) was done, and two subplots of 16 m^2 were located for shrubs and natural regeneration, plus two of 1 m^2 for herbaceous plants; for a total of 48 sampling units considering the two areas (Figure 2).

Solar radiation

In December, three aerial canopy photos were taken from the ground per canopy type, both under the canopy and between canopies, 12 photos in total, with a digital camera and hemispherical lens (Delta T-Devices). The camera was embedded in a levelling structure, 25 cm from the ground. These photographs were the input material to feed the Hemiview 2.1 SR4 program (Delta-T Devices, AT ©, Cambridge, England), together with coordinates, Julian day and altitude, to calculate total, direct, diffuse solar radiation and the percentage of visible sky.

Floristic composition and plant structure

In 2011, a sampling of trees and understory (in summer: August-September) was performed, and another sampling of understory in winter (January-February).

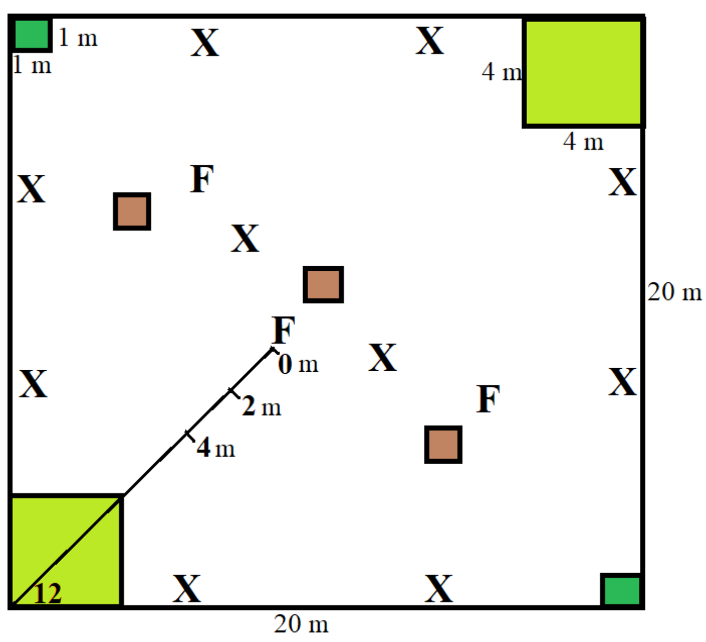

Figure 2. Sampling units used in the study. Large plot (20×20 m, 400 m^2), for tree sampling; medium plot (light green, 4×4 m, 16 m^2) for regeneration and shrubs; small plot (dark green, 1 m^2) for herbaceous. The brown boxes represent traps to capture organic matter (1 m^2); X, location points of bags with organic matter to estimate decomposition rate; F, points of the hemispherical photographs. Diagonal line, sampling of woody fuels; origin (0), point at 2 m, section for material sampling <0.6 cm, and those of 0.6-2.5 cm; 4 m, for materials with 2.6-7.5 cm, and 12 m for materials of > 7.5 cm.

The variables evaluated for the trees were: species, density (trees ha^{-1}), height (m), normal diameter (at 1.3 m, in cm) and crown diameter (m). For shrubs and herbaceous: species, density, frequency, and coverage. By stratum, species richness and percentage of importance value (PVI), α diversity (Simpson index) and β diversity (floristic similarity with the Jaccard index) were obtained.

Plant diversity was calculated by recording the species found in summer, when species richness is higher (Mostacedo and Fredericksen, 2000). For the identification of species, the samples were pressed, dried, and identified at DICIFO herbarium (División de Ciencias Forestales; Forestry Division, UACh).

Woody materials

Woody materials were estimated with the method of planar intersections (Brown, 1974). Six sampling lines were drawn in each type of cover (one line per large plot in each condition, 12 in total), of 12 m to record the number of intersections between lines and woody materials with diameter > 7.5 cm, 4 m for those with 2.5-7.5 cm, 2 m for both the 0.6-2.5 cm and <0.6 cm classes (Flores *et al*., 2008).

To estimate the total dry weight of woody fuels per hectare, the results were adjusted by the basic wood densities of the dominant species per condition.

Litter and fermentation layer

Litter and fermentation layer samples were collected in 36 randomly located 30 × 30 cm squares, with three replicates per large plot of vegetation, including each vegetation type and cover condition.

At the beginning of the study, coverage was estimated visually (%) and the depth of both layers was measured with a ruler. The collected material was separated by component and its dry weight was obtained with an electronic scale (Ohaus, Scout Pro, Mexico); then after drying in airflow oven (Ríos Rocha, N141, Mexico) in the laboratory (70 °C), until constant weight was obtained.

Fall of material for incorporation into detritus

To capture the fall of material considered debris, in December 2010 a total of 36 traps were placed in a pyramidal shape with an area of 1 m^2 at the top, 40 x 40 cm at the base and 50 cm high (Figure 3A). We placed three traps in each plot of vegetation: nine under canopies and nine between canopies, both in the reforestation and in the oak forest.

The collection of accumulated detritus was done monthly (January to June 2011), with separation of components (leaves and woody material, bark, fruits, and seeds). The material was dried in the laboratory in ovens at 70 °C, and then weighed by component.

Decomposition of organic matter

The decomposition bags were mesh-type (15×8×3 cm), 10 bags were randomly distributed in each of the 12 plots (a total of 120 bags), half under canopies and the other half between them.

Figure 3. A: traps for capturing debris; B: weighing of bags with organic materials later buried in the soil for estimation of decomposition rate.

Each one was filled with organic matter from each type of community evaluated, mainly leaf litter. The compaction used to fill the bags to the touch was the same as that in the leaf litter layer of the forest ground. All bags were weighed in the field.

On the date of establishment (December 2010), 20 samples (five per plot) were taken to the laboratory, dried in an oven at 70 °C, and weighed; the dry weight of the material in the laboratory was divided by its weight in the field and a factor was obtained to obtain the dry weight of the bags (Figure 3B). With this factor, the initial dry weight of the bags left in the field was estimated, which were used for monthly sampling from January to June. On each sampling date, another five bags were collected per plot, 20 in total (Waring and Schlesinger, 1985). In this way, for each collection date, the dry weight lost due to decomposition was obtained, which was estimated by the difference between the initial dry weight (December 2010) and that of each bag extracted in the following months.

The decomposition rate was calculated with the model $(X/X_0) = e^{-k}$, where: X = organic matter loss, X_0 = organic matter accumulated in the forest soil, k = decomposition coefficient, e = 2.71828 (Waring and Schlesinger, 1985).

Statistical analysis

The variables height, normal diameter, woody materials, litter and fermentation layer on the ground, rates of falling debris and decomposition, total direct, diffuse solar radiation, and visible sky were compared between and within each condition (forest and reforestation).

Data normality was analysed with the Anderson-Darling test (SAS© PROC UNIVARIATE). If the data were normal, they were analysed with the *t* test (Student, considering homoscedasticity or heteroscedasticity, SAS© PROC TTEST). If the data were not normal, they were analysed with the non-parametric Wilcoxon test ($p \leq 0.05$, SAS© PROC NPAR1WAY). All analyses were done with SAS© v. 9.0 (SAS Institute, 2002). The test hypothesis was Ho: $\tau 1 = \tau 2$; where τ = condition (reforestation or oak forest) or cover (under canopy and between canopies).

RESULTS AND DISCUSSION

Solar radiation

With the *t* test, statistical differences were found between forest and reforestation for visible sky and the three types of radiation evaluated (Figure 4); although no differences were observed between the condition below and between canopies ($p > 0.05$).

The visible sky was greater in the reforestation (34.3 ± 3.1%) than in the oak forest (28.8 ± 4.0%) ($p = 0.0175$), similar to the total solar radiation (5384 ± 594 MJ m^{-2} $year^{-1}$ and 4376 ± 634 MJ m^{-2} $year^{-1}$, $p = 0.0187$) in reforestation and oak forest, respectively (Figure 4A and 4B).

The respective values for direct solar radiation (4895 ± 553 MJ m^{-2} y^{-1} and 3965 ± 597 MJ m^{-2} y^{-1}, $p = 0.0157$) and diffuse solar radiation (488 ± 46.5 MJ m^{-2} y^{-1} and 411 ± 45.7 MJ m^{-2} y^{-1}; $p = 0.0239$), were also significant.

The lower incident radiation on the forest soil was related to a greater richness and diversity of understory species. Oak forests of *Q. crassifolia* in Puebla, in more humid areas than those in this study, reach a total solar radiation of 3607 ±1250 MJ m^{-2} y^{-1} (Rodríguez-Trejo *et al*., 2021) and are less altered, which contributes to its greater coverage (visible sky, 19.7%) and less solar radiation on the soil.

Floristic composition

Species richness was greater in the oak forest than in the reforestation, with 12 trees, 15 shrubs, 41 herbaceous, 68 species in all. But richness was also relevant in the

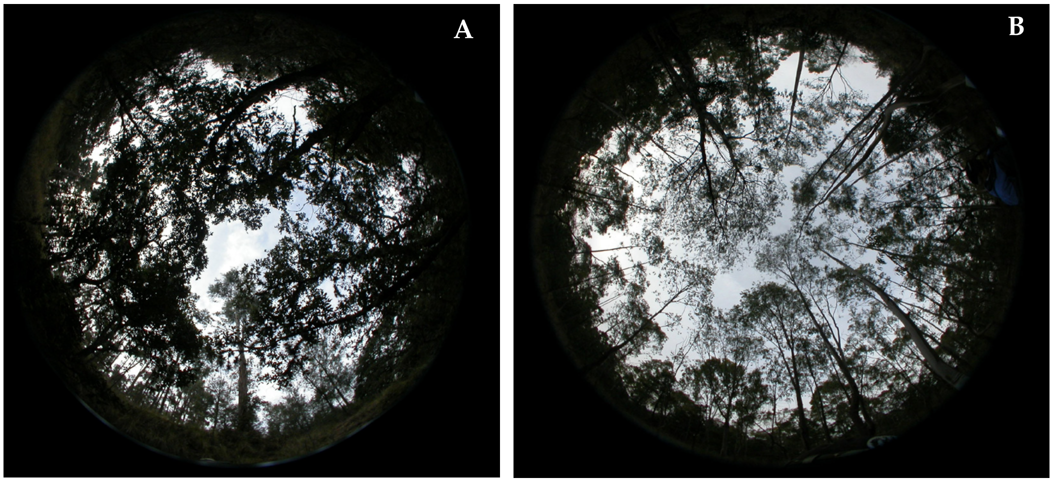

Figure 4. Hemispheric photographs in the analysis of solar radiation; A: from the canopy of the oak forest; and B: from reforestation with *Eucalyptus camaldulensis*.

reforestation where the expectation was to find only eucalyptus, 6 trees, 11 shrubs, 33 herbaceous were recorded, 50 species in all.

The Simpson diversity index for trees was higher in the oak forest than in the reforestation, but in the shrubby and herbaceous strata it was similar in both conditions (Table 1).

In shrubs, the index was similar between summer and winter in reforestation, but not in the forest. The herbaceous stratum was not similar between seasons in both conditions. Species similarity between conditions was low, with Jaccard indices of 5.9 (trees), 36.8 (shrubs), 15.6 (herbs), and 19.0 (all species). The higher species richness of the oak forest in the three strata is evidence of a greater structural complexity in the forest.

The systematic pattern when establishing reforestations (for example, the traditional staggering pattern with predetermined distances) and its monospecific character, has an influence by generating less environmental variability, for example, in solar radiation, resulting in less richness in the understory.

In Pontevedra, Spain, López *et al*. (2018) compared species richness between a plantation of *Eucalyptus globulus* Labill. and four oak stands (*Quercus robur* Pall.), and also found greater richness in the forest than in the plantation, 98 *vs*. 53 species.

The authors considered that allelopathy, fallen bark (mechanical barrier) and higher insolation in plantations are factors that explain the difference. In this study, these factors were also considered to limit understory richness and diversity. Solar radiation in the reforestation exceeded that of the oak forest, which may have also contributed to reduce the diversity of shrubs and herbaceous plants, since the locality is relatively dry.

The richness of herbaceous plants in the forest, compared to total richness (60.3%) was somewhat lower than that of an oak forest in Coahuila (72.9%) (Encina *et al*., 2009), although the oak forests are very diverse depending on the environmental conditions they are located. The highest diversity indices were those of herbaceous plants, in the oak forest during the summer. The explanation lies in the greater diversity and richness of herbaceous, compared to woody and, according to Rubio (2015), because humidity and temperature are higher during germination and the growth period in summer.

Table 1. Simpson diversity indices, by condition and season.

Stratum	Reference oak forest		Reforestation with eucalyptus	
	D_V †	D_I ¶	D_V †	D_I ¶
Arboreal	0.616		0.260	
Shrubby	0.566	0.409	0.438	0.470
Herbaceous	0.778	0.531	0.718	0.447

†D_V: Simpson diversity index in summer; ¶D_I: in winter.

Monospecific and contemporary reforestations with exotics are considered negative. Although they host less fauna than a natural forest, they can have more diversity than agricultural crops, pastures, and degraded areas (Montagnini, 2005). To promote diversity in them, Montagnini (2005) suggests establishing them at low density, mixed with native species or using only natives, thinning to favour local vegetation, and planting near natural seed sources.

The diversity indices of the oak forest, in all forms of life and times, exceeded those of reforestation, except in the shrub stratum in winter (Table 1). In shrubs and herbaceous, diversity was greater in summer than in winter.

Plant structure

The diameter and height data were not normal. The average range of the normal diameter was greater in the oak forest than in the reforestation (p = 0.046); on the contrary, the average range for height was higher in reforestation ($p \leq 0.01$). The diameter averages were 21.3 ± 8.2 cm and 13.7 ± 7.9 cm for the oak forest and reforestation, respectively, and 7.4 ± 2.4 m and 14.9 ± 4.7 m in height.

Eucalypt trees in this area are periodically affected by forest fires, which explains their relatively small height, despite being old (≥ 40 years). *Eucalyptus* foliage and bark are highly flammable, and the arrangement of its bark strips provides vertical continuity for the fire to reach the canopies. However, the lignotubers and buds under the bark allow the eucalypt to sprout and recover; it is adapted to fire (Scott *et al*., 2014).

In Las Cruces there are many bifurcated and trifurcated *Eucalyptus* trees, a sign of old regrowth as a result of fire. Despite such adaptations, the eucalypt trees grow less or show damage in their above ground part, which is why their current diameters and heights are smaller than what they should be.

The speed of growth that characterizes *Eucalyptus* explains why the reforestation trees are taller than the oaks, despite the recurring damage referred to and the shallow soil, compared to that of the oak forest. In the latter, the oaks are more robust, and the bases of their canopies are higher, which reduces the possibility that they will burn in the event of a fire; Although if this occurs, they are also capable of sprouting (Rodríguez-Trejo and Myers, 2010).

Importance values

In the oak forest there is a higher density of trees (970.8 trees ha^{-1}) than in the reforestation (816.6 trees ha^{-1}). This is understandable since it was carried out systematically, plantation density was approximately 1000-1500 trees ha^{-1}. Due to the great richness of species of the *Quercus* genus in Mexico, there is a high variability in structure (including density) and composition in their forests (Rubio, 2015).

This oak forest had 10 native tree species (8 oaks) and two exotic ones (*Eucalyptus globulus* and *Casuarina equisetifolia*). The trees showing the highest PVI as a whole were *Quercus deserticola* and *Q. laeta* (59.8 %).

In reforestation, *E. camaldulensis* was the most important (70 %) (Table 2). An oak forest dominated by *Q. crassifolia* in Villa del Carbón, Mexico, had eight tree species, including five oaks, covering two-thirds of the PVI (Rubio *et al*., 2011).

Agrociencia 2022. DOI: https://doi.org/10.47163/agrociencia.v56i3.2803
Scientific article

Table 2. Percentage value of importance (PVI) for oak trees and reforestation.

Species	DR♭ (%)	DOR¤ (%)	FR†† (%)	PVI¶¶ (%)
		Oak forest		
Quercus deserticola Trel. †	42.92	36.37	19.23	32.84
Quercus laeta Liebm. †	37.34	20.42	23.08	26.94
Quercus crassipes Bonpl. †	4.29	8.36	11.54	8.07
Casuarina equisetifolia L. ¶	2.15	5.08	11.54	6.26
Quercus rugosa Née†	3.00	4.32	7.69	5.01
Callitropsis lusitanica (Mill.) D.P.Little†	3.86	5.48	3.85	4.40
Quercus crassifolia Benth. †	1.29	6.93	3.85	4.02
Eucalyptus globulus Labill. ¶	0.86	5.85	3.85	3.52
Vachellia schaffneri (S.Watson) Seigler & Ebinger†	2.58	2.06	3.85	2.83
Quercus castanea Muhl. †	0.43	4.08	3.85	2.79
Quercus mexicana Bonpl. †	0.86	0.83	3.85	1.85
Quercus aff. *deserticola* Trel. †	0.43	0.21	3.85	1.50
SUM	100.0	100.0	100.0	100.0
		Reforestation with eucalyptus		
Eucalyptus camaldulensis Dehnh¶	81.63	88.49	40.00	70.04
Acacia retinodes Schltdl.¶	4.08	1.96	26.67	10.90
Callitropsis lusitanica¶	2.55	4.63	13.33	6.84
Schinus molle L.§	7.14	1.71	6.67	5.17
Casuarina equisetifolia¶	3.06	2.14	6.67	3.96
Eysenhardtia polystachya (Ortega) Sarg.†	1.53	1.07	6.67	3.09
SUM	100.0	100.0	100.00	100.00

†Native; ¶exotic; §naturalized; ♭DR: relative density; ¤DOR: relative dominance; ††FR: relative frequency; ¶¶PVI: importance value percentage.

The evaluation of the understory in oak forest during the summer yielded a density of 12 864.6 shrubs ha^{-1} and 235 833.3 herbaceous ha^{-1}; while in winter there were 5885.4 and 65 833.3 individuals ha^{-1}, respectively.

In the rainy season, in the reforestation, the density for shrubs and herbaceous plants was 8541.7 and 275 000 individuals ha^{-1}; but in drought it decreased (5781.3 and 116 666.7 individuals ha^{-1}).

The PVI for understory species, by evaluation season, indicates that the most important shrubs in the oak forest, in summer, were: *Helianthemum glomeratum* (Lag.) Lag. (22.5 %) and *Bouvardia ternifolia* Schltdl. (22.5 %).

In the herbaceous, it was *Stipa ichu* (Ruiz & Pav.) Kunth (12.9 %). The most important shrubs in winter were *H. glomeratum* (37.2 %) and *Gymnosperma glutinosum* Less. (12.8 %). In herbaceous they were *S. ichu* (43.4 %) and *Muhlenbergia confusa* (E.Fourn) Swallen (10.9 %).

The different species of oak and the environment cause variability in the understory species. Environments with high cover favour a low presence of shrubs. Rubio *et al*. (2011) recorded in Villa del Carbón seven shrub species, with a density of 40 ha^{-1} one species covering a third of the PVI. In dry oak forests of Coahuila (497 mm MAP), with less coverage, there were densities of 3307 bushes ha^{-1} (Encina *et al*., 2009). The difference may be due to the fact that the latter are shrub communities, while in the former the shrubs are part of a forest.

For reforestation in summer, the most abundant or dense shrubs were *G. glutinosum* (22.1 %), *Eupatorium* sp. (19.9 %), and *B. ternifolia* (15.5 %), and among the herbaceous *Pappophorum pappiferum* (Lam.) Kuntze (8.2 %), *Aristida divaricata* Humb. & Bonpl. ex Willd., *S. jorullensis* Kunth, and *S. tomentosa* S.Schauer (7.3 % each). In winter, the most abundant were *G. glutinosum* (65.9 %) and *S. ichu*, in shrubs and herbs, respectively.

The higher humidity and number of available light hours in summer explain the greater dominance of understory species in that season. Despite the allelopathic nature of various species of eucalyptus, such as *E. camaldulensis*, which contains inhibitory substances in its leaves and bark (phenolic acids, flavonoids, tannins and phytotoxic monoterpenoids *in vitro*) (Espinosa, 1996), no allelopathy was found in the reforestation studied.

Woody materials

The data recorded were not normal and there was no statistical difference between the mean intervals when comparing the total dry biomass of woody materials between reforestation and the oak forest (p = 0.1741).

Mean values were 18.003 ± 14.156 and 26.259 ± 27.282 Mg ha^{-1}. Partial loads per dimetric class for reforestation were 0.542 Mg ha^{-1} (< 0.6 cm diameter), 2.885 Mg ha^{-1} (0.6-2.5 cm), 11.114 Mg ha^{-1} (2.5-7.5 cm), 3.462 Mg ha^{-1} (> 7.5 cm, firmwood).

For the forest, the loads in equal order reached: 0.632, 3.175, 13.340, 6.761, and 2.352 Mg ha^{-1} (the latter for materials > 7.5 cm in decomposition). Oak forests of *Q. crassipes* Bonpl. in the Sierra Norte of Puebla have higher loads of woody materials, 31.726 Mg ha^{-1} with 81.1 % of materials > 7.5 cm (Bonilla *et al*., 2012), which may be due to the fact that these are wetter oak forests, with deep soils, and therefore more productive.

Leaf litter and fermentation layer

The data obtained were not normal. The averages in the oak forest were higher ($p \leq$ 0.05), with a mean biomass of 18.195 ± 11.824 Mg ha^{-1}; while in the reforestation it was 9.209 ± 3.434 Mg ha^{-1}. On average, the depths of the litter and fermentation layers were 8.0 and 2.0 cm in the oak forest, and 4.2 and 0.5 cm in the reforestation.

The oak species studied are deciduous to semi-deciduous, and due to their higher cover, the accumulation of debris in the forest exceeds that of reforestation. The eucalyptus species under study is evergreen; the foliage that falls is mainly due to the irregular death of their leaves and the wind.

The biomass of the material considered as detritus (woody materials, leaf litter, and fermentation layer) in the oak area corresponds with the 48.1 Mg ha^{-1} estimated by Martínez *et al*. (2018) in an oak forest (*Q. crassipes*, *Q. rugosa* and *Q. laeta*) in the same area, but at a higher altitude. The presence of this biomass on the forest soil is important as a reservoir for water, nutrient cycling, and habitat for soil organisms, where 25% of the biodiversity usually found in temperate forests (Dudley and Vallauri, 2005).

Falling debris

Regarding the composition of the detritus material, in the reforestation area, we found leaves (49.7%), fruits (22.3%), twigs (15.7%), and bark (12.3%); and in the oak forest, leaves (73.8%), fruits (7.4 %), twigs (16.4%), and bark (2.4%). Leaf litter was predominant, especially in the oak forest. The detritus accumulation data showed normality and the mean in the forest (0.606 Mg ha^{-1} per month) almost doubled that of the reforestation (0.321 Mg ha^{-1} per month) ($p \leq 0.05$). For each cover type there was no statistical difference ($p > 0.05$) between the conditions under and between canopies (Figure 5), probably due to the small size of the gaps.

Falling debris is part of the recycling process of organic matter and nutrients. The availability of more moisture in oak woodlands contributes to the accumulation of a greater tree biomass and consequently, more production of detrital material (Scott *et al*., 2014).

Due to the fact that oak trees are deciduous and to the greater biomass of their canopies, the accumulation of debris, particularly leaves, was greater in the oak forest than in the reforestation (Figure 5).

The contribution of organic matter to the system, mainly the foliar fraction, added to the woody materials, represented 65.4% in the reforestation, and 90.2% in the oak forest. These figures are higher than those recorded by Pérez-Suárez *et al.* (2009) in

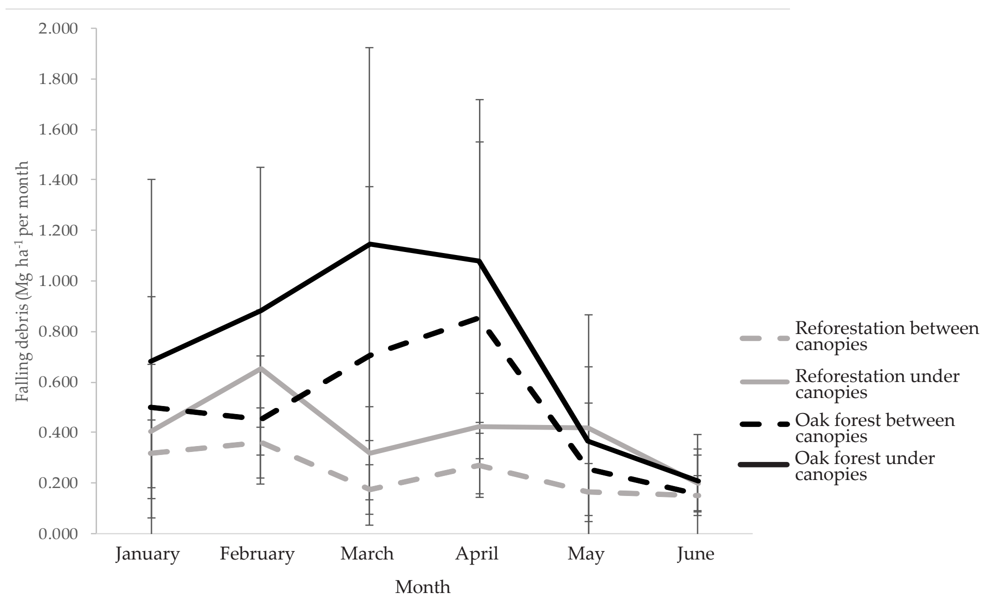

Figure 5. Monthly drop (Mg ha^{-1}) of organic matter in the sampling area. Error bars represent standard deviation.

the *Quercus potosina* Trel. oak forest (0.406 Mg ha^{-1}), in north-central Mexico, where leaves constituted the highest fraction of organic matter contributed, 60 %, and small branches 20-30 %.

Debris collection reached a pronounced peak around March-April in the oak forest, while in the reforestation it was obtained in February, which denotes phenological differences (deciduous foliage) among the species. Strong winds are typical in February and March, which contributed to the maximum falling debris in the *Eucalyptus* area.

Decomposition of organic matter

The mean decomposition rates for reforestation and forest were 0.251 and 0.443 Mg ha^{-1} month^{-1}. In open and shaded reforestation, mean decomposition was calculated at 0.221 and 0.281 Mg ha^{-1} per month, respectively.

In the forest, 0.332 Mg ha^{-1} per month were decomposed in the open space, and 0.554 Mg ha^{-1} per month under shade. The monthly decomposition factor between forest types showed normality and statistical differences (p = 0.0333), with means of 0.0649 for oak forest, and 0.0457 in reforestation.

There were no statistical differences between open sky and shade ($p > 0.05$) in any case. The highest decomposition values for oak forest and reforestation occurred in April and March, respectively (Figure 6).

The decomposition rate depends on the chemical composition of the materials. Long-lived leaves, such as those of eucalypt trees, invest more in defence products that slow down their decomposition, and the lignin content of *E. camaldulensis* ranges from 24.7 to 29.9 % (Terdwongworakul *et al*., 2005).

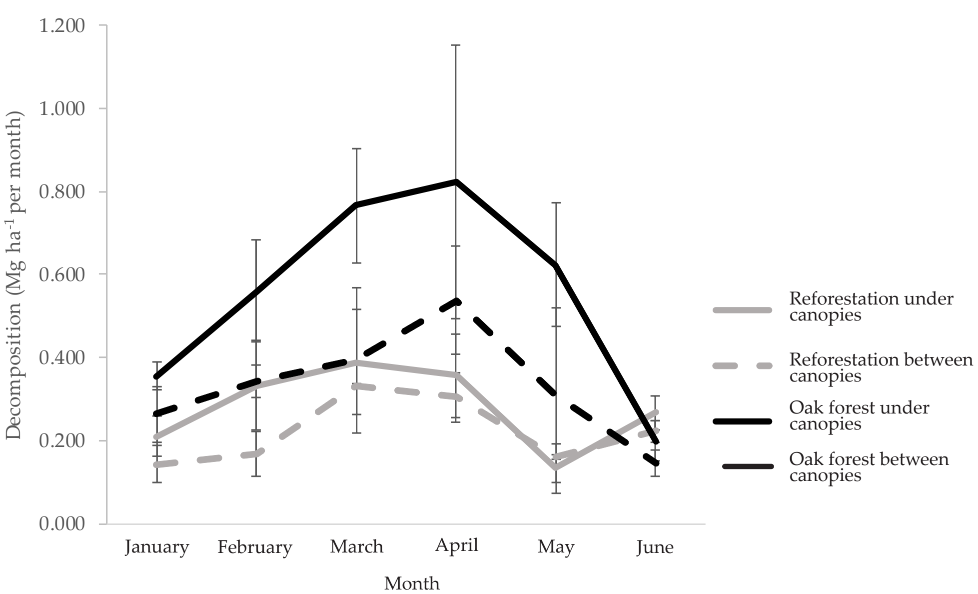

Figure 6. Monthly average decomposition (Mg ha^{-1}) of organic matter. Error bars represent standard deviation.

Bautista and Salazar (2005) argue that the lignin:N concentration ratio is negatively correlated with decomposition rate in *Q. rugosa*, where lignin content is 20.4-23.4 %. Deciduous oak leaves have more phenols that make them resistant to decomposition. In the case of eucalypt leaves, these combined factors contribute to a slower net decomposition.

Wood density is another characteristic that influences the decomposition of organic matter and wood density is inverse to the decomposition rate. *E. camaldulensis* has a density of 0.71-0.83 kg dm^{-3} (Nogueira *et al*., 2018), while for *Q. laeta* it reaches 0.61-0.75 kg dm^{-3} (Ordóñez *et al*., 2015). *Eucalyptus* wood is denser and therefore takes longer to decompose.

In the oak forest, the characteristics of leaves and wood favour a higher rate of decomposition, and the lower radiation and higher humidity favour fungi and decomposing microorganisms (Waring and Schlesinger, 1985). Root expansion and organic matter inputs in casuarinas (*Casuarina equisetifolia* L.) and cedars (*Cupressus lindleyi* Klotzch ex Endl.) promote faster soil formation in the tepetates of the study area compared to pines and eucalypts (Ávila *et al*., 2011).

The slow degradation of *Eucalyptus* debris was verified in this study; in the oak forest a greater amount of dead biomass was found on the ground, and we observed that it forms soil faster than reforestation. The accumulation of organic matter in the forest was double than that of the reforestation.

In reforestations, species follow a systematic pattern, so that the process of restoration to forest is initially deterministic. Then the recruitment of other species by germplasm dispersal begins in a stochastic or probabilistic process (Ceccon, 2013).

Ventura *et al*. (2017) compared in Hidalgo, a reforestation of *P. greggii* Engelm. ex Parl. with forest of *Pinus cembroides* Zucc. as reference, those authors found that reforestation can achieve some recovery of structural and functional variables, after 14 years of planting, but without reaching the levels of the reference forest.

This is similar to this study, although in the evaluated reforestation with *E. camaldulensis*, there were no signs of regeneration or ecological succession towards a natural type of tree vegetation.

CONCLUSIONS

The evaluated indicators show a low similarity in composition, structure and processes between oak forest and reforestation. Nevertheless, reforestation has been maintained and provides environmental functions. *Eucalyptus camaldulensis* seems to facilitate the presence of other species in the understory that increase heterogeneity and diversity at the landscape scale, although the site has not recovered ecological integrity.

Reforestation did not limit the establishment of an abundant understory cover, although different from that of the oak forest. If *sensu stricto* restoration is desired, oaks are the best choice on available land and in gaps, as long as the optimal establishment and growth characteristics of these species are present. Whilst the establishment of *E. camaladulensis* in this degraded area more than 50 years ago has shown to have recovered or facilitated certain characteristics or conditions that currently may favour the establishment of native species.

Finally, the indicators defined in this study can contribute to reorient restoration and reforestation in the area. For example, to initiate assisted reforestation with native oaks in areas previously reforested with *Eucalyptus*. Monitoring those areas subject to restoration or ecological rehabilitation is key in forest administration to provide feedback on restoration and management plans or practices.

REFERENCES

Ávila GR, Gutiérrez MC, Ortiz-Solorio CA, Ángeles E, Sánchez P. 2011. Evaluación de las reforestaciones en la formación de suelo a partir de tepetates. Revista Chapingo Serie Ciencias Forestales y del Ambiente 17: 303–312. https//doi.org/10.5154/r.rchsc/2010.11.113

Bautista HR, Salazar AH. 2005. Composición química de la madera de cuatro especies del género *Quercus*. Revista Mexicana de Ciencias Forestales 30: 25–50.

Bonilla E, Rodríguez-Trejo DA, Borja A, Cíntora C, Santillán J. 2012. Dinámica de combustibles en rodales de Encino-pino de Chignahuapan, Puebla. Revista Mexicana de Ciencias Forestales 4: 20–33.

Brown JK. 1974. Handbook for Inventorying Downed Woody Material. General Technical Report INT-16. USDA Forest Service, IFRES. Ogden, UT, USA. 30 p.

Calva SK, Pavón NM. 2018. La restauración ecológica en México: una disciplina emergente en un país deteriorado. Madera y Bosques 24: 1–12. https//doi.org/10.21829/myb.2018.2411135

Ceccon E. 2013. Restauración en Bosques Tropicales: Fundamentos Ecológicos, Prácticos y Sociales. UNAM, México D.F., México. 288 p.

CONAFOR (Comisión Nacional Forestal). 2019. El Sector Forestal Mexicano en Cifras. Comisión Nacional Forestal. Ciudad de México, México. 96 p.

Dudley N, Vallauri D. 2005. Restoration of deadwood as a critical microhabitat in forest landscapes. *In* Forest Restoration in Landscapes, Mansourian S, Vallauri D, Dudley N. (Eds.); Springer-WWF: New York, NY, USA, 203–207. https://doi.org/10.1007/0-387-29112-1_29

Encina JA, Zárate A, Estrada E, Valdés J, Villarreal JÁ. 2009. Composición y aspectos estructurales de los bosques de encino de la Sierra de Zapalinamé, Coahuila, México. Acta Botánica Mexicana 86: 71–108.

Espinosa, FJ. 1996. Revisión sobre la alelopatía de *Eucalyptus* L'Herit. Boletín de la Sociedad Botánica de México 58: 55–74. https//doi.org/10.17129/botsci.1487

Flores J, Rodríguez O, Meléndez M, Rosas O. 2008. Sitios de muestreo para el monitoreo de combustibles forestales (SIMMCOF). Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP). Centro de Investigación Regional del Pacífico Centro, Campo Experimental Centro Altos de Jalisco, Tepatitlán, Jalisco, México. 47 p.

López BF, Martínez GC, Ceccon E. 2017. Ecología de la restauración en México: estado actual y perspectivas. Revista Mexicana de Biodiversidad 88: 97–112. https//doi.org/10.1016/j.rmb.2017.10.001

López SB, Rivera JG, Sobral M. 2018. Biodiversidad en plantaciones de eucalipto y en robledales del sur de Galicia: plantas y aves. Nova Acta Científica Compostelana (Bioloxía) 25: 71–81.

Martínez JL, Rodríguez-Trejo DA, Borja A. Rodríguez GA. 2018. Propiedades físicas y dinámica de los combustibles forestales en un bosque de encino. Madera y Bosques 24: 1–14. https//doi.org/10.21829/myb.2018.2421467

Montagnini F. 2005. Attempting to restore biodiversity in even-aged plantation. *In* Forest Restoration in Landscapes: Beyond Planting Trees, Mansorian S, Vallauri D, Dudley N. (Eds.; Springer-WWF: New York, NY, USA, 384–391.

Mostacedo B, Fredericksen TS. 2000. Manual de Métodos Básicos de Muestreo y Análisis en Ecología Vegetal. BOLFOR: Santa Cruz, Bolivia. 87 p.

Nogueira CJA, De Araujo VA, Vasconcelos JS, Gutiérrez CM, da Cruz JN, Vasconcelos C, Prataviera F, Christoforo AL, Lahr AR. 2018. Caracterización físico-mecánica de la madera de *Eucalyptus camaldulensis* para uso estructural proveniente de Restinga, Brasil. Revista Forestal del Perú 33: 52–62. https//doi.org/10.21704/rfp.v33i1.1155

Ordóñez, JAB, Galicia A, Venegas NJ, Hernández T, Ordóñez MJ, Dávalos R. 2015. Densidad de las maderas mexicanas por tipo de vegetación con base en la clasificación de J. Rzedowski: compilación. Madera y Bosques 21: 77–126. https//doi.org/10.21829/myb.2015.210428

Pérez-Suárez M, Arredondo-Moreno JT, Huber-Sannwald E, Vargas-Hernández JJ. 2009. Production and quality of senesced and green litterfall in a pine–oak forest in central-northwest Mexico. Forest Ecology and Management 258: 1307–1315. https//doi.org/10.1016/j.foreco.2009.06.031

Rodríguez-Trejo DA, Myers RL. 2010. Using oak characteristics to guide fire regime restoration in Mexican pine-oak and oak forests. Ecological Restoration 28 (3): 304–323.

Rodríguez-Trejo DA, Rodríguez-Aguilar M, Villanueva-Morales JA, Bonilla-Padilla E. 2021. Estimación de combustibles en bosque de *Quercus crassifolia* en México central. Revista Incendios y Riesgos Naturales 4: 33–35.

Romahn CF, Ramírez H. 2010. Dendrometría. División de Ciencias Forestales, Universidad Autónoma Chapingo: Chapingo, Edo. de México, México. 294 p.

Rubio, LE. 2015. Aspectos ecológicos. *In* Encinos de México (*Quercus*, Fagaceae): 100 Especies, Romero S, Rojas EC, Rubio LE. (Eds.); Universidad Nacional Autónoma de México: Ciudad de México, 65–90.

Rubio LE, Romero S, Rojas EC. 2011. Estructura y composición florística de dos comunidades con presencia de *Quercus* (Fagaceae) en el Estado de México. Revista Chapingo Serie Ciencias Forestales y del Ambiente 17: 77–90.

SAS Institute (Statistic Analysis System Institute). 2002. SAS Program, v. 9.0. SAS Institute Inc. Cary, NC, USA.

Scott C, Bowman DMJS, Bond WJ, Pyne SJ, Alexander ME. 2014. Fire on Earth. An Introduction. Wiley Blackwell. Chichester, England. 413 p.

SER (Society for Ecological Restoration). 2004. Principios de SER Internacional sobre Restauración Ecológica. SER. Tucson, AZ, USA. 15 p.

Terdwongworakul A, Punsuwan V, Thanapase W, Tsuchikawa S. 2005. Rapid assessment of wood chemical properties and pulp yield of *Eucalyptus camaldulensis* in Thailand tree plantations by near infrared spectroscopy for improving wood selection for high quality pulp. Journal of Wood Science 51: 167–171. https//doi.org/10.1007/s10086-004-0633-3

Ventura-Ríos A, Plascencia-Escalante FO, Hernández-de la Rosa P, Ángeles-Pérez G, Aldrete A. 2017. ¿Es la reforestación una estrategia para la rehabilitación de bosques de pino? Una experiencia en el centro de México. Bosque 38: 55–66. https//doi.org/10.4067/S0717-92002017000100007

Waring RH, Schlesinger WH. 1985. Forest Ecosystems. Concepts and Management. Academic Press Inc. San Diego, CA, USA. 340 p.