Spatial Analysis for Management and Conservation of Cactaceae and Agavaceae Species in Central Mexico

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Abstract

Recognition of the accurate spatial distribution of species in the habitat is fundamental to analyze species interactions (positives as nurse plant interactions and negatives such as competition) and also to create viable conservation and management plans. We present here three study cases to illustrate the power of spatial analysis by distance indices (SADIE) as a tool to understand the ecological associations between the subject species and the associated flora: 1) We studied the positive and negative interactions of *Ariocarpus kotschoubeyanus* a small cactus with the dominant shrub species of a desert; since these interactions are crucial to understand the establishment, distribution pattern, and viability of their populations. *A. kotschobeyanus* distributes in gaps with *I_a* = 2.144 and associated positively with *Tiquilia* sp (X = 0.379, P < 0.0001) and *Opuntia meijmeri* (X = 0.2753, P < 0.0001), and negatively with *Karwinskia humboldtiana* (X = -0.1948, P < 0.9803) and *Calanticaria bicolor* (X = -0.2568, P < 0.9982). 2) To improve the process of locating new populations of *M. mathildae*, because their location was indirectly detected by screening conspicuous associated tree species such as *Bursera fagaroides* and *Lysiloma microphylla*. For this study case we combine the SADIE analysis with GARP niche prediction models to improve the location for new populations. 3) We evaluated the spatial distribution of *Agave americana* and *Agave salmiana* under different traditional management strategies; the spatial distribution was predominantly aggregated in patches with average aggregation indices (*I_a* = 1.09, sd = 0.38). *Agave* species tend to be dissociated with each other and also to pine and juniper trees. The spatial distribution of agaves and associates species changes among different management strategies and in cultivars.

Keywords: SADIE; Spatial indices; Endangered cacti.
1. INTRODUCTION

The study of the spatial distribution of organisms is essential for management and conservation of populations and communities (1,2). Usually, management decisions are based on crude maps, using polygons that enclose known occurrences generated from records of flora and fauna collections, scientific papers, and informal reports (3). These maps generally have deficient spatial statistics analysis (4).

Commonly, the negative binomial and Poisson probabilistic distribution are used to determine the randomness of a spatial distribution. These methods consider the frequency of individuals per unit area by default. A different method for determining the spatial distribution of organisms is “SADIE” (Spatial Analysis for Distance Index). This method indicates the heterogeneity in the spatial distribution for organisms, and evaluates the randomness of interactions between individuals. SADIE analyzes the spatial pattern of counts data, and measures the clustering of the data as patches or gaps (5).

SADIE uses information on two coordinates and data in the form of counts (5). This software permits calculating an aggregation index ($I_a$). SADIE also generates information of spatial associations between two populations estimating the contribution of each sample unit to the overall correlation coefficient called “X” (2,5). This system has been used to analyze different types of associations, such as the nurse plant phenomenon (4,6), models of space-time relations (7) and patterns of infection (8). The development of detailed, fine scale and validated maps is preponderant to improve management decision procedures. The aim of the study cases presented in this paper is to provide an integrated technique that involves the use of spatial indices and gap analysis with the aim of study the spatial distribution and spatial association of plant species in central México.

2. MATERIALS AND METHODS

Study areas

Three wild species from arid and semiarid environments in central México were selected to perform studies involving spatial analysis; two small endangered cacti (Ariocarpus kotschoubeyanus and Mammillaria mathildae) and an Agave complex (Agave americana and A. salmiana).

1. The population of A. kotschoubeyanus inhabit a small region of the Municipality of Cadereyta, Querétaro (20° 41’ 14.8” N and 99° 35’ 21.1” W). The climate is partially temperate dry (BS1k) with an average annual precipitation of 535 mm, and the vegetation is a xeric mycrophyile shrubland. This type of vegetation is typical of lutite soils with medium slopes; the most frequent species are Acacia vernicosa, Fouquieria splendens, Larrea tridentata and Prosopis laevigata (9).

2. Mammillaria mathildae inhabit at North of Querétaro City, between 20° 41’ 35.2” N and 100° 27’ 16.4” W (10). The climate is BS1k (partially dry temperate); the average temperature is 18°C and average annual precipitation is 549.3 mm (11). Around Queretaro City, remnant tropical deciduous forests and xerophilous shrub persist with Bursera fagaroides, Cedrela dugesii, Ceiba aesculifolia, Prosopis laevigata and Ipomoea murucoides as dominant tree species. During the rainy season, abundant shrubs considerably increase their foliage (e.g. Anisacanthus quadrifidus, Calliandra eriophylla, and Jatropha dioica). Soil is scarce with good drainage, and the area is composed of igneous rocks (12).

3. The Agaves species complex is located in the Sierra of “El Doctor”, an area that forms part of the Sierra Madre Oriental; it belongs to the Espolón-Cerro del Ángel (13). Its vegetation is comprised by Quercus, Pimus and Juniperus forests. The climate is C(w2) that corresponds to temperate sub humid with an annual temperature of 14° C and an annual precipitation of 874.6 mm (14).

Management categories for Agave spp. populations

The criteria base for the management categories were centered on the type of vegetation patches where agave populations were found. Therefore, three management intensities were detected: 1) incipient management. 2) In situ management which belongs to locations with intermediate management; and 3) cultivation that is referred to the intense management (ex situ) where the farmers extract the products and they re-plant. “Sánchez-Maqueda” is a location with incipient management i.e., considered a conserved
place due to its vegetation and Agave population’s characteristics. The locations belonging to “Los Hernández” and “Los Juárez” possess patches of vegetation of Agave species with low replanting and pruning; due to this the type of management is in situ. Finally, “Chavarrías” and “El Doctor” are cultivation zones where the dominant vegetation is Agave sp.

Spatial analysis

SADIE was used to obtain the association index between the selected species and neighboring flora. Using this program an aggregation index ($I_a$) and the spatial association index of two populations ($\chi$, Greek chi) were calculated, and tested for aggregates or random distribution. Data show aggregated distribution if $I_a > 1$, regular distribution with an $I_a < 1$, and random arrangement if $I_a \approx 1$. Species may be spatially dissociated when $X < 0$, associated if $X > 0$; or present a random placement when $X = 1$.

Data for *A. kotschoubeyanus* were registered in four consecutive plots of 100 m$^2$ divided in a grid of 1m$^2$ subplots, and conforming a superplot (400 m$^2$) where the position of each individual species was mapped in two dimensions. *Mammillaria mathildae* were registered in three plots of 100 m$^2$ (located in the main aggregation area of *M. mathildae*). The spatial distribution for *Agave americana, A. salmiana* and *A. salmiana* var. *ferox* with their associated species were determined by 900 m$^2$ plots; each plot was subdivided in 100 subplots of 3 x 3 m$^2$. Trees and shrubs in each plot were identified and measured. Spatial analysis was performed with SADIEShell 1.22 software running 75 simulations and 26,108 permutations. Maps were constructed using Surfer 8.0.

3. RESULTS

1. *Ariocarpus kotschoubeyanus*

SADIE suggested that *A. kotschoubeyanus* distributes in aggregated patches. This spatial distribution was significant in both scales 10x10m and 20x20m ($I_a = 1.8$ and $I_a = 2.11$ respectively, $P_a < 0.005$). The associated arboreal vegetation species also exhibited aggregated distribution for the two scales: *Turnera diffusa* ($I_a = 1.4$, $P_a < 0.05$), *Agave striata* ($I_a = 1.8$, $P_a < 0.05$), and *Zaluzania sp* ($I_a = 1.5$, $P_a < 0.005$). Smaller shrubs such as *Jatropha dioica* and *Opuntia imbricata* also have aggregated distribution (Table 1). The spatial association index indicated that *A. kotschoubeyanus* presents negative associations with plant species with greater importance values or (IV): *Calanticaria bicolor* ($\chi = 0.256$, $P < 0.998$, IV = 130.3), *Karwinskia humboldtiana* ($X = 0.194$, $P < 0.980$, IV = 134.7), and *Turnera diffusa* ($X = 0.100$, $P = 0.835$, IV=105.2), although those values were not statistically significant (Figure 1). In contrast, *A. kotshobeyanus* was positively associated with *Tiquilia sp* ($X = 0.379$, $P < 0.0001$) and *Opuntia mejmeri* ($X = 0.2753$, $P < 0.0001$, IV=51.6). *A. kotschoubeyanus* did not provide positive associations with perennials discarding the phenomenon of nurse plants. The study of the spatial pattern of *A. kotschoubeyanus* indicates aggregated distribution. Apparently *A. kotschoubeyanus* does not need nurse plants in contrast to the positive associations detected for *A. trigonus* (15).

2. *Mammillaria mathildae*

Spatial distribution of *M. mathildae* presented an aggregated distribution. The $V_i$ values for *M. mathildae, Bursera fagaroides* and *Senna polyantha* indicate their strong tendency to form patches (Table 2). Tropical deciduous forest exhibited a canopy cover without clear gaps, but with a shading pattern that can drastically vary, leading to the aggregate spatial distribution of the sensitive species, this phenomenon facilitates nurse-plant interactions (4). Canopy architectures of each species have particular shading patterns which vary in intensity, *S. polyantha* produced the less intense shading while *Prosopis laevigata* generates more profuse shading. Both shading pattern did not favor the establishment of *M. mathildae*, as shown by the association indexes (Table 3); under such conditions *M. mathildae* cannot germinate (16), since cactus seeds are positively photoblastic (17). On the other hand, *B. fagaroides* generated favorable microclimate for germination and establishment of *M. mathildae*. 
### Table 1. Aggregation indices ($I_a$) of 400m$^2$ quadrant for the vegetation in the community of Vista Hermosa, Cadereyta, Querétaro. Data obtained from 2730 permutations in SADIE 1.22 program. $I_a$= index of aggregation; $V_i$= mean index of clustering for patches; $V_j$= mean index of clustering for gaps.

| Species                   | $I_a$ | $P_{(I_a)}$ | $V_i$ | $P(V_i)$ | $V_j$ | $P(V_j)$ | $X$   | $P(X)$ |
|---------------------------|-------|-------------|-------|----------|-------|----------|-------|--------|
| Ariocarpus kotschoubeyanus | 2.1   | 0.0004      | -1.908| 0.0000   | 2.0   | 0.0000   | 0.257 | 0.0100 |
| Tiquilia sp.               | 1.9   | 0.0004      | -1.837| 0.0004   | 1.6   | 0.0022   | 0.2611| 0.0100 |
| Opuntia imbricata          | 1.0   | 0.3462      | -1.037| 0.3505   | 1.1   | 0.2927   | 0.3258| 0.0136 |
| Turnera diffusa            | 1.6   | 0.0055      | -1.351| 0.0275   | 1.3   | 0.3888   | 0.2204| 0.0483 |
| Calanticaria bicolor       | 2.1   | 0.0004      | -1.901| 0.0000   | 1.9   | 0.0000   | 0.2204| 0.0483 |
| Zaluzania sp               | 1.5   | 0.0081      | -1.505| 0.0066   | 1.5   | 0.0062   | 0.4018| 0.0366 |
| Opuntia lindheimeri        | 1.3   | 0.0491      | -1.305| 0.0520   | 1.3   | 0.0418   | 0.1546| 0.0154 |
| Agave striata              | 1.4   | 0.0077      | -1.439| 0.0088   | 1.4   | 0.0366   | 0.1546| 0.0154 |
| Chrysactinia mexicana      | 1.2   | 0.0934      | -1.226| 0.0952   | 1.1   | 0.1546   | 0.1546| 0.0154 |
| Karwinskia humboldtiana    | 1.3   | 0.0341      | -1.320| 0.0396   | 1.4   | 0.0154   | 0.1546| 0.0154 |
| Jatropha dioica            | 1.0   | 0.3425      | -1.044| 0.3520   | 0.9   | 0.6810   | 0.1546| 0.0154 |

Figure 1. Maps of the spatial negative association between $A$. kotschoubeyanus and $C$. bicolor ($X$= -0.257, $Pa$ = 0.9982) (A) and $Tiquilia$ canescens ($X$= -0.197, $Pa$ = 0.9803) (B). The blue areas represent positive values (>0.025), while the white areas represent negative or dissociation values (<0.975).

SADIE demonstrated that $M$. mathildae was strongly associated with $B$. fagaroides and Lysiloma microphylla. Its association with Myrtillocactus geometrizans was positive, but not significantly (table 2). In contrast, $P$. laevigata and $S$. polyantha are not associated with this cactus. $M$. mathildae was associated to $B$. fagaroides, both dissociated from $S$. polyantha; these tree species tend to aggregate forming clearly differentiated patches within the vegetation. During field surveys this characteristic was useful in locating significant patches of associated trees that grew in visible uplift rocks, allowing us to ignore sites with high densities of non associated flora. Following this procedure, location of cactus populations was highly efficient. Survey time for locating $M$. mathildae was reduced from 86 man-hours to 2-10 man-hours.

### Table 2. Aggregation index ($I_a$) and association index ($X$) of $M$. mathildae and neighbor vegetation

| Species       | $I_a$ | $P(I_a)$ | $V_i$ | $P(V_i)$ | $V_j$ | $P(V_j)$ | $X$   | $P(X)$ |
|---------------|-------|----------|-------|----------|-------|----------|-------|--------|
| L. microphylla| 1.655 | 1.532    | 0.0000| -1.676   | 0.0000| 0.2611   | 0.0100|        |
| B. fagaroides | 1.628 | 1.464    | 0.0128| -1.628   | 0.0000| 0.3258   | 0.0136|        |
| M. geometrizans| 0.868 | 0.881    | 0.8205| 0.927    | 0.7051| 0.2204   | 0.0483|        |
| P. laevigata  | 1.823 | 1.823    | 0.0000| -1.860   | 0.0000| -0.2431  | 0.8949|        |
| S. polyantha | 1.677 | 1.779    | 0.0000| -1.692   | 0.0000| -0.3127  | 0.9876|        |
| M. mathildae  | 1.509 | 1.493    | 0.0000| -1.505   | 0.0000| –        | –     |        |
3. *Agave* species

*Agave americana* and *A. salmiana*, exhibited high values for the aggregation index (*Ia*) for sites under *in situ* management and cultivation. The *V* index values indicates formations of patches for both Agaves species (table 3). Figure 3 shows the map of spatial distribution of the sites under cultivation and no intensive management. The clustered distribution of Agaves is the result of its modular architecture.

The local association (X) shows that Agave species are disassociated. This involves little or no competition between species by nutrients or space. In the preserved site *Agave salmiana* shows a tendency to dissociation with *Juniperus monosperma* (X=-0.1034, P= 0.8738) and with *Pinus cembroides* (X=-0.3025, P= 0.9993). In both cases, the species of Agave is neutral in space with two representative tree species. At the *in situ* management sites similar results were detected since strong spatial dissociation were detected with important tree species (*Pinus, Juniperus* and *Quercus*), and a lack of positive association with other species of the community.

**CONCLUSIONS**

Spatial analysis techniques proved to be an efficient method for the basic characterization of plants populations from arid and semiarid environments, especially for those species endangered or in risk. The method also provides important information about spatial interactions between species such as facilitation or competition, and therefore, for *in situ* management of the target species.

**Table 3.** Data comparison of the spatial distribution and aggregation in sites where *Agave americana* and *A. salmiana* were detected. *In situ man* = *in situ* management.

| Specie       | Category    | Sites                | *Ia* | *P(Ia)*  | *V* | *P(V)*  | *V* | *P(V)*  |
|--------------|-------------|----------------------|------|----------|-----|----------|-----|----------|
| *A. americana* | *in situ man.* | Los Juárez           | 1.004| 0.4234   | -1.005| 0.4038    | 1.04| 0.3391   |
|              | cultivar    | El Doctor            | 0.76 | 0.9694   | -0.76 | 0.9732    | 0.806| 0.8957   |
|              | cultivar    | Chavarrías           | 1.507| 0.0068   | -1.463| 0.0103    | 1.364| 0.02     |
| *A. salmiana* | *in situ*   | Los Hernández        | 0.885| 0.7504   | -0.848| 0.8576    | 0.897| 0.7391   |
|              | *in situ*   | Los Juárez           | 1.192| 0.1255   | -1.184| 0.1309    | 1.228| 0.0923   |
|              | Cultivar    | EL DOCTOR            | 0.885| 0.7279   | -0.888| 0.7142    | 1.037| 0.3426   |
|              | Cultivar    | Chavarrías           | 0.973| 0.5003   | -0.974| 0.4956    | 1.043| 0.3326   |

Figure 3. Map of patches and gaps areas under intensive management or cultivation (Chavarrías site A), and *in situ* or intermediate management (Juárez site B). This distribution map (Vi 1.5) patches are displayed in blue and clear (Vj - 1.5) in red.

**REFERENCES**
[1] Nathan R, Muller-Landau HC. Spatial patterns of seed dispersal, their determinants and consequences for recruitment. *TREE* 2000; 15:278-285.
[2] Perry JN. Measures of spatial pattern for counts. *Ecology* 1998; 79(3):1008-1017.
[3] Solano E, Feria PT. Ecological niche modeling and geographic distribution of the genus *Polianthes L.* (Agavaceae) in Mexico: using niche modeling to improve assessments of risk status. *Biodivers Conserv* 2007;16:1885–1900.
[4] Zúñiga B, Malda G, Suzán H. Interacciones planta-nodriza en *Lophophora diffusa* (Cactaceae) en un desierto subtropical de México. *Biotrópica* 2005;37:351–356.
[5] Perry JN, Dixon P. A new method for measuring spatial association in ecological count data. *Ecoscience* 2002;9:133–141.
[6] Suzán H, Sosa V. Comparative performance of the giant cardon cactus (*Pachycereus pringlei*) seedlings under two leguminous nurse plant species. *J. Arid Environ* 2006;65:351-362.
[7] Winder L, Alexander CJ, Holland HM, Woolley C, Perry JN. Modeling the dynamic spatio-temporal response of predators to transient prey patches in the field. *Ecol Let* 2001;4: 568-576.
[8] Turechek WW, Madden LV. Spatial pattern analysis of strawberry leaf blight in perennial production systems. *Phytopathology* 1999;89:421-433.
[9] Zamudio RS, Rzedowski J, Carranza GE, Calderon de Rzedowski G. *La vegetación del Estado de Querétaro. CONCYTEQ, Querétaro México*; 1992.
[10] García-Rubio, OR, Malda-Barrera G. Phenological changes of *Mammillaria mathildae* associated to climatic change in a deciduous tropical forest. Smithsonian Scholarly Publications. In: Dallmeier F, Fenech A, Maciver D, Szaro R, editors. *Climate Change, Biodiversity, and Sustainability in the Americas*. Smithsonian Institution's Scholarly Press; 2010, p. 101-113.
[11] PNUMA-SEDESU-CONCYTEQ. *Perspectivas del medio ambiente urbano: GEO zona metropolitana Querétaro*. PNUMA, SEDESU, CONCYTEQ, Querétaro, México; 2008.
[12] Baltazar RJ, Mahinda M, Hernández S. *Guía de Plantas Comunes del Parque Nacional “El Cimatario” y sus Alrededores*. Universidad Autónoma de Querétaro; 2004.
[13] Carrillo-Martínez M. *Contribución al Estudio Geológico del Macizo Calcáreo El Doctor, Querétaro*. Universidad Nacional Autónoma de México, Instituto de Geología; 1981.
[14] Fernández-Nava R, Colmenero-Robles JA. *Notas sobre la Vegetación y Flora del Municipio de San Joaquín Querétaro, México. Instituto Politécnico Nacional, Mexico*; 1997.
[15] Suzán HA, Malda G, Lara VM, Casas GS, Martínez AG, Villa MS, Loya L, López F. *Reporte Final de Actividades. Proyecto G037 CONABIO: Análisis de Viabilidad para Poblaciones de la Cactacea Amenazada Ariocarpus Trigonus*. Universidad Autónoma de Tamaulipas; 1997.
[16] García-Rubio, OR. Protocolo para la Restauración de una Población de *Mammillaria mathildae* en la Provincia de Juriquilla, Querétaro. Thesis. UAQ, Querétaro, Mexico; 2010.
[17] Rojas-Aréchiga M, Vázquez-Yanes C. Cactus seed germination: a review. *J Arid Environ* 2000;44:85–104.