Proposal of Differentiating Components for the Multiscale Classification of the Landscape

Propuesta de componentes diferenciadores para la clasificación multiescalar del paisaje

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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 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 adaptada a diversas condiciones y áreas, y constituye una fundamentación cartográfica de amplia aplicabilidad en estudios enfocados en el planeamiento del uso del suelo.

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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-conocológico, geosistema, integración ambiental, Ciudad de México.

INTRODUCCIÓN

Desde los últimos decenios del siglo XX, el deterioro de la calidad del medio ambiente ha aumentado la importancia de la clasificación y mapeo del paisaje como instrumento de intervención y control. Las investigaciones en este campo han sido realizadas en diversas culturas y contextos, con el fin de entender la relación entre los seres humanos y su entorno natural. En este marco, se han propuesto diferentes métodos y enfoques para la clasificación de paisajes, que han permitido entender mejor la naturaleza y el funcionamiento de estos espacios.

En México, y en otras regiones de América Latina, la clasificación del paisaje ha sido objeto de estudio y discusión en diferentes contextos. En este sentido, el trabajo propuesto se enmarca en el marco de la investigación en este campo, con el objetivo de contribute to describing it (supplementary landscape components). The differentiating landscape 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 “geosytemic” 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 contexts and processes that govern its dynamics (Bertrand, 1968; 1978; Martínez de Piérola, 1998; González-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 (Gragon, 1998; García-Romero and Muñoz, 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 Ortiz, 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) uses a taxonomic-hierarchical classification, 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 start by considering that the landscape universe is 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) that contribute to describing it (supplementary landscape components). The differentiating landscape components are relief, vegetation, and land use...
It is characterized by the combination of a relief visually homogeneous. It corresponds to the basic extension (up to hundreds of square meters), but comprises the following three taxonomic levels.

The type of relief (Figures 1 and 3). It is clearly expressed in the landscape through the processes such as erosion and water distribution, the case of terrain slopes, whose major effect on the landscape units does not depend on them. However, their importance as landscape elements must be understood 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 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.

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.
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, biotic, and land-use systems.
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 and 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 2). 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 km²), 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 km²).** 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 firs 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 (3.5% 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 uses (3.52 km²).** The relief unit consists of an extensive area of peaks that range between 3600 and 4000 m a.s.l. (Cruz del Manzán). 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 mesoclimates correspond 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.

#### Natural Region of Chichinautzin Volcanic Field, with temperate forest, agriculture and forestry uses, and human settlements
This natural region (568.72 km²) 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 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 (9°–15°). The local topography 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 development 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 km²).** It is distributed in two extensive mountain peak areas separated by the vast Acopixco volcano agricultural area. The relief unit consists of the most extensive tephra 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 climate.
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 (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 km²). 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 relief unit consitute the landscape pattern, with only 27 geofacies types distributed in 114 polygons. The largest geofacies allows a temperate and subhumid mesoclimate and a potential vegetation of oak forest.

Heavy deforestation and urbanization processes in Tlalpan translate into a relative homogenous 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 and open pine forest patches growing over steep 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, volcanoc, 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 km²) 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 endoreic basin hydrology, favor a pattern of potential vegetation represented by different types of temperate forest.

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-oak 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).

c) Geosystem of Low Slope of the Chichinautzin Volcanic Field, with oak forest, agriculture and forestry uses, and urban development (113.50 km²). 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 mesoclimatic 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.

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

The map of landscape types in Figure 5 shows 113 types of geofacies 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 landscape classification system for the area under study, a taxonomic-corological classification 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 region, 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.

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