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Ecological Attributes of the Shrubby Community of Sotol (*Dasylirion leiophyllum*) in the Chihuahuan Desert, Mexico

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Abstract: Sotol (*Dasylirion leiophyllum*) is a shrubby species that grows in the Chihuahuan Desert. Sotol plants are commonly used to produce an alcoholic beverage, also known as "sotol". A study was carried out to assess the composition and structure of shrubby communities where sotol inhabits in northern Mexico. The importance value index (IVI), diversity indexes, and structural attributes of the sotol community were estimated. Furthermore, a principal component and a cluster analysis were conducted in order to identify possible associations of species along the sotol distribution area. A total of 10,273 plants belonging to 17 families and 46 species were recorded, where the *Agave lechuguilla* and *Tiquilia greggi* were the most abundant species. Higher abundances of sotol and higher diversity indexes were observed in hillside areas and eastern aspects. The multivariate analyses revealed five shrubby groups in the distribution area of sotol, which grows in valleys, hillsides, and also on the top of mountains. The main communities found where sotol grows are rosetophyllous, microphyllous, and mesquite communities, and also, in higher altitudes, sotol is associated with oak species. This information is not only useful for a better species knowledge, but also for the protection of shrubby communities where *Dasylirion leiophyllum* inhabits.

Keywords: sotol ecology; *Dasylirion leiophyllum*; shrubby communities; arid lands

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1. Introduction

The Xerophytic shrub communities extend from the state of Baja California in the north down to Oaxaca in the south of Mexico, where these communities cover 40% of the arid and semi-arid zones of the Chihuahuan Desert, and also the Sonoran Desert [1]. In recent years, xerophytic shrubs have decreased by 26%, mainly due to land use changes, leaving only 40.95 million hectares of land, of which 70% seems to be overgrazed [2]. In the state of Chihuahua, Mexico, xerophytic shrubs cover 32.41% of the land, which is basically divided into microphyllous desert scrubland (79.53%) and rosetophyllous desert scrubland 20.47% [3]. The microphyllous desert scrubland is dominated by small-leaved shrubs such as *Larrea tridentata* and *Flourensia cernua*, while the rosetophyllous desert scrubland is dominated by species with leaves clustered at the base such as *Agave lechuguilla*, *Dasylirion* spp., and *Yucca* spp. [4–6].

In Mexico, *Dasylirion*, commonly called sotol, is composed of 16 species [7,8], and at least 5 of these species are located in the state of Chihuahua, Mexico, where *Dasylirion leiophyllum* is widely distributed [9]. There is evidence that sotol was used by the tribes of northern Mexico for food, medicine, and to make clothing and footwear [10]. Currently, there are many uses for this species among the people living in the arid land where *Dasylirion* species are naturally distributed, but the main use is for the production of an alcoholic beverage, also known as sotol [11].

Mexican regulations of the utilization of wild sotol plants indicate that after harvesting them, at least 20% of mature plants must be protected and left in field, mainly for seed production in order to promote natural regeneration [12]. However, it is unknown whether this harvesting rule is sufficient to maintain the structure and function of natural ecosystems [13]. Harvesting should be a topic for potential new research on the impact of the harvesting intensity on the stability and regeneration of these communities [14].

The raw material for the production of sotol beverage is mainly supplied by wild plants, which are harvested from natural ecosystems [15]. This practice could place *Dasylirion* populations at risk, mainly because of the intensity of the use of sotol commercially, and also, this harvesting might initiate gradual processes of change in the structure and composition of the rosetophyllous desert scrubland communities, soil erosion, or disturbances of environmental services, such as carbon sequestration [13,16]. Therefore, several authors suggest establishing commercial *Dasylirion* plantations to avoid overexploitation [13,17,18]; however, so far, the area of commercial forest plantations has been reduced to only dozens of hectares.

There are sufficient reasons to carry out studies to provide information on the plant communities where sotol grows in order to improve decision making in the management and conservation of natural resources. The purpose of this study is to describe the composition and structure of vegetation in a plant community where *Dasylirion leiophyllum* grows in the state of Chihuahua, Mexico, which is located in the core of the Chihuahuan Desert.

2. Materials and Methods

2.1. Study Area

This study was conducted in the arid land of northern Mexico. Three sites (Morrion Rabch, Tascate Ranch, and Arcoiris Ranch) with wild populations of sotol (*Dasylirion leiophyllum*) located in the state of Chihuahua were sampled (Figure 1).

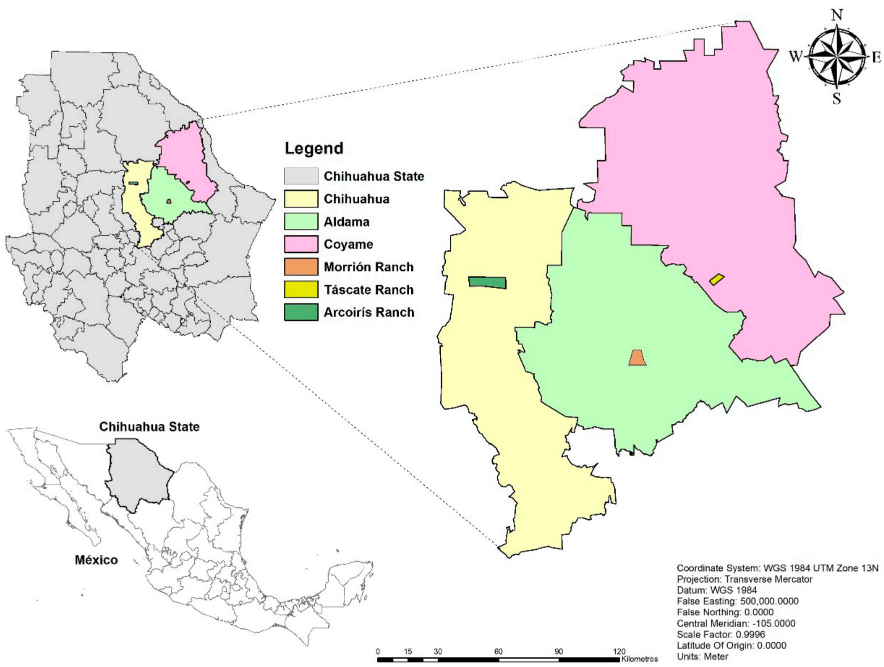

Figure 1. Geographical location of the study sampling sites.

The sampling sites were located in an area that is associated with hills, interrupted by small elongated mountain ranges and areas of desert plains [5]. The climate of the area is described by the climatic formula BWhw, which corresponds to an arid climate (BW) with a range of temperatures from 18 to 22 °C (h), rainfall in summer (w), and an annual precipitation ranging from 200 to 400 mm [19,20]. The predominant soils are regosol and xerosol, which are generally shallow and associated with rocky structures. And the primary vegetation is xerophytic scrubs [5].

2.2. Sampling

At each of the three sampling sites, a hill with a presence of *Dasylirion leiophyllum* without evidence of harvesting was selected; then, 12 circular plots measuring 250 m^2 were established on each hill, 36 plots as a total. The plots where placed in accordance with an orographic gradient considering three levels (hilltop, hillside, and valley), as well as four cardinal aspects, including the north, south, east, and west [21]. Additionally, sites were chosen based on three altitude levels (Table 1): one at high altitude >1500 m above sea level (masl), one at medium altitude (1330–1500 masl), and one at low altitude (<1330 masl).

Table 1. General characteristics of selected sampling sites.

Sampling Sites	Municipality	Latitude (N)	Longitude (W)	Altitude (masl)	Slope (%)
AR	Chihuahua	29°19′18″	106°37′06″	1627	0–100
MR	Aldama	28°59′03″	105°37′06″	1348	0–35
TR	Coyame	29°21′25″	105°12′37″	1306	0–30

AR: Arcoíris Ranch, MR: Morrión Ranch, TR: Táscate Ranch.

Once we defined the exposures and orographic gradient in the field, the plots were established randomly following each combination of aspect (north, south, east, west) with orography (hilltop, hillside, and valley).

Each circular plot was divided into four quadrants, and all species of shrub and cactaceae species (N) were identified, and all the plants for each species were counted within each quadrant. Then, one mode plant (a plant with the most repeatable size) for each species within each quadrant was selected and measured [13,22]. The measured variables are shown in Table 2.

Table 2. Measured variables and descriptive statistics.

Variable	Units	Method
Abundance	N	Number of plants within the sampling plot
Average crown diameter	ACD (m)	Average of the two crossed crown diameters
Base diameter	BD (m)	Base diameter of the plant, measured 10 cm above ground
Crown area	CA (m^2)	$\pi \cdot r^2$, r = ACD/2, estimated for each plant
Height	H (m)	Height of the plant measured from bottom to top
Canopy cover	(m^2)	Sum of the crown area of all species within the sampling plot
Plants/plot	N(abundance)	Sum of plants per sampling plot considering all the species
Coverage	(m^2/ha)	Extrapolation to one hectare from the average sampling plot canopy cover (including all plants and all species)
Abundance	(N/ha)	Extrapolation to one hectare from the average sampling plot abundance (including all plants and all species)

2.3. Data Analysis

For each species, abundance (number of plants·ha^{-1}), dominance (m^2 of canopy cover·ha^{-1}), and frequency based on species presence or absence in sampled plots where calculated. The importance value index (IVI) was built using the community values of abundance, dominance, and frequency [23]. Additionally, abundance values were utilized to estimate α diversity indexes by using the Shannon–Weaver and Simpson equations [24,25]. Calculations were conducted using the equations presented in Table 3.

Table 3. Equations for determining structure and diversity parameters.

Parameter	Equation	Description
Abundance	$A_i = N_i/E$ $AR_i = \left(A_i \Big/ \sum_{i=1}^{n} Ai \right) \times 100$	A_i = Absolute abundance AR_i = Relative abundance of species *i* with respect to total abundance. N_i = Number of individuals of species *i* E = Sampling area (ha)
Dominance	$D_i = Ab_i/E$ $DR_i = (D_i/\sum_{i=1...n} Di) \times 100$	D_i = Absolute dominance DR_i = Relative dominance of species *i* with respect to total dominance Ab_i = Species *i* crown area E = Surface area (ha)
Frequency	$F_i = P_i/NS \times 100$ $FR_i = \times 100$	F_i = Absolute frequency FR_i = Relative frequency of species *i* with respect to the total frequency. P_i = Number of sampling plots with species *i* present NS = Total number of sampling plots
Importance Value Index (IVI)	$IVI = (AR_i + DR_i + FR_i)/3$	AR_i = Relative abundance DR_i = Relative dominance FR_i = Relative frequency
Shannon–Weaver Index (H′)	$H' = -\sum_{i=1}^{s} P_i * ln(P_i)$ $P_i = n_i/N$	P_i = Proportion of individuals of species *i* in relation to the total number of individuals n_i = Number of individuals of species *i* N = Total number of individuals
Simpson Index (D)	$D = \sum P_i^2$	P_i = Proportion of individuals of species *i* in relation to the total number of individuals

2.4. Statistical Analysis

To describe the variation in the community structure, a principal component analysis (PCA) was conducted using the PRINCOMP procedure by SAS Inc., Cary, NC, USA [26]. Furthermore, a cluster analysis (CA) was conducted using the CLUSTER procedure [26] with the correlation matrix and WARD linkage method to identify group similarities based on R^2, T^2 pseudo-statistics, and the Cubic Clustering Criterion (CCC). Descriptive statistics were performed on morphometric and ecological variables of sotol, and data were checked for normality using the Shapiro–Wilk test, and variances homogeneity assumption was performed by the Levene test. Since the analyzed variables did not meet the assumptions of normality and homogeneity of variances, a Kruskal–Wallis nonparametric test was performed ($p \leq 0.05$). Finally, variables that showed significant differences were compared pairwise using the Kruskal–Wallis nonparametric test ($p \leq 0.05$).

3. Results

3.1. Floristic Composition

A total of 10,273 shrubs were recorded, representing 46 species distributed in 17 families (Table 4). The families with the highest species richness were *Fabaceae* (10 species), *Cactaceae* (10 species), *Asparagaceae* (6 species), and *Asteraceae* (5 species). The genera with the highest number of species were *Opuntia* (4 species), *Yucca*, *Quercus*, and *Mimosa* (with 3 species each). The species with the highest relative dominance were *Dasylirion leiophyllum*, *Tiquilia greggii*, and *Agave lechuguilla*. The most abundant species were *Agave lechuguilla* and *Tiquilia greggii* with 4275 and 2787 plants * ha^{-1}, respectively, representing 61.8% of the abundances. The average height of species was 0.69 m, and the tallest species were *Quercus grisea* with 4.4 m, *Q. durifolia* with 3.2 m, and *Yucca carnerosana* with 1.9 m, while the average height of *Dasylirion leiophyllum* was 1.07 m. Additionally, the species *Agave lechuguilla*, *Tiquilia greggii*, and *Dasylirion leiophyllum* reached the highest values of importance (IVI) among the studied shrubby community (Table 4).

Table 4. Ecological features of species recorded in a xerophytic shrub with sotol (*Dasyliriom leiophyllum*) distribution in Chihuahua, Mexico.

Species	Family	Dominance (m^2/ha)	Abundance (N/ha)	Frecuency (%)	APH (m)	RD (%)	RA (%)	RF (%)	IVI
Acacia constricta	Fabaceae	42.68	56.67	13.89	0.83	1.19	0.50	1.58	1.09
Acacia spp.	Fabaceae	14.48	45.56	16.67	0.51	0.40	0.40	1.89	0.90
Agave lechuguilla	Asparagaceae	500.13	4275.56	61.11	0.39	13.98	37.46	6.94	19.46
Agave parryi	Asparagaceae	3.45	26.67	11.11	0.32	0.10	0.23	1.26	0.53
Aloysia wrigthii	Verbenaceae	101.88	291.11	50.00	0.60	2.85	2.55	5.68	3.69
Ariocarpus fissuratus	Cactaceae	0.04	8.89	8.33	0.02	0.00	0.08	0.95	0.34
Baccharis glutinosa	Asteraceae	1.78	8.89	5.56	0.55	0.05	0.08	0.63	0.25
Berberis trifoliata	Berberidaceae	0.22	1.11	2.78	0.45	0.01	0.01	0.32	0.11
Brickellia spinulosa	Asteraceae	13.50	33.33	19.44	0.60	0.38	0.29	2.21	0.96
Condalia ericoides	Rhamnaceae	74.24	144.44	13.89	0.48	2.08	1.27	1.58	1.64
Condalia warnockii	Rhamnaceae	17.92	38.89	11.11	0.52	0.50	0.34	1.26	0.70
Coryphantha echinus	Cactaceae	0.02	5.56	11.11	0.07	0.00	0.05	1.26	0.44
Cylindropuntia imbricata	Cactaceae	0.05	1.11	2.78	0.13	0.00	0.01	0.32	0.11
Dasylirion leiophyllum	Nolinaceae	978.17	627.78	100.00	1.07	27.35	5.50	11.36	14.73
Echinocactus horizonthalonius	Cactaceae	0.03	2.22	2.78	0.15	0.00	0.02	0.32	0.11
Echinocereus enneacanthus	Cactaceae	0.04	1.11	2.78	0.09	0.00	0.01	0.32	0.11
Ephedra trifurca	Ephedraceae	39.30	117.78	55.56	0.54	1.10	1.03	6.31	2.81
Euphorbia antisyphilitica	Euphorbiaceae	119.41	846.67	36.11	0.33	3.34	7.42	4.10	4.95
Flourensia cernua	Asteraceae	0.32	2.22	2.78	0.49	0.01	0.02	0.32	0.11
Fouquieria splendens	Fouquieriaceae	12.87	13.33	22.22	0.90	0.36	0.12	2.52	1.00
Glandulicactus uncinatus	Cactaceae	0.01	1.11	2.78	0.17	0.00	0.01	0.32	0.11
Jatropha dioica	Euphorbiaceae	84.37	241.11	44.44	0.38	2.36	2.11	5.05	3.17
Koeberlinia spinosa	Koeberliniaceae	1.55	6.67	5.56	0.44	0.04	0.06	0.63	0.24
Krameria bicolor	Krameriaceae	0.09	4.44	2.78	0.38	0.00	0.04	0.32	0.12
Larrea tridentata	Zygophyllaceae	235.00	401.11	58.33	0.70	6.57	3.51	6.62	5.57
Leucophyllum minus	Scrophulariaceae	50.01	194.44	25.00	0.53	1.40	1.70	2.84	1.98
Mimosa aculeaticarpa	Fabaceae	3.24	12.22	11.11	0.71	0.09	0.11	1.26	0.49
Mimosa biuncifera	Fabaceae	169.44	637.78	50.00	0.54	4.74	5.59	5.68	5.33
Mimosa dysocarpa	Fabaceae	4.30	10.00	2.78	0.51	0.12	0.09	0.32	0.17
Nolina texana	Asparagaceae	3.41	3.33	2.78	0.75	0.10	0.03	0.32	0.15
Opuntia azurea	Cactaceae	2.57	4.44	5.56	0.45	0.07	0.04	0.63	0.25
Opuntia engelmannii	Cactaceae	3.51	10.00	13.89	0.50	0.10	0.09	1.58	0.59
Opuntia imbricata	Cactaceae	1.17	4.44	2.78	0.30	0.03	0.04	0.32	0.13
Opuntia rastrera	Cactaceae	0.07	1.11	2.78	0.35	0.00	0.01	0.32	0.11
Parthenium incanum	Asteraceae	2.12	8.89	5.56	0.58	0.06	0.08	0.63	0.26
Prosopis glandulosa	Fabaceae	54.57	55.56	19.44	0.90	1.53	0.49	2.21	1.41
Prosopis juliflora	Fabaceae	2.31	2.22	2.78	1.20	0.06	0.02	0.32	0.13
Quercus durifolia	Fagaceae	93.79	7.78	11.11	3.23	2.62	0.07	1.26	1.32
Quercus emoryi	Fagaceae	0.49	1.11	2.78	0.65	0.01	0.01	0.32	0.11
Quercus grisea	Fagaceae	26.40	1.11	2.78	4.40	0.74	0.01	0.32	0.35
Tecoma stans	Bignoniaceae	79.32	155.56	13.89	0.75	2.22	1.36	1.58	1.72
Tiquilia greggii	Boraginaceae	775.41	2787.78	66.67	0.39	21.68	24.42	7.57	17.89
Yucca carnerosana	Asparagaceae	2.58	1.11	2.78	1.90	0.07	0.01	0.32	0.13
Yucca elata	Asparagaceae	25.52	57.78	36.11	0.79	0.71	0.51	4.10	1.77
Yucca filifera	Asparagaceae	22.66	85.56	33.33	0.86	0.63	0.75	3.79	1.72
Zinnia acerosa	Asteraceae	12.43	168.89	2.78	0.20	0.35	1.48	0.32	0.71
Total		3576.86	11,414.44	880.56	0.69	100.0	100.0	100.0	100.0

APH = average plant height, RD = relative dominance, RA = relative abundance, RF = relative frequency, IVI = importance value index.

Based on these findings, it is possible to assume that this is a desert rosetophyllous scrubland community that is dominated by *Agave lechuguilla*, with high values of abundance and dominance of *Dasylirion leiophillum* and *Tiquilia greggii*. This type of community is prevalent in the northern part of the Chihuahuan Desert, which encompasses the states of Durango, Coahuila, and Chihuahua, Mexico. Shrub communities of rosetophyllous scrubland are low-growing (less than 1.5 m in height), with an evident dominance of species with rosette leaves [27], and high values of importance concentrated in a few populations influence the diversity indexes and maintain a particular structure in the ecosystem.

3.2. Shrub Community's Richness and Diversity

Based on the descriptive information on richness and diversity by the orographic gradient, it is possible to point out that the regions with the greatest number of species are the valleys and the hillsides, where up to 35 shrub species were identified; additionally, in the valley zone is where the highest diversity index (Shannon–Weaver and Simpson) were estimated, which indicates that there is a greater equity of species in these land systems (Table 5). On the other hand, the abundance of sotol seems to be higher on hillsides compared with gentle slopes. In addition, the analysis of richness and diversity based on exposure shows that the highest shrub richness was found in northern and zenith exposures (32 species), while the highest Shannon–Weaver and Simpson diversity indices were estimated in northern, southern, and eastern exposures, and the highest abundance of sotol was estimated on the eastern hillside (Table 5). Therefore, based on the description provided by this qualitative evaluation, it is possible to suggest that sotol populations are associated with the levels of species richness and diversity; furthermore, sotol plants are distributed with higher densities in hillside areas, where slopes are gentle, but with a preference towards eastern exposures.

Table 5. Diversity and richness of communities in which sotol (*Dasyliriom leiophyllum*) grows in Chihuahua, Mexico.

	No Species	Shannon W	Simpson	*Dasylirion* Abundance (plants·ha^{-1})
Community	46	2.09	0.78	627
Hilltop	32	1.85	0.74	533
Hillsides	35	1.97	0.77	1016
Valleys	35	2.3	0.84	333
Exposures				
Zenith	32	1.58	0.65	142
East	29	2.08	0.8	1451
South	26	2.1	0.82	502
West	29	1.81	0.75	662
North	32	2.19	0.82	468

Table 6 shows the morphometric, abundance, and morphometric shape of sotol plants. Mexican regulations state that only adult plants may be harvested [12], so the sizes of harvested plants are generally at the upper end of the range shown in Table 6. In relation to the abundance and dominance of species, minimum values were found, with a low number of individuals per hectare and consequently low coverage per hectare (40 plants * ha^{-1} and 69 m^2 * ha^{-1}), while the maximum values found showed sotol densities of up to 6400 plants * ha^{-1} and canopy cover of up to 10,400 m^2 * ha^{-1}. The maximum abundance and dominance values found in natural ecosystems could be a reference for sotol plant densities in plantation projects for commercial purposes.

Table 6. Descriptive statistics of morphometric variables of sotol (*Dasyliriom leiophyllum*) plants sampled in study area.

Variable	Mean	Deviation Standard	Coefficient Variance	Minimum Value	Maximum Value
Crown diameter (m)	1.26	0.29	22.9	0.65	1.84
Crown area (m^2)	1.39	0.54	38.9	0.34	2.67
Base diameter (m)	0.22	0.01	0.07	0.10	0.40
Height (m)	1.07	0.19	17.71	0.65	1.45
Plants/plot (N)	15.8	26.7	169.2	1	160
Coverage (m^2/ha)	987.3	1771	179.3	69.42	10,394
Abundance (N/ha)	632.2	1070	169.23	40	6400

N = number of individuals, m = meters, ha = hectares.

3.3. Shrubby Community Grouping

The principal component analysis reveals that the first two components account for 88.98% of the variability in the shrub community's composition. CP1 explains 68.16% of the total variation, with an Eigenvalue of 3.36, while CP2 explains 20.82% of the variation, with an Eigenvalue of 1.04. Variables mainly associated ($p < 0.0001$) with CP1 were the number of individuals (N) and their size (crown area (ACO), cover (COB), and abundance (ABU)), while CP2 showed a high correlation ($p < 0.0001$) with plant height (ALT). Therefore, groups were formed by abundance and sizes on the *x*-axis, while on the *y*-axis, they were grouped by the height of the plants.

Figure 2 illustrates the 88.11% of the multivariate variation of species based on the resultant CP1 and CP2. In the third quadrant, species of larger sizes but lower abundance were grouped. In this group, we found *Yucca carnerosana*, *Quercus gricea,* and *Quercus durifolia*. The second group comprised *Dasylirion leiophyllum*, *Prosopis juniflora*, *Nolina tejana*, *Prosopis glandulosa*, *Founqueira splendes,* and *Acacia constricta*, which are medium-sized species with an average height of 0.94 m and low cover and abundance. These species form a type of vegetation known as a mesquite community, with sotol presence. Finally, a third group was formed including, the remaining 37 species; this group contains the most common species of the microphyllous and rosetophyllous desert scrublands.

The cluster analysis based on T^2 pseudo-statistics, Cubic Clustering Criterion (CCC), and similarity coefficient R^2 = 90.0 formed five groups of species (Figure 3). Group I comprises five species that generally define the microphyllous desert scrubland (Table 7). Group II is composed of 22 species with higher abundances, group III includes 11 species, mostly from the cactaceae family with low cover and abundance values, and group IV consists of 5 species, among which *Dasylirion leiophyllum*, *Prosopis galdulosa*, and *P. juliflora* stand out. In contrast, group V only includes three species: *Quercus durifolia*, *Q. gricea,* and *Yucca carnerosana*, which are arboreal species with greater heights. Although the cluster analysis revealed two more groups than those observed in the multivariate variation with principal components, the grouping turned out to be very similar. Based on the analysis, it can be concluded that in the distribution area of sotol, most of the species belong to the microphyllous desert scrubland; however, *Dasylirion leiophyllum* is predominantly associated with species of rosetophyllous desert scrubland, which seems to dominate the community, as is shown in the importance values in Table 4.

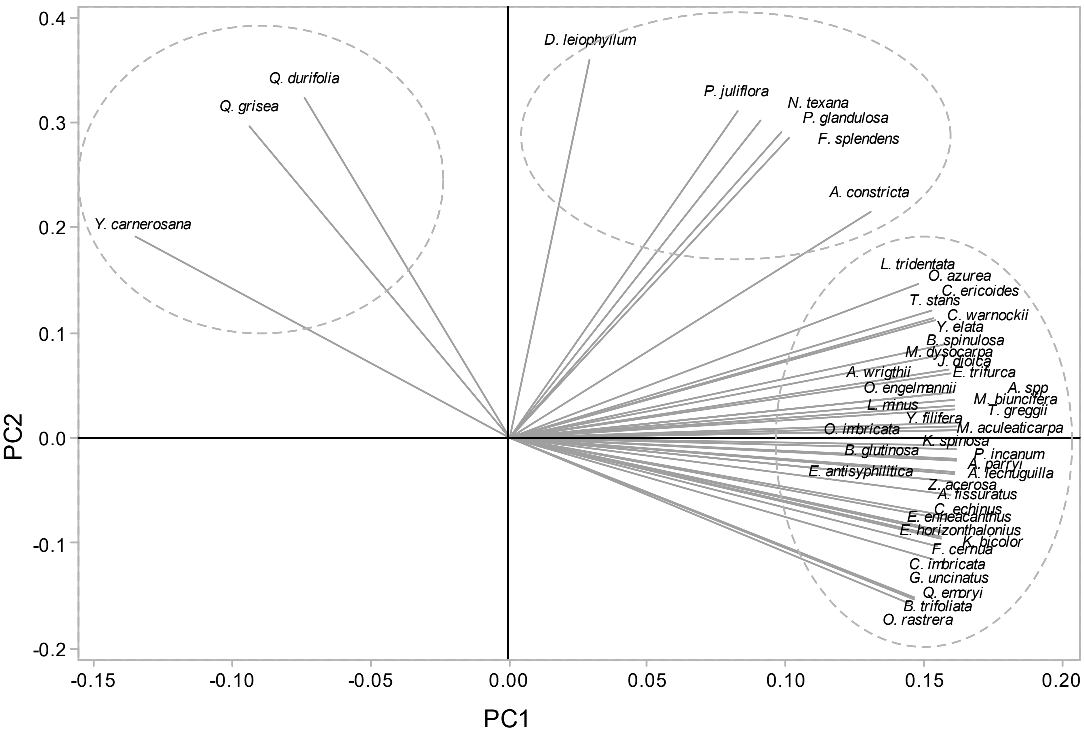

Figure 2. Multivariate distribution of shrub species based on principal components 1 and 2 (88.11% of the total variation).

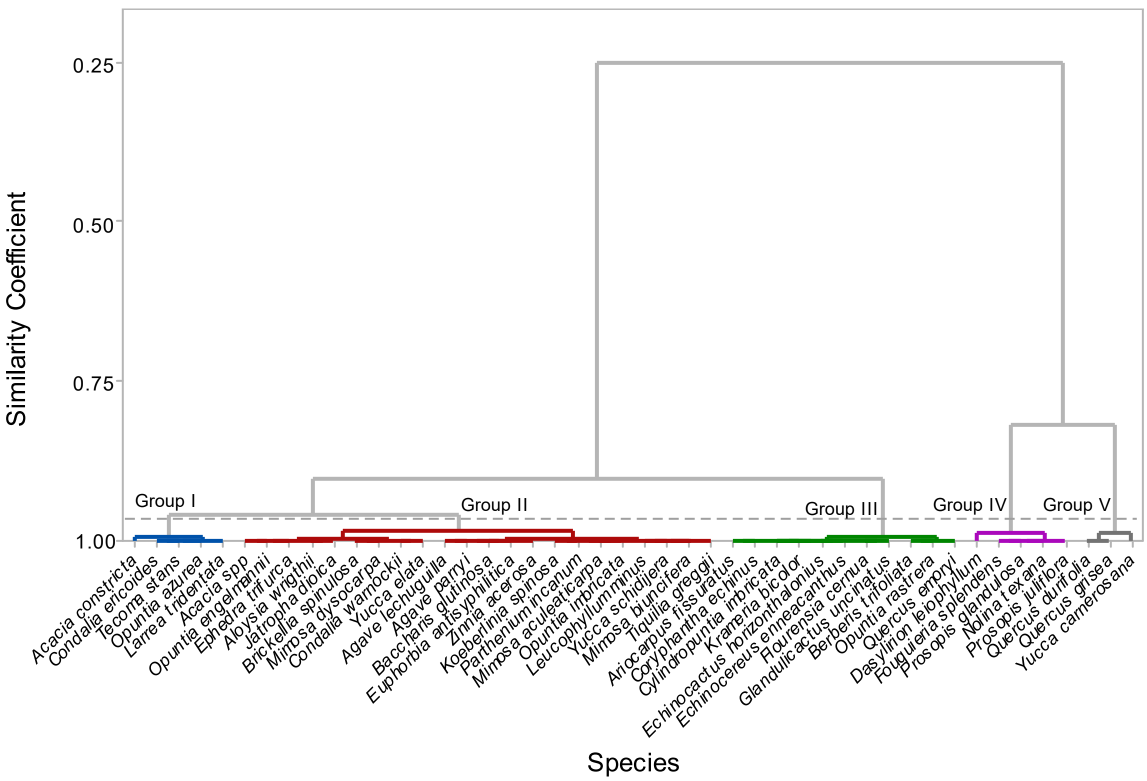

Figure 3. Clustering of subcommunities in the xerophytic shrub of the state of Chihuahua.

Table 7. Groups of plant species obtained from the cluster analysis.

Group	Species
I (5)	*Acacia constricta*, *Condalia ericoides*, *Larrea tridentata*, *Opuntia azurea* and *Tecoma stans.*
II (22)	*Acacia* spp. *Agave lechuguilla*, *Agave parryi*, *Aloysia wrigthii*, *Baccharis glutinosa*, *Brickellia spinulosa*, *Condalia warnockii*, *Ephedra trifurca*, *Euphorbia antisyphilitica*, *Jatropha dioica*, *Koeberlinia spinose*, *Leucophyllum minus*, *Mimosa aculeaticarpa*, *Mimosa biuncifera*, *Mimosa dysocarpa*, *Opuntia engelmannii*, *Opuntia imbricata*, *Parthenium incanum*, *Tiquilia greggii*, *Yucca elata*, *Yucca schidijera* and *Zinnia acerosa*
III (11)	*Ariocarpus fissuratus*, *Berberis trifoliate*, *Coryphantha echinus*, *Cylindropuntia mbricata*, *Echinocactus horizonthalonius*, *Echinocereus enneacanthus*, *Flourensia cernua*, *Glandulicactus uncinatus*, *Krameria bicolor*, *Opuntia rastrera* and *Quercus emoryi*
IV (5)	*Dasylirion leiophyllum*, *Fouquieria splendens*, *Nolina texana*, *Prosopis glandulosa* and *Prosopis juliflora*
V (3)	*Quercus durifolia*, *Quercus grisea*, *Yucca carnerosana*

Regarding the ecological indicators of sotol plants, the Kruskal–Wallis test detected significant differences (χ^2 = 14.75, p = 0.002) for the crown cover variable when comparing populations according to their distribution in height above sea level. The crown cover of sotol at lower altitudes was 204.6 m^2/ha, while at higher elevations, the average cover was 2032.6 m^2/ha. Furthermore, significant differences were found in plant height (χ^2 = −14.75, p = 0.002). Average height values were 1.19 m for heights above 1330 masl and 0.92 at heights below 1330 masl. Likewise, the means of the IVI varied with respect to the taltitude above sea level evaluated: for heights above 1330 masl (χ^2 = 13.83, p = 004) and for heights below 1330 masl (χ^2 = 12.41, p = 012). These results indicate that although *Dasylirion leiophyllum* is distributed over a large part of the state of Chihuahua, the abundance and size of mature plants in their populations seems to be bigger at higher altitudes above sea level. This might be important information to be considered for the selection of lands with productive potential to establish sotol commercial plantations. However, it is also necessary to carry out more detailed analyses of the soil and the nutrients in the soil.

4. Discussion

The Chihuahuan Desert is home to a great richness of species; for this land in North America, 3382 species are reported, of which 826 are endemic to this region [28]. These species have been classified into different types of vegetation according to their distribution patterns and their interaction with the climate, soil, and relief [1,28–30]. The vegetation types with the greatest distribution in the region are microphyllous desert scrubland, rosetophilous desert scrubland, mezquites, and grasslands [13,30]. Currently, changes in land use, intensive use of species, and drought seem to affect the distribution and abundance of species [28,31,32], especially those that are used for commercial purposes [13], such as sotol.

Most of the ecological studies of the genus *Dasylirion* have focused on its botanical description and taxonomy [7–11], and 17 species have been reported (melgoza), which are distributed all along the Chihuahuan Desert [9,11]. Several authors agree that these species grow in shallow soils with few nutrients and in places with low precipitation [30,32,33]. Unfortunately, there are few reports that describe these relationships in detail. For instance, for *D. cedrosanum*, the better habitat seems to be on a slope ranging from 10% to 30%, living in grasslands and shrub deserts at 1000 to 2200 masl [33]; meanwhile, most of the reports for the species of the genus *Dasylirion* indicate their distribution from 1000 to 2200 masl [9,33] and growing in different types of vegetations, from grasslands in the valleys up to oak communities at the highest elevations [1,9,33].

The shrub community composition where sotol (*Dasylirion leiophyllum*) grows in Chihuahua consisted of 46 species, mainly species associated with rosetophyllous and mycophyllous desert scrublands and, to a lesser extent, species of mesquite and oak trees. This *Dasylirion leiophyllum* association shows its wide range of distribution by altitudinal gradient, as it can be found from valley portions to high areas where oak trees grow. Similar information has been reported by several authors [4,11,27,29]. The number of species found in the distribution area of sotol in Chihuahua coincides in terms of the number of shrub species reported by other authors who have studied other portions of the Chihuahuan Desert [30,34–36]; however, they are not the same species as a whole, as some species show a more local distribution range; nevertheless, *Dasylirion leiophyllum* seems to have a wide distribution in Chihuahua [11,13,37].

The descriptive results show that *Dasylirion leiophyllum* have a large variation in abundance and sizes across its range of distribution, which seems to be a common pattern in shrub populations and communities of the Chihuahuan Desert [18,38,39]. In lower-abundance plots, less than 60 sotol plants per hectare were found, without evidence of harvesting, while in higher-density sampling plots, more than 6000 plants per hectare were found, which could serve as an indicator of densities for the establishment of commercial plantations of the species. Similar findings were reported for *D. cedrosanum* in Zacatecas, Mexico, where the lowest densities found were 250 plants.ha^{-1} [33].

Considering the altitudinal gradient, it was observed that sotol reaches larger sizes and abundances when it is associated with mesquite and oak trees, which could be related to the deeper soils commonly found in the mesquite areas as well as the higher rainfall events that are associated with higher elevations where oak trees grow [1,40]. The evaluation of richness and diversity by topography and exposure showed that *Dasylirion leiophyllum* has a tendency to increase its density on slope systems (downhill and hillsides) and east-facing aspects (including northeast and southeast). Some authors have studied the distribution by the exposure of sotol species, and their reports show that at other latitudes, species increase their abundance on the southern or northern hillsides [11,13], so this attribute does not seem to follow the same pattern among *Dasylirion* species [14,31,41], which could be due to the soil origin rather than aspect.

The multivariate PCA and CCA analyses showed that *Dasylirion leiophyllum* was mainly grouped with species of the *Prosopis* and *Nolina* genera, species that are more typical of the submontane scrub, which is distributed in higher elevations [22], but it is also grouped with species such as *Fouquieria splendens* (Ocotillo) and *Larrea tridentata* (gobernadora), which mainly distributed over valley areas in the lower desert [40]. This information could suggest that sotol apparently has the ability to grow with species from different communities, which distribute over a wide range of altitude within the arid and semiarid lands in Chihuahua.

Other types of groupings found with this analysis were species with small size cover and small size height of the plants, but with high abundances, such as *Agave lechuguilla*, *Tequillia greggii*, and *Euphorbia antisyphilitica* combined with other xerophytic species and cactaceae. Various authors have documented that in the Chihuahuan Desert, the smaller-size species are associated with low rainfalls and high temperatures, and also these species mainly live in lower-altitude areas [11,33]. In this study populations of sotol were also found growing in these communities.

The highest coverages and abundances of *Dasylirion leiophyllum* were found at altitudes above 1300 masl. This could be attributed to a higher elevation being closely related to higher humidity, which could benefit the germination, establishment, and growth of the species [32]. On the other hand, the smallest plants of *Dasylirion leiophyllum* were found in valleys in the lower desert zones, influenced possibly by the low availability of soil moisture.

Our results provide ecological information that confirms the descriptions of desert vegetation made by various authors [1,20,28,30,33] and describes some specific characteristics of the shrub communities in which Dasylirion leiophyllum grows, which could be useful for sotol population management in the Chihuahuan Desert.

5. Conclusions

Dasylirion leiophyllum grows in association with at least 46 scrub species in the valleys, hillsides, and also on top of the mountains, with rosetophyllous, microphyllous, and mesquite communities. It also grows at higher altitudes that are associated with oak species.

Sotol populations reach higher abundances and larger sizes at altitudes above 1300 masl, in hillside areas, and at eastern exposures.

In areas of maximum sotol density, more than 6000 plants were found. These data may be of interest for planning the planting densities in commercial plantations.

Higher abundances and coverages of sotol were identified in communities with higher diversity indexes. Therefore, it is important to implement a system where the harvest intensity does not alter the structure of the shrub communities in order to protect the populations of the species.

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