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RESEARCH

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Structure, composition and carbon stocks of woody plant community in assisted and unassisted ecological succession in a Tamaulipan thornscrub, Mexico

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Abstract

Background: Ecological restoration is a process that helps the recovery of an ecosystem that has been degraded, damaged or destroyed. The success of restoration actions depend on the understanding of the processes, mechanisms and factors that guide vegetation dynamics. The restoration of plant communities can be made by unassisted (passive restoration, where the community recover by itself) and assisted (active restoration) ecological succession. It is imperative to know the scope of both types of activities to guide future restoration actions by evaluating the properties and functioning of the intervened communities.

Methods: Variance analysis of the carbon (C) stocks, basal area, canopy area, Shannon–Weaver index values, specific richness and abundance of three Tamaulipan thornscrub communities (assisted natural succession area, unassisted natural succession area and control area) was performed. Furthermore, a similarity analysis between the sampling areas using the floristic composition (abundance) was performed.

Results: In total, 11 families, 17 genera and 20 species of vascular plants were registered. The richness of species and abundance ranked as follows per area: assisted ecological natural succession > control > unassisted ecological natural succession. The species composition between sampling areas showed a low number of common species between plant communities.

Conclusions: The values of species richness, diversity, abundance, basal area, and canopy area of the assisted natural succession vegetal community was statistical similar to the control plan community. The values of C stocks showed that assisted ecological succession could recover not only structure and composition attributes but also this key ecosystem property.

Keywords: Ecological restoration, Plant communities, Post-agricultural restoration, Xerophytic scrub, Community ecological properties

Background

Ecological restoration is a process that helps the recovery of an ecosystem that has been degraded, damaged or destroyed [61]. Aims to recover the biodiversity and ecosystem services, considering the ecological, socio-economic and cultural processes [56]. Recently, the

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recovery of disturbed landscapes and biological communities is becoming a priority in many regions of the world [5]. However, the results of restoration are different and depends largely on the conditions and type of restoration action used to achieve the desired success.

In general terms, ecosystem ecological restoration can be classified into two types according to the strategy used: passive restoration where the ecosystem recovery by itself, like unassisted natural succession, and active restoration, where restoration activities are undertaken to accelerate the recovery of the ecosystem, like planting species to accelerate recovery in an assisted natural succession [12, 42, 61]. The unassisted ecological succession (passive restoration) can achieve good results in certain cases, but usually takes decades or centuries and generally does not guarantee a composition of species like the original state [1]. On the contrary, the assisted ecological succession (active restoration), usually shows better results, allowing the establishment of a higher canopy that improves the ecological conditions of the ecosystems in less than ten years [56, 66]. Regardless of the restoration chosen, it is imperative to carry out studies and actions that help ecological recovery in regions whose biological and ecosystem biodiversity is strongly threatened [32, 57, 58].

As mentioned on Linding-cisneros research on the challenges of a multicultural and megadiverse country like Mexico [30, 64], the government has promoted the restoration in natural protected areas and degraded communities. In this aspect, Tobon et al. developed a conceptual framework on the restoration of all terrestrial ecosystems, including xeric shrublands [64]. These plant communities occupy large areas in northern Mexico and in many cases the original vegetation has been eliminated to establish agricultural or livestock areas [6]. For this reason, restoration actions on shrublands such as the Tamaulipan thornscrub are key activities to recover and conserve vegetation structure and diversity [4, 50, 65].

The Tamaulipan thornscrub is a plant community usually found on deep clay soils, plateaus, hillocks and plains between 200 and 500 m altitude, under the influence of warm and semi-warm climates [60]. It is restricted to northeastern Mexico and southern Texas, and its original distribution in these areas has been reduced by 70% and 90%, respectively, due to changes in land use for agricultural and livestock purposes [7]. This scrub has a structure formed mainly by two strata, one shrubby (2–5 m high) usually composed of thorny elements and another herbaceous that does not exceed the height of a meter [60]. It has a high species richness ($S=21$; [33, 37], $S=29$ [24]) including species such as: *Celtis pallida* Torr. (Cannabaceae), *Opuntia leptocaulis* DC. (Cactaceae), *Prosopis glandulosa* Torr. (Fabaceae) *Acacia rigidula* Benth. (Fabaceae) and *Ruellia nudiflora* (Engelm. & A. Gray) Urb. (Acanthaceae), being some of these, important forestry and silvopastoral species [19].

Although it has been observed that the ecological restoration increases biodiversity and ecosystem services in general, results can be different for the different types of restoration and ecosystems [10, 26, 56]. Thus, studies that systematically evaluate the results of active and passive ecological restoration in the same location after the same disturbance, related to the recovery of structure, diversity and provision of ecosystem services such as carbon sequestration, are important to be undertaked in differents ecosystem [26, 39, 53, 56]. Furthermore, although the Tamaulipan thornscrub has been intensively studied in recent years [24, 33, 53, 59], only a few investigations have evaluated the structure and composition of woody plan community after agricultural activity in this ecosystem. Until now, research efforts on the Tamaulipan thornscrub have focused on timber volume production [20, 47], species survival [4, 65] or leaf and litter biomass [48].

The objective of this study is to evaluate the structure and composition such as species richness, diversity, abundance, basal area, canopy area and carbon (C) stocks of woody plant communities of the Tamaulipan thornscrub and to compare the differences in these ecosystem attributes between assisted/unassisted ecological succession and control areas. Our hypothesis is that the assisted ecological succession and control areas will show similar vegetation structure and composition, as well as in terms of the ecosystem service carbon sequestration.

Methods

Study area

The study area is located in the municipality of Pesquería, Nuevo Leon (Northeast Mexico, Fig. 1), 25°45´17.78´´ north latitude and 99° 58´01.40´´ west longitude. The climate is very dry to semi-warm (BWhw) according to the classification of Köppen (modified by Enriqueta Garcia) [23], the average annual temperature is between 20 and 21 °C. Soil types on the site are: xerosol, castañozem, feozem, regosol and minimally, fluvisol, vertisol, and rendzina [4], The average annual rainfall on the study area is 550 mm and an altitude of 330 m.a.s.l. The representative plant community consists mainly of Tamulipan thornscrub with shrubs as secondary vegetation mainly dominated by *Acacia farnesiana* [3].

Vegetation analysis

In November of 2017, the structure and composition of woody plant communities were investigated through a floristic composition and diversity evaluation on three areas: a control area, an assisted ecological succession

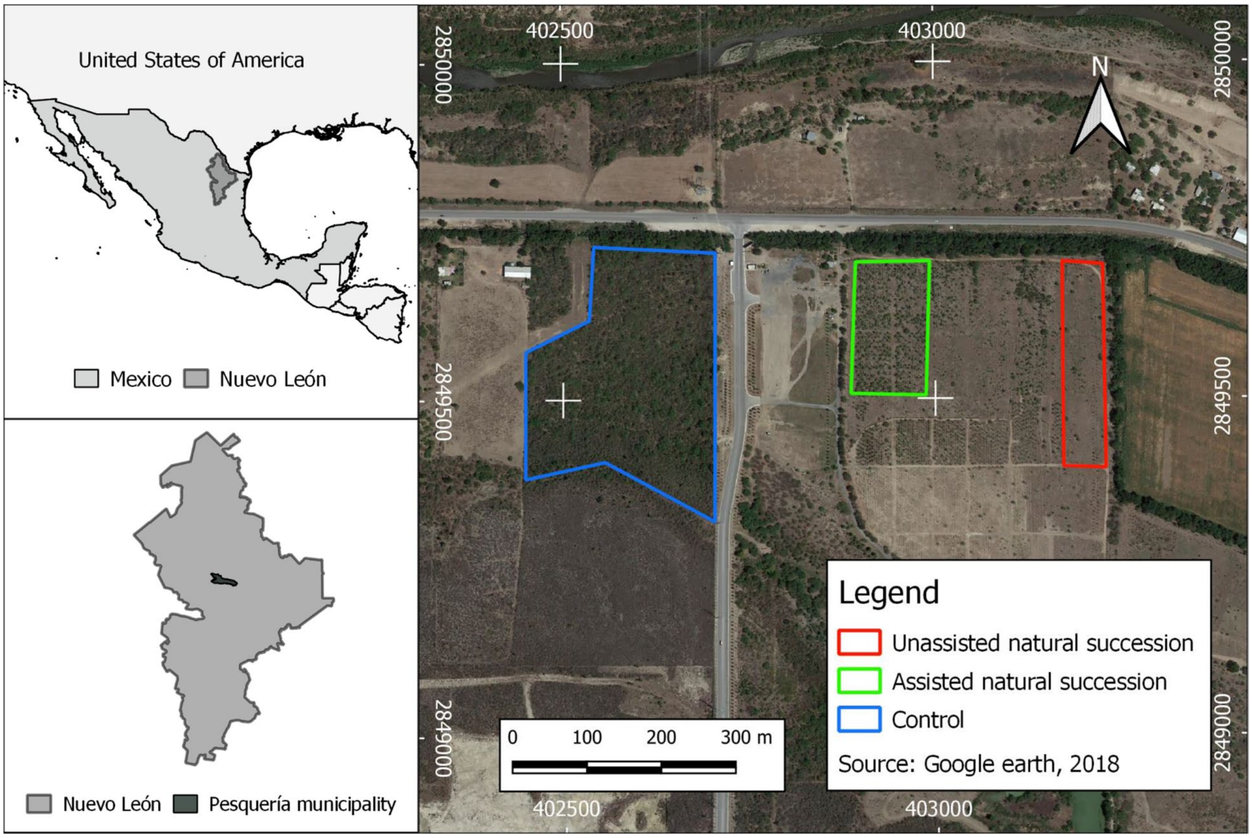

Fig. 1 Study area location

area and an unassisted ecological succession area. The species registered were identified at the species level by qualified personnel of the Faculty of Forest Science of the Universidad Autonoma de Nuevo León (UANL). Their scientific names were validated against names in Tropicos (http://www.tropicos.org) and IPNI (http://www.ipni.org) databases.

The control area is composed of a Tamaulipan thornscrub climax community where there are not records of productive activity involving total or partial removal of vegetation (such as: livestock, slaughter, agriculture etc.). The assisted ecological succession areas have a history of agricultural use and received an assisted ecological succession treatment after abandonment in September of 2009. The unassisted ecological succession area has the same history of use and abandonment as the previous mentioned site but assisted ecological succession actions were not performed. The agricultural activity mentioned on both assisted and unassisted areas consisted of plantations of oats, wheat and corn for approximately two decades (1989–2009). The crops were sowed in a rotating manner and irrigated by a gravity-driven water channel. Planting and harvesting activities were made using a farm tractor. All areas had similar characteristics: vertisol type of soil, 310 m. in elevation, the slope of < 3%.

The assisted ecological succession consisted of reforestation with native species in April of 2010. The species used for reforestation were rescued from a land-use changed area, authorized by SEMARNAT (Secretariat of Environment and Natural Resources) due the absence of nurseries producing the high diversity of native species of Tamaulipan thornscrub. The rescue started with the selection of abundant individuals of smaller size: arboreal and shrub species with heights from 0.5 to 2.0 m and basal diameters from 0.5–1.5 cm were considered, and each individual was labeled with: the common name, serial number and coordinates in where it was found. The specimen extraction process started with the pot preparation, using plastic paper to cover the roots to prevent from exposure and soil crumbling, then, the individuals were moved to a different site by trailer. When the plantation actions started, the specimens were placed in the strains and the plastic paper removed, fungicide and root promoter were applied, and plant tutor sticks were placed followed by the first irrigation. The plantation area was periodically cleaned of weeds. The plantation was made using a triangular plantation system with a distance of 1.5 m between individuals and lines having a plantation density of 992 n ha^{-1}. The process scheme can be observed in Additional file 1: Appendix.

An analysis of preliminary samples obtained for the study area was carried out seven years before (September 2017) to obtain a value of sampling units needed to register 95% of the richness of each community. For doing so, we used the equation of Mostacedo and Fredericksen [43]:

$$n = \frac{t^2 * CV^2}{E^2 + \frac{t^2 * CV^2}{N}} \quad (1)$$

where n is the adequate number of sampling areas, E is the error (20%), t is the extracted value of t student tables ($p < 0.05$), N is the total sampling unites and CV the variation coefficient. According to this mathematical model, 12 sampling plots of 10×10 m (100 m^2) were randomly established in each area. A census of all plant species higher than 10 cm was carried out. Dendrometric measurements of total height (h), basal diameter ($d_{0.10}$), which was estimated from the basal areas of all the ramifications, (cross sectional area) and canopy diameter (d_{canopy}) were carried out on each individual. Diametric classes (5, 10, 15, 20, 25, 30, 35 and > 35) were established.

Data analysis

We analyzed the relative abundance, dominance, and frequency of plant species to estimate their importance value index [43, 44]. The absolute abundance was calculated using the number of individuals found on the plots and was extrapolated to hectare, using the following formula: $A_i = N_i/S$, where A_i is the absolute abundance of species i, N_i is the number of individuals of species i, and S the sample surface (in hectares). The relative abundance of species was calculated using the equation: $Ar_i = (A_i/\Sigma A_i)$*100, where Ar_i is the relative abundance and ΣA_i is the total abundance of species i. To estimate dominance the basal area for each individual was calculated. The basal area was calculated with the formula $A = \pi/4^* d^2$, where A is the basal área, π is a constant value of 3.14, and d is the basal diameter ($d_{0.10}$). The absolute dominance is $D_i = Ab_i/S$, where D_i is the absolute dominance of species i, Ab_i is the basal area (in square meters) of species i, and S the sample surface (in hectares). The relative dominance was calculated using the equations $Dr_i = (D_i/\Sigma D_i)$*100, where Dr_i is the relative dominance of species i total dominance over and ΣDi is the total dominance of species. The relative frequency is $Fr_i = (F_i/\Sigma F_i)100$, where Fr_i is the relative frequency of species i over the total frequency, F_i is the number of plots that present the species i and ΣF_i is the total frequency of all species. The importance value index (IVI) was calculated as follows: IVI = ($\Sigma Ar_i + Dr_i + Fr_i$)/3, where Ar_i is relative abundance, Dr_i is relative dominance and Fr_i is relative frequency [43, 44].

To determine the alpha diversity of the studied communities, two indices were used: Margalef (DMg), which is based on the quantification of the number of species present (specific wealth), and Shannon (H´), which refers to the numerical structure of the community or proportional distribution of the abundance of each species [40]. The Margalef index was calculated with the following equation DMg = (S-1) / ln (N), where S is the number of species present and N the total number of individuals.

The similarity assessment between the sampling areas was performed using the floristic composition (abundance). For this purpose, a hierarchic cluster analysis was carried out using the block-distance measure and Ward's clustering method, graphing it on a similarity dendrogram. Statistical analyzes were performed using the software R ver. 2.6.0. with cluster package [54]. In addition, the communities (control, assisted ecological succession and unassisted ecological succession area) were explored by Bray–Curtis ordination analysis [9]. The analysis is based on an algorithm allowing analyzing the similarity of the communities sampled by calculating the percentage of similarity (0–100%) in a distance measure [8]. The results were presented in a dendrogram and the statistical analyzes were performed using the software package BioDiversity Professional Ver. 2 [38].

Carbon stocks

To determine the carbon stocks of the arboreal and shrub species of Tamaulipan thornscrub, first, the aerial biomass was determined using the local allometric equation (r = 0.80). [45].

$$\begin{aligned} \mathrm{BT} = & \left(0.026884 + 0.001191 * \mathrm{d}^2 2\mathrm{h} + 0.044529 * \mathrm{d} - 0.01516 * \mathrm{h}\right) \\ & + \left(1.025041 + 0.023663 * \mathrm{d}^2\mathrm{h} - 0.17071\mathrm{h} - 0.09615 * \ln(\mathrm{h})\right) \\ & + \left(-0.43154 + 0.011037 * \mathrm{d}^2\mathrm{h} + 0.113602 * \mathrm{d} + 0.307809 * \ln(\mathrm{d})\right). \end{aligned}$$

where, BT = total aerial biomass, d = basal diameter and h = total height.

The arboreal and shrub species in the Tamaulipas thornscrub do not have allometric equations that assessment of carbon stock, therefore, the carbon stock was calculated using the 0.454 factor according to [68], where it is interpreted that 45.4% of the biomass aerial corresponded to carbon stocks.

Statistical tests using IBM SPSS Statistic ver. 19 © [69] were carried out to verify that the assumptions of the residuals were fulfilled, normality using the Shapiro–Wilk test and homogeneity of variances by the Levene test, both with a significance value ($p < 0.05$). Since they fulfilled the assumptions, a generalized linear model (glm) was used with a Gaussian distribution function for Shannon–Weaver index values, specific richness, abundance and an analysis of variance (ANOVA) of one factor (area) was performed for carbon stock, basal area and canopy area. The Duncan test was used to determine if there were significant differences ($p<0.05$) of the variables analyzed per area.

Results

In total, 11 families, 17 genera and 20 species of vascular plants were registered. Fabaceae was the family with more species with 9, followed by Boraginaceae with two. The Additional file 2: Appendix II shows the floristic inventory of the study areas in detail.

The control area had 13 species, where, *Cordia Boissieri* A. DC., *Parkinsonia texana* (A.Gray) S. Watsonhad and *Acacia rigidula* were dominant. The assisted ecological succession area had 12 species with species like *Acacia farnesiana, Leucophyllum frutescens* (Berland.) I.M. Johnst, *Cordia boissieri.* The unassisted ecological succession area registered six species; *Acacia farnesiana*, *Leucophyllum frutescens,* and *Prosopis glandulosa* were the most representative species in this area.

The richness of species using the Margalef index showed significant differences between the studied areas. The assisted ecological succession area showed greater richness with 5.58 ± 0.43 (average ± standard deviation), followed by the control area (4.41 ± 0.37) and unassisted ecological succession area (0.91 ± 0.25). The values of the Shannon index in the assisted ecological succession areas (0.64 ± 0.04) and control area (0.54 ± 0.04) showed no significant differences, and both were higher than the unassisted ecological succession (0.30 ± 0.01) (Fig. 2).

The Table 1 showed the results of the GLM, χ^2-test and the freedom degrees for each sampling area. The Shannon Index (81.429), Species richness (Margalef index) (68.411) and Abundance (155.394) the values of χ^2 were less than χ^2-table (27.59) at alpha ($\alpha = 0.05$), therefore, the null hypothesis (equality of means) was rejected. This means that the observed data fit the theoretical distribution. The results of ANOVA for basal area and canopy area were showed in the Table 1 and the F-statistic value were 15.839 and 33.407, respectively; therefore, rejected H0 (H0: $\mu1 = \mu2 = \mu3$) because these values were > 3.32 (F-table). Thus, there were difference statistically significant at $\alpha = 0.05$ between sampling areas (Control area, assisted ecological succession and unassisted ecological succession area). In the post-hoc test and their *p*-values, the mean values of the Control area and assisted ecological succession do not have significantly different, but the mean values of the assisted ecological succession and unassisted ecological succession area have significantly different for Shannon Index, Species richness (Margalef index), Abundance and basal area (Fig. 2A, B, C and D). Only canopy area had significantly different between three sampling areas (Fig. 2F). Regarding the analysis of diametric classes of each area, the control area was the only one showing individuals equal to or greater than 35 cm and registered the biggest number of individuals in the 10 cm category (more than 50% of the individuals), while the assisted ecological succession showed more than 50% in the 5 cm category. In the three areas, the greatest number of individuals was concentrated in the categories of 5, 10 and 15 cm respectively (Table 2).

Absolute density, dominance and importance value index of all the studied areas are shown in Table 3. The abundance values of the control area (1175 ± 121 N ha^{-1}) and assisted ecological succession (1416 ± 178 N ha^{-1}) areas were higher than those of the unassisted ecological succession area (100 ± 27). The basal area of the vegetation communities of the assisted ecological succession and control area showed statistical similarity (7.86 ± 1.30 and 8.31 ± 1.03 m^2 ha^{-1} respectively) and were significantly higher than the unassisted ecological succession community (0.85 ± 0.74 m2 ha^{-1}).

The canopy area of the individuals in the assisted ecological succession and control area showed statistical similarity. The control area showed overlap in the canopy area with $13{,}365 \pm 1470$ m^2 ha^{-1} and the assisted ecological succession with 9298 ± 880 m^2 ha^{-1}, which is equivalent to 92% coverage. The unassisted ecological succession community presented 1039 ± 777 m^2 ha^{-1}, equivalent to the 10% coverage.

The composition of species per sampling area is showed in Fig. 3. After clustering control area (plots 1–12) five sites were grouped in unassisted ecological succession area (plots 1, 6–8 and 11) and one in the assisted ecological succession area (4). While the unassisted ecological succession area (plots 25–36) showed similarity with the other areas, adding plots 1, 6–8, 11, 14–18, 22–23. The assisted ecological succession area (13 to 24) showed a lower similarity in species composition, only having four of the original sampling plots (13, 19, 20,21), and adding another one (4). This means that the sampling areas contain de majority of the sites with their original category (Control area, assisted ecological succession and unassisted ecological succession area), for this reason the analysis of similarity between communities was carried out. The species composition analysis showed few common species between plant communities. From the numerical classification, a group formed by control and assisted ecological succession areas was distinguished with 23% of similarity, while the similarity with unassisted ecological succession area is 16% (Fig. 4).

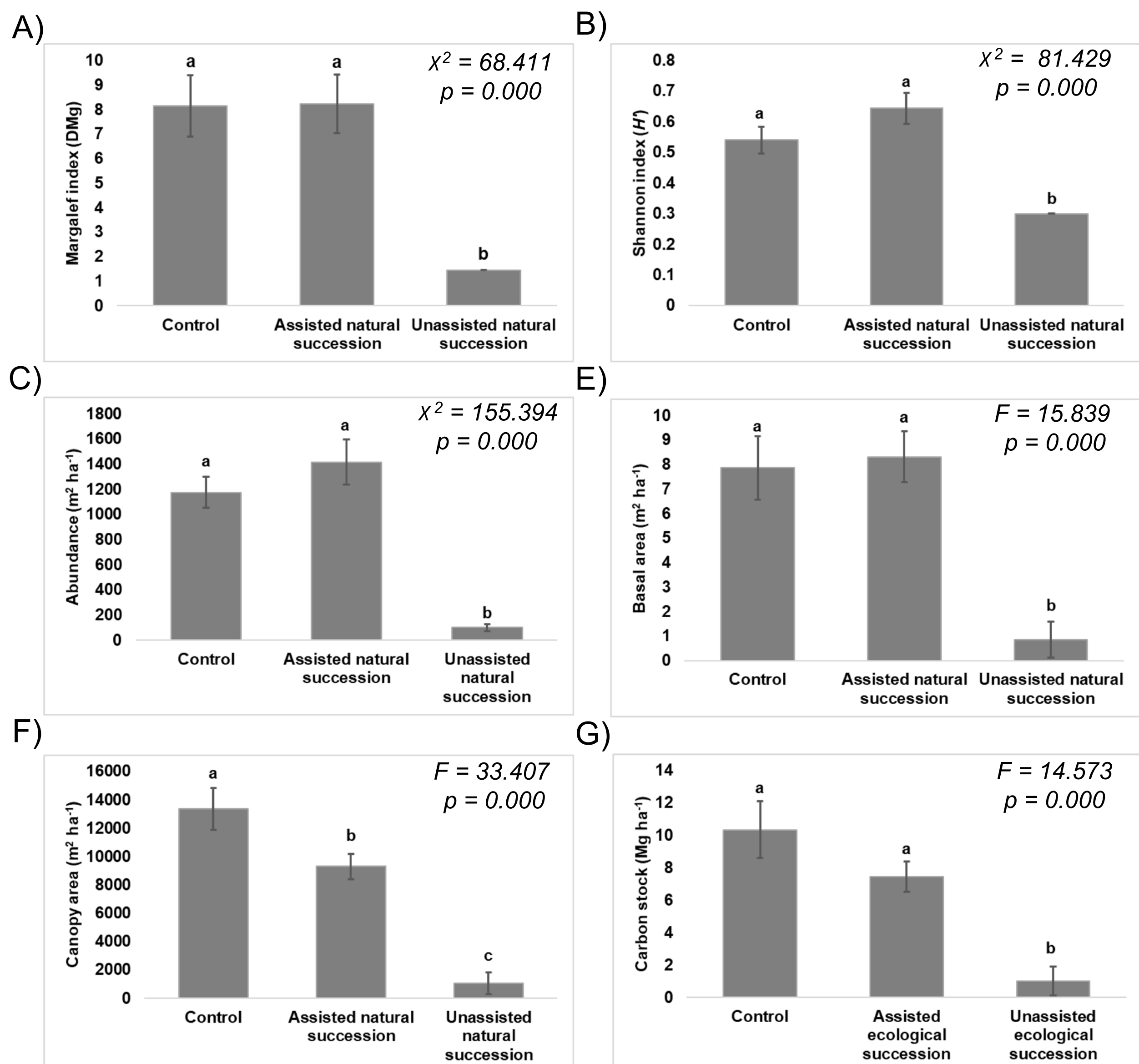

Fig. 2 A) Margalef index (D_{Mg}), Shannon index (H ') Abundance (m^2 ha^{-1}), Basal area (m^2 ha^{-1}), Plant cover (m^2 ha^{-1}) and carbon stock (Mg ha^{-1}) of the evaluated communities. Means (± standard error, n = 12) followed by different letters (a, b, c) show significant differences at $P = 0.05$ (Duncan test)

Carbon stocks

The results of ANOVA for carbon stocks are shown in the Table 1. The F-statistic value was 14.573; therefore, we rejected H0 (H0: $\mu1 = \mu2 = \mu3$) because 14.573 > 3.32 (F-table). Thus, there was a statistically difference significant at $\alpha = 0.05$ between sampling areas. In the *post-hoc* test, the mean values of the control area (10.35 ± 1.75 Mg ha^{-1}) and assisted ecological succession (7.45 ± 0.92 Mg ha^{-1}) do not showed significant statistical differences, but the mean values of the assisted ecological succession and unassisted ecological succession area (0.99 ± 0.88 Mg ha-1) showed significant statistical differences for Carbon stock (Fig. 2G). More than 50% of the concentration of carbon stock registered in both control and assisted ecological succession area was centered in diameter categories from 5 to 20 cm, in the unassisted ecological succession area the higher concentration of carbon was found in the 30 cm category.

Table 1 Generalized linear model (glm) for Shannon–Weaver index values, specific richness, abundance, and analysis of variance (ANOVA) of one factor (area) was performed for carbon stock, basal area and canopy area

			df		Chi-squared	Sig
Shannon index			17		81.429	.000
Species richness			8		68.411	.000
Abundance			18		155.394	.000
		Sum of Square	df	Mean Square	F	Sig
Carbon stock	Between Groups	550.841	2	275.421	14.573	.000
	Within Groups	623.674	33	18.899		
	Total	1174.516	35			
Basal area	Between Groups	419.906	2	209.953	15.839	.000
	Within Groups	437.442	33	13.256		
	Total	857.348	35			
Canopy area	Between Groups	946,792,272.453	2	473,396,136.227	33.407	.000
	Within Groups	467,627,393.550	33	14,170,527.077		
	Total	1,414,419,666.003	35			

Discussion

Fabaceae showed the largest number of species in the study area. The representativeness of the Fabaceae family was also reported in previous studies carried out in North Mexico, where the family was identified as a big diversity group [15] in conserved areas, in secondary vegetation communities and assisted ecological succession communities [2, 25, 35, 39].

The diversity of Fabaceae is attributed to the ecological plasticity of the group, which contains species with different seed sizes, types of dormancy, germination rates [17, 27–29], longevities [11, 14], growth rates and patterns [14, 21] and tolerance to water scarcity and to nitrogen [3, 13, 24, 50]. All above mentioned factors allow members of the Fabaceae family to be present in different environmental conditions [16, 46, 55] influencing the existence of different compositions within the same Tamaulipan thornscrub [15, 55]. Factors such as propagules availability and ecological performance, along with the interactions between other taxonomic groups presented in the Tamaulipan thornscrub community are responsible of determining vegetation performance [52].

Table 2 Number of individuals per hectare in each diametric category

Diameteric category	Control area Ind / ha	Assisted ecological succession area Ind / ha	Unassisted ecological succession area Ind / ha
5	425	717	75
10	517	383	0
15	125	175	8
20	58	108	8
25	17	33	0
30	8	0	8
35	8	0	0
> 35	17	0	0
Total	**1175**	**1417**	**100**

The comparison of richness and diversity of species between sites were similar to the values reported on previous studies [2, 25, 35]. The unassisted ecological succession area low richness and diversity of species can be largely attributable to the dominance of one or two taxa over others, which can be due the action of environmental filters limiting the presence of other species (e.g., low nitrogen content, insolation and drought) as suggested by [31].

The importance value index of the control area is similar to the values reported by [39] showing the characteristics of a mature community [18]. The presence of *Cordia boissieri* and *Parkinsonia texana* in a mature secondary vegetation community like in the control area has been reported by [15, 45]. Those species are considered as pioneer species of early successional stages [11, 14], showing a life spectrum of 30–50 years [11, 14] which could explain why they exist in the control area. Besides, the rapid growth of *P. texana*, along with the high germination rate in share light conditions with *C. boissieri* [29], and the establishment capacity under shadow conditions suggested by its seed size. [30] could explain the Importance Value registered. *Acacia rigidula* has a higher germination rate than *C. boissieri* [27, 30], but the size of its seed suggests low tolerance to shade and rapid growth [22, 34], which could explain why it occupies the third important value index of the control area.

Regarding the secondary natural succession trajectory, the presence of *Acacia farnesiana* and *Prosopis*

Table 3 Absolute density (number per hectare), absolute dominance (square meters per hectare), and importance value index (IVI, percent) of the three areas evaluated

Specie	Control			Assisted natural succession			Unassisted natural succession		
	Density	Dom		Density	Dom		Density	Dom	
	N ha^{-1}	m^2 ha^{-1}	IVI	N ha^{-1}	m^2 ha^{-1}	IVI	N ha^{-1}	m^2 ha^{-1}	IVI
Acacia farnesiana	*	*	*	374	544	34.3	38	113	56.6
Acacia rigidula	181	189	16.7	11	16	2.3	*	*	*
Celtis pallida	4	15	1.1	*	*	*	*	*	*
Cordia boissieri	234	409	23.9	113	166	14.1	6	1	7.2
Diospyros palmeri	4	9	1	*	*	*	*	*	*
Ebenopsis ebano	4	25	1.3	55	28	4.6	*	*	*
Ehretia anacua	*	*	*	6	1	0.7	3	0	3.5
Foresiera angustifolia	2	2	0.7	*	*	*	*	*	*
Havardia pallens	132	174	11.5	*	*	*	*	*	*
Jatropha dioica	*	*	*	*	*	*	3	1	3.7
Leucophyllum frutescens	39	18	3	263	141	18.2	8	9	10.3
Leucaena leucocephala	*	*	*	14	8.4	1.7	*	*	*
Senegalia wrightii	37	30	*	*	*	*	*	*	*
Parkinsonia acueleata	*	*	*	40	111	8.1	*	*	*
Parkinsonia texana	201	346	19.5	9	19	1.9	*	*	*
Lantana canescens	*	*	*	24	6	1.9	*	*	*
Prosopis glandulosa	22	218	7.2	81	30	7	12	2	8.3
Baccharis salicifolia	*	*	*	43	47	5.3	*	*	*
Yucca filifera	21	68	4.1	*	*	*	*	*	*
Zanthoxylum fagara	43	102	6.2	*	*	*	*	*	*
Without Vegetation									10.4
Total Area	**924**	**1604**	**100**	**1033**	**1116**	**100**	**70**	**125**	**100**

* = NA

glandulosa in the vegetation community of the unassisted ecological succession area match the results of [15, 25] registering the species in areas that have suffered some type of disturbance due to anthropogenic activity. *A. farnesiana* is a pioneer species that presents a high germination rate in temperature ranges from 12 to 28 ^{0}C [17, 29, 30] and like *P. glandulosa*, it is characterized by their rapid growth [16, 21] and its tolerance to edaphic drought which is a common characteristic of the study area. This species also has higher values in hydric potential of the xylem on the pre-dawn and in midday, under conditions of lack of water, compared to other species [13, 24]. Its presence is also associated with low availability of nitrogen in the soil, which results in a limiting factor for other groups and an advantage for the species of this family. These aspects suggest that unfavorable habitat conditions advantage the establishment and dominance [3, 50], making it an important group in the initial stages of succession and suitable for restoration activities.

The plantation abundance of the assisted ecological succession was 992 N ha^{-1}, and after seven years it was 1416 ± 178 N ha^{-1}, which indicates that in addition to the established individuals there was a regeneration of native species. The composition of this assisted community was partly a product of the species selected for revegetation, the restoration activities, as well as of the ecological performance of the species observed at the end of the study.

The highest importance value found in *A. farnesiana* can be explained through some factors such as: the advantage of its ecological performance in harsh environments, the low mortality of seedlings and saplings in plantation conditions [21] and the high capacity for canopy development in plantation conditions (which also explains the higher basal area). The rapid development of the canopy can strongly limit the germination, establishment, and development of light-demanding species [22], which can, on the other hand, benefit the species tolerance to shading conditions like *C. boissieri*, that is also included in the actions of restoration, and that occupies the third value of importance in this area.

Leucophyllum frutescens, a pioneer species with the second most important value in the assisted ecological

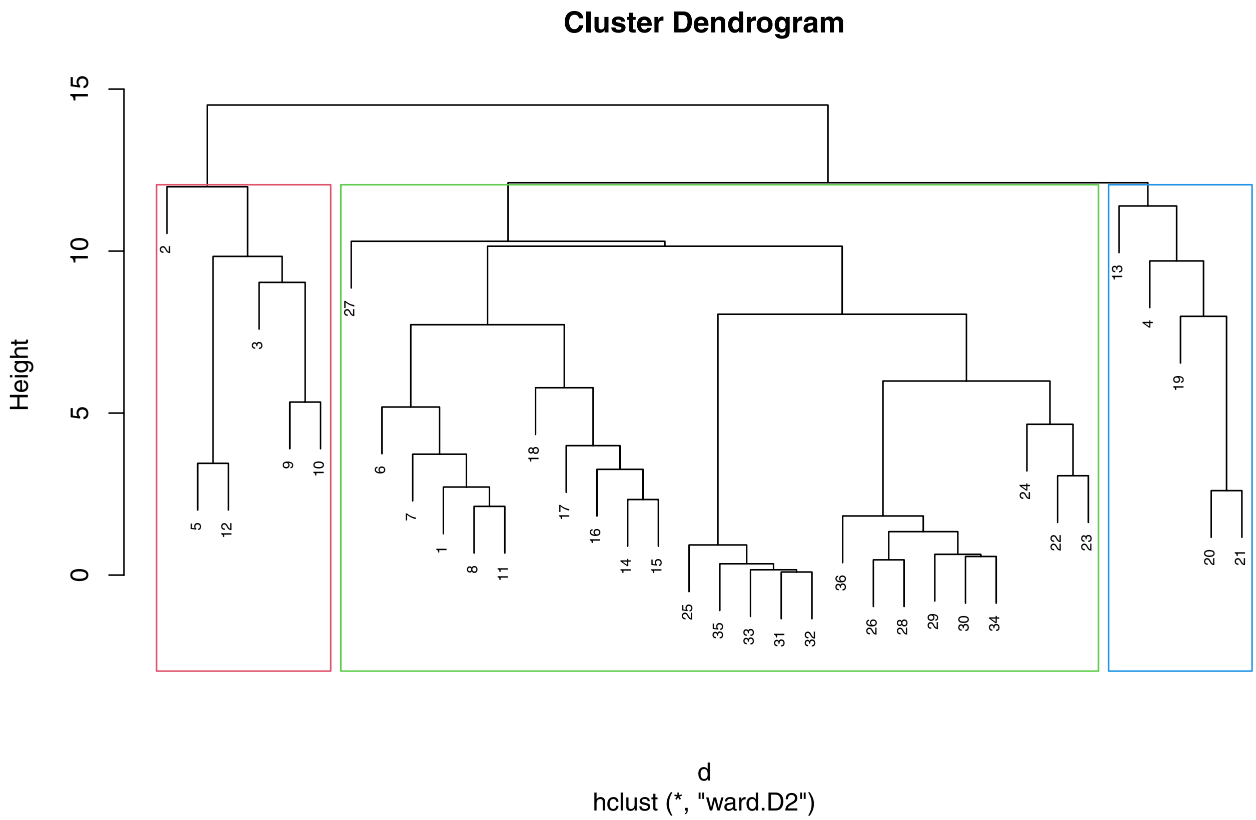

Fig. 3 Dendrogram of similarity by hierarchic cluster analysis using the block-distance measure, and Ward's clustering method between the different evaluated areas based on abundance, on the analysis. Red box: Control area, green box: Unassisted ecological succession area and blue box: Assisted ecological succession area

Fig. 4 Dendrogram of similarity between the different evaluated communities based on the Bray–Curtis analysis

succession area is commonly associated with low productivity areas, which could explain the ability to withstand limiting condition areas [47]. *P. glandulos*a was the species found in all studied areas, alongside the tolerance to adverse environmental and edaphic conditions, show low mortality in plantations with seedlings surviving rate above 85% [21]. However, as growing time passes, the plantations are susceptible to pest attacks, which can increase the mortality, this could explain the low importance value in the assisted ecological succession area (IVI = 7%).

Ebenopsis ebano (Berland.) Barneby & J.W Grimes and *Acacia rigidula* species of moderate growth [14, 28] presented on both control and the assisted ecological succession area. These species can withstand the stress conditions [21], which also makes them an adequate option for restoration actions.

Similar to what was reported in this study, other authors [36, 38] showed that the assisted ecological succession treatment was effective in terms of recovering the richness and diversity of tree and shrub species compared to passive restoration actions in northeastern Mexico, which explains to a large extent the similarity between the control and the assisted ecological succession site, unlike unassisted ecological succession area.

The dissimilarity in the composition of plant communities observed in our study is similar to the results recorded by Alanis et al. [3] on vegetation communities of the Tamaulipan thornscrub with a different productive use and obtained inferior values of similarity. The differences in species composition could be explained as differences in growing of the communities in control and unassisted ecological succession area, also the influence of the origin of the structure and composition of the control area compared to the assisted ecological succession area, which is strongly limited to the species which it was intervened. Additionally, the dissimilarity of the communities in our study and the study of Alanis et al. [3] can be explained through the heterogeneity of Tamaulipan thornscrub vegetation that usually shows different species composition according to the land use, topographic and edaphic conditions y differences in altitude [55].

The differences between assisted ecological succession and control area plant communities are determined by the dissimilarity of common species and high-density values. In the control area, the species are *Cordia boissieri* (243 N ha^{-1}) and *Parkinsonia texana* (201 N ha^{-1}) while in the assisted ecological succession area *Acacia farnesiana* (374 N ha^{-1}) and *Leucophyllum frutescens* (263 N ha^{-1}).

Carbon stocks

It is relevant to analyze the carbon stock in the three areas, since CO_2 is the main greenhouse gas, and that plant species play a fundamental role in the absorption and fixation of carbon [67]. In this regard, the highest value of captured carbon registered for the control area and assisted ecological succession communities compared to the capture of unassisted ecological succession area is mainly attributable to the higher number of individuals and the diametric categories observed in these areas (Table 2). The unassisted ecological succession area concentrates practically all the individuals of the smaller diameter category, which is logical because to reach similar values as the control area must take several years for the development of the vegetation and the recovery of the ecological and dasometric normal parameters.

Compared to the dasometric values of the control area (mature thornscrub community), the ecological, dasometrical and C Stock variables of the assisted ecological succession shrubland area were recovered in seven years after the restoration the activities. Similar distribution pattern of the individuals in the diametric classes, and thus of C stocks, were observed in other successional studies of the Tamaulipan thornscrub communities, where early successional stages concentrated the individuals of the smaller diameter category and had a low C stock [36, 67]. This pattern suggests that vegetation from assisted ecological succession shrubland follows an optimal growth trend [67].

Conclusion

Our results provide valuable information about the restoration and regeneration condition and structure and composition of woody plant community after seven years of assisted ecological succession treatment in a Tamaulipan thornscrub located in northeastern Mexico.

The values of species richness, diversity, abundance, basal area and canopy area of the assisted ecological succession vegetal community presented statistical equality with the control plant community.

The values of captured carbon showed that assisted ecological succession could recover not only structure and composition attributes but also this ecological service. These results indicate that the assisted ecological succession treatment was effective on recovering the richness and diversity of tree and shrub species compared to passive restoration actions in the Tamaulipan thornscrub studied.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40693-021-00102-6.

Additional file 1: Appendix I. Scheme of the plantation process of the assisted ecological succession.

Additional file 2: Appendix II. Scheme of the plantation process of the assisted natural succession.

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Author's contributions
EAR, VMMG, ACCC, EBR, AMO, LSC, AGAR: all authors conceived the study, designed the experiments, contributed to the data analysis, interpretation, discussion of results and writing. The author(s) read and approved the final manuscript.

Availability of data and materials
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Declarations

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Competing interests
The authors declare that they have no competing interests.

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