

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

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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 estadís-

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tica multivariada. Estos análisis permiten interpretar la naturaleza de las relaciones espaciales entre los diferentes elementos que conforman el paisaje. Por lo tanto, se exploró el grado de correlación cuantitativa entre geoformas y usos del suelo en una región tropical seca de la costa Pacífico mexicana. Se eligió al valle bajo de Nexpa, en la región Sierra-Costa del estado de Michoacán, como caso de estudio por su grado de complejidad morfogénica y por su composición litológica y estructural heterogénea. La colecta de datos se realizó en dos fases: una fase preliminar de interpretación de imágenes satelitales (Quickbird 2008) y una fase de verificación en campo y levantamiento del terreno. La clasificación del relieve se hizo utilizando pares estereoscópicos impresos a una escala 1:10 000. Los datos de uso del suelo, por otra parte, se interpretaron utilizando los datos de cubierta del terreno como insumo. Posteriormente, se clasificaron estos datos a partir de técnicas de levantamiento participativo y etnografía de campo. Las capas de información geográfica fueron digitalizadas, vectorizadas e incorporadas a un SIG. De esta forma, se pudo obtener una matriz con los datos de sobreposición espacial de los polígonos. Posteriormente, se aplicó un Análisis de Correspondencia (AC) que fue utilizado para identificar el grado de correlación entre usos y geoformas. Los resultados muestran una correspondencia significativa entre diferentes entidades. Se aplicó un primer AC con todas las clases del terreno. Los resultados revelaron

que la “planicie costera” y el “lecho mayor” se asocian, mayormente, a usos como la pesca artesanal, el nado y las actividades turísticas. Una segunda etapa fue aplicada excluyendo las clases de “planicie costera” y “lecho mayor”, que capturaron demasiada varianza en el primer análisis. La prueba posterior develó mayor detalle en asociaciones espaciales más finas y menos evidentes en el paisaje. Las geoformas de origen fluvial se asociaron con patrones más simples de actividad humana. Como contraparte, en las geoformas de denudación, el análisis reveló patrones más complejos y diversos con los usos del suelo. Las actividades agrícolas y ganaderas se presentaron, de diferentes maneras, tanto en geoformas fluviales como en las de denudación. Los usos forestales no maderables, como la caza y la extracción de leña, se asociaron con áreas de mayor pendiente y podrían haber favorecido ciertos procesos de conservación del bosque tropical seco en el área. Esta última interpretación requiere de un análisis a mayor profundidad. Los resultados se discutieron en término de su relevancia y utilidad para la planeación territorial. Este enfoque podría fortalecer los procedimientos espaciales para la toma de decisiones, particularmente en áreas en donde los datos de geografía aplicada se requieren para el sondeo de usos y actividades a escala local.

Palabras clave: geoformas; uso del suelo; SIG; correlación espacial; México

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; Migoñ 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-Abraham *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



Figure 1. Nexpa Valley bottom (March 2013).

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

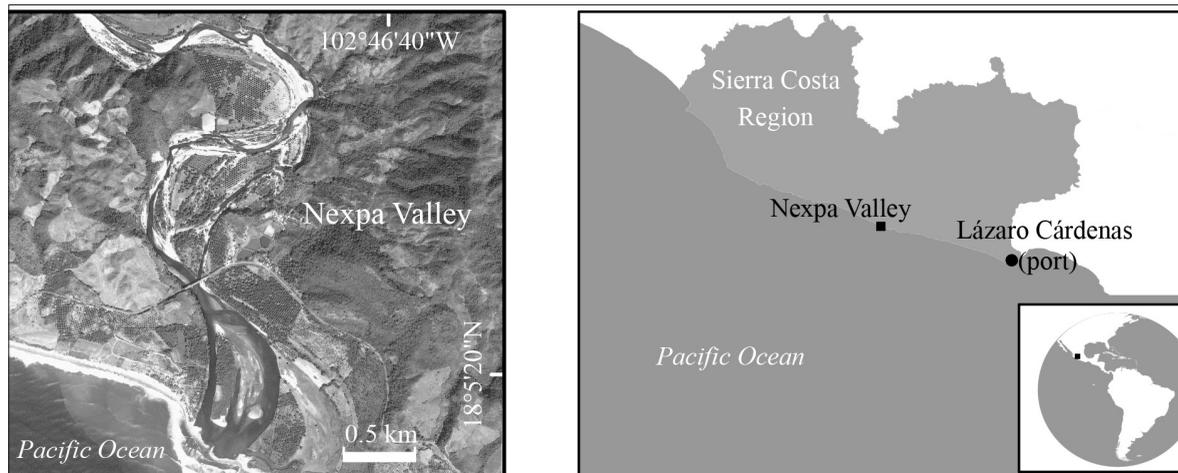


Figure 2. Location map. Source satellite image.

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

Table 2. Land cover class description of study area (modified from Brown and Duh, 2004).

Land cover class	Description
Arboreal (tree)	
Tropical dry forest	A dominantly wooded area with relatively short (in stature) vegetation (as compared to tropical wet forests); phenology strongly influenced by seasonal rainfall
Mango orchard	Mango plantations distributed mostly around the valley
Palm orchard	Palm plantations (used for coconut oil production) mostly found all over the coastal plain; a minor proportion in the valley
Riparian forest	Vertical and lateral gradients of vegetation whose distribution pattern is determined by the stream's influence, water availability and flooding
Shrub	
Scrubland	Areas dominated by shrub species that have medium vegetation cover and are mostly found in steep terrain
Herbaceous	
Undifferentiated grassland/cropland	Areas where the vegetation structure is mostly composed by gramineal species distributed both in flat and steep lands
Bare land	Displayed along vertical and lateral gradients; rocks and sediments exposed by fluvial action and have no apparent vegetative cover
Water	
Fluvial stream	The Nexpa river stream flow
Reservoir	A man-made water body of small dimensions
Seascape	The geographic unit that includes open sea

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, chili 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, <i>tilapia</i> , 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

Table 4. Input matrix for Correspondence Analysis: area values (ha) shared between landform and land use polygons. A land use unit may contain one or more activities. Key (landform): 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.

Land use / Landform	CP	DS	FS	Lt	Mj	Mn	Sd	SS	Ut
Barnyards	0.0	0.0	0.0	5.7	0.0	0.0	0.0	0.0	6.1
Swimming area (ocean) - Tourism	7.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Swimming area (river)	0.0	0.7	0.0	0.0	0.0	3.6	0.9	0.0	0.0
Brick production	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Building material	3.0	17.6	1.0	8.9	0.4	16.0	0.0	0.0	1.0
Grazing - Wood and fuel - Game hunting	0.0	188.6	5.4	9.4	0.0	0.0	0.0	3.9	0.0
Localized irrigation	0.0	1.8	1.8	0.0	0.0	0.0	0.0	0.0	0.0
Localized irrigation - Barnyards - Brick production - Residential	0.0	5.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Localized irrigation - Grazing	0.0	0.0	0.0	1.8	0.0	0.0	0.0	0.0	0.0
Localized irrigation - Grazing - Tourism	0.0	0.0	0.0	0.0	0.0	0.0	14.0	0.0	0.0
Mixed irrigation system	104.5	22.1	2.4	0.0	0.0	0.0	0.0	0.0	0.0
Mixed irrigation system- Barnyards	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mixed irrigation system - Grazing	0.7	0.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0
Rain-fed agriculture	0.0	12.1	0.0	1.6	2.6	1.1	7.8	0.0	0.0
Rain-fed agriculture - Barnyards - Brick production - Residential	0.0	5.6	0.8	0.0	0.0	0.0	0.0	0.0	0.0
Rain-fed agriculture - Grazing	0.0	48.5	2.4	1.2	0.0	0.0	31.3	1.6	22.5
Rain-fed agriculture - Grazing - Tourism	6.3	8.4	2.3	0.0	0.0	0.0	0.0	0.0	0.0
Rain-fed agriculture - Tourism	19.5	11.1	8.4	0.0	0.0	0.0	0.0	0.0	0.0
Artisanal Fisheries (river)	2.1	0.0	0.0	0.0	14.8	0.0	0.0	0.0	0.0
Artisanal Fisheries (river shrimp, tilapia) - Swimming area (river)	0.0	0.0	0.0	0.0	4.5	0.0	0.0	0.0	0.0
Artisanal Fisheries (river) -Tourism	2.5	0.0	0.0	0.0	32.9	0.0	0.9	0.0	0.0
Artisanal Fisheries (sea)	154.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tourism	12.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wood and fuel - Game hunting	3.9	478.1	26.1	14.0	0.0	3.2	0.0	20.4	0.0

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 (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).

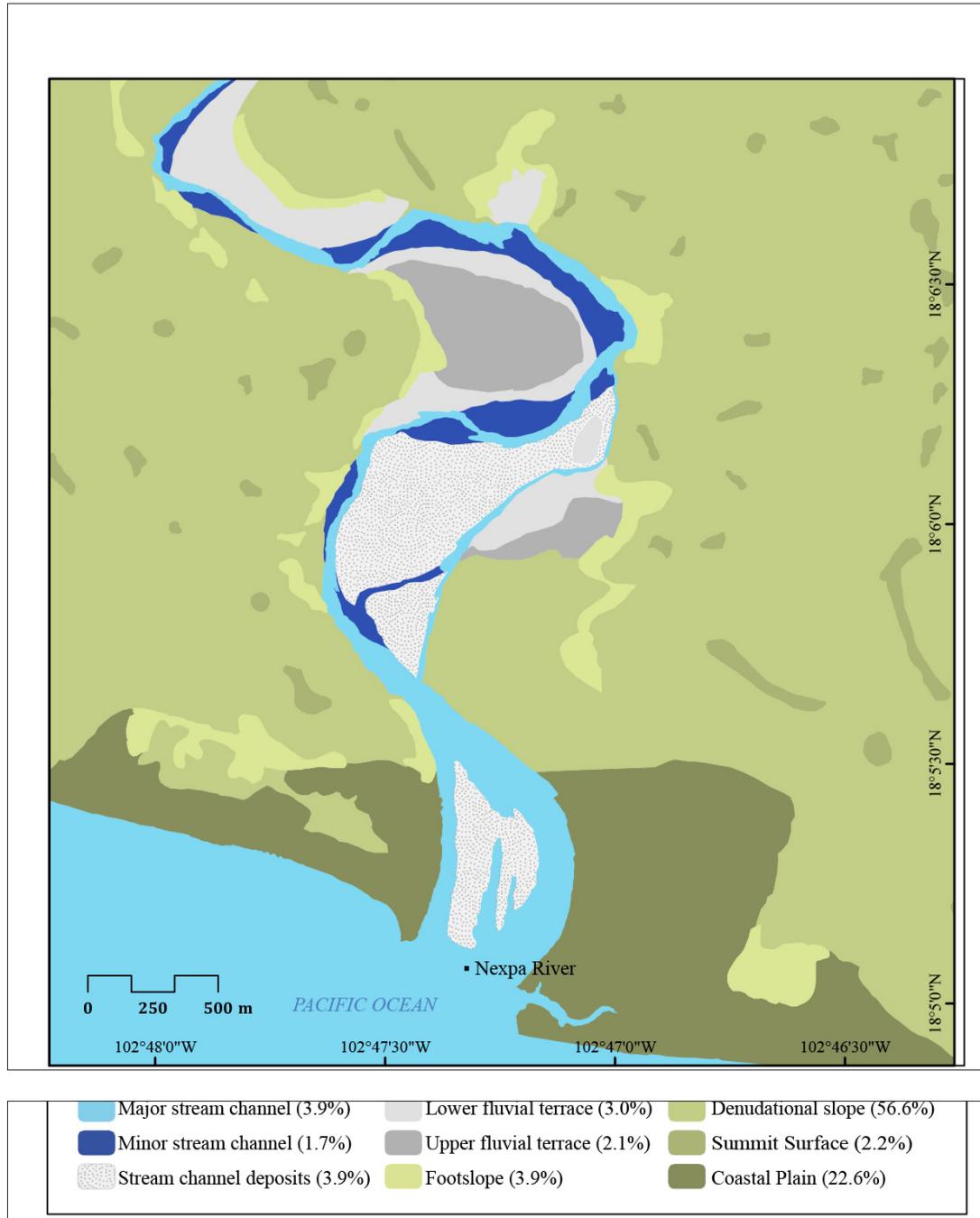


Figure 3. Landform map of the Nexpa Valley.

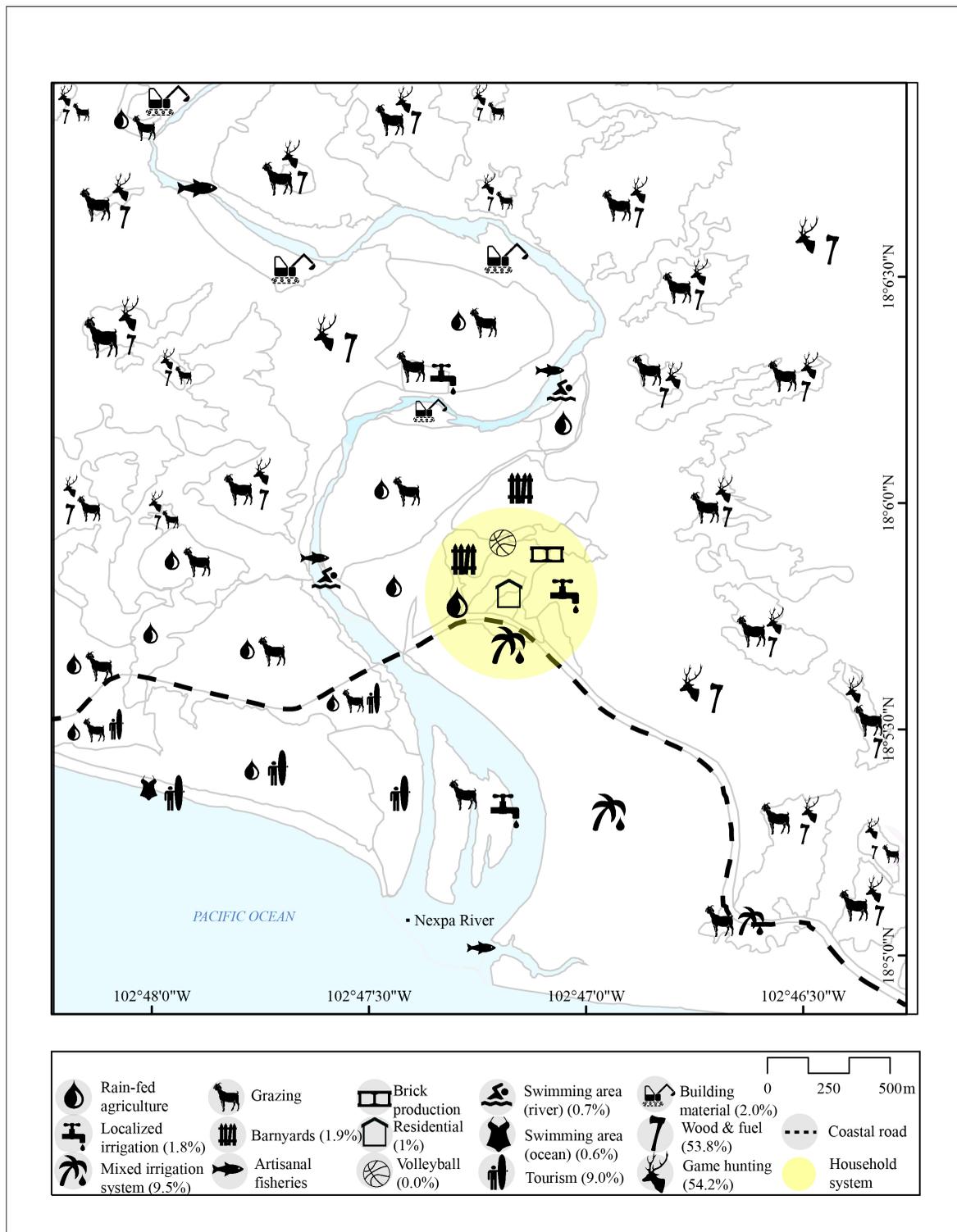


Figure 4. Land use map of the Nexpa Valley, southwest Mexico (See Table 3). Iconography from the Noun Project (<https://thenounproject.com/>). See the list of attribution per creator in the acknowledgement section below.

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-

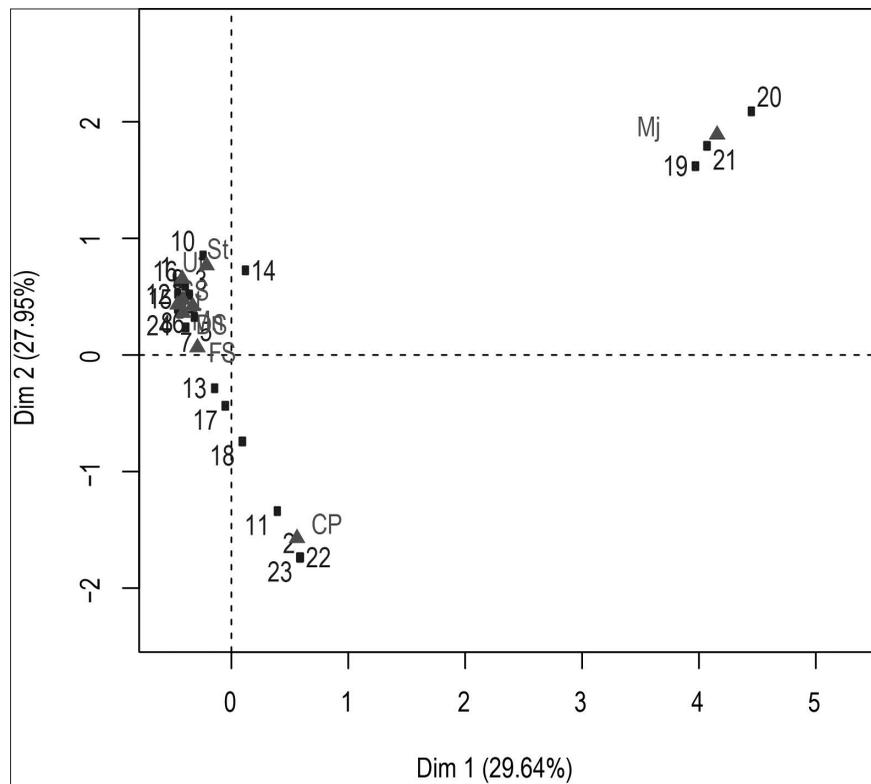


Figure 5. First Correspondence Analysis (CA) between landform and land use classes. Key (numbers): 1: barnyards; 2: swimming area (ocean) and tourism; 3: swimming area (river); 4: brick production; 5: building materials; 6: grazing, wood and fuel extraction and game hunting; 7: localized irrigation; 8: localized irrigation, barnyards, brick production and residential; 9: localized irrigation and grazing; 10: localized irrigation, grazing and tourism; 11: mixed irrigation system and barnyards; 12: mixed irrigation system and grazing; 13: mixed irrigation system and residential (household system); 14: rain-fed agriculture, barnyards, brick production and residential; 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

	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 irrigation, 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.

Table 7. Eigenvalues from second CA

Eigenvalues	Dim.1	Dim.2	Dim.3
Variance	0.5	0.4	0.2
% of variance	40.6	27.9	16.3
Cumulative % of variance	40.6	68.5	84.8

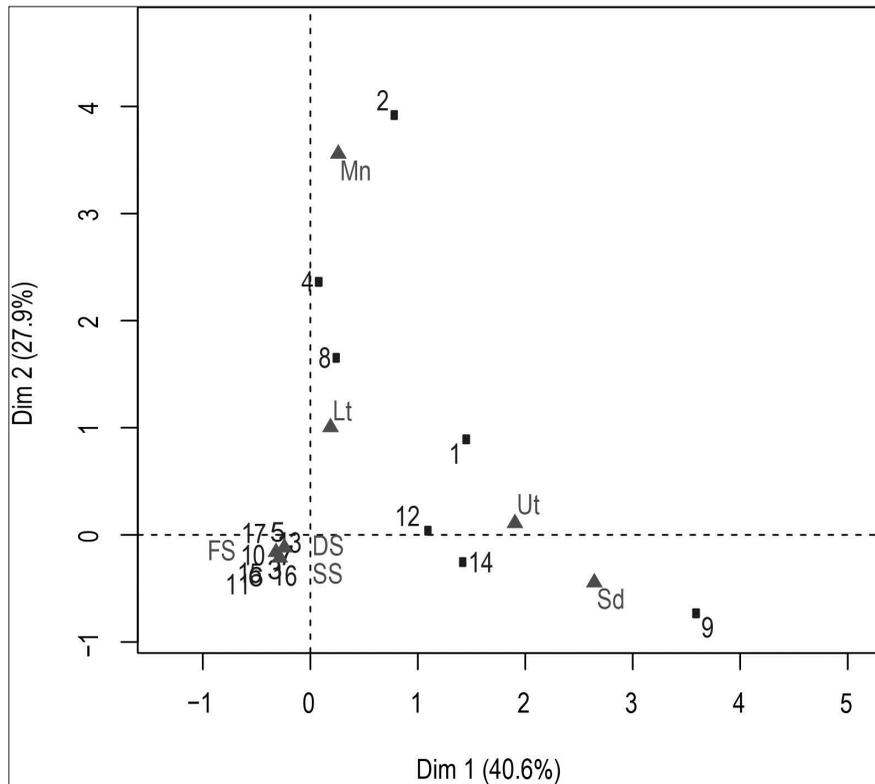


Figure 6. Second Correspondence Analysis (CA) axes 1 and 2 displayed (Dim1 and Dim2). Input data are from table 4. Key (numbers): 1: barnyards; 2: swimming area (river); 3: brick production; 4: building material; 5: grazing, wood and fuel extraction and game hunting; 6: localized irrigation; 7: localized 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 below.

The 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

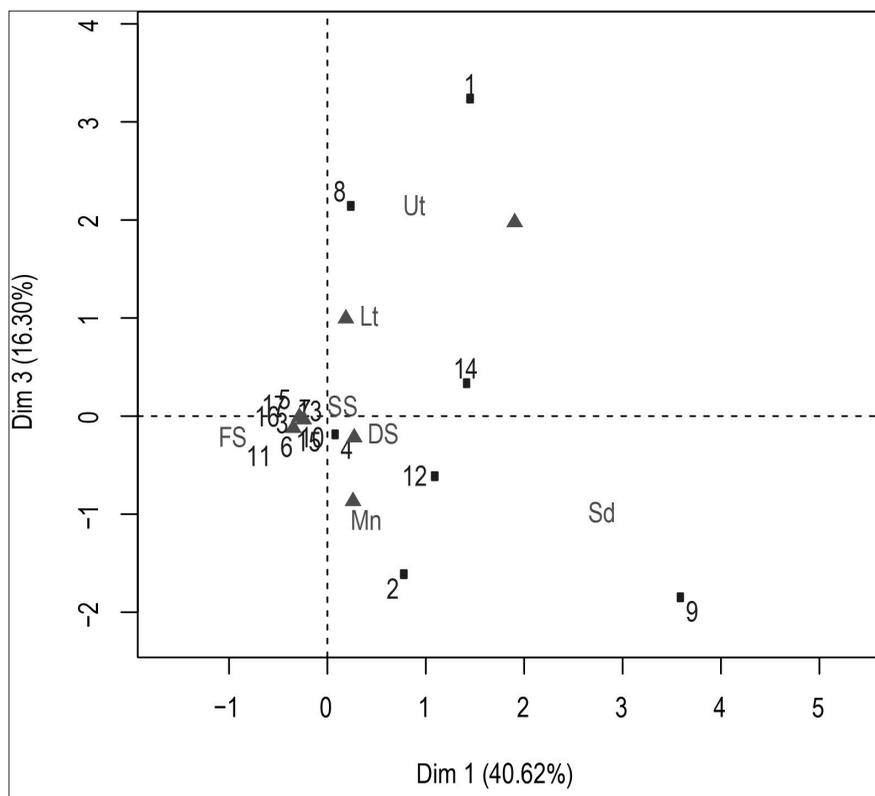


Figure 7. Second Correspondence Analysis (CA) of axes 1 and 3 displayed (Dim1 and Dim3). Input data are from table 4. Key (numbers): 1: barnyards; 2: swimming area (river); 3: brick production; 4: building material; 5: grazing, wood and fuel extraction and game hunting; 6: localized irrigation; 7: localized 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, adaptative, 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.

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