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A geomorphologic GIS-multivariate analysis approach to delineate environmental units, a case study of La Malinche volcano (central México)

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A B S T R A C T

The Environmental Units Map (EUM) is a strategic document that provides valuable information about landscape attributes for studies focused on environmental research, urban and land planning and environmental management. Traditionally, the systematic mapping of landforms has been used to integrate landforms and environmental data. Widespread availability of remote sensing data along with thematic cartography and implementation of Geographic Information Systems (GIS), allows a fast integration of landscape environmental attributes, effectively reducing time and costs. In this study we propose an approach to delineate an environmental units map using a geomorphologic map and a multivariate analysis processed in a GIS on a regional cartographic scale (1:75,000). Our study area is La Malinche volcano (located in central México) where there are highly contrasting biophysical conditions and land use over relatively short distances. By means of a Hierarchical Cluster Analysis (HCA) a total of 29 environmental units were obtained for La Malinche. The environmental units range from alpine environments to semi arid lowlands (over a wide volcanic piedmont) where crops and urban development predominate. Our results suggest that integrating environmental units using a multivariate statistical approach not only produces results in agreement with what we observe empirically, but it also allows us to identify those factors which control the grouping of environmental attributes. The method proposed here can be used to integrate environmental data in a single map, and this could prove useful for environmental management in the future.

Introduction

Maps containing information about landforms and environmental data are useful for planning purposes as well as for land and environmental management because they provide basic information of biophysical (e.g. geology, soil, vegetation, topography etc.) and human (mainly land use) attributes of landscape (Cooke & Doornkamp, 1990; Panizza, 1996; Verstappen, 1983; Verstappen & Van Zuidam, 1991). The availability of environmental data is particularly valuable in developing countries where the economy of several communities is still based on the exploitation of natural resources and there are gaps in the existing environmental data (Bocco, Mendoza, & Velázques, 2001; Bocco, Velásquez, & Siebe, 2005). Producing a suitable map in which landforms and environmental data are presented together is necessary for further studies on land and

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environmental management. Moreover, the need to integrate landforms with environmental data is still a task that must be satisfactorily fulfilled (Verstappen, 1983; Verstappen & Van Zuidam, 1991).

Linking environmental data with landforms is not an easy task. Map production will depend on the professional background of those specialists involved and results can be biased by the approach followed. An ecological approach will yield different results when representing environmental attributes of landscape if these are compared with units obtained from a soil science approach. Delineation of environmental units by ecologists will put emphasis on the ecological relationship of landscape attributes (Doing, 1997; Zonneveld, 1989), whilst a soil scientist will delineate units based on the distribution of large soil units or tracking changes in soil catena (Tricart & KiewietdeJonge, 1992). Implementation of Land System Mapping (LSM) since the early 1950s has been successfully applied for compiling biophysical data for large regions and results have been useful in evaluating the natural resources of unknown areas (Cooke & Doornkamp, 1990; Mitchell, 1973; Ollier, 1977; Van Zuidam & Cancelado, 1985/1986). The rationale for selecting landforms as a spatial unit of reference is supported by the apparent dependence of vegetal communities on the distribution of climate over landscape in which topography controls most of climate distribution, and the existing link between soil units and landform steepness (Butler, 2001; Zonneveld, 1989). Also, landforms have been found to be a component of the landscape in which other biophysical elements (e.g. soils, erosion, and hydrology) operate (Butler, 2001; Cooke & Doornkamp, 1990).

In the last two decades, the fast development of Geographic Information Systems (GIS) and remote sensing has made data acquisition and subsequent quantification of natural resources easier, reducing time and costs as well. Usage of GIS has become a powerful tool to evaluate the natural resources of a given region because it permits the fast integration and representation of several biophysical attributes (Bastian, 2000; Bocco et al., 2001; López-Blanco & Villers-Ruíz, 1995; Walsh et al., 1998).

The rationale and principles for using the land unit approach to integrate biophysical data have been previously discussed by Zonneveld (1989). When land units are used to integrate environmental data, an exhaustive process of interpretation of maps and aerial-photographs is required, and if the cartographic scale used to delineate the land units is detailed enough, fieldwork will be necessary (Zonneveld, 1989). The weakness of adopting the land unit method in its pure form occurs at the moment of delineating units. No systematic criteria have been proposed to define the spatial units of reference, though using landforms is suggested. In some cases the land units' boundaries are obtained from boundaries of other environmental attributes different from landforms (e.g. vegetation patterns, terrain roughness, etc.). A disadvantage of delineating land units using an interpretation-based approach is that other environmental attributes of landscape which may not evident in an aerial-photograph, are omitted.

Other studies focused on the acquisition of environmental units have used landforms as the spatial unit of reference to which environmental data is integrated (e.g. Bocco et al., 2001; Bocco et al., 2005; López-Blanco & Villers-Ruíz, 1995). These studies have exploited the capabilities of GIS to produce a map in which the environmental attributes are linked to landforms via the quantification of environmental attributes (Bocco et al., 2001; López-Blanco & Villers-Ruíz, 1995). Environmental data is generally obtained from thematic cartographic and/or remote sensing sources and is integrated to a landform map by calculating the coverage of area of each environmental attribute. The advantage of using landforms as spatial units of reference resides in the fact that systematic criteria to classify landforms according to type (e.g. hill, mountain, plain, piedmont) can be set at different cartographic scales (Van Zuidam & Cancelado, 1985/1986). However, the major weakness of this approach occurs when the environmental data is integrated into landforms. As mentioned above, environmental data is integrated into landforms by calculating the area of environmental attributes contained in every landform. In the next step landforms are classified in a hierarchical classification system and environmental data is used to describe the environmental properties of each landform (e.g. Bocco et al., 2001; López-Blanco & Villers-Ruíz, 1995). The acquisition of the environmental units is obtained from the classification of landforms. However, the environmental units obtained by this approach are incomplete since, the environmental attributes are not taken into account in the grouping of landforms.

Bearing in mind that the acquisition of environmental units requires the integration of environmental attributes, we decided to develop an approach in which environmental data along with landforms are used to delineate environmental units. The main goal of this research is to produce an Environmental Units Map (EUM) using the framework of the LSM, integrating landscape environmental attributes using a multivariate analysis approach on a regional cartographic scale (1:75,000) in a GIS environment. An environmental unit is defined here as a homogeneous spatial area in terms of landforms, vegetation, soils and land use. The environmental data used for the analysis has a wide spatial distribution and it is available in a thematic cartography on a regional cartographic scale (1:75,000). To test the proposed method, we selected as a study area La Malinche volcano, located in central México. Landscape attributes on La Malinche volcano have high contrasts of climate, relief, vegetation, soils and land use. We propose here that using a statistical-based approach allows us to do a delineation of units based on the interaction of all environmental variables.

Physical setting

La Malinche (4460 AMSL) is a strato-volcano located on the eastern sector of the Trans-Mexican Volcanic Belt (Fig. 1). The volcanic structure is placed between two geological domains: (1) the cretaceous limestone of the Orizaba Formation, located at the southern and eastern limit of the volcano, characterized by folded rocks in the Oligocene and which constitutes the regional basement (Mooser, Montiel, & Zuniga, 1996), and (2) the oligocenic rocks of the known Tlaxcala block, characterized by volcanic rocks which erupted in the Oligocene and faulted during the Quaternary with scarp faults facing the south (Hilger, 1973; Mooser et al, 1996).

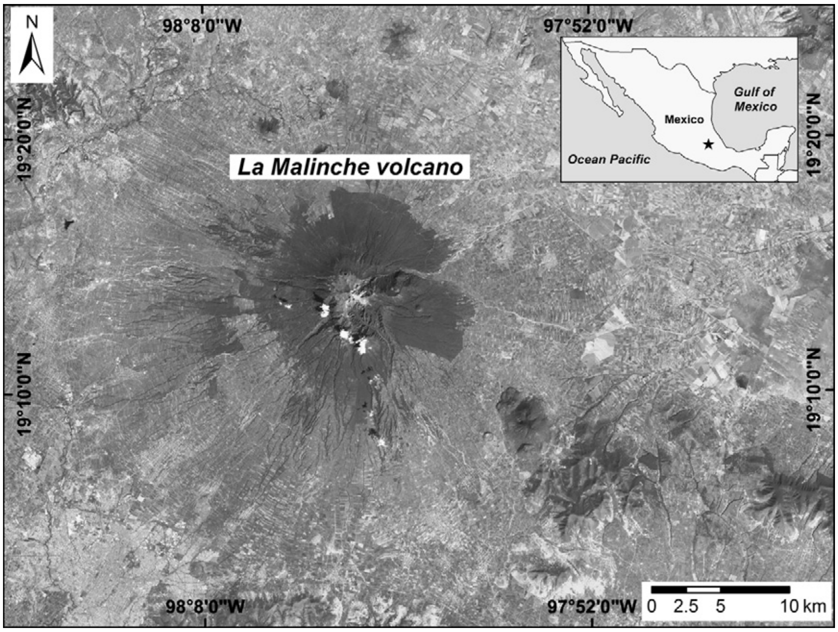

Fig. 1. Location map of La Malinche volcano (4460 m). Dark areas on the central image show the forest area on mountainous zone. The crops are widely distributed on the piedmont and light gray areas indicate urban areas.

The most recent volcanic activity recorded for the edifice occurred 3100 yr B.P. as dating of ^{14}C pyroclastic deposits have shown (Castro, 1999; Castro & Siebe, 2007). The oldest deposits have been dated to 40,000 yr B.P. (Castro, 1999; Heine & Heide-Weise, 1973). Nevertheless, it is thought that volcanic activity started around the Late Pliocene (Mooser et al., 1996).

The main edifice has a mountainous topography of $\sim$211 km^2. The lithology is made up of dacitic and andesitic domes and lava flows, surrounded by a broad piedmont formed by alternating thick layers of pyroclastic rocks (mainly pumice and ash) intercalated with lava flows. The volcanic piedmont covers an area of $\sim$896 km^2 (Castro & Siebe, 2007). At the lower part of the volcanic piedmont, small scoria cones have been formed during the Holocene (Mooser et al., 1996). Scoria cones are covered by a thick mantle of weathered pyroclastic deposits related to La Malinche's eruptive sequences, they form a hilly topography with an area of $\sim$97 km^2.

Biophysical environment

Climatic conditions on La Malinche volcano are mostly controlled by altitude and the seasonality of hurricanes generated in the Gulf of México during summer (Garcia, 1988; Jáuregui, 1968). Two well defined climatic domains prevail on the edifice: (1) a cold rainy area with rainfall concentrated in summer, this climate is distributed above 3500 m and (2) a temperate sub-humid season with a rainy season in summer which is widely spread between $\sim$2200 m and 3500 m. Mean annual temperature ranges from the lowlands to the summit between 17 °C and 6 °C, respectively. Mean annual rainfall changes with altitude from 400 mm to 1200 mm at the volcano's peak (Lauer & Stiehl, 1973).

Vegetation at La Malinche volcano, as well as most of the mountain ranges in central México is controlled by elevation (Rzedowski, 1998). Mixed forest is widely distributed on the volcano's slopes and is dominated by oaks and pines at an elevation of 2700 m. From 2700 m to 3000 m pine forest predominates. Above 3000 m to approximately 3800 m fir forest is widely distributed on the landscape. Altitudes above 3800 m to approximately 4100 m resemble alpine vegetation, and are dominated by grass lands and Pinus hartwegii. Altitudes above 4100 m do not exhibit vegetation due to the extreme climatic conditions. Human activities have caused dramatic changes on vegetation cover on the piedmont, original mixed forest has been replaced by crops and urban areas (Arellano, López-Blanco, & Villers-Ruíz, 2001).

Soils formed on the volcano slopes using FAO-WRB (1998) classification are: (1) regosols, located on mountain slopes and some sections of the piedmont area, (2) fluvisols, developed on alluvial fans and in lower sectors of the volcanic piedmont as well as on the plains, (3) cambisols, formed in wide sectors of the volcanic piedmont, and (4) leptsols, located on the steepest slopes of the volcano.

Materials and methods

Mapping of landforms was done following the principles of LSM (Van Zuidam & Cancelado, 1985/1986) interpreting aerial-photographs at a scale of 1:75,000 that were exported to the GIS Ilwis Academic 3.3 (ITC, 2005). A 20 m Digital Elevation Model (DEM) derived from topographic maps at a scale of 1:50,000 (INEGI, 1983a) was used as a cartographic base, the

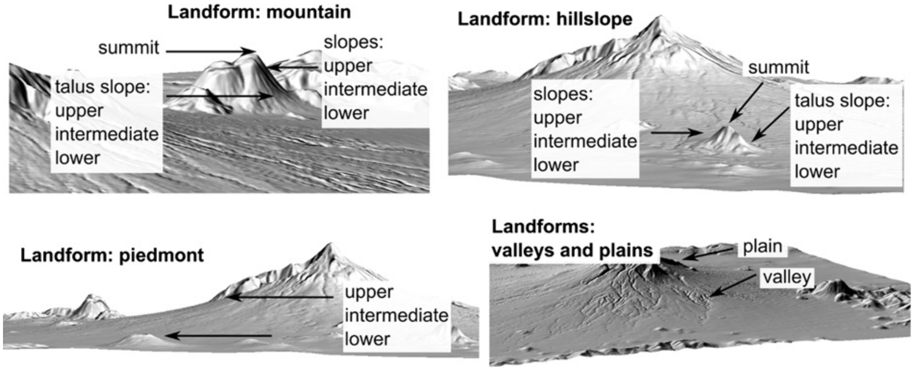

Fig. 2. Landform classification following the LSM approach. Where possible, landforms were re-fragmented based on a topographic classification of landforms. Note that re-fragmented landforms contain a set of topographic elements classified by their topographic position.

maximum vertical resolution is of 20 m as the DEM was obtained from the interpolation of 20 m contour lines. From the interpretation of aerial-photographs five types of landforms were recognized: mountain slopes, hill slopes, valley slopes, piedmont and plains. The recognized landforms were re-fragmented based on a simple slope classification (Fig. 2). Based on our photo-interpretation and supported with previous published data, we identified six geomorphic domains for the volcano which are homogeneous regions in terms of topography and geomorphic processes (Table 1).

In the GIS we obtained the topographic data of altitude, slope, shape, and aspect calculated from the DEM. The topographic data was integrated to every landform mapped. Additional biophysical data was obtained from thematic cartography of soils, land use, vegetation cover and temperature. Rainfall data is not available for periods longer than 30 years. To overcome the problem of gaps in rainfall data, vegetation cover was considered to be a rough proxy of rainfall conditions due to the observed dependence between rainfall, altitude and vegetation cover distribution (Rzedowski, 1998). Land use and vegetation cover data were extracted from the map produced by Arellano et al. (2001), obtained from an interpretation of aerial-photographs at a scale of 1:75,000. A soil units map was obtained from the thematic cartography of a governmental institution at a scale of 1:50,000 (INEGI, 1983b). Mean annual air temperature was obtained from a national meteorological database ERIC2 (SMN, 2000) from twelve meteorological stations located around the volcano between ~2000 m and 2500 m. Lack of temperature data for the summit area was resolved using the predicted values of mean annual temperature from the regression coefficients of the temperature–elevation relationship (Fig. 3) applied to the available DEM.

Environmental data of vegetation, soils and land use were compiled in several thematic maps and were integrated into landforms calculating their percentage area of coverage with respect to the landform area. The physical attributes obtained from the DEM were computed for every landform. The landform map produced, named here landforms unit map, contains an attribute table of 430 rows that correspond to all recognized landforms, and 28 columns which contain the environmental attributes.

The multivariate analysis of environmental data was done using the free software R (The R Foundation for Statistical Computing, 2009) available online (http://www.r-project.org). Using a matrix of 430 rows which contain landforms by 28

Table 1
Geomorphic domains of La Malinche volcano. The six domains shown here were obtained from the interpretation of aerial-photographs and from consulting published works on the study area. Every domain is composed by a set of landforms classified by their basic type (e.g. mountain, valley, plain, etc.).

Landform domain	Morphogenesis	Surface processes
High mountain slopes	Volcanic edifices and slopes of andesitic and dacitic lava flows. Landforms eroded by glacial processes in the Little Ice Age (LIA)	Periglacial frost shattering, creeping and rockfall
Mountain slopes	Volcanic edifices and slopes made of dacites and andesites with alternating layers of pyroclastic flows. Slopes >2900 m of altitude were eroded by glacial and periglacial processes during the late Quaternary up to the LIA	Fluvial erosion, mass wasting processes on steep slopes
Valleys	Erosive landforms	Fluvial erosion, mass wasting on channel walls
Piedmont	(1) Volcanic piedmont made of lava flows and pyroclastic flows (2) Volcanic fans, complex genesis deposits of lahars, volcanic material and fluvio-glacial sediments	(1) Fluvial erosion, formation of ravines (2) Accumulation of sediments during large floods events
Hills	(1) Volcanic cones composed of basaltic and andesitic lava mantled by pyroclastic sediments (2) Tuff cones	(1,2) Fluvial erosion
Plain	(1) Accumulation of volcanic material (pyroclastic flows) (2) Volcanic and fluvio-glacial accumulation (3) Deposition of alluvial material	(1) Stable landforms (2) Accumulation of fluvial sediments (3) Accumulation of fluvial sediments on large flood events

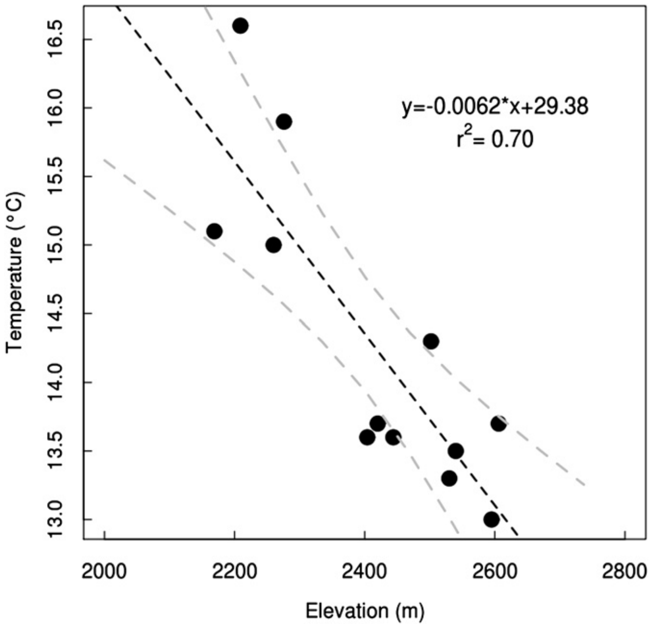

Fig. 3. Linear regression of elevation versus temperature. Coefficients from the equation of the regression line were extracted and applied to the DEM to obtain the mean annual air temperature on the summit area. The regression line is significant at $p < 0.01$.

columns which correspond to the environmental attributes, a Principal Component Analysis (PCA) was performed following the regular procedure for exploring data using a multivariate approach (Johnson, 1998; Rogerson, 2001). From the PCA those factors which control the distribution of the environmental attributes of La Malinche volcano were identified. Before evaluating the similarities of environmental attributes on the landforms mapped, the landform map was reclassified according to the geomorphologic domain (see Table 1). This step was necessary to avoid the grouping of landforms from different geomorphologic domains. Six matrices containing the environmental units and landforms were created. A Hierarchical Cluster Analysis using the complete method was applied to all landforms contained in the six geomorphic domains and a set of six tree graphs plotted on Euler distance were produced (Fig. 4). The grouping in units was done by interpreting the clusters observed on the tree graphs. An ID number was assigned to every unit. The integration of the environmental attributes to landforms is synthesized in Fig. 5.

Results

The PCA results indicate that one factor explains most of the variance (~30%) in the correlation matrix of the environmental attributes of La Malinche volcano (Fig. 6A). Plotting the coordinates of the first two factors from the PCA, shows that altitude, temperature and slope are the most important variables controlling the correlation of biophysical attributes for La Malinche volcano (Fig. 6B). Altitude and temperature are expected to determine vegetation distribution due to the sensitivity experienced by vegetal communities to changes in temperature which in turn depend on changes in elevation.

A total of 29 environmental units were obtained for La Malinche volcano (Fig. 7). Units delineated by the Hierarchical Cluster Analysis have a unique combination of environmental attributes and they are grouped depending on their biophysical attributes (e.g. similar altitude, soils, vegetation or land use). Here we highlight their major characteristics.

Units of a high mountain environment are confined to the volcano summit where cold weather and freezing conditions are common most days of the year. Past periglacial environment and high slope values have impeded soil formation (Castillo-Rodriguez, Lopez-Blanco, & Palacios, 2007; Vázquez-Selem & Heine, 2004) and only alpine vegetation can grow. The mountain zone is characterized by the predominance of a steep topography; fir, pines, and oak forests on poorly developed soils (regosols) prevail in this zone. Human activities are regulated in the forest and on the summit as long as it is a National Park (Vargas, 1997).

A different type of scenario can be observed on the piedmont surface. Human activities have modified native forests by introducing crops. Natural conditions like a well defined seasonality of rainfall and a low topographic gradient illustrated by a gentle sloping of the piedmont, have been favorable for the development of crop lands. Different units of the piedmont area could be differentiated by their altitude, vegetation and soil types.

Environmental units on valleys have well defined characteristics such as a cooler climate and the predominance of natural forest. During fieldwork it was observed that wide and deep valleys exhibit high contrasts with their surrounding area. In some valleys fir forest is prone to persist due to shading, the predominance of moisture and a cooler climate (Rzedowski, 1998).

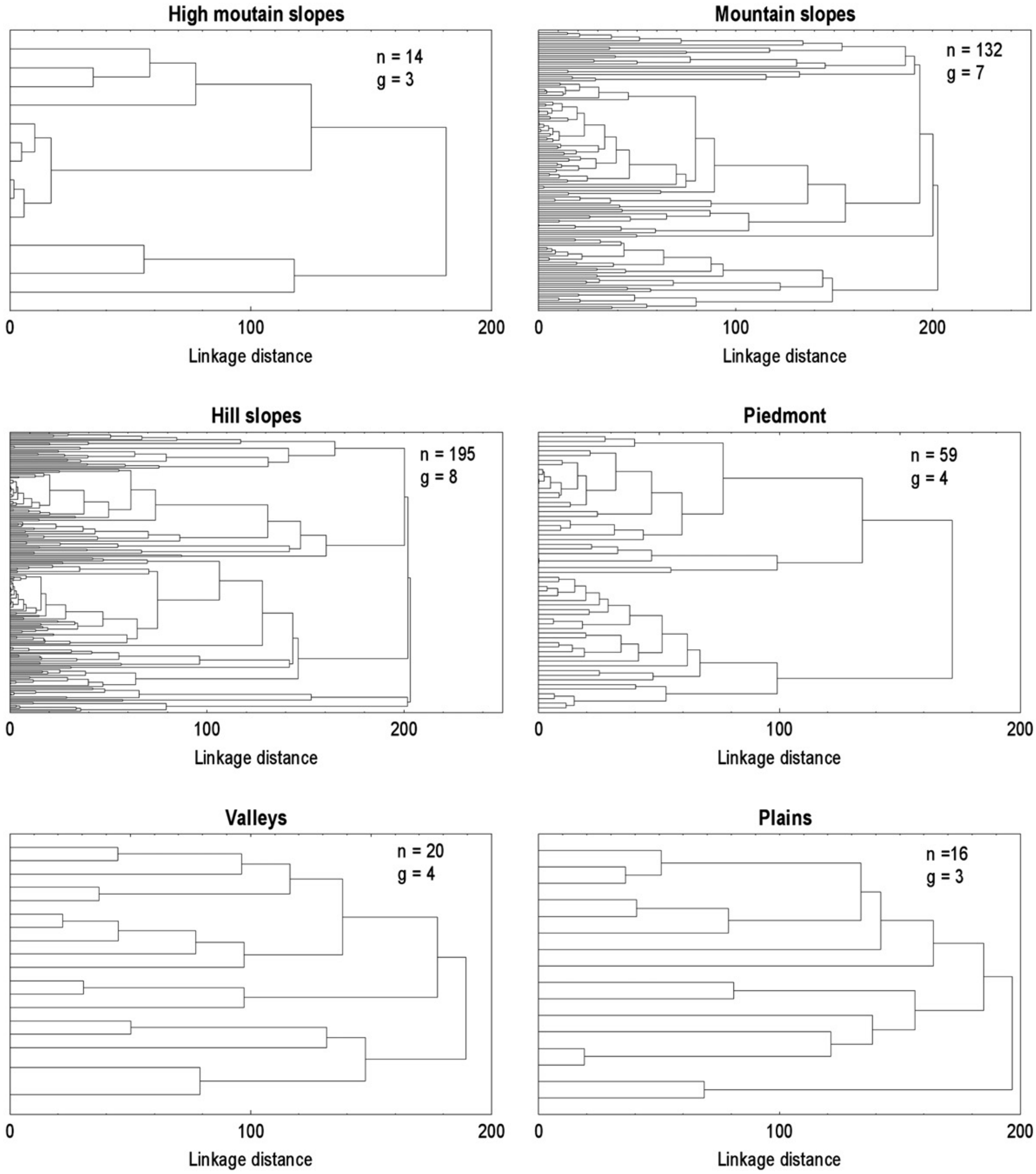

Fig. 4. Tree graphs obtained from the HCA and plotted on Euler distance. On the graphs '*n*' is the number of landforms contained on the geomorphologic domain and '*g*' corresponds to the number of units interpreted. Labels on graphs were removed here for representation purposes.

Units on hills and plains are mostly affected by human activities such as crop introduction and the development of urban areas. Besides the physical effects on the landscape caused by human activity, the predominance of non-native vegetation and grass lands give a rough indication of human pressure on past natural areas. Low topographic barriers and rainfall seasonality (as in the case of the piedmont area) are conditions which have allowed a massive exploitation of natural resources.

Discussion

Using landforms to delineate environmental units was found useful here since the LSM can be performed at different cartographic scales and landforms classification does not require details of morphological features, just the recognition of the basic types (mountain, hill, plain, valley, piedmont). If fragmentation inside landforms is required, a topographic classification

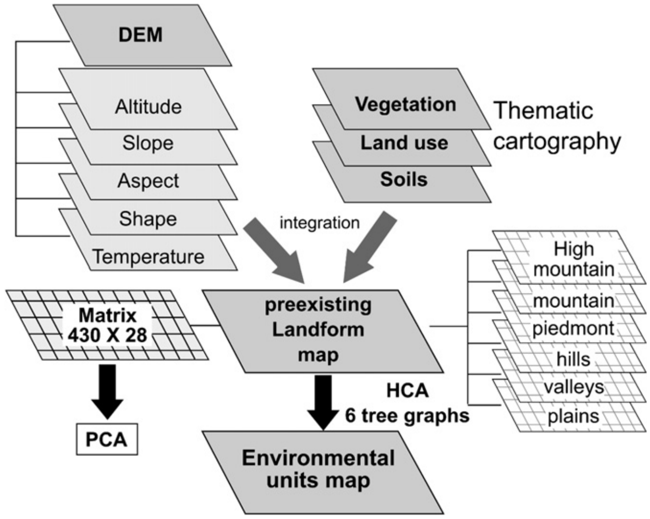

Fig. 5. Method followed for the integration of the physical and environmental data. The environmental attributes of landscape were integrated to the landform map obtained from the interpretation of aerial-photographs. Matrices for the HCA were extracted from the six geomorphic domains of La Malinche volcano.

can be used to distinguish those different elements which constitute a landform (see Fig. 2). Specialists involved in the delineation of environmental units using the LSM will be focused on distinguishing topographic contrasts instead of looking into other aspects of landforms (e.g. erosion patterns, scars caused by mass wasting on slopes). In this way, the interpretative process for the delineation of landforms is reduced.

Another advantage of using landforms to integrate environmental data is demonstrated by the role played by topography in relation to other environmental attributes like soils, vegetation and hydrology (Zonneveld, 1989). Most of the biophysical attributes of landscape depend on local topographic conditions (Butler, 2001). Steeper topography will exhibit more contrast in its biophysical attributes over short distances than wide flattened terrains, which may have a homogeneous distribution of soils and vegetation. Topography can indeed be an important factor in the development of certain human activities which may be directly observed on the landscape. Flat terrains are better for agriculture or urban settlements when compared to mountainous areas, which may be kept for other purposes (e.g. recreational areas, natural parks).

Implementing a multivariate analysis to delineate environmental units in this research was helpful in two ways. The PCA was useful to detect those factors which control the spatial correlation of the environmental attributes. Even though the PCA is generally regarded as a statistical exploratory technique (Johnson, 1998), it can yield interesting results which explain the distribution of the environmental attributes of a given landscape. In the case of La Malinche volcano, the PCA indicated that altitude, temperature and slope are important variables which may control the distribution of variables. Results from the PCA are consistent with observations made on the vertical distribution of vegetation on tropical mountainous areas where altitude and temperature play an important role in the presence of certain species (Rzedowski, 1998). Also, the spatial distribution of

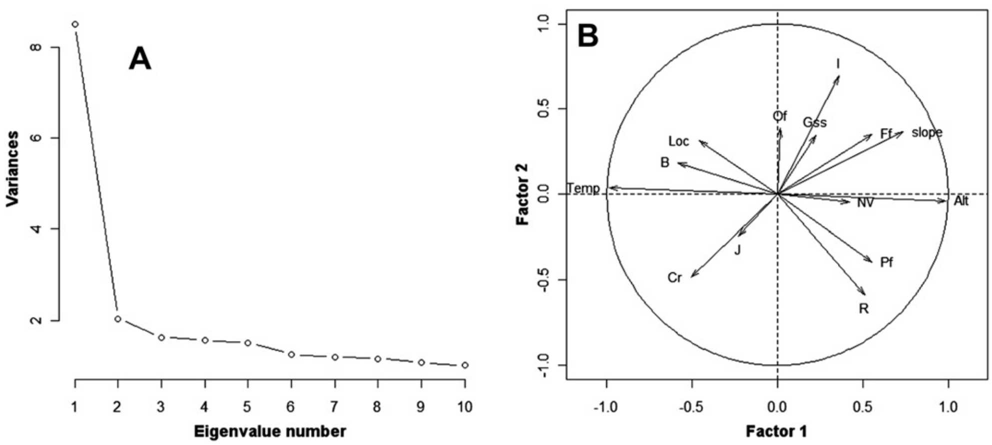

Fig. 6. On A is shown the screeplot of the eigenvalues of the correlation matrix of La Malinche volcano. The screeplot indicates that two factors control the correlation matrix on all the environmental variables analyzed. On B are plotted the coordinates of the two firsts factors. It can be observed that altitude, slope and temperature are the most important variables which explain the matrix correlation.

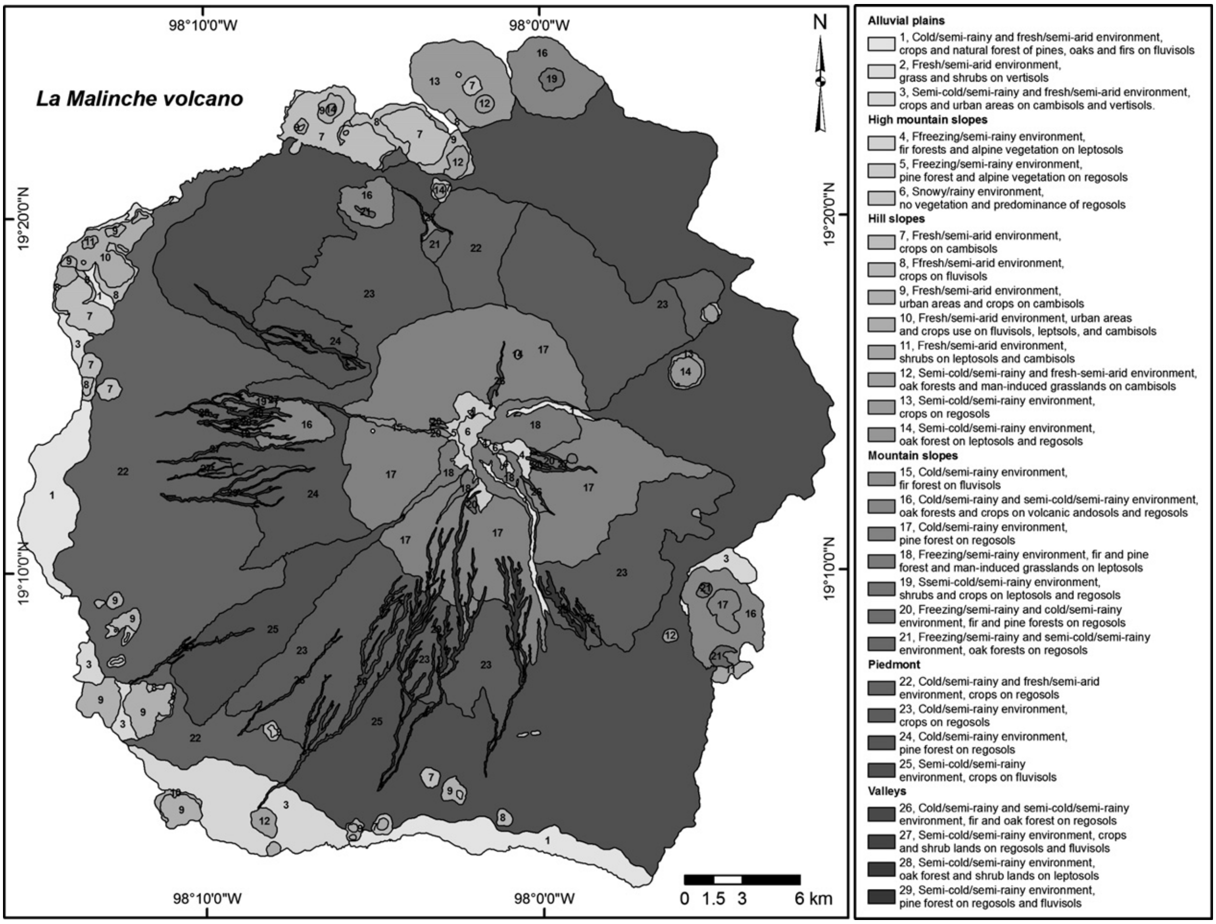

Fig. 7. Environmental units map of La Malinche volcano. A total of 29 units were delineated from the results of the HCA. Each unit comprises a set of landforms which have similar environmental attributes.

human activities on La Malinche volcano, was somewhat related to the factors identified by the PCA; low gradient terrains on plains and in piedmont are areas with an urban and agriculture use, forestry has been kept on the mountainous areas at an altitude above 2800 m.

The HCA was useful to identify those landforms which are similar in terms of their environmental attributes. Results from the HCA can be presented on tree graphs in which every cluster contains landforms that share similarities in their environmental attributes. In order to know which variables exert a control on the correlation of all the variables involved, the PCA must be applied beforehand. It is noteworthy to emphasize that in order to avoid inconsistencies in the elements grouped by the HCA, a previous selection of those elements which will be grouped together must be done. Inconsistencies could occur with the grouping of some elements with similar attributes but from different domains. An example would be the grouping of some units with more or less the same environmental attributes but which are different in landform type. In this research the selection of landforms was based on the classification of the geomorphologic domains (Table 1, Fig. 5). In this way the grouping of different type of landforms from two different geomorphic domains was avoided.

The environmental units obtained in this study were based on the results provided by the HCA for six geomorphologic domains. Using the HCA reduces the process of interpretation when the environmental units are defined. However, some interpretation is required when a cluster is divided in order to define a unit. In this case branches and distance in tree graphs need to be carefully examined. Other studies use landforms as spatial units of reference to delineate environmental units (e.g. Bocco et al., 2001; López-Blanco & Villers-Ruíz, 1995). Integration of environmental data is done by calculating the area of the environmental attribute with respect to the landform to which it belongs. The final result is a landform map with an attached table or legend in which the main characteristics of the environmental attributes are displayed. In the approach proposed here, units are delineated taking into account their variables which comprise a set of landforms which have similarities in their environmental attributes.

Difficulties observed in the methodology proposed here occurred when the physical data of altitude, slope, shape and aspect was integrated to landforms. Assigning a single value of physical data to landforms may produce errors. This is of particular importance when landforms comprise large areas or contain high contrasts in their topography. To evaluate the

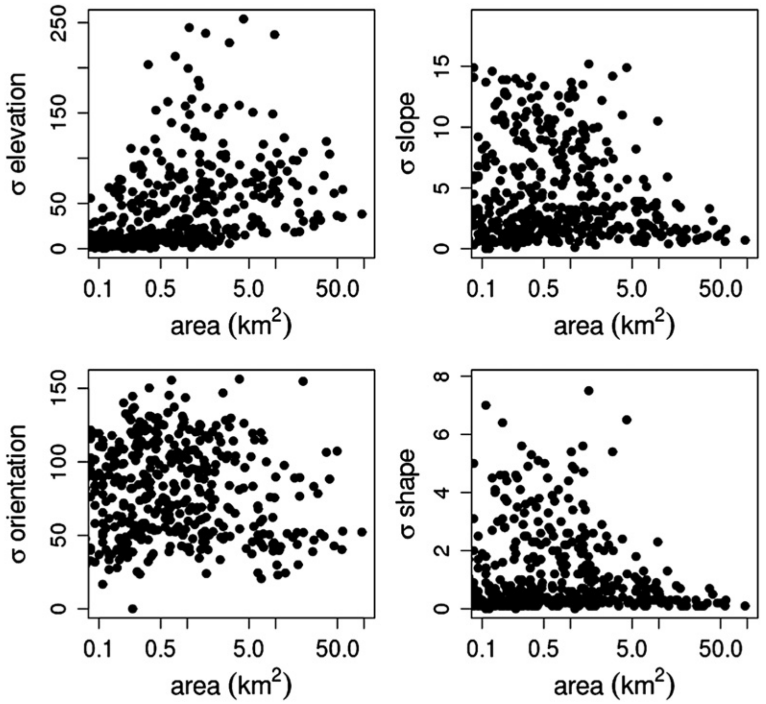

Fig. 8. Plots of the standard deviation values of DEM derived maps against landform area. Randomness of standard deviation values indicates that the area of a landform is not an important source of error. However, the slight concentration of dispersion values in the center of the plots suggests that landforms like mountains, valleys and hills may be an important source of error due to variability in their slope, altitude, orientation and shape.

dispersion of physical data assigned to landforms, the landform's area was plotted against standard deviation values of altitude, slope, shape and orientation (Fig. 8). Plots in Fig. 8 exhibit certain randomness in the distribution of the standard deviation values with respect to the landform area. This indicates that the size of landforms does not have a profound effect on the assigned value and is not a significant source of error. Potential sources of error are possibly due to pronounced topographic contrasts on landforms with more relief like mountains, hills and valleys. These landforms in La Malinche volcano have areas of $\sim$0.5 km^2 to $\sim$5 km^2 where standard deviation values are slightly higher (Fig. 8). The environmental data obtained from the thematic cartography and subsequently assigned to landforms is obtained from the calculation of areas. This minimizes the dispersion of data since area is measured in percentage of coverage with respect to landforms. However, results heavily depend on the quality of cartography and limitations imposed by scale. A potential source of error can occur if some environmental attributes cross the boundaries of landforms to which they do not belong. To reduce the possibility of including an environmental attribute which does not belong to a particular landform a weighting factor (e.g. computation or area by the number of pixels) can be used.

Conclusion

Using landforms as spatial units of reference to delineate environmental units seems to be optimum for environmental planning and management since it allows a fast integration of several environmental attributes into a single landform that can be grouped with other landforms to conform environmental units. The production of a landform map can be obtained in a relatively short time if the LSM approach is used for landform delineation. The PCA and HCA used here as a tool for integration and regionalization (synthesizing) of data are reliable since they allow us: (1) to recognize those factors involved in controlling the correlation of variables of the landscape and (2) to group those landforms that share similarities in their environmental attributes. The methodology proposed here to delineate the environmental units for La Malinche volcano allowed us to produce a map which is consistent with the distribution of the environmental attributes observed on the landscape. The approach suggested here can easily be tested in other areas where gaps in environmental information exist, as long as some basic cartographic and image sources are available.

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