

A new method to estimate areas of occupancy using herbarium data

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Received: 23 June 2006 / Accepted: 29 September 2006 / Published online: 13 February 2007
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Abstract The World Conservation Union (IUCN) Red List of Threatened Species is an important instrument to evaluate the conservation status of living organisms. However, Red List assessors have been limited by the lack of reliable methods to calculate the area of occupancy (AOO) of species, which is an important parameter for red list assessments. Here we present a new practical method to estimate AOO based on herbarium specimen data: the Cartographic method by Conglomerates (CMC). This method, which combines elements from the Areographic and Cartographic methods previously used to calculate AOO, was tested with ten cactus species from the Chihuahuan Desert Region. The results derived from this novel procedure produced in average AOO calculations 3.5 and 5.5 smaller than the Areographic and Cartographic methods, respectively. The CMC takes into account the existence of disjunctions in the distribution range of the species, producing comparatively more accurate AOO estimations. Another advantage of the CMC is that it generates results more harmonic with the current Red List criteria. In contrast, the overestimated results of the Areographic and Cartographic methods tend to artificially categorize the species, even extremely narrow endemics, in lower endangerment status.

Keywords Areographic · Cactaceae · Cartographic · Distribution size · Opuntioideae · Red List

Introduction

The World Conservation Union (IUCN) Red List of Threatened Species (<http://www.iucnredlist.org>) is the most comprehensive and authoritative resource dealing with the conservation status of living organisms (Butchart et al. 2004, 2005;

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Rodrigues et al. 2006). To date, the Red List project has achieved significant progress on the evaluation of the conservation status of several groups of organisms. For example, all of the bird and amphibian species, and nearly all mammals have been assessed (Baillie et al. 2004). However, progress on the world flora as a whole has been rather modest, with the exception of gymnosperms (conifers and cycads). It has been estimated that the world flora comprises 260,000 species (Thorne 2002), and only 11,824 of these (4.55%) have been evaluated for the IUCN Red List (see summary statistics in <http://www.iucnredlist.org>).

The slowness in evaluating the conservation status of the world's flora is particularly important in view of the adoption of the Global Strategy for Plant Conservation (GSPC) by the Conference of the Parties to the Convention on Biological Diversity (GSPC 2002). The GSPC establishes fourteen targets to be met by 2010, whose ultimate objective is to halt current trends of loss of plant diversity. In particular, target 2 sets the goal for "A preliminary assessment of the conservation status of all known plant species, at national, regional and international levels". In turn, this target is essential to reach target 7: "60 percent of the world's threatened species conserved in situ" (GSPC 2002).

To reach target 2, at least at a preliminary stage, is a daunting task because we just lack the most fundamental information on population densities, demography, etc. for most of the species. In addition, in many of the plant groups there are numerous unresolved taxonomic problems. However, it has been demonstrated (Golding 2001, 2004; Schatz 2002; Willis et al. 2003) that the specimens deposited in herbaria contain a wealth of information that can be used to deduct geographic distribution parameters at different taxonomic levels. Thus, herbarium specimen data can be used for defining categories of threat and other conservation-related work. Herbarium data, together with published floras, are very often the only reliable information on plant species.

Herbarium collections, in particular the geographical and ecological data contained in the specimen labels, are thus an invaluable source of information for calculating extent of occurrence (EOO), area of occupancy (AOO), and, in cases, fragmentation. AOO is defined as the area occupied by a taxon within its more general EOO (IUCN 2001), and it is usually taken as a measure of species distribution size. In particular, one of the more commonly used parameters in Red List assessments is the AOO of species.

In an attempt to contribute to the red listing process, and to make assessments more objective, in this paper we present a new simple method to calculate AOO. This method can be used consistently and objectively by different people and with different sets of data. The novel procedure, which we call Cartographic Method by Conglomerates (CMC), was tested with ten species of Cactaceae, subfamily Opuntioideae, endemic or nearly endemic to the Chihuahuan Desert Region (Hernández et al. 2004). The results derived by the CMC were contrasted with calculations made with other methods to estimate species distribution size, such as the Areographic (Rapoport 1975; Rapoport and Monjeau 2001) and Cartographic methods (IUCN 2001).

Method

The CMC proposed here incorporates elements of the Areographic and Cartographic methods, previously used by different authors to calculate distribution size. The three methods are explained below:

Areographic method

Originally proposed by Rapoport (1975), this method uses geo-referenced locality data. Locality points are interconnected to form an open, minimum spanning tree, where all points are connected by their shortest distance (Fig. 1A). Minimum distances between pairs of points are measured and the average distance (mean propinquity index) is calculated. This average figure is used as a radius to trace a circle around each point (Fig. 1B). The cumulative area of the circles (deducting overlapping fragments) is taken as the species distribution area. One advantage of the mean propinquity index is that it is derived from the characteristics of each particular species. In addition, this method allows to identify possible disjunctions. According to Rapoport (1975) disjunctions are identified where the distance between two circles at their center is greater than twice the average distance.

Cartographic method

This method is currently being used in Red List assessments to calculate AOO. According to the Cartographic method, the AOO is calculated superposing a grid to a map containing recorded localities of a given taxon; the AOO is the sum of occupied grid squares. The results of this simple procedure are dependent on the scale (grid cell size) used in the calculation. Consequently, when a fine scale is used the resulting AOO will be small and unrecorded occurrences derived by poor collecting will be overlooked. In contrast, in larger scale mapping large unoccupied areas will be incorporated resulting in range overestimations. Therefore, the choice of a scale is not a simple matter, and could be a source of inconsistency and bias (IUCN 2001). A reasonable solution to the problem of assigning a suitable scale was provided by Willis et al. (2003). These authors suggested that grid cell size could be defined as 10% of the distance between the most distant pair of points (Fig. 2A). This criterion allows to calculate a specific scale to each particular species depending on its range configuration (Fig. 2B).

Cartographic method by conglomerates

The CMC recognizes the existence of discrete aggregations of points (*conglomerates*) as well as isolated, single localities (*satellites*), both of which are clearly and objectively identifiable. The most fundamental difference of the CMC is that the area of each conglomerate is calculated individually. The CMC procedure consists of the following steps:

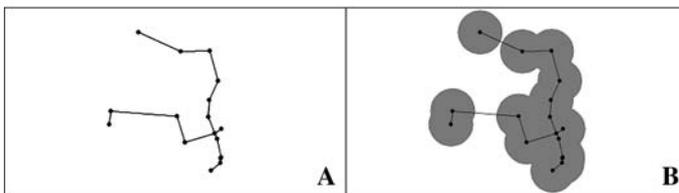


Fig. 1 Areographic method applied to *Opuntia xandersonii*. **(A)** Lines uniting the closest pairs of localities to form a minimum spanning tree. **(B)** The mean propinquity index determines the radius of the circles

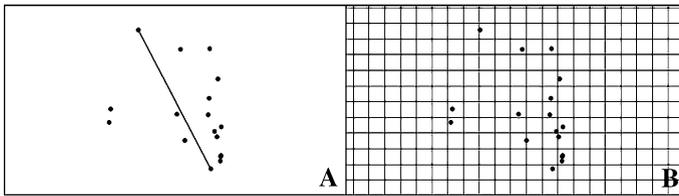


Fig. 2 Cartographic method applied to *Opuntia xandersonii*. Ten percent of the distance between the most distant pair of points (**A**) determines the grid cell size (**B**)

- (1) The geo-referenced localities of each species are plotted over a map. In our study, we used a map of the Mexican Republic at a 1:250,000 scale (<http://www.conabio.mx>), projected in UTM's.
- (2) As in the Areographic method, a minimum spanning tree is created by uniting the closest pairs of points (Rapoport 1975), taking care of avoiding forming loops (Fig. 3A).
- (3) The average distance between pairs of points is calculated (mean propinquity method; Rapoport 1975); this is done by adding all the distances and dividing the product between the number of lines. The resulting figure is taken as the radius of a circle encircling each point (Fig. 3B). At this stage, the disjunct conglomerates of two or more partially overlapping circles and the single, isolated (non-overlapping) satellites may be clearly identified. In the example of Fig. 3B, the hybrid species *Opuntia xandersonii* has two distinct conglomerates and one satellite.
- (4) The area of each conglomerate is then calculated separately by means of the Cartographic method. In order to define the scale for each conglomerate, the distance between the two more distant points in each conglomerate is measured (Fig. 3C); 10% of the maximum distance defines the grid cell size in each conglomerate (Willis et al. 2003). Thus, in the case of *Opuntia xandersonii* (Fig. 3D) the largest distance within each conglomerate (5.57 km and

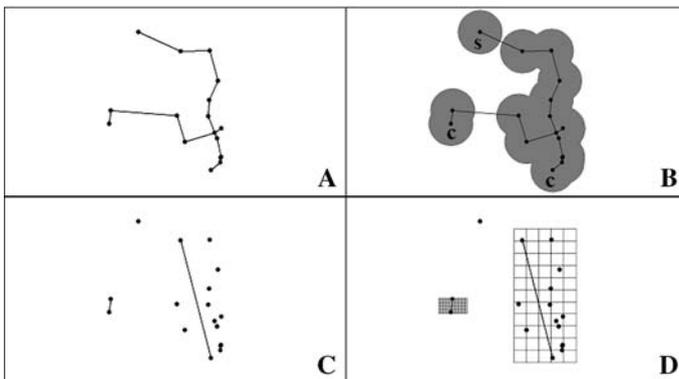


Fig. 3 Cartographic method by Conglomerates applied to *Opuntia xandersonii*. (**A**) Minimum spanning tree. (**B**) The overlapping circles differentiate the two distinct conglomerates (c) from the isolated satellite (s). (**C**) The distance between the most distant pair of points within each conglomerate is calculated. (**D**) Ten percent of the distance between the most distant pair of points determines the scale in each conglomerate

- 50.61 km) determine two different scales: the smaller one (grid cell size = $0.557 \times 0.557 = 0.31 \text{ km}^2$) for the western conglomerate and the larger one (grid cell size = $5.061 \times 5.061 = 25.61 \text{ km}^2$) for the eastern one (Fig. 3D).
- (5) Finally, the area occupied by the species in each conglomerate is calculated by adding the grid cell areas where the species is present. As for the satellites, according to our field experience, each of these are assigned a constant area of 2 km^2 . The AOO of the species is then calculated as the sum of the areas of all of its conglomerates and satellites.

A Geographic Information System (ArcView 3.2) was used to plot the point distribution maps, to measure all distribution parameters, as well as to generate grids, and to make all measurements for AOO calculation. For maximum accuracy, all connecting lines of the tree of maximal connectivity were united to the points at a 1:1 zoom. One of the advantages of using GIS technology is that all measurements are more accurate; also, it eliminates inconsistencies derived from an arbitrary positioning of the grids.

The cactus species selected in this paper to test the proposed method were chosen because they were well defined taxonomically and adequately represented by herbarium collections. Geographically, these vary from narrowly endemic species, such as *Opuntia chaffeyi* and *O. megarrhiza*, to widespread ones in the Chihuahuan Desert (e.g., *O. kleiniae*, *O. rufida*, *O. stenopetala*).

The locality information of the species was extracted from the Database of Cactus Specimens from North America. This database has been developed along a 15-year period and contains over 26,000 specimen records of 35 herbaria from Mexico, United States and European institutions. About 28% of the information in the database has been derived from fieldwork conducted by the senior author and his collaborators since the early 1990s. This database clearly is the world's most comprehensive source of information on Mexican cactus species distributions.

A total of 451 geo-referenced records were used for this analysis. Data on the general geographic distribution of the studied species may be found in Hernández et al. (2004) and Navarro (2006), and is summarized in Table 1.

Results and discussion

Figures 4–6 are graphic representations of the distribution range of 3 of the 10 studied species resulting from the application of the three methods described in the previous section. Each figure comprises two maps of the same species, one with the distribution areas calculated with the Areographic and Cartographic methods (A) and the other with the CMC (B). It is important to emphasize that all maps were produced with the same data.

The results are summarized in Table 2 for the Areographic method, Table 3, for the Cartographic, and Table 4 for the CMC. When the results derived from the three methods are compared (Table 5 and Fig. 7), it becomes apparent that the resulting AOO figures for each one of the species differ drastically, in cases by more than two orders of magnitude. As shown in Fig. 7, the Areographic and Cartographic methods consistently produced overestimated AOO figures when compared to the CMC. In fact, the average area calculated by means of those methods was 3.5 and 5.5 times

Table 1 General distribution of the studied species

Species	Chihuahuan Desert endemic	State distribution	Database records
<i>Cylindropuntia anteojoensis</i> Pinkava	Yes	Coah	6
<i>C. kleiniiae</i> (DC) F. Knuth	No	Ariz, Tex, Hgo, Qro, SLP, NL, Coah, Dgo, Zac, Tamps, Pue	75
<i>Grusonia bradtiana</i> (Coulter) Britton et Rose	Yes	Coah, Dgo	20
<i>G. grahamii</i> (Engelm.) H. Rob.	Yes	Tex, Chih, Coah, Dgo, Zac	27
<i>Opuntia chaffeyi</i> Britton et Rose	Yes	Zac	5
<i>O. megarrhiza</i> Rose	Yes	SLP	8
<i>O. pachyrrhiza</i> Hernández, Gómez-Hinostrosa et Bárcenas	Yes	SLP, Tamps, Qro	20
<i>O. rufida</i> Engelm.	Yes	Tex, Coah, Chih, Zac, Dgo	54
<i>O. stenopetala</i> Engelm.	Yes	Coah, NL, SLP, Tamps, Zac, Qro, Gto, Hgo	220
<i>O. xandersonii</i> Hernández, Gómez-Hinostrosa et Bárcenas	Yes	SLP, Tamps	16

State distribution: Ariz = Arizona, Chih = Chihuahua, Coah = Coahuila, Dgo = Durango, Gto = Guanajuato, Hgo = Hidalgo, NL = Nuevo León, NM = New Mexico, Pue = Puebla, Qro = Querétaro, SLP = San Luis Potosí, Tamps = Tamaulipas, Tex = Texas, and Zac = Zacatecas

larger, respectively, than that derived by the CMC. In particular, the area estimations resulting from the Areographic method were unconvincingly large for narrow endemic species such as *C. anteojoensis*, *O. chaffeyi* and *O. megarrhiza*. Known only from 5, 3 and 6 locations, respectively, these species have extremely restricted ranges. As for the wide-ranging species such as *C. kleiniiae*, *G. grahamii*, *O. rufida*, and *O. stenopetala*, the performance of the Areographic and Cartographic methods varied, but the estimated areas were also substantially larger than those derived by the CMC (Table 5 and Fig. 7).

One of the disadvantages of using the Areographic and Cartographic methods is that these imply that the species distribution ranges are spatially continuous. However, it has been stated that no species is continually distributed in the geographic space (Gaston 2003). Numerous examples in the literature show that gaps of different magnitude interrupt the species distribution ranges, primarily as a consequence of historical and contemporary ecological factors (see for example, Turner et al. 1995; Brown and Lomolino 1998; Gaston 2003). As for the Cactaceae in particular, in a study of species turnover (β diversity) in cactus assemblages along a 250 km long transect in the southeastern segment of the Chihuahuan Desert, Goettsch and Hernández (2006) showed that cactus distributions in this region are mostly discontinuous, displaying an intermittent distribution pattern where the constituent populations are very often widely separated (see Fig. 3 in Goettsch and Hernández 2006).

Contrasting with the Areographic and Cartographic methods, the CMC has the advantage of being sensitive to the existence of disjunctions in the geographical distribution of the species. This method allows to objectively detect isolated populations (conglomerates and satellites) that may be a reflection of real disjunctions in nature. Consequently, the areas calculated by this method are theoretically more

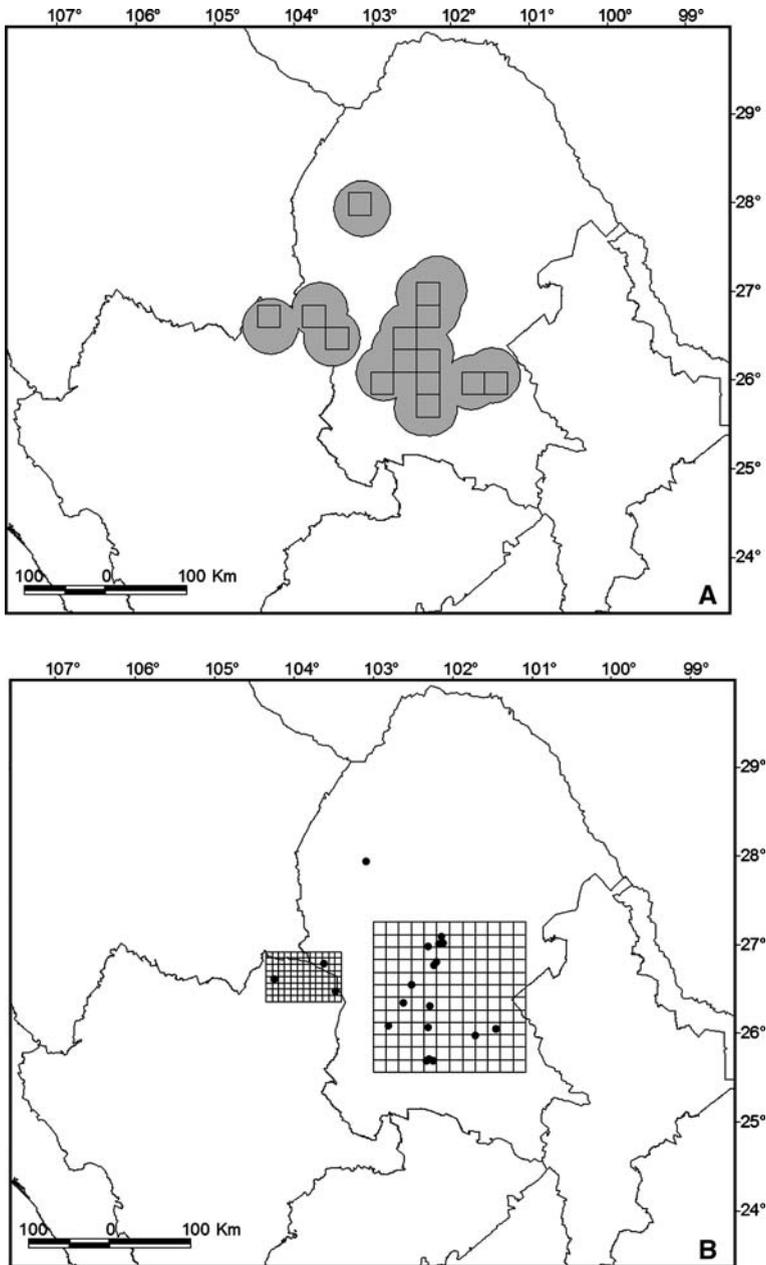


Fig. 4 Area of occupancy of *Grusonia bradtiana*. **(A)** Areographic and Cartographic methods. **(B)** Cartographic method by Conglomerates

accurate. Given this, and considering our field experience, we believe that the results derived from the CMC approximate more closely to reality than those of the other methods, which greatly overestimate AOO's.

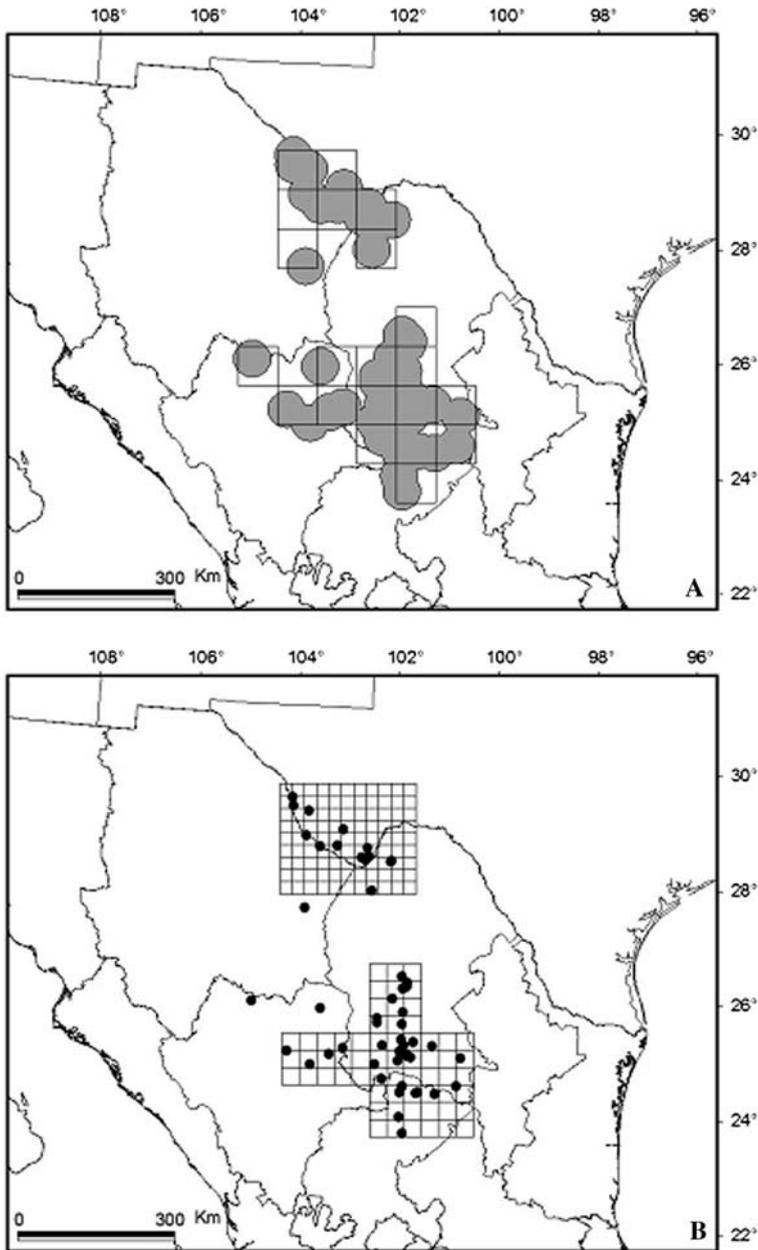


Fig. 5 Area of occupancy of *Opuntia rufida*. (A) Areographic and Cartographic methods. (B) Cartographic Method by Conglomerates

A particular problem inherent to the CMC (as well as the other methods) is presented by the species that inhabit extremely specialized habitats (e.g., gypsum formations, aquatic habitats in arid regions, mountain peaks, etc.), which very often

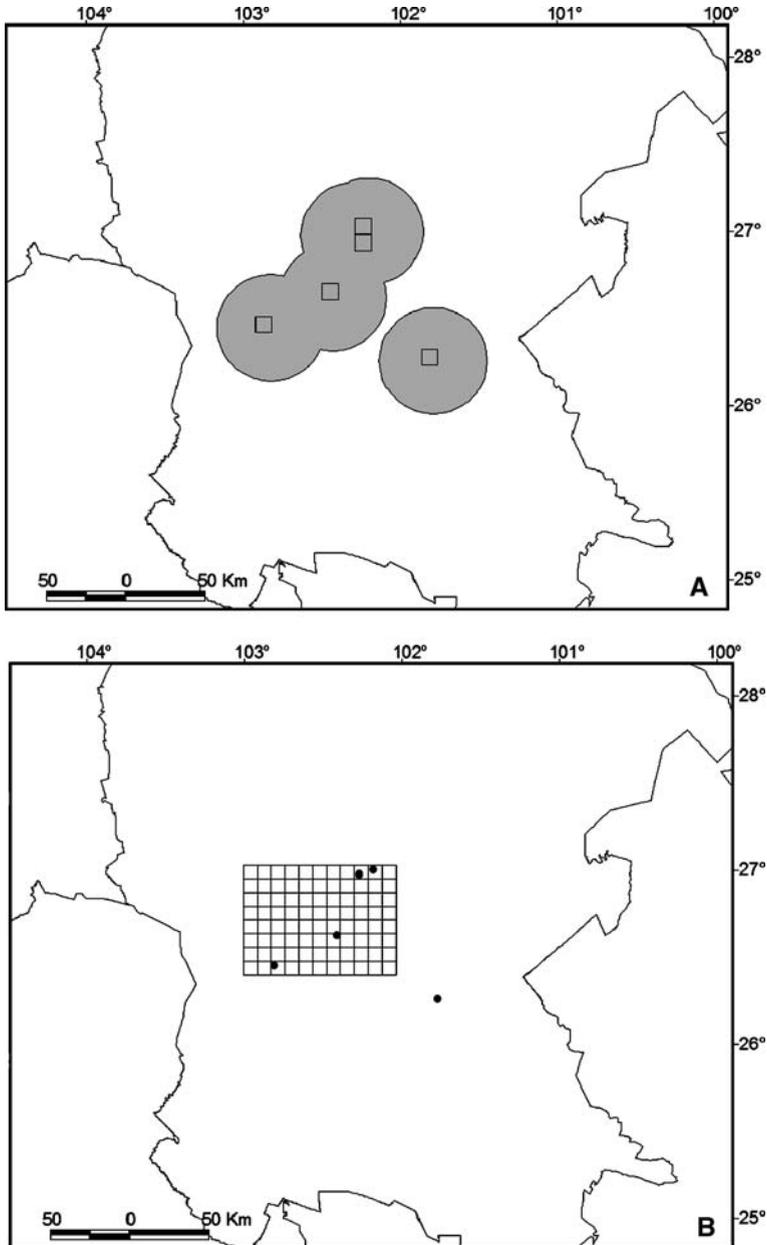


Fig. 6 Area of occupancy of *Cylindropuntia antejoensis*. (A) Areographic and Cartographic methods. (B) Cartographic Method by Conglomerates

are scattered across large areas and function as ecological islands. This case is clearly illustrated by *Ariocarpus kotschoubeyanus* (Fig. 8), a Mexican cactus species that has been found in 35 discrete locations along a large portion of the Chihuahuan desert region. This species occurs exclusively in silty, dry lake beds found in six

Table 2 Areas of occupancy estimated by the Areographic method

Species	Median propinquity index	Total area (km ²)
<i>C. kleiniae</i>	54.83	267,553.3
<i>G. grahamii</i>	66.62	184,516.6
<i>O. rufida</i>	38.66	118,452.1
<i>G. bradtiana</i>	34.43	38,004.1
<i>O. stenopetala</i>	9.15	21,078.6
<i>O. pachyrrhiza</i>	24.78	13,805.2
<i>C. anteojoensis</i>	33.86	13,116.8
<i>O. chaffeyi</i>	22.1	4,532.4
<i>O. megarrhiza</i>	15.86	3,003.6
<i>O. xandersonii</i>	8.98	2,328.4

Table 3 Areas of occupancy estimated by the Cartographic method

Species	Max. distance (km)	10% Distance	Grid cell area (km ²)	No. of squares	Total area (km ²)
<i>C. kleiniae</i>	2,171.08	217.108	47,135.88	15	707,038.2
<i>O. rufida</i>	822.26	82.226	6,761.11	21	141,983.3
<i>G. grahamii</i>	942.25	94.225	8,878.35	14	124,296.9
<i>O. stenopetala</i>	566.58	56.658	3,210.13	23	73,833.0
<i>G. bradtiana</i>	280.17	28.017	784.95	14	10,989.3
<i>O. pachyrrhiza</i>	295.43	29.543	872.79	8	6,982.3
<i>C. anteojoensis</i>	104	10.4	108.16	5	540.8
<i>O. xandersonii</i>	64.33	6.433	41.38	15	620.7
<i>O. megarrhiza</i>	79.18	7.918	62.69	5	313.5
<i>O. chaffeyi</i>	82.32	8.232	67.76	3	203.3

different states (Querétaro, San Luis Potosí, Zacatecas, Tamaulipas, Nuevo León, and Coahuila) across this region. If the AOO of this species is calculated by means of any of the methods discussed in this paper, the resulting area is unrealistically large (Areographic = 54,683.28 km², Cartographic = 67,000.21 km², CMC = 3,104.86 km²). In cases such as this we have opted to consider each locality as a 2 km² satellite. Consequently, the resulting area for *A. kotschoubeyanus* applying this criterion is 67.95 km², a more convincing figure for this highly specialized species. This same criterion was applied in the present study to *Opuntia chaffeyi* (Table 4), a peculiar species restricted to the same type of habitat as *A. kotschoubeyanus*. Examples like this one are not rare in nature; however, their detection require a minimum knowledge of the ecology and distribution patterns of the species.

In connection to the previous paragraph, it is important to mention that satellites are circular areas with a radius = 797.88 m, rather than squared ones. This is particular important when we use the satellite criterion to species with extremely patchy distributions, such as *A. kotschoubeyanus*. The use of circles instead of grid-squares here allows us calculate AOO more accurately, because in these cases the “satellites” may overlap.

The results derived from the CMC are optimal when the geographic range of the species is known at a fine resolution, and can be continuously updated with the discovery of new localities. However, as shown in this paper, the application of this method on species from the tropics and subtropics would be highly satisfactory, although collecting effort in these regions is more limited than in temperate

Table 4 Areas of occupancy estimated by the Cartographic Method by Conglomerates

Species	Satellites	Conglomerates	Max. distance	10% Distance	Grid cell area (km ²)	No. of squares	Area (km ²)
<i>C. kleiniae</i>	4	1	92.36	9.236	85.304	3	255.912
		2	20.27	2.027	4.109	3	12.327
		3	72.34	7.234	52.331	5	261.655
		4	613.79	61.379	3,767.38	30	113,021.40
							113,559.3
<i>G. grahamii</i>	0	1	123.61	12.361	152.794	5	763.97
		2	546.75	54.675	2,989.36	12	35,872.32
		3	105.01	10.501	110.271	4	441.084
							37,077.4
<i>O. rufida</i>	3	1	256.73	25.673	659.103	12	7,909.24
		2	362.7	36.27	1,315.51	15	19,732.65
							27,647.9
<i>O. stenopetala</i>	20	1	143.73	14.373	206.583	38	7,850.15
		2	69.91	6.991	48.874	8	390.992
		3	60.47	6.047	36.566	13	475.358
		4	24.75	2.475	6.125	3	18.375
		5	15.94	1.594	2.541	3	7.623
		6	8.93	0.893	0.797	2	1.594
		7	18.91	1.891	3.576	3	10.728
		8	1.21	0.121	0.015	2	0.03
							8,794.9
<i>G. bradtiana</i>	1	1	156.25	15.625	244.141	13	3,173.83
		2	77.15	7.715	59.521	3	178.563
							3,354.4
<i>O. pachyrrhiza</i>	3	1	94.51	9.451	89.321	11	982.53
							988.5
<i>C. anteojensis</i>	1	1	86.91	8.691	75.533	4	302.13
							304.1
<i>O. xandersonii</i>	1	1	50.61	5.061	25.61	11	281.75
		2	5.57	0.557	0.31	2	0.62
							284.4
<i>O. megarrhiza</i>	2	1	20.08	2.008	4.032	5	20.16
							24.2
<i>O. chaffeyi</i>	3						6

In the last column, the figures in bold represent the total area of the species. In the case of *Opuntia chaffeyi*, its three known localities were considered as satellites (see text)

Table 5 Comparison of areas of occupancy calculated by the methods Areographic, Cartographic, and Cartographic by Conglomerates

Species	Areographic (Km ²)	Cartographic (Km ²)	CMC (Km ²)
<i>C. kleiniae</i>	267,553.3	707,038.2	113,559.3
<i>G. grahamii</i>	184,516.6	124,296.9	37,077.4
<i>O. rufida</i>	118,452.1	141,983.3	27,647.9
<i>O. stenopetala</i>	21,078.6	73,833.0	8,794.9
<i>G. bradtiana</i>	38,004.1	10,989.3	3,354.4
<i>O. pachyrrhiza</i>	13,805.2	6,982.3	988.5
<i>C. anteojensis</i>	13,116.8	540.8	304.1
<i>O. xandersonii</i>	2,328.4	620.7	284.4
<i>O. megarrhiza</i>	3,003.6	313.5	24.2
<i>O. chaffeyi</i>	4,532.4	203.3	6

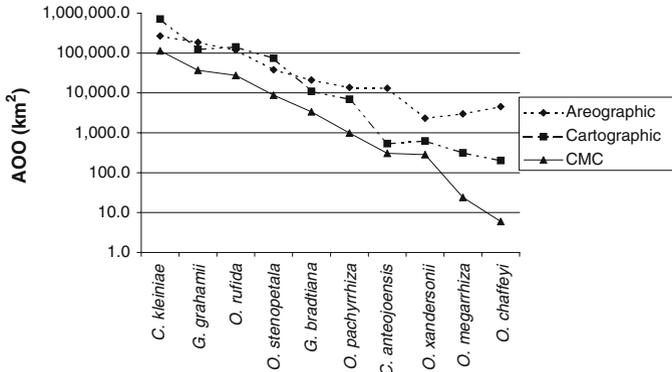


Fig. 7 Comparison of areas of occupancy calculated by the methods Areographic, Cartographic, and Cartographic by Conglomerates. Data taken from Table 5

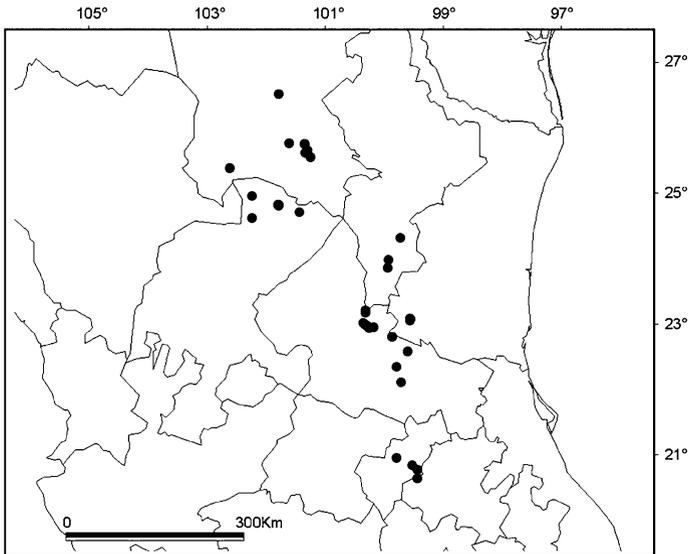


Fig. 8 Known localities of *Ariocarpus kotschoubeyanus*

countries (Prance et al. 2000). The CMC is suitable for calculating AOO in species that are known from at least three localities. For the narrowly endemic species known only from one or two sites, a solution would be to consider the individual locations as satellites, such as in the case described in the previous paragraph.

Another aspect worth considering is that the results of the CMC are more harmonic with the Red List criteria established by the IUCN (2001). For example, for *Opuntia pachyrrhiza*, *O. megarrhiza*, and *O. chaffeyi*, respectively, classified as vulnerable, endangered, and critically endangered in the current Red List, we report here AOO's of 988.5, 24.2, and 6 km² respectively, which fit perfectly well with the thresholds set for vulnerable (< 2,000 km²), endangered (< 500 km²), and critically endangered (< 10 km²) species in criterion B. *Opuntia chaffeyi*, with its exceedingly restricted range and extremely low population density, is among the rarest and most endangered Mexican cactus. On the other hand, only considering their AOO, and

pending the analysis of additional factors, *Cylindropuntia anteojoensis* (304.1 km²) and the hybrid *Opuntia xandersonii* (284.4 km²) would qualify as endangered, and the remaining widespread species (*C. kleiniae*, *G. grahamii*, *O. rufida*, *O. stenopetala* and *O. bradtiana*) as low concern.

In sum, the CMC proposed here is a practical method to calculate consistently and objectively AOO's using herbarium and other biological collections. The adoption of this method by plant taxonomist, ecologists, conservation biologists, etc. associated to institutional herbaria would contribute to make progress towards the evaluation of the conservation status of the world flora in the context of the targets established in the GSPC. However, it must be emphasized that, although the CMC makes an important contribution to the refinement of methodologies for red listing, the IUCN criteria stress the need for demographic, genetic, and other sets of information, when it is available.

Acknowledgements We would like to thank Carlos Gómez-Hinostrosa, George Schatz, and an anonymous reviewer for making useful comments to the original manuscript.

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