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A Landscape Perspective on Biodiversity Conservation

The Case of Central Mexico

The aim of this article is two fold: first, to depict key species and relate them to landscape units (LUs) to define habitats; second, to generate a sound network of protected areas to ensure the functional integrity of the ecosystem. In the present study, 6500 vertebrate and vascular plant species records were gathered into a database. A total of 137 sampling units were surveyed to verify key species and depict discrete LUs (scale 1:25,000). Using multivariate statistics (detrended correspondence analysis and canonical correspondence analysis), key species were selected and associated with LUs in a geographical information system. From the 1162 species recorded, 122 were identified as key species based on their endemicity and conservation status (12 amphibians, 42 reptiles, 37 birds, 11 mammals, and 20 vascular plants). Volcanic bodies and Holocene lava flows contain most key species but harbor less species overall, whereas mixed forest, meadows and crops, foot slopes, and accumulation plains harbor fewer key species but a greater number overall. These patterns were spatially displayed and discussed in light of their role in conservation and participatory management after over 15 years of research.

Keywords: *Conservation; key species; mountainous landscape; habitats; participatory management; Mexico.*

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Introduction

Large-scale human-induced environmental degradation is currently causing drastic reduction in the quality of life worldwide (Lambin et al 2001). Most conservation efforts, as well as current scientific knowledge, lag far behind in addressing the current rate of environmental deterioration (Myers 2000). Given this situation, there is a need for innovative approaches to retard current loss of biodiversity (Velázquez et al 2001). Traditionally, conservation has aimed at numerous levels of organization (Chung and Weaver 1994), although major emphasis has been given to single species (Mayr 2000). Sound species conservation relies on habitat maintenance (Velázquez et al 1996; Velázquez and Romero 1999). A habitat approach implies coherent integration of biotic and environmental attributes linked in geographical space (Kirby 1996). But this conceptual framework has not yet been fully implemented because most conservation efforts approach habitat management from a purely ecological viewpoint (Spellerberg 1996), ignoring social driving forces and relations between biotic communities and their physical environment. Hence, there is a need to search for innovative ways of achieving sound, long-term conservation because protected areas alone will not meet the demands of conservation (Hansen et al 1991; Vanclay et al 2001). This is especially relevant in tropical and subtropical regions, where most biodiversity occurs.

A major challenge in the integration of a holistic habitat management approach into conservation of biodiversity is the translation of point data into spatial units. Gap analysis (Scott et al 1993) has been widely used as a more robust approach to provide geographic reference to biological records. This approach aims to predict species distribution ranges by using environmental data such as land cover, assuming that species recorded at a given site may also be encountered at other sites with similar environmental conditions (eg, Butterfield et al 1994; Bojorquez-Tapia et al 1995). Species are considered the major attribute to depict habitats. In landscape ecology, geomorphological features are used to delineate natural entities and can then be used to depict biophysical habitats as discrete units (Velázquez and Bocco 2001). Species and geomorphological data sets together enhance the possibility of more robust delineation of habitats, rather than blocks delineated by Cartesian boundaries.

The present article depicts key species and links them to landscape units (LUs) to generate a sound network of protected areas to ensure the functional integrity of the ecosystem. This approach also provided a robust basis for further spatial modeling and conservation planning efforts using a participatory approach (Velázquez and Bocco 1994). The approach was tested using environmental data from Neotropical Mexican Plio-Pleistocene volcanic mountain ecosystems and biological data of vertebrates and vascular plant species. The study area is currently experiencing rapid habitat depletion, harbors an outstanding number of species, and has been regarded as crucial for balancing the functional integrity of the watershed of Mexico City.

Methodology

Study area

The approach was tested in Sierra Chichinautzin and Sierra de las Cruces, Quaternary volcanic units in Central Mexico, 15 km south of Mexico City (Figure 1). These are located between 19°23'N–99°22'W and 19°03'N–98°55'W (extreme coordinates). The elevation ranges between 2500 and 3660 m, and the total surface covers about 900 km^2. Leptosol and Regosol soil types

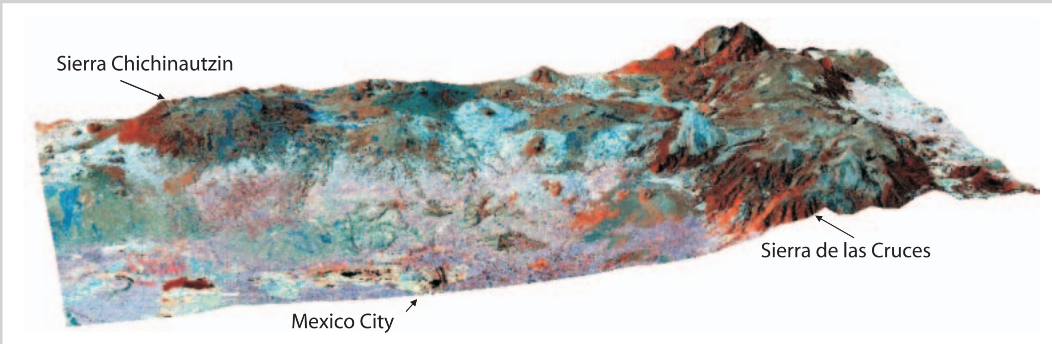


FIGURE 1 Digital terrain model of the study area. Land mosaic derived from a satellite image (Landsat ET+7) including Sierra de las Cruces and Sierra Chichinautzin as the main mountainous landscapes. Purple color shows human settlements, blue shows crops, red and brown show forested areas. (Courtesy of Institute of Geography, UNAM)

prevail. Climate types vary from temperate mild to temperate cool (mean annual temperature, 8°C), and mean annual rainfall is 1000 mm. Temperate vegetation types prevail, dominated by fir, pine, oak, and alder forests. The area experienced drastic landscape transformation at the end of the 19th century, from pristine forest types to forage production (mainly wheat and oat). Only areas with bare soil, rock outcrops, and steep slopes remained forested. Forage demand declined at the end of the 20th century, so the remaining forested areas were expected to encroach. Currently, both traditional agriculture and pristine forests are threatened by urbanization. A thorough description of the study area is presented elsewhere by Velázquez and Romero (1999).

Definition of LUs

Geomorphological units were delineated on a set of 1:20,000 panchromatic black and white aerial photographs; contacts were digitized and geometrically corrected (according to Zonneveld [1995]). The area was stratified into major cover–geomorphological zones. A digital elevation model was created by digitizing and further interpolating data from topographic maps (1:50,000 scale) with a contour interval of 20 m. Slope gradient and slope aspect maps were derived using standard filtering techniques (Burrough 1988), and these, in turn, were used to check for homogeneity within geomorphological units.

Within every geomorphological unit, sampling units were randomly selected. In total, 137 sampling units (625 m^2 each) were surveyed to describe all cover types hierarchically. The sampling units were allocated in such a way that all geomorphological units were surveyed proportionally. During fieldwork, geomorphological boundaries depicted from aerial photographs were verified and adjusted as necessary.

Plant communities were distinguished by means of classification analysis. Two nested levels of vegetation clusters, alliances and associations, were depicted and characterized by floristic composition and physiognomy, according to the method of Velázquez and Cleef (1993). Furthermore, 5 environmental variables were measured at each sampling unit: soil moisture, soil depth, elevation, slope steepness, and slope length (Velázquez 1994). Geomorphological units and vegetation clusters (at the alliance level) were used to typify and delineate LUs (Küchler and Zonneveld 1988). Final LUs were plotted on a scale of 1:25,000.

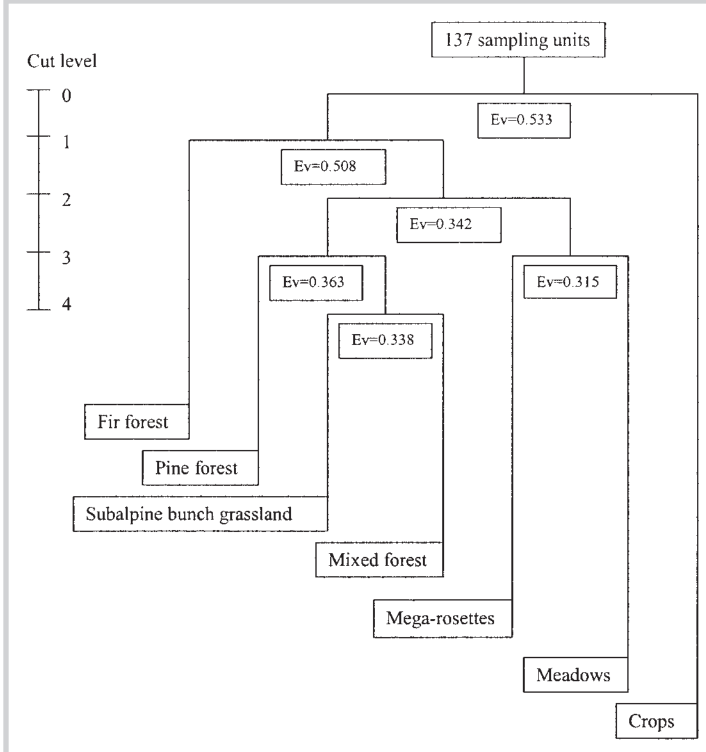
Vertebrate and vascular plant assemblages

To document the number of sympatric species within the study area, 6500 species records of vertebrates and vascular plants were gathered from different biological collections and from those cited in the literature. A species record means a species was found at a specific location and a given time. The collection sources were: Instituto de Biología (IBUNAM) and Museo de Zoología and Plantas Vasculares, Facultad de Ciencias (FCUNAM) of the Universidad Nacional Autónoma de México (UNAM); Escuela Nacional de Ciencias Biológicas (ENCBIPN); Colección de Mamíferos de la Universidad Autónoma Metropolitana (UAMI); and Centro de Investigaciones Biológicas (CIBUAEM) of the Universidad Autónoma del Estado de México.

A total of 846 vascular plant species and 316 vertebrate species were included in the final database obtained from records starting from the late 19th century up to 1995. To focus the conservation effort, all endemic and threatened species were considered as potential "key" species (CIPAMEX 1993; Instituto Nacional de Ecología 1994; Baillie and Groombridge 1996). All species records from potential key species were pooled into a database. A normalized frequency value of every potential key species per LU was calculated. This value was obtained by plotting every record on maps (scale 1:50,000) where landscape boundaries had been transferred previously. Because not all species were recorded in the same way and not all LUs sampled evenly, a random selection of a proportionally equal number of biological records was made to achieve sound comparisons.

A database on biological records was derived from preexisting collections and literature. In addition,

FIGURE 2 Dendrogram obtained by classification analysis to distinguish major vegetation clusters. In total, 137 sampling units and 345 plant species were analyzed to define the 6 vegetation clusters. A thorough description of all vegetation types occurring in the area is given in Velázquez and Cleef (1993).



data from fieldwork conducted during the 1980s by the authors were also included. We conducted 3 months of intensive fieldwork (October to December 1997) to survey all LUs evenly and to validate the current presence of potential key species. In this way, our database was updated, and it was comparable among LUs. During fieldwork, 3 different actions took place: the first was to sample vegetation communities using *relevés* (according to Velázquez and Cleef [1993], the method used since the beginning of the 20th century by most European vegetation scientists to describe, classify, and name vegetation communities); the second was to sight and trap vertebrates occurring at the *relevé* site; and the third was to validate land form and soil attributes depicting LUs. A detailed description of the results is provided by Velázquez and Romero (1999).

To detect species with similar distribution patterns along LUs, we performed ordination analysis (detrended correspondence analysis, Hill and Gauch 1980). Species with specific habitat requirements and restricted distribution ranges were finally selected as key species. All species grouped within a similar ordination space were considered to have similar environmental requirements (Velázquez and Heil 1996). Individual species records were further treated as species assemblages (SAs).

The 5 land attributes measured during fieldwork (soil moisture, soil depth, elevation, slope steepness, and slope length) were also analyzed using ordination techniques (canonical correspondence analysis [CCA], Ter Braak 1990). This procedure was conducted to detect (dis)similarities among LUs. LUs distributed along similar ordination space have similar environmental affinity. This procedure resulted in landscape clusters (LCs) that were further used as the basis for spatial analysis.

Spatial analysis

Plant communities, derived from clustering species records by ordination techniques, were related to geomorphological (geomorphology and soil) units by point-in-polygon operations (Aronoff 1989) using a geographic information system (Integrated Land and Watershed Information System 1999). The rules implemented in the simulations and used throughout the entire spatial modeling procedure were based on field-verified data (Velázquez and Bocco 1994) and validated habitat distribution patterns of key species (eg, Velázquez and Heil 1996). These rules included significant correlation among SAs and LCs. Those SAs and LCs with equal distribution patterns along ordination space were represented as different spatial units.

Statistical analysis

Floristic affinity among sampling units was calculated through reciprocal averaging (Hill 1979). The (dis)similarity among vegetation clusters (alliances and associations) was measured from dendrograms, where eigenvalues ≥0.250 were considered as significant among vegetation clusters. LCs were then correlated with vegetation clusters through CCA (Ter Braak 1990; Velázquez 1994). Validated criteria were thus obtained to identify differences among SAs and LCs. The score coordinates were corrected according to the percentage of variance explained by each axis. CANOCO version 3.1 (Ter Braak 1990) was used for classification and ordination purposes, and the Monte Carlo Permutation test was used to measure the significance of the eigenvalue along ordination axes. In all tests, 99 permutations were run.

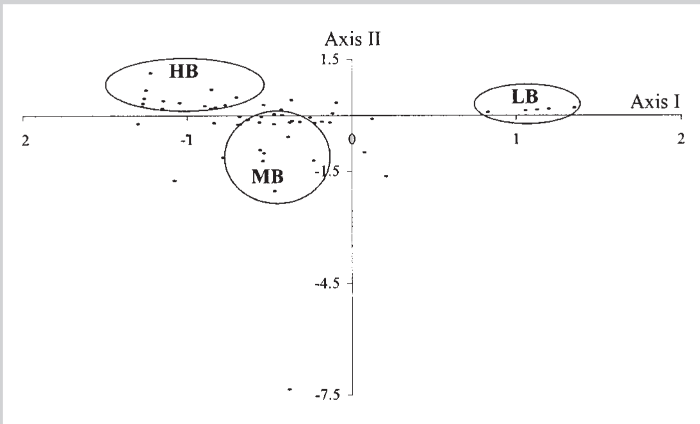
Results

The following 5 major geomorphological units were recognized in the study area: volcanic cone, foot slope, low hills, Holocene lava flow, and accumulation plain. The first occurs under cooler climatic conditions in higher areas, whereas the last is indicative of milder conditions found at lower elevations. Furthermore, 6 vegetation clusters were distinguished (Figure 2). These were the following: (1) Subalpine bunch grassland. (2) Fir forest. (3) Pine forest. (4) Mixed forest and mega-rosettes. (5) Mixed forest and meadows. (6) Crops. As a major output, 9 LUs (LU I–IX) were recognized from the combination of geomorphological and vegetation clusters. In

TABLE 1 List of key species used in spatial modeling, with an indication of their conservation status (categories: T = threatened; E = endangered), according to CIPAMEX (1993), Instituto Nacional de Ecología (1994), and Baillie and Groombridge (1996).

Family	Genus and species	Category
Amphibians		
Ambystomatidae	*Rhyacosiredon altamirani, R. zempoalensis*	T
Hylidae	*Hyla plicata*	T & E
Leptodactylidae	*Eleutherodactylus hobartsmithi, E. nitidus*	T
Plethodontidae	*Chiropterotriton chiropterus*	T
	Pseudoeurycea altamontana, P. belli, P. cephalica. P. leprosa	T & E
Ranidae	*Rana montezumae*	T & E
	R. spectabilis	T
Reptiles		
Anguidae	*Abronia deppei, Barisia imbricata, B. rudicollis*	T & E
Colubridae	*Conopsis biserialis, Nerodia melanogaster, Pituophis deppei, Rhadinaea hesperia, Salvadora bairdi, Tantilla deppei, Thamnophis scalaris, T. scaliger*	T & E
	Coniophanes lateritius, Leptodeira splendida, Pseudoficimia frontalis, Rhadinaea laureata, R. taeniata, Storeria storerioides, Tantilla bocourti, T. calamarina, Toluca lineata	T
Iguanidae	*Ctenosaura pectinata*	T & E
Kinosternoidae	*Kinosternon integrum*	T & E
Leptotyphlopidae	*Leptotyphlops maximus*	T
Phrynosomatidae	*Phrynosoma orbiculare*	T & E
	Sceloporus spinosus, S. aeneus, S. anahuacus, S. horridus, S. mucronatus, S. ochoterenae, S. palaciosi, S. torquatus, Urosaurus bicarinatus	T
Polychridae	*Anolis nebulosus, A. nebuloides*	T
Scincidae	*Eumeces copei*	T & E
	Eumeces brevirostris	T
Teiidae	*Cnemidophorus sackii*	T
Viperidae	*Crotalus polystictus, C. transversus, Sistrurus ravus*	T & E
	Crotalus triseriatus	T
Birds		
Accipitridae	*Accipiter striatus, Buteo jamaicensis*	T
Apodidae	*Streptoprocne semicollaris*	T
Dendrocolaptidae	*Lepidocolaptes leucogaster*	T
Emberizidae	*Atlapetes pileatus, A. virenticeps, Dendroica virens, Ergaticus ruber, Geothlypis nelsoni, Helmitheros vermivorus, Icterus wagleri, Melozone kieneri, Myioborus miniatus, M. pictus, Oriturus superciliosus, Peucedramus taeniatus, Pianga erythrocephala, Pipilo ocai, Seiurus motacilla, Xenospiza baileyi*	T
Falconidae	*Falco sparverius*	T
Mimidae	*Melanotis caerulescens, Toxostoma ocellatum*	T
Muscicapidae	*Catharus occidentalis, Ridgwayia pinicola, Turdus rufopalliatus, T. infuscatus*	T
Phasianidae	*Dendrortyx macroura*	T & E
	Cyrtonyx montezumae	T
Strigidae	*Bubo virginianus, Glaucidium gnoma, Otus flammeolus*	T
Trochilidae	*Atthis heloisa, Cynanthus sordidus*	T
Troglodytidae	*Campylorhynchus megalopterus, Thryothorus felix*	T
Vireonidae	*Vireo hypochryseus*	T
Mammals		
Geomydae	*Pappogeomys alcorni*	T & E
Leporidae	*Romerolagus diazi, Sylvilagus cunicularius*	T & E
Muridae	*Neotomodon alstoni, Peromyscus maniculatus*	T & E
	Peromyscus difficilis, Reithrodontomys chrysopsis, Sigmodon leucotis	T
Phyllostomatidae	*Leptonycteris nivalis*	T
Sciuridae	*Spermophilus adocetus*	T
Soricidae	*Sorex oreopolus*	T
Vascular plants		
Agavaceae	*Furcraea bedinghausii*	T & E
Apiaceae	*Angelica nelsonii*	T
Asteraceae	*Brickellia scoparia*	T
Boraginacea	*Lithospermum calycosum*	T
Caryophyllaceae	*Cerastium orithalis, Draba nivicola*	T & E
Caryophyllaceae	*Arenaria paludicola, Cerastium brachypodium, C. molle*	T
Fabaceae	*Astragalus tolucanus*	T & E
	Lupinus campestris	T
Gentianaceae	*Gentiana spathacea*	T
Pinaceae	*Pinus patula*	T
Poaceae	*Festuca livida*	T
Potamogetonaceae	*Potamogeton illinoensis*	T
Rubiaceae	*Galium seatonii*	T
Salicaceae	*Salix cana*	T & E
	Salix paradoxa	T
Saxifragaceae	*Ribes microphyllum*	T
Scrophulariaceae	*Pedicularis orizabae*	T

FIGURE 3 Ordination of (terrestrial vertebrate–vascular plant) key species obtained by DCA. The cumulative variance explained by the axes reached 40% (axis I = 24%, $\lambda = 0.799$ and axis II = 16%, $\lambda = 0.368$). The circle embodies 3 major SA defined on the basis of the mean value of scores (at 95% CI). The 3 clusters obtained were high biodiversity (HB), medium biodiversity (MB), and low biodiversity (LB).



other words, certain vegetation clusters occur in certain geomorphological units, so that the unique relation between geomorphological units and vegetation clusters described landscape patterns. The 9 LUs were integrated into the Integrated Land and Watershed Information System. To achieve geographic correction, polygons drawn on the aerial photographs were georeferenced by linking ground- and photocontrol points.

On the whole, 1162 sympatric terrestrial vertebrate and vascular plant species were recorded in the study area from 1890 to 1996. Of these, 122 were taken as potential key species (about 9% of the total number of species recorded during 116 years of records). The vast majority of amphibians (71%) and reptiles (75%) were reckoned as key species, whereas other taxa contained lower percentage values (mammals, 38%; birds, 19%; vascular plants, 2%). Only a small percentage (12%) of the total number of records was suitable for mapping purposes at a scale of 1:25,000 (Table 1). In other words, 780 records for 122 species were georeferenced within a range of ±1 second latitude and longitude (minimum spatial resolution, 3.5 km^2). Additionally, 20 vascular plant species considered endemic were included as key species.

From the ordination analysis, the total cumulative variance explained by the axes reached 40% (axis I = 24%, $\lambda = 0.799$ and axis II = 16%, $\lambda = 0.368$). Clusters obtained by using the scores of the species along axes I and II suggest that species clusters were distributed along minor environmental differences but were dissimilar enough from one cluster to the other to form significantly different SAs. The clusters followed a species richness gradient, from the group comprising the most species (high biodiversity [HB]) to the group with a medium number of species (medium biodiversity [MB]) and ending with the group that included the fewest species (low biodiversity [LB]). The latter differed significantly from groups HB and MB along axis I. In contrast, significant differences were found among the groups HB and MB along axis II, whereas HB and LB showed a similar distribution along axis II (Figure 3).

LUs were also clustered into 3 groups (Figure 4). The total cumulative variance explained by the axes reached 64% (axis I = 37%, l = 0.798 and axis II = 27%, l = 0.494). The first LC (LC I) was formed by the mixed-forest mega-rosettes on low hills and Holocene lava flows (LUs VI and VII) and meadows and crops on accumulation plains (LUs VIII and IX). The second cluster (LC II) comprised fir and pine forests on foot slopes (LUs IV and V), and LC III included subalpine bunch grassland and fir forest found on volcanic cone and foot slopes.

Discussion and conclusions

Habitat mapping

Habitat definition on a species basis is not feasible worldwide because data (quality and quantity) on current species distribution patterns for most species are scanty (Grehan 1993; Bojorquez-Tapia et al 1994). Current spatial approaches, such as the so-called gap analysis (Scott et al 1993), assume that present species records have been sampled without bias, although this assumption has been shown to be inaccurate in most cases (Bojorquez-Tapia et al 1994). The landscape approach taken in the present study allowed linking of biological records to aerial units. These units can be regarded as polygons of a homogenous nature that share similar environmental conditions, which in turn is reflected in similar species composition. This approach is independent of the causes that have favored such patterns, either historical or ecological, because LUs integrate interactions between physical conditions and biological records at all temporal and spatial scales (Zonneveld 1995). For mapping purposes, accurate spatial reference (both geometric and topologic) needs to be considered. Topographic attributes (altitude, longitude, and latitude) have been favored to depict biodiversity patterns. Topologic (land form, soils, and vegetation) relationships between species records and geographic patterns have been largely neglected. These topologic attributes become relevant when representing biological data spatially. Species distribution patterns at all scales are strongly influenced by environmental features such as topologic and human actions. In our study, it was inferred that LUs represent homogenous areas sharing topological attributes, which in turn may better explain the biodiversity patterns found in the region. This tied relation between topological and biodiversity attributes has been reported in different situations regardless of climatic, edaphic, ecological, and cultural conditions (Butterfield et al 1994; Zonneveld 1995; Velázquez and Heil 1996; Hansen and Rotella 2002; Hoersch et al 2002).

FIGURE 4 Ordination of LUs (LCs I–X) based on their DCA attributes, resulting in 64% cumulative variance shown on 2 axes (axis I = 37%, l = 0.798 and axis II = 27%, l = 0.494). Three major significantly different LCs were distinguished.

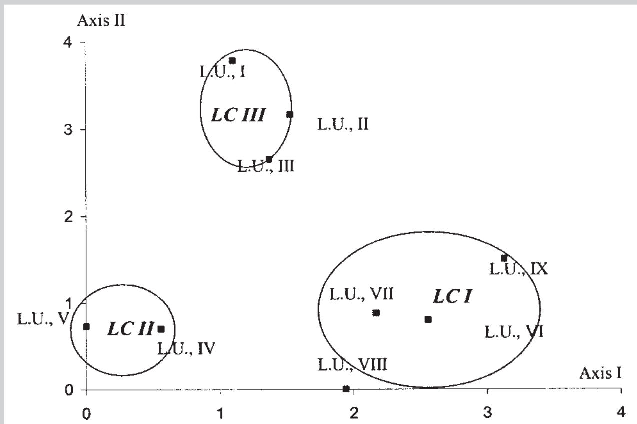
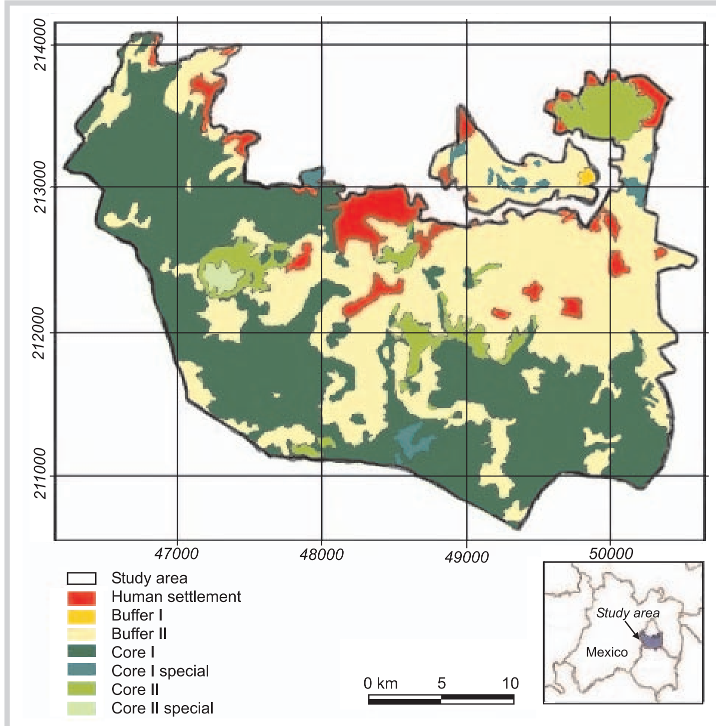


FIGURE 5 Spatial representation of the current proposal obtained by the participatory approach. Three main clusters of regions were distinguished: buffer I, area for low-impact traditional cropping activities; buffer II, area for sound agroforestry practices; 4 core areas according to different conservation needs.



Translating science into applied conservation action

The results have served to translate pure academic outputs into sound conservation actions (Velázquez and Romero 1999). This was also inherent in the landscape approach, given that the social component is regarded as the major driving force in delineating current landscape patterns (Velázquez et al 2001). This last experience comprised a thorough evaluation of the environmental services provided by the study region to people living in Mexico City (see Figure 1). Every LU was ranked according to its importance in providing environmental services, mainly water harvest, land-use change, and large concentrations of biodiversity. The project became known by the local government, which eventually supported it financially. The specific request from the government was to assemble all current biophysical information to pinpoint areas of focus for conservation efforts. Because all data were spatially explicit through the geographical information system, cross-matrices were built by map overlay functions. Three types of areas were distinguished: buffer I (area for low-impact traditional cropping activities); buffer II (area for sound agroforestry practices); and core areas typifying the different degrees of conservation need.

- Buffer I is comprised of LUs with large anthropogenic transformation where rural land use still prevails, with LB and low value for water harvest (LB in Figure 3 and LC I in Figure 4).
- Buffer II embodies LUs harboring MB values (Figure 3), with no land-use change, covered by agricultural fields devoted to forage production (LC I and LC II in Figure 4) but playing an important role in rainwater filtration.
- Core areas include LUs crucial for watershed functional integrity, with no drastic land-use change in original forest vegetation, HB (in Figure 3), and steep slopes and lava flows (LC III in Figure 4).

The output made it possible to define a new network of priority areas for conservation to guarantee watershed integrity and biodiversity conservation (Figure 5). Local indigenous communities, which have helped us during these 15 years of research, also became acquainted with the ecological importance of their lands, for themselves as well as for urban areas. Through a large number of participatory workshops with over 20 communities, 3 have so far signed up to adopt the new network for conservation. New mechanisms for re-funding conservation efforts for rural people by urban settlers need to be designed. Finally, social, political, and ecological driving forces need to be holistically addressed to achieve sound, long-term conservation for most tropical and subtropical regions. In this sense, the landscape approach presented here attempts to provide a conceptual as well as a pragmatic alternative for land-use planning and conservation.

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