On the relationship between landforms and land use in tropical dry developing countries. A GIS and multivariate statistical approach

Recibido: 1 de julio de 2016. Aceptado en versión final: 6 de diciembre de 2016. Publicado en línea (versión e-print): 18 de abril de 2017.

Itzi Gael Segundo Méty,*
Gerardo Bocco**, Alejandro Velázquez***
Konrad Gajewski****

Abstract. Geomorphological inquiry has addressed the relation of cultural landscape features, such as land use, with landforms in different environments and under different land use regimes. Usually, these complex relationships have been pursued by simple map overlaying in a geographic information system (GIS). This research argues that the results of map overlaying need to be followed by statistical analyses to properly depict the nature of such relationships. The paper explores the quantitative relation between landforms and land use in a highly geographically complex region in the tropical dry Mexican Pacific coast. Data collection encompassed two phases: preliminary satellite image interpretation, and field verification and ground survey. Digitized and orthorectified layers were incorporated and overlain in a GIS. Correspondence Analysis (CA) was used to identify correlations among land uses and landforms. Results showed a significant correspondence between geomorphic and land use entities. Fluvial landforms were associated to simpler patterns of human activity. Denudational landforms, on the other hand, depicted more complex and diverse land use patterns. Agricultural and grazing activities occurred in both gentle, fluvial landforms, and steep denudational landforms. Results were discussed in the light of their relevance for land use planning. This approach may strengthen decision making procedures particularly in such areas where applied geographic data need to be created to perform sound land use planning at the local scale.

Keywords: landforms; land use; GIS; spatial correlation; Mexico

Sobre la relación entre geoformas y usos del suelo en ambientes tropicales secos usando SIG y estadística multivariada

Resumen. Las investigaciones geomorfológicas han estudiado la relación entre los aspectos culturales del paisaje, como los usos del suelo, con las geoformas en diferentes contextos geográficos. De manera más específica, estas líneas de investigación se han enfocado a la manera como el terreno condiciona las actividades humanas. El estudio de estas relaciones, que generalmente son complejas, ha tendido a simplificarse a partir de meras sobreposiciones cartográficas en los sistemas de información geográfica (SIG). El presente artículo argumenta que los resultados de la sobreposición de datos geográficos pueden beneficiarse, para comprender los resultados, de un análisis de estadis-
INTRODUCTION

The analysis of human-environment interactions (Turner, 2002) has been a recurrent topic in geomorphological inquiry in different environments world-wide (Campos et al., 2012; Knight and Harrison, 2013; Migoń and Latocha, 2013). Other studies have addressed the relation between cultural landscape features, such as land use, with fluvial landforms (Hudson et al., 2006). Specifically, most research has focused on geomorphic response to human-induced environmental change (Fang et al., 2005; Vanacker et al., 2005; Knox, 2006; García-Ruiz et al., 2010; Castaldi and Chiocchini, 2012; González-Abrahám et al., 2015).

Understanding the way in which humans use fluvial landforms is important for maintaining vital environmental and social processes (Miller and Doyle, 2014). Geomorphological inventory and mapping, despite of a long standing tradition, may still be valuable tools to unravel the quantitative and functional relationships within landscape. Study cases depicting these links are especially important in highly complex geographical regions, particularly in tropical developing countries, where land management is badly needed (Paneque-Gálvez et al., 2013).

Usually, these spatial relationships are not of the one-to-one or one-to-many type. This implies that more than one landform map unit may be under more than one land use and vice versa. In other words, simple correspondence of a land use pattern to a landform unit hardly ever exists in the tropics, where mosaics of land use occupy different terrains. However, in many case studies (e.g., Bocco et al., 2001 and literature therein), these relationships are somehow arbitrarily simplified. In fact, the relations are established only by map overlaying in a geographic information system (GIS). This is a simple GIS operation where the landform map is overlapped by the land use map, both in the same geometry. The intersected area per map unit is calculated and results report the area of overlap per landform map unit. Nevertheless, every landform unit may be occupied by many land uses, and these may be present in many other landforms.
This research argues that the results of map overlaying need to be followed by statistical analyses to properly depict the nature of such complex relationships. The objective of the paper is to explore the quantitative relationship between fluvial landforms and land use in a highly geographically diverse region in the tropical dry Mexican Pacific coast using Correspondence Analysis. The ultimate goal is to strengthen mapping tools for land use planning purposes.

A landscape classification system was put together with special attention on the conceptual background regarding land use. We have focused on the land use concept as a part of the human dimension of landscape that is essentially different from land cover. Land use is functional; it implies a human activity as taking place in a given portion of land, whereas land cover encompasses the biophysical characteristics of the object occupying a certain tract of land (Rhind and Hudson, 1980; Foody, 1996; Bibby and Shepherd, 2000; Johnston and Sidaway, 2004; Latocha, 2009; Bakker and Veldkamp, 2012; Downs et al., 2013). Therefore, understanding land use trends implies depicting underlying functional process (Vitousek et al., 1997). To satisfy the research needs, land use map units relied on land cover units coupled to a participatory field survey involving local inhabitants of the valley area.

**Method, data collection and techniques**

**Study area**
The lower valley of the Nexpa river (ca 1,400 ha; Fig. 1) belongs to the Sierra Madre del Sur, a mountainous physiographic province that extends along the entire Pacific coast of Michoacan State (Fig. 2). Morphogenesis is complex because of the heterogeneous structural and lithological conditions of the Sierra. In addition, the climate varies from tropical to temperate with a seasonal rainfall regime following altitudinal change and distance from the coast (Krasilnikov et al., 2011).

The Nexpa River discharges into the Pacific Ocean where the coastal plain interrupts the rocky, abrupt coast. Sedimentary environments within the fluvio-marine area include the beach, a spit-barrier and a coastal lagoon. The climate of the valley is tropical subhumid with an average annual temperature of 27.8 °C and a summer rainy season. Leptosols and Regosols are common on the Sierra slopes; Fluvisols are prominent in lowlands of fluvial origin (Ramírez-Herrera et al., 2012). During (dry) winters, water availability for crops and pasture is scarce and becomes a severe limiting factor for rural productivity. Land cover is dominated by tropical dry forests on the slopes and riparian vegetation on the valley bottom, while mangroves and coastal dune vegetation are present on the coastal plain.

**Data collection**
The strategy for data collection encompassed two phases: (1) preliminary satellite image stereoscopic interpretation using standard visual interpretation techniques, and (2) field verification and participatory land survey using basic ethnographic techniques. Both land cover and landforms were delineated on orthorectified, 0.6 m cell resolution, 2008 dry season Quickbird natural color stereopairs printed at a 1:10,000 scale. Resulting polygons were labeled according to categories of two hierarchical classification systems, one for land cover.
Table 1. Landform class description of study area (modified from van Zuidam, 1986).

| Landform class          | Description                                                                                                                                 |
|-------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| Summit surface (SS)     | Nearly flat, undulating and rather small area on top of denudational slopes                                                                |
| Denudational slope (DS) | Gentle to moderately steep slopes/undulating to rolling topography. Slightly to moderately dissected                                         |
| Footslope (FS)          | Relatively short, nearly horizontal to gentle slopes. Not or slightly dissected                                                              |
| Valley Area             |                                                                                                                                              |
| Major stream channel (Mj)| A river bed, with nearly flat, irregular topography and varying presence of water, with erosion and accumulation portions                |
| Minor stream channel (Mn)| Nearly flat, slightly irregular topography, regular/seasonally flooded; basically subject to silting up by fluvial accumulation       |
| Stream channel deposits (Sd)| Clay plugs developed by slow accumulation of fine materials and organic matter over major stream channel due to topographic unevenness |
| Lower fluvial terrace (Lt)| Relatively flat, horizontal, or gently sloping surfaces, sometimes long and narrow, which are bound by steeper ascending slope on one side and by a steeper descending slope on the opposite side. This class makes reference to the most recently formed terraces |
| Upper fluvial terrace (Ut)| The highest (upper) terrace seems to be the oldest with more rounded forms and more extensive vegetation                                    |
| Coastal plain (CP)      | Mostly beaches. Nearly flat, gentle slopes, regularly flooded at high tide, frequently irregular topography due to beach lines, bars, swales and sand deposits reworked by wind |
and the other for landforms. The landform classification scheme (Table 1) was based on criteria proposed by van Zuidam (1986) who used a terrain analysis mapping approach at different scales and level of detail (Bocco et al., 2001). The land cover classification system was based on Brown and Duh (2004) (Table 2). Both set of polygons were digitized and the two vectorial data bases were input to a geographic information system (GIS) (ArcGIS 9.3.1). Both maps were extensively field verified, together with local producers; particular attention was paid to polygon boundaries.

The land use data base was first determined from land cover information depicted on the satellite images, followed by an exhaustive, participatory field survey. This procedure fully involved local producers in semi-structured interviews, field recognition of land cover and terrain classes, and field mapping. The land cover classes thus determined are listed in table 3 as “dominant land cover type”, where land cover is given as a prevailing attribute of land use.

### Data analyses

A matrix containing overlapping area values of landform and land use classes was created by map overlaying in the GIS (table 4). Correspondence analysis (CA) was used as the primary ordination technique mostly because it is simple and relatively easy to interpret. It is also a versatile tool that is useful for exploratory analyses of categorical data (Beh, 2007).

This type of multivariate statistical analysis serves the purpose of depicting landscape patterns
Table 3. Land use class description of study area

| Land use class | Dominant land cover type | Description |
|----------------|--------------------------|-------------|
| Agriculture    |                          |             |
| Rain-fed       | Grassland/cropland       | Crop and orchard production delimited area identified by its seasonal attributes. Summer rainfall is the main water supply. Maize, tomatoes and beans are examples of products raised by rain-fed agriculture. |
| Localized irrigation | Grassland/cropland | Portion of the area where the irrigation is carried on by an engineered system that pumps water from shallow wells directly into the plantation. Mango, beans, tomato, papaya, chilli are mostly produced by means of this technique. |
| Mixed irrigation system | Mango/Palm orchard | Palm and mango plantations that are mostly located in wetlands naturally humid; localized irrigation systems have been also installed to manage water availability and piping. |
| Cattle grazing |                          |             |
| Grazing        | Scrubland                | Portion of the space that is intended for livestock grazing. Areas of planted or natural pastures are used for this purpose. |
| Barnyards      | Mango/Palm orchard       | Place where livestock is kept and that forms part of a household system. |
| Artisanal fisheries | Fluvial stream/seascape | Place where fish and crustacean harvesting is developed, typically using self-made, improvised nets or traps. River shrimp, tilapia, bass, catfish and other marine and river species are obtained from this activity. |
| Residential    | Mango/Palm orchard       | Household system (the Nexpa settlement). |
| Recreation     |                          |             |
| Swimming area (river) | Fluvial stream | This activity is developed in suitable river tracts, and is carried on by villagers, especially during the mid-dry season, in their spare time. Barbecues and social gatherings are associated with this activity. |
| Volleyball (sports) | Mango/Palm orchard | Volleyball courts scattered over the lowlands. |
| Swimming area (ocean) | Seascape | On the beaches all year long. |
| Tourism        | Seascape                 | Unlike recreational activities, tourism applies mostly to foreigners that visit Nexpa to enjoy the seascape especially during winter. |
| Extractive activities |                     |             |
| Building material | Bare land            | This class relates to the extraction of raw materials such as gravel and sands for construction purposes. |
| Wood and fuel   | Tropical dry forest     | Extraction of timber and firewood. |
| Brick production | Scrubland              | A manufacture activity where clays and sands are extracted from the soil in order to produce building materials; bricks are dried using solar radiation or open oven. |
| Game hunting    | Tropical dry forest     | This is found in the relatively most isolated places of the area. Deer and mourning doves are hunted seasonally. |
and structure. The outputs are interpreted through an arrangement of data in a low-dimensional space where the similar entities are close and dissimilar entities are far apart (Gauch, 1982). In this low-dimensional space, dimensions are represented graphically by axes which simplify the interpretation of spatial patterns. CA and other similar multivariate statistical treatments have been applied in other studies to examine the relation between geomorphic and other environmental variables (Osterkamp et al., 1995; Lechterbeck et al., 2009; Castillo-Rodríguez et al., 2010; Zhao et al., 2015). To our knowledge, CA has not been used for the purposes of the present exercise.

In order to explore data grouping and potential relationships between landforms and land use classes, correspondence analysis (CA) was performed using R© 3.1.0 with the FactomineR package. The input matrix for CA, shown in Table 4, reveals the area values (ha) shared between landform and land use polygons. A land use unit may contain one or more activities. The key (landform) includes coastal plain (CP), denudational slope (DS), footslope (FS), lower luvial terrace (Lt), major stream channel (Mj), minor stream channel (Mn), stream channel deposits (Sd), summit surface (SS), and upper luvial terrace (Ut). The analysis helps in understanding the spatial relationships and potential interactions between land use and landform conditions.
package (Husson et al., 2007). The results produce a graphical output and a summary of indicators (contribution, square cosine and eigenvalues). The contribution indicates which classes are the most representative of each dimension while square cosine measures, in a scale from 0 to 1, indicates the quality of the representation of a particular class (Lê et al., 2008). Eigenvalues represent the proportion of variance that is explained by each particular dimension (Husson et al., 2010).

Figure 3. Landform map of the Nexpa Valley.
Figure 4. Land use map of the Nexpa Valley, southwest Mexico (See Table 3). Iconography from the Noun Project (https://thenounproject.com/). See the list of attribution per creator in the acknowledgement section below.
Results

Descriptive attributes of polygons and classes
Eighty-nine landform polygons were delimited; 42 out of them belonged to the summit surface class which happened to be, in area covered, one of the smaller categories. The denudational slopes and hills occupy the largest proportion of land (794 ha, 56.6%), followed by the coastal plain (317 ha, 22.6%). The valley area represents 14.7% of total surface (Fig. 3). Agriculture occurred in approximately 29.3% of the total area, whereas rain-fed agriculture occupied about 18.0% of the total area, and extensive irrigated agriculture occurred in 9.5%, and localized irrigated agriculture in 1.8% (Fig. 4).

Correspondence Analysis
Correspondence analysis (CA) arranged entities based on their mutual correspondence. A first analysis, including all classes, produced unclear patterns of activity distribution over fluvial and denudational landforms (Fig. 5). The first three dimensions explain 75.5% of the total variance (Table 5). The results suggest that the major stream channel and coastal plain associate most-

Figure 5. First Correspondence Analysis (CA) between landform and land use classes. Key (numbers): 1: barnyards; 2: swimming area (ocean) and tourism; 3: swimming area (river); 4: brick production; 5: building materials; 6: grazing, wood and fuel extraction and game hunting; 7: localized irrigation; 8: localized irrigation, barnyards, brick production and residential; 9: localized irrigation and grazing; 10: localized irrigation, grazing and tourism; 11: mixed irrigation system; 12: mixed irrigation system and barnyards; 13: mixed irrigation system and grazing; 14: rain-fed agriculture; 15: rain-fed agriculture, barnyards, brick production and residential (household system); 16: rain-fed agriculture and grazing; 17: rain-fed agriculture, grazing and tourism; 18: rain-fed agriculture and tourism; 19: artisanal fisheries (river shrimp, tilapia, catfish); 20: artisanal fisheries (river shrimp, tilapia, catfish) and swimming area (river); 21: artisanal fisheries (river shrimp, tilapia, catfish) and tourism; 22: artisanal fisheries (sea products); 23: tourism; 24: wood and fuel extraction and game hunting. Key (letters): CP: coastal plain; DS: denudational slope; FS: footslope; Lt: lower fluvial terrace; Mj: major stream channel; Mn: minor stream channel; Sd: stream channel deposits; SS: summit surface; Ut: upper fluvial terrace.
Table 5. Eigenvalues from the first correspondence analysis

| Eigenvalues             | Dim.1 | Dim.2 | Dim.3 |
|-------------------------|-------|-------|-------|
| Variance                | 0.9   | 0.8   | 0.5   |
| % of variance           | 29.6  | 28.0  | 17.9  |
| Cumulative % of variance| 29.6  | 57.6  | 75.5  |

Table 6. Correlation values from the first CA including all categories. Key: Dim: dimension; ctr: contribution; cos2: square cosine

| Category                        | Dim.1  | ctr  | cos2 | Dim.2  | ctr  | cos2 | Dim.3  | ctr  | cos2 |
|---------------------------------|--------|------|------|--------|------|------|--------|------|------|
| Coastal plain (CP)              | 0.6    | 8.2  | 0.1  | -1.6   | 68.3 | 0.9  | 0.1    | 0.6  | 0.0  |
| Denudational slope (DS)         | -0.4   | 11.2 | 0.4  | 0.4    | 9.0  | 0.3  | -0.3   | 9.8  | 0.2  |
| Footslope (FS)                  | -0.3   | 0.4  | 0.0  | 0.1    | 0.0  | 0.0  | -0.3   | 0.7  | 0.0  |
| Lower fluvial terrace (Lt)      | -0.4   | 0.6  | 0.0  | 0.5    | 0.8  | 0.1  | 0.2    | 0.2  | 0.0  |
| Major stream channel (Mj)       | 4.2    | 78.3 | 0.8  | 1.9    | 17.2 | 0.2  | -0.3   | 0.5  | 0.0  |
| Minor stream channel (Mn)       | -0.3   | 0.2  | 0.0  | 0.4    | 0.4  | 0.0  | 0.2    | 0.2  | 0.0  |
| Stream channel deposits (Sd)    | -0.2   | 0.2  | 0.0  | 0.8    | 2.8  | 0.1  | 3.0    | 67.4 | 0.8  |
| Summit surface (SS)             | -0.5   | 0.5  | 0.3  | 0.4    | 0.4  | 0.2  | -0.4   | 0.5  | 0.2  |
| Upper fluvial terrace (Ut)      | -0.4   | 0.4  | 0.0  | 0.7    | 1.1  | 0.0  | 2.2    | 20.2 | 0.4  |

ly with artisanal fisheries, swimming areas and tourism. While this statement seems accurate, it reveals that major stream channel and coastal plain are capturing too much variance in the analysis (Table 6). Thus, a second analysis was performed excluding both, major stream channel and coastal plain classes.

In this second analysis, the first three dimensions now explain close to 85% of the total variance (Table 7). The first dimension (axis I) indicates a difference between components such as the stream channel deposits and upper fluvial terraces, with footslopes, denudational slopes and hills, and summit surfaces; the second dimension (axis II) explains the variance between minor stream channel and lower fluvial terraces, with denudational slopes and hills, and summit surfaces (Fig. 6).

Stream channel deposits are strongly correlated to localized irrigation, grazing and tourism; while the upper fluvial terraces are correlated to rain-fed agriculture and grazing (Table 8). The lower fluvial terraces associate with extraction of building material, localized grazing, and grazing. The footslopes, denudational slopes and hills, and summit surfaces show a complex pattern of activities strongly associated with grazing, wood and fuel extraction and game hunting. These activities are consistently distributed outside the valley bottom.
he third dimension (16.3%) (Fig. 7) explains the variance within the valley components, specifically between the upper and lower terraces and the minor and main stream channel deposits. Productive activities such as localized irrigation, grazing or barnyard systems can be found in terraces whilst recreation and touristic activities are associated with minor and main stream channel deposits.

**Discussion**

The analysis has indicated a significant correspondence between geomorphic and land use patterns. There was a lack of correlation between land uses in the fluvial landforms at the valley bottom, and the denudational landforms. Within fluvial elements in the valley, the minor stream channel was significantly different from the lower fluvial terrace and the other fluvial entities. This suggests that the activities were well differentiated in terms of their correlation with the valley entities.

The distribution of land uses as related to landforms showed both simple and complex results. Land uses associated with fluvial landforms depicted rather simple associations. The upper fluvial terraces and stream channel deposits, for example, are clearly linked with agricultural practices (Kariya et al., 2005; Akça et al., 2008; Romic et al., 2012). This is due to the presence of relatively good quality, fertile soils with an adequate moisture regime. Lower fluvial terraces, on the other hand,
Table 8. Correlation values from the second CA. Key: Dim: dimension; ctr: contribution; cos2: square cosine

|                                | Dim.1 | ctr | cos2 | Dim.2 | ctr | cos2 | Dim.3 | ctr | cos2 |
|--------------------------------|-------|-----|------|-------|-----|------|-------|-----|------|
| Denudational slope (DS)        | -0.2  | 8.4 | 0.7  | -0.1  | 2.9 | 0.2  | 0.0   | 0.4 | 0.0  |
| Footslope (FS)                 | -0.3  | 1.1 | 0.0  | -0.2  | 0.5 | 0.0  | -0.1  | 0.4 | 0.0  |
| Lower fluvial terrace (Lt)     | 0.2   | 0.3 | 0.0  | 1.0   | 11.6| 0.3  | 1.0   | 19.5| 0.3  |
| Minor stream channel (Mn)      | 0.3   | 0.3 | 0.0  | 3.6   | 81.7| 0.9  | -0.9  | 8.3 | 0.1  |
| Stream channel deposits (Sd)   | 2.6   | 69.7| 0.9  | -0.4  | 2.9 | 0.0  | -0.9  | 18.3| 0.1  |
| Summit surface (SS)            | -0.3  | 0.4 | 0.3  | -0.2  | 0.3 | 0.2  | 0.0   | 0.0 | 0.0  |
| Upper fluvial terrace (Ut)     | 1.9   | 19.8| 0.4  | 0.1   | 0.1 | 0.0  | 2.0   | 53.1| 0.5  |

Figure 7. Second Correspondence Analysis (CA) of axes 1 and 3 displayed (Dim1 and Dim3). Input data are from table 4. Key (numbers): 1: barnyards; 2: swimming area (river); 3: brick production; 4: building material; 5: grazing, wood and fuel extraction and game hunting; 6: localized irrigation; 7: localized irrigation, barnyards, brick production and residential activities; 8: localized irrigation and grazing; 9: localized irrigation, and tourism; 10: mixed irrigation system and barnyards; 11: mixed irrigation system and grazing; 12: rain-fed agriculture; 13: rain-fed agriculture, barnyards, brick production and residential activities; 14: rain-fed agriculture and grazing; 15: rain-fed agriculture, grazing and tourism; 16: rain-fed agriculture and tourism; 17: wood and fuel extraction and game hunting. Key (letters): see table 8 above.
were associated with material extraction because of the abundance of gravel and coarse sands in these locations along with an acceptable accessibility. In fact, this activity may be causing channel degradation and diversions, bank erosion, increased sediment loads, and new patterns of deposition (Erskine, 1990; Gaillot and Piégay, 1999). A more complex pattern of land use distribution occurred on denudational slopes and hills, and footslopes, which are difficult-to-access landforms covered by tropical dry forest and scrubland. Despite accessibility problems, land use patterns on steep lands are highly diverse and encompass rain-fed agriculture and grazing. In this case, adaptive, cultural and historical strategies rather than only land qualities (Hudson, 2004) seem to better explain land use occupation. Agricultural activities are being and have been developed over the area in both steep and gentle landforms for decades, as reported long time ago by cultural geographic surveys (Sauer, 1941).

In tropical regions, land use and land management are complex and so is their relationship with terrain itself. Remotely sensed land cover data is a good departing point to approach land use distribution, but it is not sufficient to fully understand the nature and dynamics of these human practices, particularly not in tropical rural mosaics. For example, non-timber forest management activities, such as game hunting and fuel extraction, seem to have promoted conservation of the tropical dry forest, but this observation needs further research. Quantitative analyses are useful to describe patterns while qualitative analyses derived from participatory field research are crucial to understand patterns. In this sense, CA yield best results when coupled to additional evaluations.

Conclusions

Correspondence analysis proved to be an effective tool to identify the spatial correlation of land use and landform entities. Through CA, the results of simple GIS map overlaying are further exploited to reach more robust outcomes. The complexity of land use and landform patterns is thus better described. Though this approach was tested at the local scale, this method could be also be applied, by providing properly gathered data, at a regional level. The classification schemes are as relevant as data analyses; field work, especially using a participatory perspective proved crucial. The results can be easily transferred to local decision-makers and rural producers; they are understandable, and refer to entities and relationships recognized by all stakeholders. In addition, this exercise allowed, with limited effort, the fast mapping of flooding prone areas based on land use and terrain delineations (Segundo-Métay and Bocco, 2015).

This approach could be effective for achieving sound rural land use planning in developing countries. The method is relatively simple and the participation of local producers in the definition of map units is insured. The spatial arrangement of human activities, that would otherwise remain invisible with mere remote sensing and a GIS-based approach, is cleared out.

Several limitations of this study may be considered for future research on the relationships between landforms and land use particularly in tropical dry regions. First, the boundaries of land use polygons may be transition zones which are not adequately represented by segments. A fuzzy classification (Gurnell et al., 1996; Thapa and Murayama, 2009; Da Silva et al., 2015) or a multi-point-and-attribute data structure (Huck et al., 2014) may help deal with this problem. A pixel-based classification instead of a vector data structure could also help this kind of analysis. Second, a historical appraisal of land use development over time would shed light on the analysis of the correlation with landforms (Briggs et al., 2006; Neil et al., 2014). This would provide more explanatory rather than exploratory results as was the case in our study.

Acknowledgements

Research on which this paper is based was funded by PAPIIT-UNAM projects IN301914 and IN305010. The first author was granted a CONACYT scholarship to pursue a Masters degree in Geography (UNAM), and benefited from the
Student Mobility Program between UNAM and the University of Ottawa (agreement 28293-373-22-II-11). We thank each of the informants for participating in the field research. Last but not least, we give credit to each of the Noun Project icon creators: drop by Wayne Tyler Sall, faucet by Kenneth Von Alt, palm by Stephanie Wauters, icon creators: drop by Wayne Tyler Sall, faucet by Kenneth Von Alt, palm by Stephanie Wauters, etc.

REFERENCES

Akça, E., K.M. Çimrin, J. Ryan, T. Nagano, M. Topaksu & S. Kapur (2008), "Differentiating the natural and man-made terraces of Lake Van, Eastern Anatolia, utilizing earth science methods", *Lakes & Reservoirs: Research & Management*, vol. 13, issue 1, pp. 83–93. DOI: 10.1111/j.1440-1770.2007.00357.x

Bakker, M. & A. Veldkamp (2012), "Changing relationships between land use and environmental characteristics and their consequences for spatially explicit land-use change prediction", *Journal of Land Use Science*, vol. 7, issue 4, pp. 407–24. DOI: 10.1080/1747423X.2011.595833

Beh, E.J. (2007), "Simple Correspondence Analysis: A Bibliographic Review", *International Statistical Review*, vol. 72, issue 2, pp. 257–84. DOI: 10.1111/j.1751-5823.2004.tb00236.x

Bibby, P. & J. Shepherd (2000), "GIS, land use, and representation", *Environment and Planning B: Planning and Design*, vol. 27, issue 4, pp. 583–98. DOI: 10.1068/b2647

Bocco, G., M. Mendoza & A. Velázquez (2001), "Remote sensing and GIS-based regional geomorphological mapping: A tool for land use planning in developing countries", *Geomorphology*, vol. 39, issues 3-4, pp. 211–19. DOI: 10.1016/S0169-555X(01)00027-7

Briggs, J.M., K.A. Spielmann, H. Schaafsm, K.W. Kintigh, M. Kruse, K. Morehouse & K. Schollmeyer (2006), "Why ecology needs archaeologists and archaeology needs ecologists", *Frontiers in Ecology and the Environment*, vol. 4, issue 4, pp. 180–88. DOI: 10.1890/1540-9295(2006)004[0180:WENAAA]2.0.CO;2

Brown, D.G. & J.D. Duh (2004), "Spatial simulation for translating from land use to land cover", *International Journal of Geographical Informa
tion Science*, vol. 18, issue 1, pp. 35–60. DOI: 10.1080/1365881031001620906

Campos, M., A. Velázquez, G.B. Verdinelli, M. Skutsch, M.B. Juncà & Á.G. Priego-Santander (2012), "An interdisciplinary approach to depict landscape change drivers: A case study of the Ticuiz agrarian community in Michoacan, Mexico", *Applied Geography*, vol. 32, issue 2, pp. 409–19. DOI: 10.1016/j.apgeog.2011.06.004

Castaldi, F. & U. Chiocchini (2012), "Effects of land use changes on badland erosion in clayey drainage basins, Radicofani, Central Italy", *Geomorphology*, vol. 169, pp. 98–108. DOI: 10.1016/j.geomorph.2012.04.016

Castillo-Rodríguez, M., J. López-Blanco & E. Muñoz-Salinas (2010), "A geomorphologic GIS-multivariate analysis approach to delineate environmental units, a case study of La Malinche volcano (central México)", *Applied Geography*, vol. 30, issue 4, pp. 629–38. DOI: 10.1016/j.apgeog.2010.01.003

Da Silva, A.F., A.P. Barbosa, C.R.L. Zimback, P.M.B. Landim & A. Soares (2015), "Estimation of croplands using indicator kriging and fuzzy classification", *Computers and Electronics in Agriculture*, issue 111, pp. 1–11. DOI: 10.1016/j.compag.2014.11.020

Downs, P.W., S.R. Dusterhoff & W. Sears (2013), "Reach-scale channel sensitivity to multiple human activities and natural events: Lower Santa Clara River, California, USA", *Geomorphology*, issue 189, pp. 121–34. DOI: 10.1016/j.geomorph.2013.01.023

Erskine, W. (1990), "Environmental impacts on sand and gravel extraction on river systems", in Davie, P. (ed.), *The Brisbane River: a source book for the future*, Australian Littoral Society, Moorooka, pp. 295–302.

Fang, H., G. Liu & M. Kearney (2005), "Georelational Analysis of Soil Type, Soil Salt Content, Landform, and Land Use in the Yellow River Delta, China", *Environmental Management*, vol. 35, issue 1, pp. 72–83. DOI: 10.1007/s00267-004-3066-2

Foody, G.M. (1996), "Approaches for the production and evaluation of fuzzy land cover classifications from remotely-sensed data", *International Journal of Remote Sensing*, vol. 17, issue 7, pp. 1317–40. DOI: 10.1080/01431169608948706

Gaillot, S. & H. Piégay (1999), "Impact of Gravel-Mining on Stream Channel and Coastal Sediment Supply : Example of the Calvi Bay in Corsica (France)", *Journal of Coastal Research*, vol. 15, issue 3, pp. 774–88.

García-Ruiz, J.M., N. Lana-Renault, S. Beguería, T. Lasanta, D. Regiës, E. Nadal-Romero, P. Serrano-Muela, J.I. López-Moreno, B. Alvera, C. Martí-Bono & L.C. Alatorre (2010), "From plot to regional scales:..."
Interactions of slope and catchment hydrological and geomorphic processes in the Spanish Pyrenees”, *Geomorphology*, vol. 120, issues 3-4, pp. 248–57. DOI: 10.1016/j.geomorph.2010.03.038

Gauch, H. G. (coord.; 1982), *Multivariate Analysis in Community Ecology*, Cambridge University Press, vol. 34, Cambridge.

González-Abraham, C., E. Ezcurra, P.P. García-Rubio, M. Kolb, J.E. Bezaury (2015), "The Human Footprint in Mexico: Physical Geography and Historical Legacies”, *PLOS ONE*, vol. 10, issue 3, pp. e0121203. DOI: 10.1371/journal.pone.0121203

Gurnell, A., P. Angold & P. Edwards (1996), "Extracting information from river corridor surveys", *Applied Geography*, vol. 16, issue 1, pp. 1–19. DOI: 10.1016/0143-6228(95)00224-4

Huck, J.J., J.D. Whaytt & P. Coulton (2014), "Spraycan: A PPGIS for capturing imprecise notions of place", *Applied Geography*, issue 55, pp. 229–37. DOI: 10.1016/j.apgeog.2014.09.007

Hudson, P.F. (2004), "Geomorphic context of the prehistoric Huastec floodplain environments: lower Pánuco basin, Mexico”, *Journal of Archaeological Science*, vol. 31, issue 6, pp. 653–68. DOI: 10.1016/j.jas.2003.06.002

Hudson, P.F., R.R. Colditz & M. Aguilar-Robledo (2006), "Spatial relations between floodplain environments and land use - land cover of a large lowland tropical river valley: Pánuco basin, México."., *Environmental management*, vol. 38, issue 3, pp. 487–503. DOI: 10.1007/s00267-003-0157-4

Husson, F., J. Josse, S. Le & J. Mazet (2007), "FactoMineR: Factor Analysis and Data Mining with R. R package version 1.04”, CRAN R project, november 3 2015. [https://cran.rproject.org/web/packages/FactoMineR/index.html]

Husson, F., S. Le & J. Pages (coord.; 2010), *Exploratory Multivariate Analysis by Example Using R*, CRC Press, vol 15, Boca Raton.

Johnston, R. J., & J.D. Sidaway (coord.; 2004), *Geography & Geographers: Anglo-American Human Geography Since 1945*, Arnold, London.

Kariya, Y., S. Iwata & T. Inamura (2005), "Geomorphology and pastoral-agricultural land use in Cotahuasi and Punca, southern Peruvian Andes”, *Geographical Review of Japan*, vol. 78, issue 12, pp. 842–62. DOI: 10.4157/grj.78.78.842

Knight, J. & S. Harrison (2013), "'A land history of men': The intersection of geomorphology, culture and heritage in Cornwall, southwest England", *Applied Geography*, issue 42, pp. 186–94. DOI: 10.1016/j.apgeog.2013.03.020

Knox, J.C. (2006), "Floodplain sedimentation in the Upper Mississippi Valley: Natural versus human accelerated”, *Geomorphology*, vol. 79, issues 3-4, pp. 286–310. DOI: 10.1016/j.geomorph.2006.06.031

Krasilnikov, P.V., N.E. García-Calderón, A. Ibáñez-Huerta, M. Bazán-Mateos & J.R. Hernández-Santana (2011), "Soilscapes in the dynamic tropical environments: The case of Sierra Madre del Sur”, *Geomorphology*, vol. 135, issues 3-4, pp. 262–70. DOI: 10.1016/j.geomorph.2011.02.013

Latocha, A. (2009), "Land-use changes and longer-term human–environment interactions in a mountain region (Sudetes Mountains, Poland)”, *Geomorphology*, vol. 108, issue 1-2, pp. 48–57. DOI: 10.1016/j.geomorph.2008.02.019

Lé, S., J. Josse & F. Husson (2008), "FactoMineR: An R package for multivariate analysis”, *Journal of Statistical Software*, vol. 25, issue 1, pp. 1–18. DOI: 10.1109/j.envint.2008.06.007

Lechtenberg, J., A.J. Kalis & J. Meurers-Bakke (2009), "Evaluation of prehistoric land use intensity in the Rhenish Loessboerde by canonical correspondence analysis—A contribution to LUCIFS", *Geomorphology*, vol. 108, issues 1-2, pp. 138–44. DOI: 10.1016/j.geomorph.2008.08.019

Migoń, P. & A. Latocha (2013), "Human interactions with the sandstone landscape of central Sudetes”, *Applied Geography*, issue 42, pp. 206–16. DOI: 10.1016/j.apgeog.2013.03.015

Miller, B.W. & M.W. Doyle (2014), "Rangeland management and fluvial geomorphology in northern Tanzania.", *Geomorphology (Amsterdam, Netherlands)*, issue 214, pp. 366–77. DOI: 10.1016/j.geomorph.2014.02.018

Neil, K., K. Gajewski & M. Betts (2014), "Human–ecosystem interactions in relation to Holocene environmental change in Port Joli Harbour, southwestern Nova Scotia, Canada”, *Quaternary Research*, vol. 81, issue 2, pp. 203–12. DOI: 10.1016/j.qres.2014.01.001

Osterkamp, W.R., C.R. Hupp & M.R. Schening (1995), "Little River revisited — thirty-five years after Hack and Goodlett”, *Geomorphology*, vol. 13, issues 1-4, pp. 1–20. DOI: 10.1016/0169-555X(95)00063-B

Paneque-Gálvez, J., J.F. Mas, G. Moré, J. Cristóbal, M. Orta-Martínez, A.C. Luz, M. Guèze, M.J. Macía & V. Reyes-García (2013), "Enhanced land use/cover classification of heterogeneous tropical landscapes using support vector machines and textural homogeneity”, *International Journal of Applied Earth Observation and Geoinformation*, issue 23, pp. 372–83. DOI: 10.1016/j.jag.2012.10.007
Ramírez-Herrera, M.T., M. Lagos, I. Hutchinson, V. Kostoglodov, M.L. Machain, M. Caballero, A. Gojtuichaihvili, B. Aguilar, C. Chagué-Goff, J. Goff, A.-C. Ruiz-Fernández, M. Ortiz, H. Nava, F. Bautista, G.I. Lopez & P. Quintana (2012), "Extreme wave deposits on the Pacific coast of Mexico: Tsunamis or storms? – A multi-proxy approach", Geomorphology, issues 139-140, pp. 360–71. DOI: 10.1016/j.geomorph.2011.11.002

Rhind, D., & R. Hudson (coord.; 1980), Land Use, Methuen, London.

Romic, D., M. Romic, M. Zovko, H. Bakic & G. Ondrasek (2012), "Trace metals in the coastal soils developed from estuarine floodplain sediments in the Croatian Mediterranean region.", Environmental geochemistry and health, vol. 34, issue 4, pp. 399–416. DOI: 10.1007/s10653-012-9449-z

Sauer, C. (1941), "The Personality of Mexico", Geographical Review, vol. 31, issue 3, pp. 353–64.

Segundo-Métay, I. & G. Bocco (2015), "Vulnerable and Invisible : Impact of Hurricane Activity on a Peasant Population in a Mountainous Region on the Mexican Pacific Coast", Journal of Latin American Geography, vol. 14, issue 2, pp. 159–79. DOI: 10.1353/lag.2015.0016

Thapa, R.B. & Y. Murayama (2009), "Urban mapping, accuracy, & image classification: A comparison of multiple approaches in Tsukuba City, Japan", Applied Geography, vol. 29, issue 1, pp. 135–44. DOI: 10.1016/j.apgeog.2008.08.001

Turner, B.L. (2002), "Contested Identities: Human-Environment Geography and Disciplinary Implications in a Restructuring Academy", Annals of the Association of American Geographers, vol. 92, issue 1, pp. 52–74. DOI: 10.1111/1467-8306.00279

Vanacker, V., A. Molina, G. Govers, J. Poesen, G. Dercon & S. Deckers (2005), "River channel response to short-term human-induced change in landscape connectivity in Andean ecosystems", Geomorphology, vol. 72, issues 1-4, pp. 340–53. DOI: 10.1016/j.geomorph.2005.05.013

Vitousek, P.M., H.A. Mooney, J. Lubchenco & J.M. Melillo (1997), "Human Domination of Earth’s Ecosystems", Science, vol. 277, issue 5325, pp. 494–99. DOI: 10.1126/science.277.5325.494

van Zuidam, R. A. (coord.; 1986), Aerial Photo-interpretation in Terrain Analysis and Geomorphic Mapping, Smits Publishers, The Hague.

Zhao, J., L. Lin, K. Yang, Q. Liu & G. Qian (2015), "Influences of land use on water quality in a reticular river network area: A case study in Shanghai, China", Landscape and Urban Planning, issue 137, pp. 20–29. DOI: 10.1016/j.landurbplan.2014.12.010