Investigaciones Geográficas • Instituto de Geografía • UNAM
eISSN: 2448-7279 • DOI: dx.doi.org/10.14350/rig.60539 • ARTICLES
Num. 107 • April • 2022 • e60539
www.investigacionesgeograficas.unam.mx

Proposal of Differentiating Components for the Multiscale Classification of the Landscape

Propuesta de componentes diferenciadores para la clasificación multiescalar del paisaje

Ian Dassaef Espinosa-Pérez,* Arturo García-Romero** and Luis Fernando Cruz-Fuentes***

Received: 20/10/21. Accepted: 16/01/2022. Published: 04/03/2022.

Abstract Landscape classification and mapping have raised interest in Latin America. There is an increasing number of studies conducted in this region; however, they show marked differences in the establishment of the hierarchy and subordination of landscape components within classification systems. The aim of this article is to propose a multiscale integration method of the "differentiating landscape components" – relief, vegetation, and land use – for landscape classification and mapping at three levels: natural region, geosystem, and geofacies. The landscape map was constructed through three stages: 1) environmental analysis and synthesis; 2) environmental integration and landscape classification; and 3) classification validation. The method was applied to the Tlalpan and Milpa Alta municipalities (southern Mexico City), and resulted in a classification of the landscape into three natural regions, six geosystems, and 113 geofacies, where each level was defined by the spatial-temporal resolution and the relative weight of its differentiating components. This methodological approach can be adapted to various conditions and areas, and constitutes a cartographic foundation of broad applicability in studies focused on land-use planning.

Key words: landscape mapping, hierarchical-corological method, geosystem, environmental integration, Mexico City

Resumen. La clasificación y la cartografía del paisaje han cobrado gran interés en el ámbito latinoamericano, contando con un creciente número de estudios que, sin embargo, presentan amplias diferencias al momento de establecer la jerarquía y subordinación de los componentes del paisaje dentro de los sistemas de clasificación. El objetivo de este artículo es proponer un método de integración multiescalar de los "componentes diferenciadores del paisaje" –relieve, vegetación y uso de suelo–, para la clasificación y cartografía del paisaje en tres niveles: región natural, geosistema y geofacies. El mapa de paisajes se obtuvo en de tres etapas: 1) análisis y síntesis ambiental; 2) integración ambiental y clasificación del paisaje, y 3) validación de la clasificación. El método fue aplicado a las alcaldías Tlalpan y Milpa Alta (al sur de la Ciudad de México), y dio como resultado una clasificación del paisaje con tres regiones naturales, seis geosistemas y 113 geofacies, donde cada nivel fue definido por la resolución espacio-temporal y el peso relativo de sus componentes diferenciadores. Esta propuesta puede ser

* Instituto de Geografía, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica, Ciudad Universitaria, 04510, Coyoacán, México. ORCID: https://orcid.org/0000-0001-8235-2891. E-mail: dassaef@yahoo.com.mx
** Instituto de Geografía, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica, Ciudad Universitaria, 04510, Coyoacán, México. ORCID: https://orcid.org/0000-0002-6339-1577. E-mail: agromero@geografia.unam.mx
*** Instituto de Geografía, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica, Ciudad Universitaria, 04510, Coyoacán, México. ORCID: https://orcid.org/0000-0001-5262-207X. E-mail: cruz.fuentes.luis@gmail.com

adaptada a distintas condiciones y áreas, y constituye una base cartográfica de amplia aplicabilidad en estudios de planificación y ordenación del territorio.

Palabras claves: cartografía del paisaje, **método** jerárquico-corológico, geosistema, integración ambiental, Ciudad de México.

INTRODUCTION

Since the late decades of the twentieth century, environmental damage afflicting humanity has raised growing interest in approaches focused on the landscape, as it is considering a unifying concept within environmental systems (Simensen *et al.*, 2018). These approaches are highly synthetic and informative, and with great visual qualities, allowing it to be accessible and understandable to a wide public; therefore, they are highly significant in terms of identity and appropriation of, and awareness about, the transformations of the territory (Méndez-Méndez *et al.*, 2018). The different approaches include those addressing landscape classification and mapping as an instrument for the protection, organization, and management of land and its uses (Consejo de Europa, 2000; Swanwick, 2002; Jones, 2007; Mata, 2014; Simensen *et al.*, 2018).

In Mexico and several Latin American countries, interest in landscape classification and mapping reflects the predominant influence of three European schools. On the one hand, the Russian-Soviet school, which has had a wide impact through the *Geografía Física Compleja* (Complex Physical Geography) or *Geografía de los Paisajes* (Landscape Geography) of José Manuel Mateo Rodriguez (2002). Countries worth mentioning are Cuba (Ramón *et al.,* 2009; Salinas *et al.*, 2013; García-Espino and Valdés, 2019), Mexico (Priego *et al.,* 2004; Hernández-Trejo *et al.,* 2006; Carbajal *et al.*, 2010; Martínez, 2017; Valdés-Carrera and Hernández-Guerrero, 2018), Brazil (Amorim y Olivera, 2008; Lima y Oliveira, 2018), and Argentina (Mazzoni, 2015). On the other hand, there is the French school of the *Géographie Physique Globale* (Global Physical Geography) by Georges Bertrand (1968, 1978), present in Mexico (García-Romero *et al.*, 2005; Arredondo-León *et al.*, 2008; Méndez-Méndez *et al.*, 2018; Serrano-Giné *et al.*, 2019) and Brazil (Estêvez *et al.*, 2011; Alves *et al.*, 2017; Santos *et al.*, 2019). Last, there is the British school of *Landscape Character Assessment* by Carys Swanwick (2002), which was recently applied in Colombia (Muñoz and Gómez-Zotano, 2016; Muñoz, 2017).

Under such approaches, the production of landscape classification studies, with local, regional, and national scopes, increased in Mexico and Latin America to address environmental planning issues (Abalakov and Sedykh, 2010; Serrano-Giné *et al.*, 2019); landscape assessment, protection, and sustainable management (Muñoz and Gómez-Zotano, 2016); assessment of potential uses of landscapes (Acosta *et al.,* 2016), with emphasis on tourism (Méndez-Méndez *et al.,* 2018; Carbajal *et al.,* 2010); diagnosis of environmental stability and fragility (Priego *et al.,* 2003; García-Romero *et al.,* 2005*;* Amorim and Oliveira, 2008), as well as the impact of changes of land use on territorial dynamics (Arredondo-León *et al.,* 2008), among others.

Most cases highlight the interest in the "landscape type", understood as an actual and objective fact (Muñoz, 1998; García-Romero and Munoz, 2002) that results from integrating natural, sociocultural, or visual elements, which are relevant to define its inclusion into a given category (Bastian *et al.*, 2002; Salinas *et al.*, 2019). In this sense, landscape classification consists of setting a typology or differentiation of the landscape types occurring in a given place (Muñoz, 1998; Abalakov and Sedykh, 2010; De Montis, 2014). Classifications generally adopt a multiscale structure, the aim of which is to establish the taxonomy or division of landscape types according to a vertical hierarchy or arrangement (Gómez-Zotano *et al.*, 2018), in which low-rank (large-scale) landscapes are subordinated to higher-rank (small-scale) landscapes (Swanwick, 2002; Gómez-Zotano *et al.*, 2018).

Some Latin American countries, including Mexico, have achieved significant advances in landscape classification and mapping. However, progress is required in the multiscale integration of landscape components and attributes that are

considered for the typological and spatial differentiation of landscapes at various scales, giving more weight to abiotic, biotic, and anthropic components as landscape differentiators, especially at the upper classification levels.

This work proposes a landscape classification method including three taxonomic-hierarchical levels, each of which is defined by the dimensional scale, resolution, and relative weight of abiotic (relief and climate), biotic (vegetation), and anthropic (land use) components, hereafter named "differentiating landscape components", which set the bases for the typological and spatial differentiation of landscapes at the three levels. The proposed method uses criteria that guarantee the complete and effective multiscale integration of landscape components, proving to be flexible enough to allow customization to various environmental conditions.

ON THIS PROPOSAL

Given the polysemic nature of landscape, the present proposal for the classification of landscapes is addressed from the "geosystem" perspective proposed by Viktor B. Sochava in 1960 as a theoretical model that allowed the landscape to be understood as an open, dynamic, and hierarchically organized system (Bollo, 2017). However, the method described herein adopts the geosystem model devised by Georges Bertrand (1968), which considers the landscape as a spatial, holistic, and synthetic entity in which physical, biological, and cultural components converge in both their "phenosystemic" (or visual) and "crypto-systemic" expressions, the latter referring to the underlying contents and processes that govern its dynamics (Bertrand, 1968, 1978; Martínez de Pisón, 1998; Gonzalez-Bernaldez, 1981; Frolova, 2006; Arias, 2015).

In the geosystem, landscape components are understood as subsystems that, as part of their internal activity, produce materials, energy, and information that are conveyed from one component to another, causing alterations in their composition, functioning, and products (Gragson, 1998; García-Romero and Munoz, 2002). The relationships and interdependence between landscape components are so close that they confer strong structural and dynamic cohesion to the landscape (Bertrand, 1968; Mateo and Ortíz, 2001) — what other authors have also referred to as the "character of the landscape" (Swanwick, 2002; Tudor, 2014; Gómez-Zotano *et al.*, 2018).

While the original G. Bertrand's geosystem model (1968, 1978) is maintained, conceptual and methodological inputs are also proposed and discussed in the following clauses:

a) With the aim of contributing to the necessary systematization of the spatial scales that define the landscape level (Simensen *et al.*, 2018), we started by considering that the landscape occurs along a spatial-temporal gradient that includes three of Bertrand's (1968, 1978) intermediate classification levels: natural region, geosystem, and geofacies. Hence, this is a taxonomic-hierarchical classification system where changes of scale between landscape levels lead to differences in magnitude, resolution, complication, and degree of control and independence between components (Zonneveld, 1995; Mateo and Ortiz, 2001; Bertrand and Bertrand, 2007; García-Romero, 2014).

b) In G. Bertrand's classification, the biotic and anthropic aspects of the landscape are precisely defined at the lower landscape levels: the geofacies and the geosystem. In contrast, the natural region corresponds to a higher landscape level, which is spatially extensive and environmentally diverse, defined by structural and climatic elements that control the biotic and anthropic characters that are, nonetheless, inaccurately defined. For this reason, we propose including the "pattern of potential vegetation" and the "pattern of land-use systems" as differentiators of potential vegetation clusters and land-use systems that characterize the geosystems contained within natural regions (Figure 1).

c) To contribute to the complex environmental integration in the landscape, a difference is made between the components that allow delimiting it in spatial and typological terms (differentiating landscape components) and those that contribute to describing it (supplementary landscape components). The differentiating landscape components are relief, vegetation, and land use

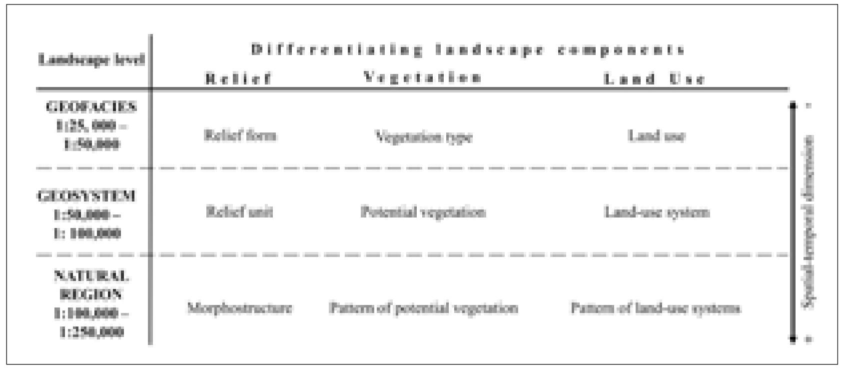


Figure 1. Model for the multiscale integration of differentiating landscape components. Source: constructed from the reinterpretation of the landscape classification by G. Bertrand (1968).

(Figure 1), since they summarize the contribution of other environmental components, in addition to having broad phenological qualities that allow them to be accessible and comprehensible to the different sectors of society (Méndez-Méndez *et al.*, 2018).

Additional environmental components such as climate, groundwater, soil, fauna, land-use history, and economic activities are considered supplementary landscape components, since they are not visually apparent in the landscape and, hence, the spatial and typological delimitation of landscape units does not depend on them. However, their importance as landscape elements must be addressed when characterizing and explaining landscapes. For instance, climate is a fundamental component that provides caloric energy and water for the development of biota; however, vegetation is the differentiating component that indirectly, but objectively and visually, expresses the influence of climate in the landscape. Another example is the case of terrain slopes, whose major effect on processes such as erosion and water distribution, is clearly expressed in the landscape through the type of relief (Figures 1 and 3).

Considering the information outlined above, the landscape classification proposed herein comprises the following three taxonomic levels.

Geofacies. Landscape of the smallest territorial extension (up to hundreds of square meters), but with the greatest resolution and detail, making it visually homogeneous. It corresponds to the basic unit of the landscape pattern within a geosystem. It is characterized by the combination of a relief form, a type of natural vegetation, and a particular land use, i.e., the most dynamic and unstable differentiating components of the landscape.

The relief form resulting from bioclimatic modeling tends to be the most independent component (Bertrand, 1968; Drdos, 1992; García-Romero and Muñoz, 2002), the stability of which supports the development and conditions of the soil and natural vegetation, either mature or under a regeneration state. The latter reflects the impact of anthropic actions on the biotic system of the landscape and its regeneration potential. Land use may or may not be consistent with the natural potentials and constraints of the system; thus, the strategies of land use and occupation and their relationship with the natural environment should be determined.

Geosystem. Medium-scale landscape (covering hundreds of square kilometers) that results from the combination of a relief unit, a potential vegetation type, and a land-use system. It corresponds to the clustering of geofacies that are functionally interrelated by sharing the same physical environment, represented by a relief unit that is homogeneous in origin, age, morphology, and lithology, and by sharing a common type of mesoclimate or variant of the regional climate.

The physical components provide the resources and constraints that allow a certain natural biotic load, which is expressed in the potential vegetation. The land-use system (e.g., urban, forestry-tourism, industrial) is made up of the existing uses in the geofacies that integrate the geosystem. Occasionally, the land-use system can exceed the intrinsic

potential of the natural environment, resulting in contradictions that jeopardize the sustainable development of the system. Therefore, the historical evolution of land uses and their cultural, economic, and political components is key for an in-depth understanding of the geosystem.

Natural region. Landscape of the largest territorial extension (hundreds to thousands of square kilometers), but with less resolution and detail. It corresponds to a cluster of geosystems that are functionally related for sharing a common physical base, defined by regional morphostructure and climate, which are components of a large spatial-temporal dimension, being dynamically stable and independent. Morphostructures are major features of the relief, resulting from a common geological history and the control of tectonics and geological structure. Their orographic attributes impact on the regional atmospheric dynamics (vertical zonation) and the thermal and pluviometric characteristics of climate.

Morphostructural and climatic organization controls the abiotic natural resources and constraints that support other components (hydrological, geomorphological, biogeographical, and others), including the pattern of potential vegetation, which groups together different types of potential vegetation (e.g., different types of temperate forests). Similarly, land use gives rise to patterns or clusters of land-use systems that result from geosystemic variants within a natural region.

MATERIALS AND METHODS

Study Area

The study area includes the municipalities of Tlalpan and Milpa Alta (19°04′–19°19′ N and 98°57′–99°19′ W), located in southern Mexico City (Figure 2). Both municipalities comprise an area of 613 km^2 and are part of the Trans-Mexican Volcanic Belt Province and the Lakes and Volcanoes of the Anahuac Subprovince (Mooser, 1996; Lugo, 1984; Bloomfield 1975). The great variety of volcanic relief forms and steep bioclimatic gradients give rise to a wide environmental and landscape diversity, which increases when considering that the area has been profusely transformed throughout the history of land uses. Today, the pressures and dynamics of land use and occupation threaten the potential of the area as a supplier of water resources, which are essential for the functioning of the Mexico City urban system (Ruíz-Gomez, 2006; SEDEMA, 2016), and for displaying great forest richness and unique natural characteristics, with important flora and fauna reserves of high landscape value. However, the recent literature does not report any cartography illustrating the diversity of environments with different potential and that limit development.

METHODOLOGY

The methodological procedure consists of three sequential stages that are replicated for each landscape level (Figure 3).

Stage 1. Environmental analysis and synthesis

It consists of the mapping of the differentiating landscape components (relief, vegetation, and land use) that are used for the characterization and typological and spatial definition of landscapes, as well as of the supplementary components that support the characterization of both the differentiating components and landscapes, at the various taxonomic classification levels (Figure 3).

To avoid topological errors in the spatial delimitation and overlap of units within and between the three landscape levels, the cartographic series is built at an intermediate scale (1:50 000) and with the same degree of resolution (minimum mapping area of 1 hectare) for all topics and classification levels. This requires designing processes for the analysis and synthesis of the information available in literature, statistical, and cartographic sources at different spatial and temporal scales. In other cases, automated procedures based on digital models are used, as well as visual interpretations based on satellite images and thematic cartography. The cartographic results are validated through field verification trips.

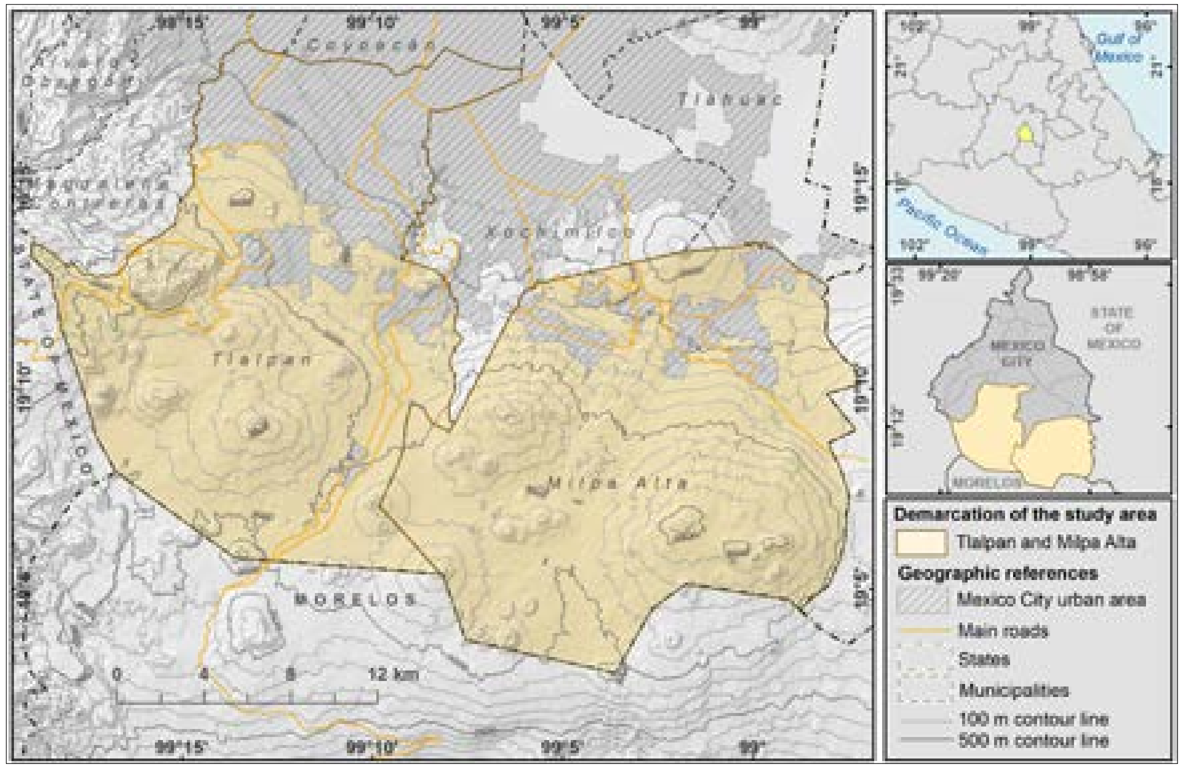


Figure 2. Location of the study area. Source: Own elaboration.

Stage 2. Environmental integration and landscape classification

It consists of the integration and reinterpretation of the cartography obtained for the differentiating components (relief, vegetation, and land use), and the spatial and typological classification of landscapes. The use of a single scale (1:50 000) facilitates the organic and spatial integration of landscape units at the three classification levels, so that the boundaries of a natural region coincide with those of the pattern of geosystems within its area, while the boundaries of a geosystem match those of the geofacies within it.

The reinterpretation of thematic information aims to identify environmentally homogeneous units at the three classification levels, in accordance with the resolution adopted by the differentiating components. It is obtained from visual (deductive and associative) interpretation techniques, which require a broad knowledge of the study area and experience by the interpreter, as well as a holistic and inclusive approach for the delimitation of landscape units.

In addition, consideration should be given to the environmental variability of supplementary components, and even of the original sources of information, to avoid topological errors when assigning categories. For instance, natural regions result from the combination of a morphostructure, a pattern of potential vegetation and a pattern of land-use systems; in the case of Tlalpan and Milpa Alta, reconsidering the geological history of the pattern of relief units was useful for setting the spatial boundaries and typology of landscapes (Figure 3).

The overlay of thematic layers is a procedure that produces a high number of residual polygons that do not meet the minimum mapping size required (one hectare); thus, it is necessary to make a mapping adjustment to integrate these polygons into units of greater representativeness or meaning.

Finally, landscape units are named according to descriptive criteria that refer to the abiotic,

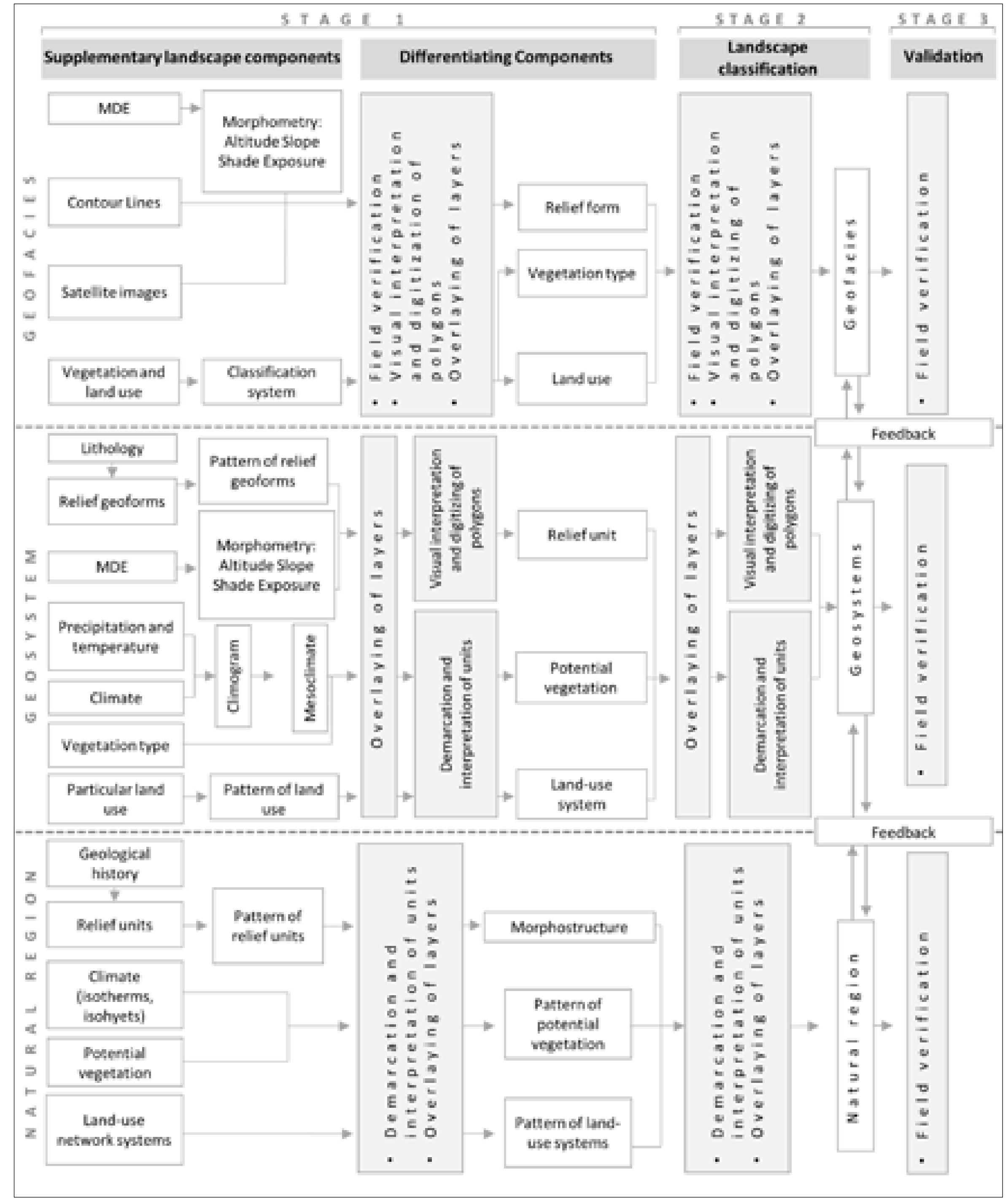


Figure 3. Schematic mapping of landscape levels. Source: Own elaboration.

biotic, and anthropic elements that best represent unique landscape types. For the natural region and geosystem categories, the names assigned refer to the geographic environment of the landscape. This possibility is reduced in the case of geofacies because each category usually occurs in multiple polygons.

Stage 3. Classification validation
It consists of a manual and qualitative revision of the typology, distribution, and spatial boundaries of the landscape units obtained. To this end, a stratified random sampling is followed, which serves to check the quality and consistency of the cartography in relation to the actual characteristics observed in the field, aiming to make any adjustments required. A good level of knowledge of the study area is useful for performing this stage successfully. The procedure is carried out in a similar way for each taxonomic level.

RESULTS

The landscapes of the Tlalpan and Milpa Alta municipalities are arranged according to three natural regions, six geosystems, and 113 geofacies (Figure 4 and Table 1). Natural regions are shown in single polygons and geosystems in one or two polygons, while the degree of detail used to demarcate geofacies identified more than 1200 polygons.

Natural Region of Sierra de Las Cruces and Ajusco Volcano, with temperate forest and forestry and tourism uses

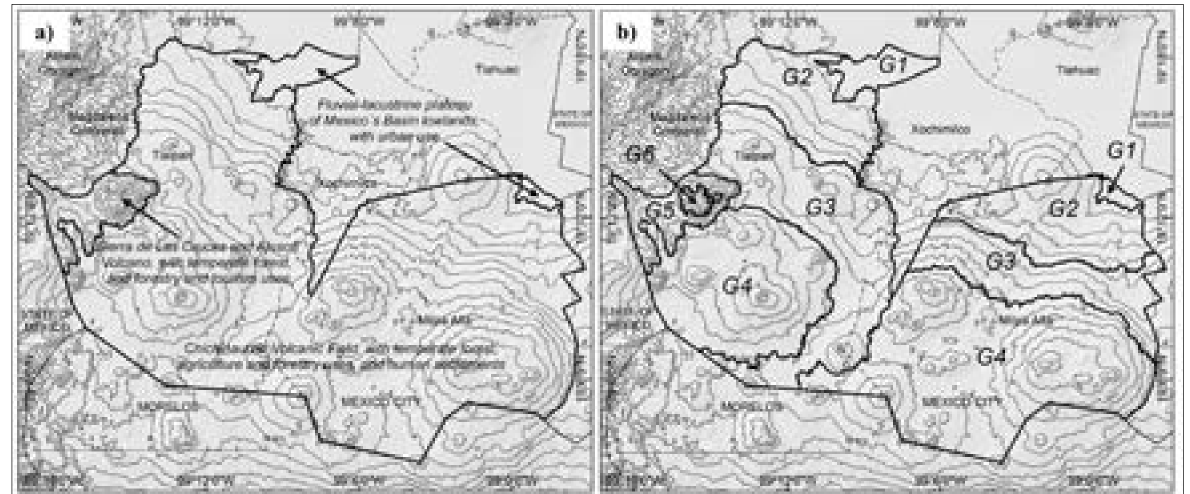
It includes the Ajusco volcano and a southern portion of Sierra de Las Cruces (25.86 km^2), which are part of the polygenetic volcanic mountain ranges of the Trans-Mexican Volcanic Belt (Mooser, 1996). These are volcanic morphostructures that formed from late Pliocene to Pleistocene. Orography plays a major role in the landscape, allowing a marked transition of climates and a pattern of potential vegetation characterized by various bioclimatic layers of temperate forest. Deep ravines run along the altitudinal gradient; however, the area is naturally stable, according to a pattern of low-impact land-use systems that include forestry and tourism activities. This landscape unit is organized into two geosystems.

A) *Geosystem of Sierra de Las Cruces and Ajusco Volcano Slopes, with conifer forest and grassland, and forestry and tourism uses* (22.34 km^2). The relief unit comprises complex slopes (lava and pyroclastic material of andesitic-dacitic composition), modeled by fluvial erosion. Its altitudinal location (3200 to 3600 meters a.s.l.) corresponds to a semi-cold subhumid mesoclimate, and a potential vegetation of conifer forest, with pines and fir mixed and pure communities. Notwithstanding the limitations imposed by topography, the land-use system includes agriculture, logging and forestry, and tourism around the main accesses to the Ajusco volcano.

Anthropic geofacies are concentrated in small alluvial plains (3.3% of the area), being one of the best-conserved geosystems, with a high plant regeneration capacity that gives rise to a moderately diverse landscape pattern. It comprises 16 types of geofacies distributed in 35 polygons that include complex slopes with conifer forest (80% of the area) and domes and ravines with a diverse forest cover (Figure 5 and Table 2).

B) Geosystem of Ajusco Volcano Peak, with highland pine forest and alpine grassland, and tourism use (3.52 km^2). The relief unit consists of an extensive area of peaks that range between 3600 and 4000 m a.s.l. (Cruz del Marqués). It was formed in the Pleistocene by the accumulation of andesitic and dacitic lavas and comprises a series of rocky ridges that are emblematic of the Ajusco volcano. The cold and subhumid mesoclimate corresponds to a potential vegetation of highland pine (Pinus hartwegii) open forest. Thermal limitations and poor accessibility restrain the land-use system, characterized by low-scale conservation and tourism activities.

The landscape pattern is defined by the simplicity of its internal organization, with only 4 types of geofacies distributed in seven polygons, mainly highland natural landscapes that include open grasslands growing on complex slopes, domes, and ravines (99% of the area) and scarce pine forest patches on complex slopes (Figure 5 and Table 2).



Natural Region	Geosystem
Fluvial-lacustrine plateau of Mexico's Basin lowlands, with urban use	**G1.** Marginal Fluvial-lacustrine plateau, with urban development
Chichinautzin Volcanic Field, with temperate forest, agriculture and forestry uses, and human settlements	**G2.** Low slope of the Chichinautzin Volcanic Field, with oak forest, agriculture and forestry uses, and urban development
	G3. High slope of the Chichinautzin Volcanic Field, with mixed forest, agriculture and forestry uses, and human settlements
	G4. Peak of the Chichinautzin Volcanic Field, with conifer forest and agriculture, forestry and tourism uses
Sierra de Las Cruces and Ajusco Volcano, with temperate forest and forestry and tourism uses	**G5.** Sierra de Las Cruces and Ajusco Volcano Slopes, with conifer forest and grassland, and forestry and tourism uses
	G6. Ajusco Volcano Peak, with highland pine forest and alpine grassland, and tourism use

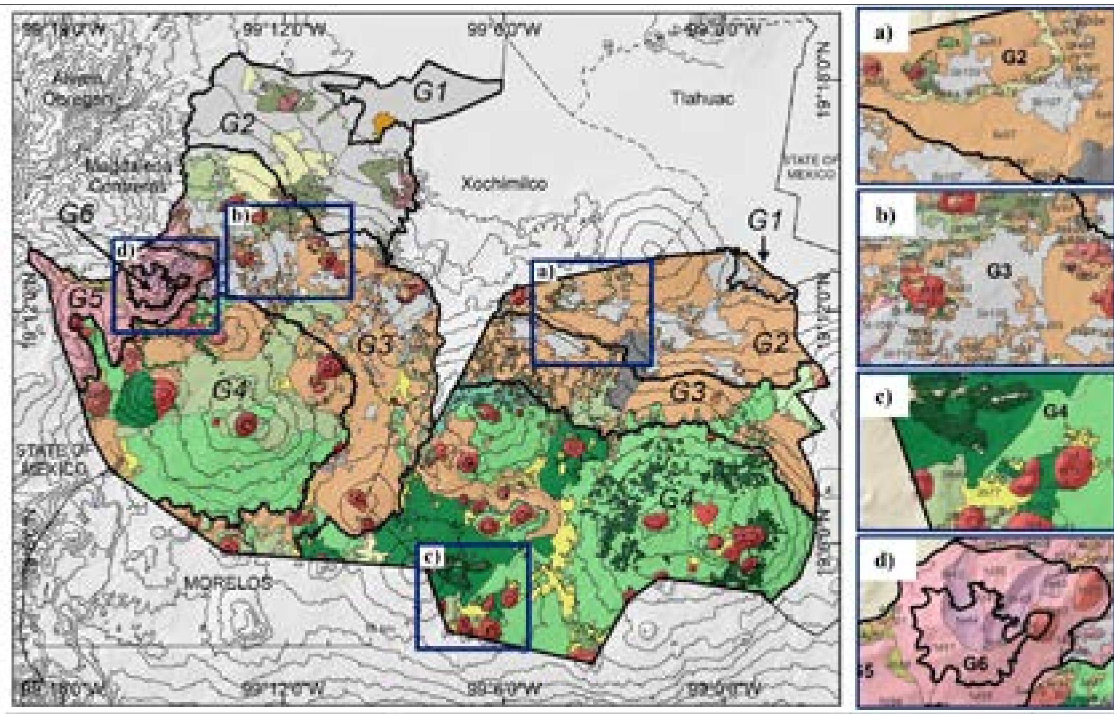
Figure 4. Organization of the landscape into Natural Regions (a) and Geosystems (b); Tlalpan and Milpa Alta municipalities, Mexico City. Source: Own elaboration.

Natural Region of Chichinautzin Volcanic Field, with temperate forest, agriculture and forestry uses, and human settlements

This natural region (568.72 km^2) is located on the morphostructure of the Chichinautzin Volcanic Field, which developed during the Quaternary from strombolian vulcanism, leading to one of the highest concentrations of monogenetic volcanoes in central Mexico. Its morphology is characterized by an extensive area of mountain peaks and slopes that reach a level of ~500 m relative to the Mexico's Basin lowlands. It comprises 73 volcanic cones separated by lava spills and depressions covered with pyroclastic material and alluvial deposits, with gentle to moderate slopes (3º–15º). The local orography favors a temperate subhumid climate at the base of the mountain range and semi-humid at the summits, as well as a pattern of potential vegetation characterized by different bioclimatic layers of temperate forest.

The pattern of land-use systems reflects the influence of the distribution of lavas and alluvial deposits on the develop of forests, agriculture, and urban areas. In this region, the landscape is organized into three geosystems:

A) Geosystem of Peak of the Chichinautzin Volcanic Field, with conifer forest and agriculture, forestry, and tourism uses (282.01 km^2). It is distributed in two extensive mountain peak areas separated by the vast Acopiaxco volcano agricultural area. The relief unit consists of the most extensive tefra and shield volcanic cones of the mountain range, including the Pelado volcano in Tlalpan, and the Chichinautzin, Tlaloc, and Cuatzin volcanoes in Milpa Alta. The altitudinal range of 3100 to 3600 m a.s.l. gives rise to a cold and subhumid



Group of geofacies	Main geofacies component	Geofacies	Color
1. Natural landscapes on volcanic edifices	1a. Tefra cone and volcanic crater	19	
	1b Volcanic dome	9	
	1c. Intensely modelled lava slope	4	
	1d Complex modelled slope	10	
	1e. Main ravine	2	
2. Forest landscapes on lava spills	2a. Fir forest	4	
	2b. Alder forest	1	
	2c. Pine forest	4	
	2ca. Pine-alder forest	2	
	2d. Oak forest	2	
	2da. Open oak forest	1	
	2e. Conifer forest	4	
	2ea. Open conifer forest	3	
	2f. Mixed forest	4	
	2fa. Open mixed forest	3	
3. Shrubland and grassland landscapes on lava spills	3a. Secondary shrubland	3	
	3b. Secondary grassland	4	
	3c. Bare soil	2	
4. Natural landscapes on alluvial plains	4a. Alluvial plain with forest	5	
	4b. Alluvial plain with secondary grassland	1	
	4c. Alluvial plain with bare soil	1	
5. Artificial landscapes on volcanic edifices, lava spills and alluvial plains	5a. Mosaic of crops	10	
	5aa. Mosaic of abandoned crops	1	
	5ab. Mosaic of crops with pine forest	1	
	5ac. Mosaic of crops with open pine forest	1	
	5b. Human settlement	9	
	5c. Urban park	1	
	5d. Quarry	2	

Figure 5. Map of landscape geofacies of the Tlalpan and Milpa Alta municipalities. Boxes illustrate details of the pattern of landscapes in various gesystems. Source: Own elaboration.

mesoclimate, with a potential vegetation of conifer forest growing on poorly developed soils. The land-use system is forestry, with agricultural activities on floodplains with suitable soil.

The landscape pattern is diverse and fragmented, with 74 geofacies types distributed in 617 polygons. It is the best-conserved geosystem of the mountain range, with abundant forest geofacies, mostly pine forest patches growing over steep lava spills (23.8% of the area) and shield volcanoes (13.2%). However, the constraints imposed by the lava environment, forestry, and fires promote geofacies of open pine forest, alnus forest, grassland, shrubland, and bare soil. Agriculture is restricted to the interior of craters and small alluvial plains, while human settlements are located in geofacies of ancient lava spills (Figure 5 and Table 2).

b) *Geosystem of High Slope of the Chichinautzin Volcanic Field, with mixed forest, agriculture and forestry uses, and human settlements* (173.20 km^2). It is distributed around mountain peaks, where the relief unit consists of gentle to steep lava slopes alternating with scattered shield volcanoes, domes, and volcanic cones. The altitude ranges from 2700 to 3100 m a.s.l. and corresponds to a semi-cold and subhumid mesoclimate with mixed pine-oak forest as potential vegetation. This context is characterized by plains of pyroclastic material and alluvial sediments, which were favorable for the historical development of small agricultural villages. In the second half of the 20th century, the growth of Mexico City and the construction of railroads and motorways that run across the study area favored the transformation of the land-use system as a result of population growth and urbanization of the old rural villages in both municipalities.

The diversity of environments and the anthropization of rural areas have led to a complex landscape pattern, with 76 geofacies types distributed in 512 polygons. The dominant geofacies comprise an array of crops and human settlements over lava spills (33.0% and 11.3%, respectively), while native pine-oak forest geofacies have been fragmented and transformed into open pine and alnus forests and shrubland due to fires and forestry (Figure 5 and Table 2).

c) *Geosystem of Low Slope of the Chichinautzin Volcanic Field, with oak forest, agriculture and forestry uses, and urban development* (113.50 km^2). It comprises the base of the northern slope of the Chichinautzin mountain range, where the relief unit is defined by the lava spills located in the most remote areas within the mountain range, with few volcanic cones and remains of the ancient Xochitepec mountain range located in the Tlalpan municipality. The altitude of 2300 to 2700 meters allows a temperate and subhumid mesoclimate and a potential vegetation of oak forest. While in Milpa Alta the predominant land-use system is agriculture, along with larger human settlements concentrated in villages and high deforestation levels, the expansion of the Mexico City urban areas in Tlalpan completely displaced agricultural land uses; consequently, only a few natural geofacies have managed to survive in protected zones.

Heavy deforestation and urbanization processes in Tlalpan translate into a relative homogeneous landscape pattern, with only 27 geofacies types distributed in 114 polygons. The largest geofacies are human settlements on recent lava spills (35.8% of the area, concentrated in Tlalpan) and a mosaic of crops on recent lava spills (24.5% in Milpa Alta). In contrast, forest geofacies are restricted to a few fragments of oak and alnus forests, shrubland and grassland on recent lava spills, volcanic cones, craters, and the Teuthli shield volcano (Figure 5 and Table 2).

Natural Region of the Fluvial-Lacustrine Plateau of Mexico's Basin Lowlands, with urban use

Mexico's Basin is an extensive morphostructure (32.02 km^2) of flat and multi-layer morphology that was formed in the Plio-Quaternary from the accumulation of volcanic, alluvial, and lacustrine sediments carried from the volcanic mountain ranges that border it (Mooser, 1996). The subhumid and temperate climate, combined with the endorreic basin hydrology, favor a pattern of potential vegetation represented by different types of temperate forest. The large extension and heterogeneity of the basin translate into a complex pattern of land-use systems, which, however, is not apparent in the small area of the basin represented in the study area, where only a single geosystem is recorded.

a) Geosystem of Marginal Fluvial-lacustrine Plateau, with urban development (17.66 km^2). The edges of the plateau in the Mexico's Basin penetrate the territory studied in two areas: one north of Tlalpan (14.42 km^2) and another north of Milpa Alta (3.24 km^2). The relief unit consists of sloped plains formed in the Holocene from the accumulation of volcanic material and alluvial sediments from the Las Cruces (Tlalpan) and Chichinautzin mountain ranges. Its altitudinal range, between 2200 and 2300 m a.s.l., is suitable for a potential vegetation of oak forest, currently inexistent. The availability of stable land, soil, and water resources allowed the development of agriculture until the second half of the 20th century, when the expansion of Mexico City urban area transformed the land-use system, currently dominated by urban uses.

The small surface area and environmental homogeneity translates into the simplest landscape pattern of the whole study area, with seven geofacies types distributed in 14 polygons. While in Tlalpan the largest geofacies corresponds to the Mexico City urban area on the alluvial plain (77.4% of the area), a rural environment predominates in Milpa Alta, with a mosaic of crops (7.4%) and human settlements (5.3%).

The map of landscape types in Figure 5 shows 113 types of geofacies distributed in the six geosystems that make up the municipalities of Tlalpan and Milpa Alta. While geofacies is a landscape resolution level that integrates three components (relief form, vegetation type, and land use), to facilitate reading the map, the 113 geofacies types were pooled into five groups and 28 classes based on the most distinctive differentiating component (relief form, vegetation type, or particular land use).

CONCLUSIONS

The study outlines the conceptual and methodological bases of an original proposal for landscape classification and mapping. In contrast with other methodologies that consider that the differentiating landscape components change according to the scale, the present proposal supports the idea that the landscape is a geographic entity defined and distinguished by being of a prominently integral character. Therefore, while the resolution of the environmental components changes according to the geographic scale, they nonetheless play a role at the different levels of the spatial-temporal gradient of the landscape.

Given the complexity intrinsic to the integration of environmental (physical, biological, and anthropological) components into the landscape, the method outlined herein proposes "differentiating landscape components": relief, vegetation, and land use, with broad phenological qualities that facilitate comprehension by society. In addition, their consideration in the landscape summarizes the role played by "supplementary components", which are useful in characterizing and explaining landscapes, although the typological and spatial definition of landscapes does not depend on them.

To facilitate the multi-scale understanding of the spatial relationships between landscape components and the landscape reality of the site under study, a taxonomic-corological classification was proposed, which includes three levels: natural region, geosystem, and geofacies. In the natural region, the differentiating landscape components adopt the broadest spatial-temporal resolution: morphostructure (relief), pattern of potential vegetation (vegetation), and pattern of land-use systems (land use); these components adopt an intermediate resolution in the geosystem: relief unit, potential vegetation, and land-use system; and geofacies have the finest-scale resolution: relief form, vegetation type, and particular land use.

The application of the method described herein yielded satisfactory results in the case of the Mexico City municipalities of Tlalpan and Milpa Alta, an area of great environmental and socio-cultural interest, although heavily transformed, for which there are no records of landscape classification or mapping. The landscape classification system for this area reveals three types of natural regions, six geosystems, and 113 geofacies. Natural regions are shown in single polygons; geosystems, in one or two polygons; the degree of detail used to delimit

geofacies allowed the identification of more than 1200 polygons.

The landscape map constructed from the present study should be understood as a valuable tool for environmental and land-use planning and management, as documented in multiple works where these types of products have been used under different environmental settings and application objectives. These include mainly European studies focused on the valuation, management, and protection of the landscape as a resource and heritage. In our case, future studies should assess the effectiveness of this landscape map in the diagnosis of various environmental, ecological, and sociocultural issues that are priorities in the south of Mexico City.

ACKNOWLEDGMENTS

The first author thanks the National Council of Science and Technology (Conacyt) for the scholarship granted to carry out the doctoral studies from which this work derives. We thank the Support Program for Research and Technological Innovation Projects (PAPIIT) of the DGAPA-UNAM, which allowed the research through the IN300821 project.

REFERENCES

Abalakov, A. D. y Sedykh, S. A. (2010). Regional-typological study and mapping of geosystem analysis of the implementation. *Geography and Natural Resources*, *31*, 317-323. http://doi.org/10.1016/j.gnr.2010.11.016

Acosta, J., Suango, V., Proaño, J. y Zambrano, J. (2016). Determinación de la capacidad de acogida por medio de la zonificación paisajística para el Ecuador continental. *Ecuador es Calidad*, *4*(1).

Alves, N. M. S., Silva, D. B., Carvalho, I. S. My Menezes, A. A. (2017). Análise geossistêmica da bacia hidrográfica do Rio Aningas-Pirambu, Sergipe. En A.Perez-Filho y R. R. Amorim, (Org.), *Os Desafíos da Geografía Física na Fronteira do Conhecimento* (pp. 618-629). Campinas, Instituto de Geociencias.

Amorim, R. R. y Olivera, R. C. (2008). As unidades de paisagem como uma categoría de análise geográfica: o exemplo do municipio de São Vicente-SP. *Sociedad y Natureza*, *20*(2), 177-198.

Arias, J. (2015). *Identificación, caracterización y cualificación de los paisajes de las grandes cuencas endorreicas de Andalucía: ensayo metodológico para la implementación del Convenio Europeo del Paisaje en sistemas lacustre-palustres*. Tesis doctoral. Universidad de Granada. España.

Arredondo-León, C., Muñoz-Jiménez, J. y García-Romero, A. (2008). Recent changes in landscape-dynamics trends in tropical highlands, central México. *Interciencia*, *33*(8), 569-577.

Bastian, O., Beierkuhnlein, C., Klink, H. J., Löffler, J., Steinhardt, U., Volk, M. y Wilmking, M. (2002). Landscape structures and process. En O: Bastian (Ed), *Development and Perspectives of Landscape Ecology* (pp. 49-65). Springer. http://doi.org/10.1007/978-94-017-1237-8

Bertrand, G. (1968). Paysage et géographie physique globale. Esquisse méthodologique. *Revue géographique des Pyrénées et du Sud-Ouest*, *39*(3), 249-272. http://doi.org/10.3406/rgpso.1968.4553

Bertrand, G. (1978). Le paysage entre la nature et la societé. *Revue Géographique des Pyrénées et du Sud-Ouest*, *49*(2), 239-258. https://doi.org/10.3406/rgpso.1978.3552

Bertrand, C. y Bertrand, G. (2007). *Geografía del medio ambiente el sistema GTP: geosistema, territorio y paisaje*. Granada. España: Editorial Universitaria de Granada (EUG).

Bloomfield, K. A. (1975). A late-Quaternary monogenetic volcano field in central México. *Geol Rundsch.*, *64*, 476-497.

Bollo, M. (2017). La geografía del paisaje y la geoecología. Teoría y enfoques. En M. Checa-Artasu y P. Sunyer (Coords.), *El Paisaje: Reflexiones y métodos de análisis*. Ciudad de México: Ediciones del Lirio.

Carbajal, J. C., Hernández, J. R. y Bollo, M. (2010). Paisajes físico-geográficos del Circuito Turístico Chilpancingo-Azul, estado de Guerrero, México. *Investigaciones Geográficas, 73*, 71-85.

Consejo de Europa (2000). Convenio europeo del paisaje, 2000. https://www.coe.int/en/web/landscape/home. Consultado el 29 de abril de 2020.

De Montis, A. (2014). Planning systems: A comparative investigation of six case studies. *Landscape and urban Planning*, *124*, 53-65. http://dx.doi.org/10.1016/j.landurbplan.2014.01.005

Drdos, J. (1992). On the carrying capacity of environment. *Geografía y Desarrollo*, *3*(7), 19-24.

Estêvez, L. F., Cunico, C., Mezzomo, M. M., Biesek, A. S. y Maganhotto, R. (2011). Análise da paisagem da Bacia Hidrográfica do Rio Marumbi, Morretes-

PR: unidades de paisagem, fragilidade potencial e hemerobia. *Raega-O Espaco Geográfico em Análise*, *23*, 428-447.

Frolova, M. (2006). Desde el concepto de paisaje a la Teoría de geosistema en la Geografía rusa: ¿hacia una aproximación geográfica global del medio ambiente? *Ería*, *70*, 225-235.

García-Espino, J. C. y Valdés, C. L. (2019). Estabilidad, sensibilidad y antropización de los paisajes de la Reserva de la Biosfera Buenavista, Cuba. *Revista Geográfica de América Central, 63*(2), 189-213.

García-Romero, A., Mendoza, K. I., y Galicia, L. (2005). Valoración del paisaje de la selva baja caducifolia en la Cuenca baja del río Papagayo (Guerrero), México. *Investigaciones Geográficas*, *56*, 77-100.

García-Romero, A. (2014). El orden natural del paisaje en la geografía actual. En M. M. Checa, A. García, P. Soto y P. Sunyer (Ed.)*, Paisaje y territorio. Articulaciones teóricas y empíricas* (pp. 89-105). Ciudad de México: Tirant Lo Blanch.

García-Romero A., y Muñoz J. (2002). *El paisaje en el ámbito de la Geografía*. *Temas Selectos de la Geografía de México*. Ciudad de México: Instituto de Geografía, UNAM.

Gómez-Zotano, J., Riesco-Chueca, P., Frolova, M., y Rodríguez-Rodríguez, J. (2018). The landscape taxonomic pyramid (LTP): a multi-scale classification adapted to spatial planning. *Landscape Research, 43*(7). http://doi.org/10.1080/01426397.2017.1404021

González-Bernáldez. B. F. (1981). *Ecología del paisaje*. España: Blume Ediciones.

Gragson, T. (1998). Potential versus actual vegetation: human behavior in a landscape medium. En W. Balée (Ed.), *Advances in historical ecology* (pp. 213-231). Nueva York: Columbia University.

Hernández-Trejo, H., Priego-Santander, Á. G., López-Portillo, J. A. y Isunza-Vera, E. (2006). Los paisajes físico-geográficos de los manglares de la laguna de La Mancha, Veracruz, México. *Interciencia, 31*(3), 211-219.

Jones, M. (2007). The European landscape convention and the question of public participation. *Landscape Research, 32*(5), 613-633. http://doi.org/10.1080/01426390701552753

Lima, C. O. y Oliveira, R. C. (2018). Proposta de zoneamiento geoambiental para o município de Caraguatatuba-SP. *Geosul*, *33*(67), 140-161.

Lugo, H. (1984). *Geomorfología del sur de la Cuenca de México*. Ciudad de México: Instituto de Geografía.

Martínez, A. (2017). Zonificación geoecológica, un criterio para la interpretación y análisis espacial del paisaje urbano de la Ciudad de Morelia, *Boletín de la Asociación de Geógrafos Españoles, 73*, 343-367.

Martínez de Pisón, E. (1998). El concepto de paisaje como instrumento de conocimiento ambiental. En: E. Martínez de Pisón. (Coord.), *Paisaje y medio ambiente*. Seminario llevado a cabo en Soria Fundación Duques de Soria, Valladolid. España.

Mata, R. (2014). Conocimiento Geográfico del Paisaje y Políticas Públicas. Estudios y Experiencias de Gestión a Distintas Escalas: En Checa, M. M., García, A., Soto, P., y Sunyer, P. (Ed*), Paisaje y Territorio. Articulaciones teóricas y empíricas* (50-83). Ciudad de México: Tirant Lo Blanch.

Mateo, J. M. (2002). *Geografía de los Paisajes. Primera parte: paisajes naturales.* La Habana: Universidad de la Habana.

Mateo, J. M., y Ortiz, M. A. (2001). La degradación de los paisajes como concepción teórico-metodológica, *Serie Varia, Nueva Época-Instituto de Geografía UNAM,* (1), 20-40.

Mazzoni, E. (2015). Cartografía de paisajes: una herramienta para el inventario y la jerarquización de los recursos turísticos en el extremo austral de la Patagonia. *Boletín Geográfico, XXXVI*(37), 95-113.

Méndez-Méndez, A., Serrano de la Cruz, M. A., Salinas, E. y García-Romero, A. (2018). Propuesta metodológica basada en indicadores para la valoración del potencial turístico del paisaje en áreas rurales: el caso del municipio de Atlautla (México). *Cuadernos de Turismo*, *42*, 335-354. http://dx.doi.org/10.6018/turismo.42.15

Mooser, F. (1996). *Nuevo mapa geológico de las cuencas de México. Toluca y Puebla. Estratigrafía tectónica regional y aspectos geotérmicos*. Ciudad de México: C.F.E.

Muñoz, J. (1998). Paisaje y geosistema. Una aproximación desde la Geografía Física. En: E. Martínez de Pisón (Coord), *Paisaje y Medio Ambiente*. Seminario llevado cabo en Soria Fundación Duques de Soria, Valladolid. España.

Muñoz, D. A., y Gómez-Zotano, J. (2016). Propuesta metodológica para la gestión de los paisajes de páramo en el marco de la Iniciativa Latinoamericana del Paisaje (LALI). *Perspectiva Geográfica*, *21*(2), 225-250. http://doi.org/10.19053/01233769.5850

Muñoz, D. A. (2017). *La Gestión de los Paisajes de Páramo en el marco de la Iniciativa Latinoamericana del Paisaje: Propuesta Metodológica Aplicada a Nariño, Colombia.* Tesis doctoral. Universidad Pedagógica y Tecnológica de Colombia. Colombia.

Priego, A., Morales, H. y Enríquez, C. (2004). Paisajes físico-geográficos de la cuenca Lerma-Chapala. *Gaceta Ecológica*, *71*, 11-22.

Priego, A., Moreno, P., Palacio, J., López, J. y Geissert, D. (2003). Relación entre la heterogeneidad del paisaje y la riqueza de especies de flora en cuencas costeras

del estado de Veracruz, México. *Investigaciones Geográficas, 52*, 31-52.

Ramón, A., Salinas, E. y Remond, R. (2009). Diseño metodológico para la elaboración de mapas de paisajes con el uso de los SIG: aplicación a la cuenca alta del Río Cauto, Cuba. *Geografía y Sistemas de Información Geográfica, 1*, 95-108.

Ruíz-Gómez, M. (2006). El crecimiento de los asentamientos irregulares en áreas protegidas. La delegación Tlalpan. *Investigaciones Geográficas,* 60, 83-109.

Salinas, E., García, A. E., Sánchez, B. L., Remond, R. y Cruañas, E. (2013). Delimitación, clasificación y cartografía de los paisajes de la cuenca Ariguanabo, Cuba, mediante el uso de los SIG. *Revista Geográfica, 154,* 9-30.

Salinas, E., Mateo, J. M., Costa de Souza, L., y Moreira, A. (2019). Cartografía de los paisajes: teoría y aplicación. *Physis Terrae*, *1*(1), 7-29. http://doi.org/10.21814/physisterrae.402

Santos, L. S., Nahum, J. S., Santos, C. B., y Júnior, O. M. S. (2019). Paisagem rural da microrregião de Tomé-Acu sob a ótica bertrandiana. *Revista Brasileira de Geografia Física*, *12*(7), 2694-2715.

SEDEMA. (2016). *Suelo de Conservación*. Ciudad de México: Secretaría del Medio Ambiente.

Serrano-Giné, D., García-Romero, A., García-Sánchez, L. A., y Salinas, E. (2019). Un nuevo método de cartografía del paisaje para altas montañas tropicales. *Cuadernos Geográficos*, *58*(1), 83-100. http://dx.doi.org/10.30827/cuadgeo.v58i1.6517

Simensen, T., Halvorsen, R. y Erikstad, L. (2018). Methods for landscape characterisation and mapping: A systematic review. *Land use policy*, *75*, 557-569.

Swanwick. C. (2002)*. Landscape Character Assessment. Guidance for England and Scotland*. Gran Bretaña: The Countryside Agency, Scottish Natural Heritage.

Tudor, C. (2014). *An approach to Landscape Character Assessment*. Inglaterra: Natural England.

Valdés-Carrera, A., y Hernández-Guerrero, J. A. (2018). Zonas funcionales y unidades de paisaje físico-geográfico en la microcuenca Potrero de la Palmita, Nayarit, México. *Revista Geográfica de América Central, 1*(60), 189-230.

Zonneveld, I. (1995*). Land Ecology, An introduction to Landscape Ecology as base for Land Evaluation, Land Management and Conservation*. Amsterdam: SPB Academic Publishing.