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Dynamics of fire, precipitation, vegetation and NDVI in dry forest environments in NW Argentina. Contributions to environmental archaeology

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ABSTRACT

Fire has shaped the environment and has been important for human cultural development. In this paper, we propose to study past fire events using ecological modelling. For instance, the ecology of fire can help us to understand and interpret archaeological problems related to past settlement patterns or environmental scenarios. Variation in fire regimens are related to both, vegetation and precipitation fluctuations. Recently, we have model past ecosystem dynamics using remote sensing in the Ambato Valley (Catamarca NW Argentina) ranging from 442 to 1998 CE. Our aim here is to use remotely sensed vegetation data to enhance our understanding of environmental disturbance in the period 2000–2011. We characterised the spatial-time dynamics of the annual NDVI as an indicator of vegetation functioning. Then we related the NDVI dynamics to precipitation and fire events in an arid highland environment in the area. Further, we analysed the vegetation data (monthly NDVI, MODIS/TERRA satellite, 1km^2 pixels), and the climate data: annual precipitation. Then we calculated the NDVI annual average of every pixel and the NDVI anomalies of every year over the studied period. Lastly, we related NDVI data with annual precipitation and compared the NDVIs prior to and after known fire events in this period. On a spatial scale, the results show that the NDVI values were (a) low in shrublands and in cultivated areas, (b) medium in grasslands and piedmont forest with anthropic impact, and (c) high in highland forests. Within the studied time-period, extreme positive and negative anomalies were detected. The precipitation interannual variations were greater than the NDVI inter-annual variations, thus demonstrating that in some areas of the valley the horizontal precipitation can make important contributions to the ecosystem humidity. Extreme negative anomalies were observed the year of fire and fire scars at least for the next two years. These results demonstrate the relation between structure and function of vegetation, precipitation and fire. Understanding these relations can enable us to explain results when hindcasting ("predicting" what happened during past episodes of climate change) palaeoenvironmental conditions and fire events, thus helping us to interpret different archaeological contexts related to fire events.

1. Introduction

During the last couple of years, we have worked with palaeoenvironmental reconstructions in the Ambato Valley, Catamarca Province, northwestern Argentina (Lindskoug, 2010; Lindskoug, 2014; Lindskoug, 2016a; Lindskoug and Marconetto, 2014; Marconetto, 2008; Marconetto, 2009; Marconetto, 2010; Marconetto and Lindskoug, 2015; Marconetto et al., 2014; Marconetto et al., 2015). At the same time, an ethnographical work about the perception of climate and ethnometeorology was published (Bussi, 2015). We initiated these studies because of the necessity to understand the environmental context of past populations in the inhabited area. Archaeological evidence shows that the earliest occupations of the area took place during the Formative Period at the beginning of the first millennium. Settlement data seems

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to indicate that the area had been continuously occupied until around 900–1000 according to AMS dating (Marconetto et al., 2014), which corresponds to the Regional Integration Period and the last phase of Aguada occupation in the area. Several of the archaeological sites in the area, Iglesia de Los Indios, Martínez 2 and Piedras Blancas, associated to the Aguada Culture, indicated a rapid abandonment as a result of fire events (Gastaldi, 2010; Laguens, 2006; Lindskoug, 2016a; Lindskoug, 2016b; Marconetto and Gordillo, 2008). The first palaeoenvironmental studies had indicated a possible drought at the end of the occupation of the area by the Aguada culture at the end of the first millennium (Marconetto, 2009; Marconetto, 2010). These evidence led us to initiate studies about past fire regimes in the area (Lindskoug, 2010; Lindskoug, 2014; Lindskoug, 2016a; Lindskoug, 2016b; Lindskoug and Marconetto, 2014), to analyse whether the abandonment of the valley in the last phase of the Aguada occupation was related to forest fires. Further, we also applied a method to analyse the past vegetation based on an ecosystem-process model (D'Antoni, 2006; Marconetto et al., 2015) called Hindcasting Ecosystems Model (HEMO). This model uses Normalised Difference Vegetation Indexes (NDVI) to make retrodictions about past vegetation patterns in the Late Holocene. The HEMO is a model that employs non-linear methods, like the Artificial Neural Network, built from a training model with modern NDVI and growth ring data or some other annual resolution proxy. The NDVI is calculated from spectroscopic satellite data. Satellites orbiting the earth get periodical data, available at open databases such as NOAA, NASA, thus obtaining time series. The NDVI is related to the vegetation cover and productivity, and indirectly, to precipitation, temperature, drainage, mineralogical composition and soil biota, and to all those factors that determine the vegetation status. Time series from NDVI data allow supervising the ecosystem dynamics. Then, from the training model, the retrodiction of old-time NDVI (paleo-NDVI) at an annual resolution is done, employing the training model and the growth rings belonging to the period to be retrodicted.

Thus, the HEMO permits the estimation of the vegetation status and the variations suffered in the past. Those changes can be compared with other contemporaneous environmental factors. The HEMO has already retrodicted the paleo-NDVI of the Ambato having obtained the first results for the period 442–1998 CE. It also detected great intensity paleo-NDVI fluctuation periods in the V and XV centuries. Furthermore, the model proved to be sensitive to global-scale phenomena, such as the Little Ice Age and the Medieval Warm Period Valley (Burry et al., 2017; Marconetto et al., 2015).

In this paper, we aim to characterise the spatial distribution and the annual dynamics of the NDVI (period 2000–2011) in a highland forest environment northwest of Argentina and to relate the NDVI dynamics with precipitation and fire events to see possible patterns, which can help to understand the ecology of fire in the area. The knowledge of the modern ecosystem dynamics will let improve our description of the vegetation-precipitation-fire relationship of the area, which will eventually lead to the posing of more precise palaeoenvironmental inferences.

The application of this in the field of environmental archaeology can help us to understand the palaeoenvironmental context of the past Aguada society in the area and can be used in other areas with similar environmental conditions to analyse past societies from different angles.

1.1. Ecosystems

Understanding of the environmental disturbance impact over a region requires of a characterisation of the vegetation state. Ecosystems can be characterised either by their structural or by functional parameters. The characterisation of an ecosystem by their structural parameters alone shows some deficiencies, for example the inertia of the vegetation structure can defer the perception of the ecosystem response to a disturbance (Milchunas and Lauenroth, 1995) or to changes related to climatic variations; not only that, but also the ecosystem functioning usually has a more rapid response in time than it does in structure. Therefore, the use of functional attributes represents a clear advantage to the characterisation of ecosystems into bio zones (Paruelo et al., 1998). An additional benefit is that functional attributes can be monitored through satellite data (Malingreau, 1986) which apart from exploring the vegetation dynamics, help describe the spatial heterogeneity of ecosystems. Moreover, D'Antoni and Spanner (1993) used satellite images to build models for paleoecology. Time series of continuous earth surface observations based on vegetation estimates have also significantly improved the comprehension of plant variation from a regional to a global scale (Fensholt et al., 2009; Schucknecht et al., 2013). They allow monitoring the ecosystem dynamics.

1.2. NDVI

The Normalised Difference Vegetation Index (NDVI) is related to plant cover and the vigour and productivity of vegetation while time series permit the monitoring of the ecosystem dynamics. Time and space variations of the plant photosynthetic activity have close relation with the soil water availability, especially in arid to sub-humid ecosystems (Fabricante et al., 2009; Iglesias et al., 2010; Ji and Peters, 2003; Justice et al., 1985; Nicholson et al., 1990; Tucker et al., 1985). However, the warmer temperatures of the growing season increase the plant productivity in cold environments (Srur et al., 2011). In this sense, NDVI time series have been compared to climatic variable time series, with the aim of exploring correspondences between geophysical elements and variations of the green index (Herrmann et al., 2005; Hickler et al., 2005; Xiao and Moody, 2005).

1.3. Precipitation

Diverse authors have found a connection between the mean annual precipitation and the spatial variations of NDVI on a regional level (Lauenroth, 1979; Le Houérou, 1984; McNaughton, 1985); however, time patterns could be explained not only by precipitation but also by a set of factors (Jobbágy et al., 2002; Lauenroth and Sala, 1992; Le Houérou et al., 1988). Therefore, the NDVI time dynamic behave in a complex manner seemingly either because of the vegetation memory or because of the inertia with regard to previous precipitation periods (Nicholson et al., 1990; Oesterheld et al., 2001; Ogle and Reynolds, 2004; Wiegand et al., 2004).

1.4. Fire

Moreover, fire is also a factor that controls the vegetation dynamics and it frequently affects forest-shrubby/herbaceous ecotonal areas (Bond and van Wilgen, 1996). In addition, fire affects the increasing or decreasing woody biomass within a landscape (Murphy et al., 2014). Fire regimes are influenced by both climatic factors controlling the fuel production and human activity (Bond and van Wilgen, 1996; Grau and Veblen, 2000). The vegetation vigour and the hydric state of fuels can determine the ignition probability, conditioning to some extent the propagation of fire (Burgan et al., 1998). In mesic forests, fire is more frequent during continuous dry periods that can last from less than a year to many decades. In contrast, in relatively dry forests, fire can be limited by shortage of fine fuel. Moreover, fire occurrence often increases a year or a few years after above-average moisture availability (Grau and Veblen, 2000). By allowing the monitoring of vegetation conditions at a regional scale, the NDVI data can detect fire events that have already occurred and provides an insight into the potential risks of fire (Zipoli et al., 2000).

1.5. Archaeology and fire

Evidence of fire in the archaeological and geological records can

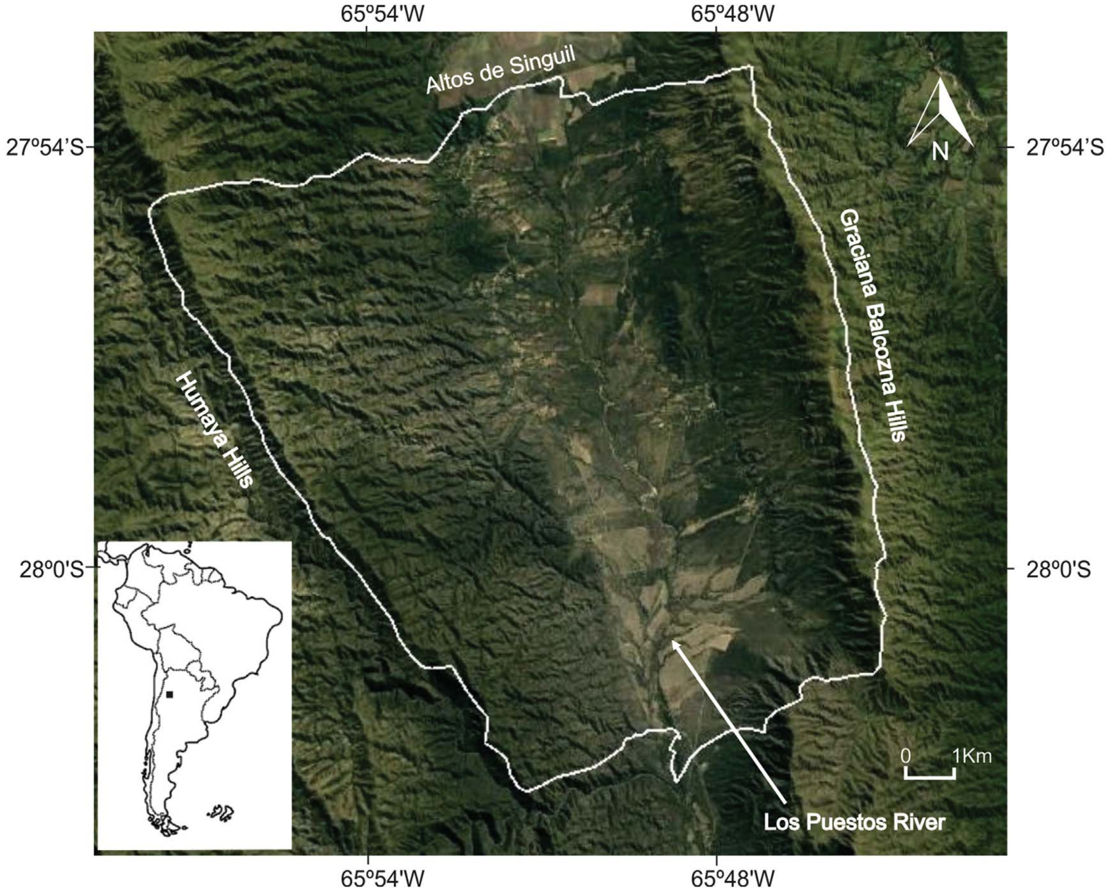

Fig. 1. Location of the Ambato Valley, Catamarca province, Argentina.

provide specific clues as to why sites or even regions were abandoned. Microcharcoal extracted from sedimentary sequences or sampled from archaeological sites can give us information on biomass burning and can be used as an indicator of past fire events. Marlon et al. (2008) have stated that ´fire is a key earth system process affecting ecosystems, land-surface properties, the carbon cycle, atmospheric chemistry, aerosols and human activities.' In some cases, fire can be seen as a transformer on a social-cultural level in society, as in the case of different resources such as food; also, in the burning of the dead in death rituals, and, most importantly, as will be discussed in this paper, as a transformer of the surrounding environment. Verhoeven (2000) has argued for close links among death rituals, fire, and abandonment as transformers of both human and material life in Neolithic sites in the Near East. According to him, ritual practises of intentionally burnt settlements can be associated with mortuary rituals in the area, and a posterior abandonment of the settlement. Ethnographical evidence of fire associated to rituals and house abandonment after someone passed away exists for Amazonas and the Chaco area (Kopenawa and Albert, 2013; Tola, 2006). In these cases, fire is seen as a kind of purification. It is also possible that fires could have covered up traces of abandonment patterns as has been discussed in the case of our study area (Lindskoug, 2016a; Lindskoug, 2016b).

1.6. *Traces of fire in the Ambato Valley*

Our earlier studies in the area had confirmed important information about the ecology of fire in the Ambato Valley. To study the past fire regimens in the area 17 locations were sampled in the valley. Two hundred and fifteen sediment samples were analysed for microcharcoal showing that since at least 4500 BP the area had been regularly affected by fire, according to 10 AMS dates obtained (Lindskoug, 2016a; Lindskoug and Marconetto, 2014). We could determine that fire was an integral part of the landscape before human occupation. The sampled stations demonstrated a varying pattern of fire regimes in the Ambato Valley. It could also be determined that the landscape in some ways must have been shaped by these fire regimes. The analysed stations showed that fire was recurrent and was part of the ecosystem in the area, and that during the occupation of the valley there were several fluctuations throughout time (Lindskoug, 2016a).

The conditions for fires were present in the Ambato Valley. Ignition sources existed, both natural, in the form of lightning strikes, and anthropogenic. Increasing human activity in the area would have made the anthropogenic sources increasingly common. In the case of the Ambato Valley, there is high biomass availability, with a dominance of forest on the valley floor and on the lower hillsides, while higher up on the hillsides grasslands dominate. The natural vegetation must have been a highly available source of fuel for the fires, with all of the different fuel sizes present in our study area: fine, medium, and coarse. Some areas, especially the grasslands higher up on the slopes, have abundant fine-sized fuel and are therefore highly flammable. In these areas, fire would have spread very quickly. The climatic conditions must have increased the risk of fire immensely, especially since there was a drought in the final phase of the occupation. Although low precipitation during drought does not increase the biomass (fuel load), it affects the available fuel in the area by causing the vegetation to grow slowly. However, drought also affects fuel availability by making the existing biomass drier, so the total available fuel in the area increases. If wetter years were present prior to the drought detected in the final phase, there would have been a larger accumulation of biomass and an increased amount of fuel in the area. When a fire hit it could have been devastating because of this large biomass build-up. Regular fires are necessary to prevent large biomass accumulations that can later create extensive fires with great intensity and severity. All this evidence led us to further investigate the past and present fire regimens in the area.

2. Study area

2.1. Natural environment

The Argentine north-west is characterised by arid environments, which evidence low-dynamic ecosystemic processes and a highly variable productivity in time and space (Iglesias et al., 2010; Noy-Meir, 1973; Noy-Meir, 1985). Within this area and under the influence of an arid climate the Ambato Valley is located in a highland environment made up of sub-parallel belts (Difrieri, 1958). This valley is located in the province of Catamarca (Argentina) and is situated between 27°54′ to 28°03′S and 65°45′to 65°55′W forming part of Río Los Puestos basin. The valley lies in the Sierras Pampeanas, a highland environment and limits with the summits of Sierra de Humaya to the west and Graciana Balcozna to the east (Fig. 1). The precipitation regime varies from 500 to 800 annual mm and most of the rain falls in summer (October through March), with a mean temperature of 24–26 °C in the warmest month and 8–10 °C in the coldest month (De la Orden and Quiroga, 1997; Palmieri et al., 2005). The elevation and exposure of the slopes furnish the different sectors with climatic peculiarities.

As for the phytogeographic characterisation, the Ambato Valley, belongs to the Monte Province (xerophytic shrubland) (Cabrera, 1976). The valley is located in a transition zone leading to the Chaqueña Province (xerophilous forest); it limits to the west with the Prepuneña Province (xerophytic shrubland with cacti) and to the northeast and east with the Yunga (Subtropical Montane Cloud Forest), which receives water not only from rainfall but also from fog precipitation, the so-called ‘horizontal precipitation’. The particular situation of the valley, in close contact with different phytogeographic regions, allows it to hold representative species of every region with noticeable differences among slopes (Marconetto, 2008). Within this frame, De la Orden and Quiroga (1997) have established different vegetation units (Fig. 2 and Table 1). Each vegetation unit is defined by the altitudinal variable and the floristic composition. The vegetation close to the river comprises the units/area most exploited by the past population. Several wildland fires have hit the area, including an extensive fire in December 2009. The fire started in an eastern valley parallel to Ambato Valley, ran down Sierra Graciana Balcozna and it propagated southwards (Lindskoug, 2016a).

2.2. The archaeological landscape in the Ambato Valley

> 700 archaeological sites, including agricultural terraces and structures for animal herding and settlement units, have been recorded in the Ambato Valley, around 130 of which are settlement units. Most of the residential units are found on the fluvial plain, between the first and second terraces of the Los Puestos River, between approximately 1050 and 1090 m asl. The agricultural terraces are located on the third natural terrace and in the piedmont area. In the area between the agricultural terraces, the landscape is also dotted with residential units (Assandri, 2007; Figueroa, 2010). The sites recorded are concentrated in the southern part of the valley, but this probably reflects the fact that this area has been more intensively surveyed than the northern part. The residential sites are usually rectangular but have different sizes and compositions.

The Formative Period is represented in the valley by two mound sites, El Altillo and Martínez 3, although most sites in the valley have been radiocarbon dated and are chronologically situated between the sixth and eleventh centuries AD (Marconetto et al., 2014). This period corresponds to the development of the Aguada culture in the Ambato Valley and is known as the Regional Integration period according to Pérez Gollán (1994). The radiocarbon dates associated with the fire regimes are also discussed in Marconetto et al. (2014). The end of the valley's occupation was first dated to around 1000 ± 100 CE (Gordillo, 2005; Marconetto, 2007). However, new analysis and calibration of the radiocarbon dates has established that the event most probably took place no later than 900 CE (Marconetto et al., 2014). We based this interpretation not just on the radiocarbon dates, but also mainly on the stratigraphic relationships between different objects in settlement units at the Piedras Blancas site.

3. Materials and methods

3.1. Vegetation data

We worked with monthly NDVI data from the time record of the spectrometer MODIS, TERRA (code: MOD13A3). We used images 1 km^2 pixels (years 2000 to 2011) from the Ambato Valley (http://LPDAAC.usgs.gov).

3.2. Precipitation data

Due to the absence of climatic data for the Ambato Valley, we used annual precipitation data from the Estación Aero Catamarca (28°28′S, 65°47′W) at 50 km south of the valley issued by the National Meteorological Service (SMN).

3.3. Data analysis

NDVI monthly data were averaged to obtain the annual NDVI ($NDVI_a$) for every pixel, where a = 2000 to 2011.

3.3.1. Spatial scale

We calculated for every pixel the average NDVI for the period 2000–2011 ($NDVI_p$), where p = period 2000–2011, with the aid of the programme GRASS (2012). From the resulting data, an $NDVI_p$ map was made.

3.3.2. Time scale

For every pixel, the difference between $NDVI_a$ and $NDVI_p$ was calculated for every year: $NDVI_d = NDVI_a - NDVI_p$.

Then, the standard deviation (sd) for each year and for every pixel was calculated.

With the aim of visualizing the magnitude of the deviations of the $NDVI_a$, anomalies were calculated. The anomalies are deviations from the NDVI values of a period with respect to an average value of a reference period (López et al., 1991), represented here by the ratio $NDVI_d/sd$.

Maps of the anomalies from the Ambato Valley (period 2000–2011) were made with the QGIS software (2014). The following scale of deviations was used: extreme positive anomaly ($NDVI_a > 2sd$), medium positive anomaly ($1sd \le NDVI_a \le 2sd$), no anomaly ($-1sd \le NDVI_a \le 1sd$), medium negative anomaly ($-2sd \le NDVI_a \le -1sd$) and extreme negative anomaly ($NDVI_a < -2sd$) (Britos and Basconcelo, 2012).

Correlations between the $NDVI_a$ of each pixel and the annual precipitation both of the same year and the three previous years were done: (0), (−1), (−2) and (−3) for the year, one, two and three years earlier, respectively. A map was made that shows pixels with the largest correlations between $NDVI_a$ and precipitation of the year and the three lag years. The $NDVI_a$ – precipitation correlation coefficient (r^2) was calculated.

4. Results

4.1. Spatial variation of NDVI in the Ambato Valley

The $NDVI_p$ for the period 2000–2011 in the Ambato Valley ranged between 0.43 and 0.63. The lowest values were observed in the centre,

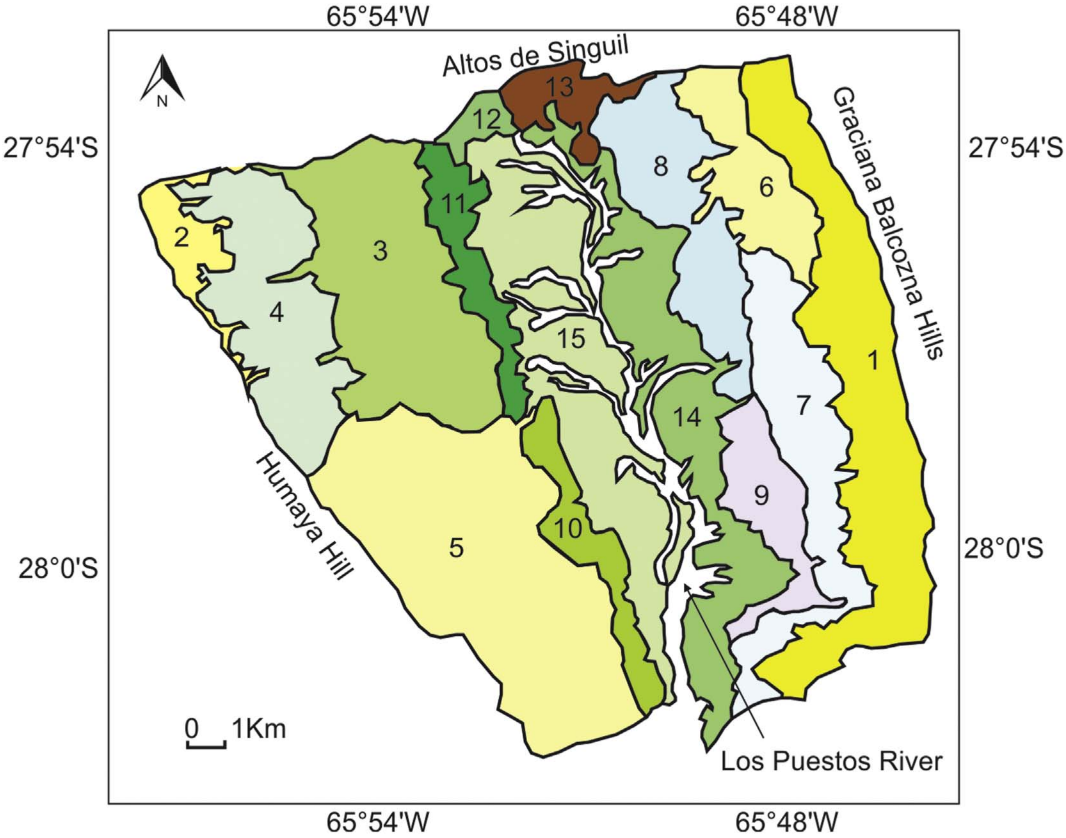

Fig. 2. Physiographic characterisation of the Ambato Valley.
(Modified from De la Orden and Quiroga, 1997).

northwestern and a small northeastern sector (Fig. 3). The highest values were evidenced in the south-west and east of the valley.

4.2. *Temporal variation of the annual NDVI (2000–2011) – anomalies*

The $NDVI_a$ condition in relation to the $NDVI_p$ for the period under study is displayed in Fig. 4. Pixels with standard deviations > 1 (medium anomaly) and 2 (extreme anomaly) were observed in all the studied period, except for the year 2006 that showed no anomalies.

In the year 2001, the anomalies were greater than the average in the entire valley. Extreme anomalies were evidenced mainly in the north-centre of the valley, and medium anomalies in the south. In contrast, in the year 2009 medium and extreme negative anomalies were observed in the slopes of the hills, while in the centre of the valley no anomalies were registered. In the year, 2010 medium negative anomalies were observed in the centre of the valley and extreme negative anomalies in the south in agreement with the area covered by the December 2009 fire. In the year, 2011 medium positive anomalies were observed in the north and east of the valley, while in the south, medium negative anomalies persisted as in 2009.

4.3. *Relation $NDVI_a$ – fire*

The $NDVI_a$ condition during 2009 (fire occurrence year), 2010 and 2011 in relation to the mean $NDVI_p$ are shown in Fig. 4. Extensive areas with extreme and medium negative anomalies were noticeable in 2009. The following years negative anomalies persisted in the south of the valley, both extreme (year 2010) and medium (year 2011).

4.4. *Relation $NDVI_a$– precipitation*

The map shows the $NDVI_a$ – precipitation correlation with rainfalls of the ongoing year (0), the previous year (-1) and the three years earlier (-3); and also pixels with $r^2 < 0.6$ and $r^2 \geq 0.6$ (Fig. 5).

Correlations $NDVI_a$ - precipitation showed that the southern and eastern piedmonts of the valley were correlated to precipitations of the year (no lag) while the central and western zones and the eastern summits were correlated with precipitations of the previous year (year -1). Few isolated pixels were correlated to three years before precipitations (-3) and none to two years before precipitations (-2).

These correlations gave an $r^2 > 0.6$, mainly in pixels of the western slope and north of the valley, which showed a one year lag (year -1); r^2 smaller than 0.6 were seen in pixels of the eastern slopes and south of the valley, most of them having no lag (Fig. 5).

5. Discussion

This model serves as a tool to fine tune paleoenvironmental reconstructions related to past fire regimens and can be of use in the field of environmental archaeology and paleoecology. As for our study area, the Ambato Valley, which has multiple archaeological sites affected by fire, the model can help in adjusting the past fire regimens associated to for example abandonment and droughts. In areas with related archaeological scenarios associated with fire events, it will be possible to analyse similar environments and/or archaeological contexts. However, we will not centre the discussion on the archaeological sites with evidence of fire here, this has been done in other cases (Lindskoug, 2016a; Lindskoug, 2016b). In the case of microcharcoal studies, this model can reinforce the reconstructions. As our earlier studies has shown the area was regularly affected by fires (Lindskoug, 2016a; Lindskoug and Marconetto, 2014) and also by drought (Marconetto, 2010; Marconetto, 2009), together with the vegetation reconstructions done by the HEMO modelling (Marconetto et al., 2015) we have been able to fine tune the past environmental context of the Aguada society. Using these tools, we

Table 1
Characterisation of Valle de Ambato, Catamarca, Argentina. Numbers refers to vegetation units in Fig. 1.
(Modified from De la Orden and Quiroga, 1997).

Great Landscape	Landscape	Vegetation units	Height m asl	Dominant species
Superior Rocky Side	Sierras Graciana Balcozna	**1.** Grassland (summits of hills)	1250–1920	*Stipa* sp.
	Sierra de Humaya	**2.** Grass	1800–2280	*Bromus* sp.
		3. Grassland-shrubland mosaic	1150–1850	*Fagara coco* *Schinopsis haenkeana* *Acacia caven* *Celtis pallida* *Stipa* sp. *Festuca* sp.
		4. Grassland-suffrutices mosaic	1500–2200	*Lippia* sp. *Baccharis* sp. *Stipa* sp. *Festuca* sp.
		5. Forest	1100–1800	*Schinopsis haenkeana Acacia visco*
Piedmont	Sierras Graciana Balcozna	**6.** Grassland	1200–1650	*Stipa* sp. *Festuca* sp.
		7. Forest-shrubland mosaic (sup.)	1100–1450	*Schinopsis haenkeana Acacia visco* *Mimosa farinosa*
		8. Forest-shrubland mosaic (inf.)	1160–1300	*Prosopis nigra* *Geoffroea decorticans* *Mimosa farinosa* *Schinus* sp.
		9. Open forest	1030–1300	*Prosopis* sp. *Aspidosperma quebracho blanco*
	Sierra de Humaya	**10.** Forest	1200–1300	*Acacia visco* *Lithraea ternifolia*
		11. Grassland-shrub mosaic	1100–1300	*Acacia aroma* *A. caven* *Stipa* sp.
		12. Grassland with shrub	1000–1200	*Stipa* sp. *Acacia aroma* *Prosopis torquata*
	Altos de Singuil	**13.** Shrubland	1280–1560	*Mimosa farinosa* *Schinus* sp.
Fluvial plain		**14.** Open forest	1000–1200	*Prosopis nigra*
		15. Gallery forest	1000–1200	*Celtis tala*

can enhance the understanding of the past environmental conditions in the area. These models can also improve the proxies to reconstruct the past environment related to periods and fluctuations in humidity and vegetation pattern. These associations are fundamental in the reconstructions; and we argue that the model can detect and reinforce these fluctuations in fire regimens related to the vegetation history, fire and variations in humidity.

In terms of wildfires, the link between drought and natural fires has been considered extensively by various scholars (see for example Long and Whitlock, 2002; Whitlock et al., 2003; Meyer and Pierce, 2003). As there have been indicators of aridity detected in the study area, the conditions of the occurrences of wildfires were established through the analysis of the anatomy of charred logs of *Geoffroea decorticans* recovered in contexts associated with final occupation of the valley (Marconetto, 2010; Marconetto, 2009). These fires may have had either natural or anthropogenic origins. The ignition sources of natural wildfires are principally associated with volcanic activity (not applicable to the study area), lighting strikes, sparks from rock falls, and spontaneous combustion, but also to accidental combustion that is anthropogenic in origin (Scott, 2000). However, lightning is the most common factor as an ignition source. In all cases moisture conditions are important (Carcaillet, 1998), since fires are more frequent when there is a large amount of fuel available and lower humidity.

The analysis of the spatial variation of the NDVI average (period 2000–2011) (NDVI_p) in the Ambato Valley, permitted the distinction of different sectors of photosynthetic activity of vegetation, according to the vegetation physiognomy and the presence - absence of agricultural exploitation.

We could establish an association between different NDVI values and the observed physiognomic units: the highest values agree with forests; the intermediate values with piedmont forests and grasslands; and the lowest ones with the shrubland, grassland-shrubland mosaic and zones with both perennial and annual cultures. Paruelo et al. (1998) arrived to similar conclusions while doing on a regional scale, an NDVI spatial zonation in Patagonia, finding high, medium and low values for the sub Antarctic forest, grass - steppe and shrub semi-desert steppe, respectively. Also, Zerda and Tiedemann (2010), through NDVI values taken in the dry Chaco (Santiago del Estero, Argentina) have shown to have more photosynthetic activity the forest than the grassland.

The low NDVI values from the cultivation area sectors would be indicative of plant cover seasonal variations. Since this work was developed at an annual time scale, seasonal differences in the phenology of crops tend to smooth out. Thus, high NDVI values in the growing season get blurred by lack or very scanty plant cover, with low NDVI in senescent or annual crops harvest periods (Goward et al., 1985), or at the dormancy time of perennial plants.

With respect to the temporal variation (2000–2011) of the NDVI in the Ambato Valley, the anomalies show the intensity of the annual variations. Negative standard deviations of the NDVI mean values are indicators of dryness; thus, anomalies represent the intensity of droughts (Britos and Basconcelo, 2012). The quantification of the standard deviations from the annual NDVI mean values (period 2000–2011) (NDVI_p) of the Ambato Valley permitted us the detection of the annual NDVI temporal variation and its magnitude. The year 2001 was a non-dry year, with medium and extreme positive anomalies, in the whole valley. Conversely, except for the centre of the valley, 2009 was a dry year. The rest of the years showed slight variations in the degree of dryness of the various areas, with isolated cases of both positive and negative anomalies in some pixels.

Fire in the central part of the Ambato Valley occurred in December 2009 when many trees were burnt. This fact was witnessed by the inhabitants of the region and could be determined in the fire coverage area through the observed medium negative anomalies in the centre of the valley and the extreme negative anomalies in the south. According to Lindskoug (2016a) this event left vegetation consequences for many years. However, according to our microcharcoal studies in the area fire has been part of the ecosystem since at least 4500 BP (Lindskoug, 2016a; Lindskoug and Marconetto, 2014). Fires in the area have been recurrent with different intensity and extension not only affecting the present population but also the past societies living in the area and especially their cultivated areas (Lindskoug, 2016a; Lindskoug, 2016b).

When summarizing the NDVI behaviour throughout the decade of study, we could detect medium and extreme positive anomalies in 2001, when abundant plant mass must have been produced. Then, non-anomaly years followed all along the valley. Medium and extreme negative anomalies extensively registered at both slopes in 2009, and later came the fire.

Thus, in that year, because of the drought, a low hydric state must have been existed, increasing the ignition probability and somewhat conditioning the propagation of fire (Burgan et al., 1998). In this sense, the relation dryness - fire has been reported by Bond and van Wilgen (1996), among others. Also, it should be considered that the abundance of plant material in the forests accumulated since 2000 was the fire fuel (Grau and Veblen, 2000). In this way, the relationship between fire

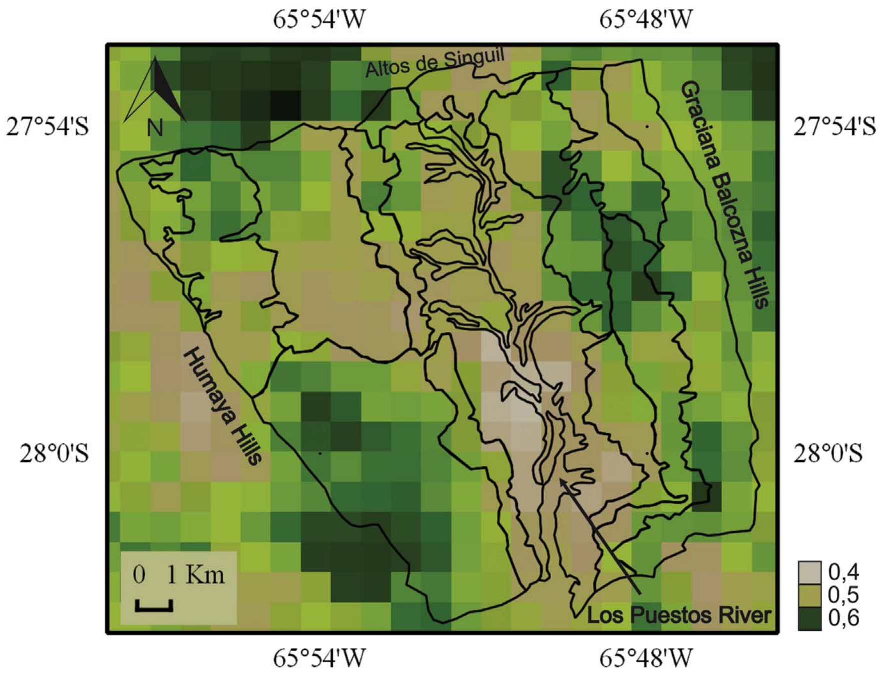

Fig. 3. Map of Valle de Ambato with $NDVI_p$, period 2000–2011.

sources and NDVI negative anomalies could be verified in this study. Therefore, we can show that the fire was related to climatic factors controlling the fuel production. This fire-anomaly relation was also demonstrated in the Spanish forest (Vázquez et al., 2001). Sectors south of the valley that had been affected by fire, the following year showed the smallest NDVI values, evidencing a low plant cover.

In 2011, all pixels had increased NDVI values. Those pixels that had shown extreme negative anomalies (burnt areas), in the last year of study showed medium negative anomalies, indicative of fire scars, while pixels with negative means in 2010, in 2011 showed no anomalies and pixels without anomalies in 2010 presented medium positive anomalies in 2011. That is, the increasing NDVI evidenced a recovery of all the vegetation units, possibly before better climatic conditions.

We found relations between NDVI and precipitation. In the Argentine Puna, Baldassini (2010), found that the annual precipitation was the main climatic factor associated to the spatial variability of primary productivity. In our present work, we detected areas with NDVI's best correlated with the year of precipitation and others with the previous year. The time-lag shows to be an important phenomenon since it reveals how quickly the ecosystem responds to the climate change impacts (Gao et al., 2016). The forest and grassland NDVI's related either with the year of precipitation or to the previous one, while shrublands correlated only with the previous year precipitation. Sectors of the valley with NDVI-precipitation correlations of more than two or more previous years were not found.

The forests which showed a relation with rainfalls of the year (no lags), were mainly in the southern and eastern piedmont (Fig. 5). Similarly, in the Sahel and East Africa, Nicholson et al. (1990) found that plant formation in arid environments respond clear and immediately to precipitation. The same responses were obtained by Wang et al. (2003) in the Central Great Plains (USA), especially after dry periods. However, many of the correlations NDVI-precipitation from the Ambato Valley were low (< 0.6), especially those southwest of the valley. This situation shows the low relationship existing between the NDVI of the forests south of the valley and the year of the precipitation.

In relation to grasslands, we have observed that the largest NDVI - precipitation correlations belong to the same or previous year. Only some pixels had high correlations. On the western side of Sierra Graciana Balcozna, in the summit of the hill at 1250–1920 m asl. The grassland was associated to precipitation of the year in its southern area and to the previous year in the north. On the eastern side of Sierras de Graciana Balcozna the Subtropical Montane Cloud Forest is located, with annual precipitation ranging between 1000 and 2400 mm (Cabrera, 1976). This Montane Cloud Forest apart from receiving water through vertical precipitation, has an important horizontal precipitation contribution; in fact, the fog represents 10–40% of the water contribution to the ecosystem (Hunzinger, 1995). This horizontal precipitation is the one that crosses through the Sierras Graciana Balcozna summits and covers the highland grassland area of the western side of the hills. Therefore, because of the fog the highland grasslands from the Ambato Valley do not depend on vertical precipitations correlations render/show/evidence low values.

The best correlations with the previous year were evidenced in the grassland-shrubland mosaic of the western side of the valley. The fluvial plain forests, now very much impacted by walnut tree, soy and corn cultures were as well better correlated with the previous year rainfalls.

The dry Chaco has, according to the NDVI dynamics and in the presence of rainfall and temperature variations, a forest with greater stability than the natural grassland due to a greater diversity of species in the forest, and mainly to rooted woody plants, which explore the deepest soil layers and do not depend on precipitations (Zerda and Tiedemann, 2010). On the contrary, the Chaco grassland immediately reacts after precipitation, which is highly expected because of the great efficiency of the root system in using water. Therefore the grasses with a more superficial root systems than trees and shrubs, show growth pulses connected to precipitation (Villagra et al., 2011).

The forest and some sectors west of the Ambato Valley have a high correlation with precipitations of the year of the rainfall or the previous year, sometimes with a low NDVI-precipitation correlation, thus demonstrating that the forest dynamic is slightly altered by rainfall variations. Particularly, in the *Prosopis nigra* and *Geoffroea decorticans* forests, woody plants have access to deep water reservoirs through the development of extensive root systems (Villagra et al., 2011; Dalmasso, 2010), and thus these species do not strictly depend on precipitations. Therefore, the low forest and grassland - precipitation correlations observed in our analysis would indicate more stability in these units than in those with shrub predominance. Our analysis showed that due to the independence between the forest and grassland vigour-rainfall, the low forest and grassland-precipitation correlations would indicate

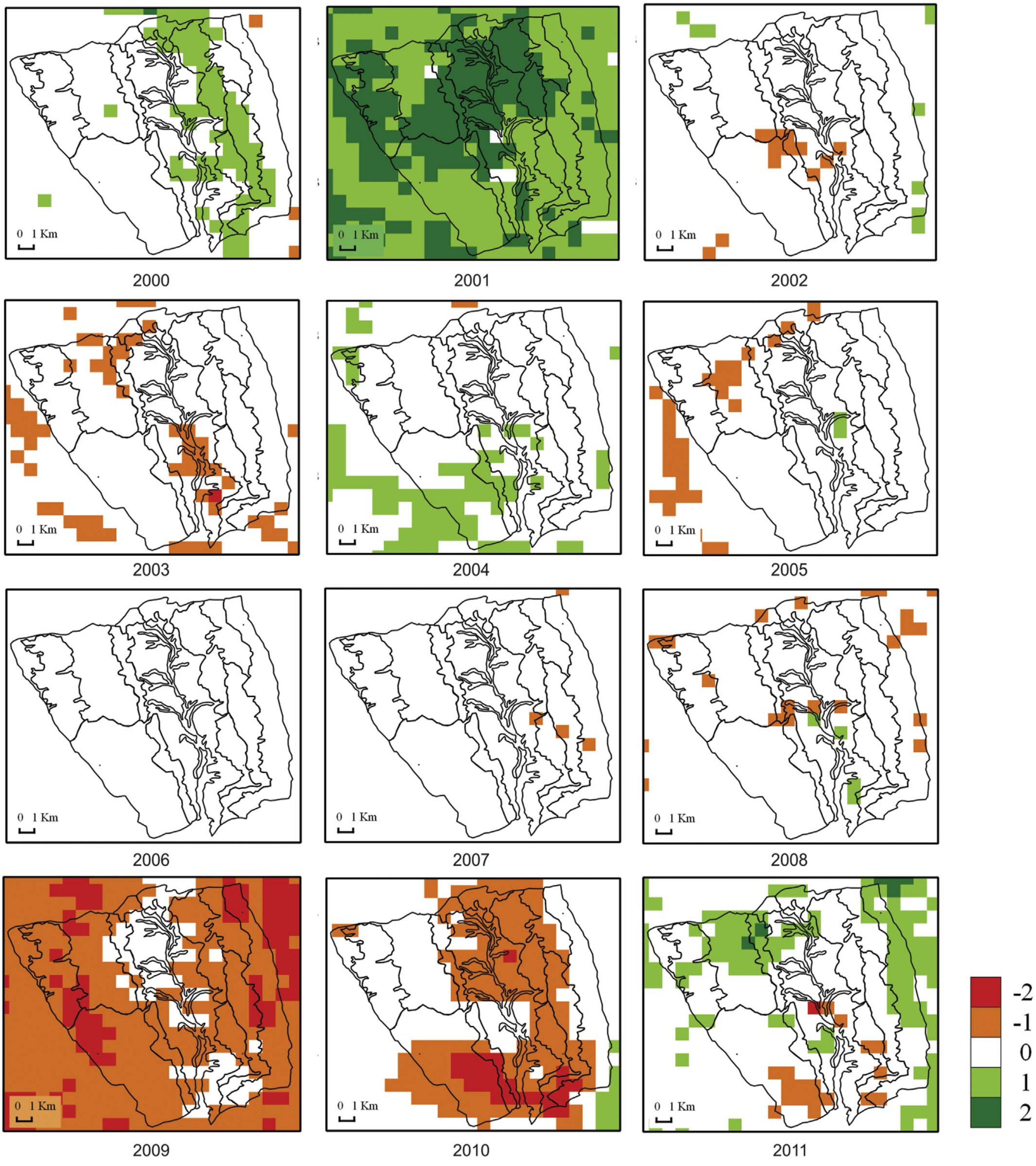

Fig. 4. NDVI anomalies, Valle de Ambato, period 2000–2011.

more stability in these units than in those with shrub predominance.

Fabricante et al. (2009) found a low correlation between the inter-annual variation of the NDVI and the annual precipitation, current and previous, in arid ecosystems of North Patagonia. In contrast, it was highly correlated to the accumulated precipitation in the few months before the growing season. Furthermore, Iglesias et al. (2010) found in dry forests of western Argentina a correlation between precipitation and NDVI, which, in general, showed to be greater when related to the previous month rainfalls. Because of this, the relationship between NDVI and precipitation of the different zones of the Ambato Valley should be explored at shorter time scales.

The absence of a closer relationship between precipitation and annual NDVI could also be related to the difference of rainfall according to the topography as well as to the lack of quantitative information on the contribution of moisture. In this study, the low spatial resolution of the precipitation data did not allow a more detailed assessment of the

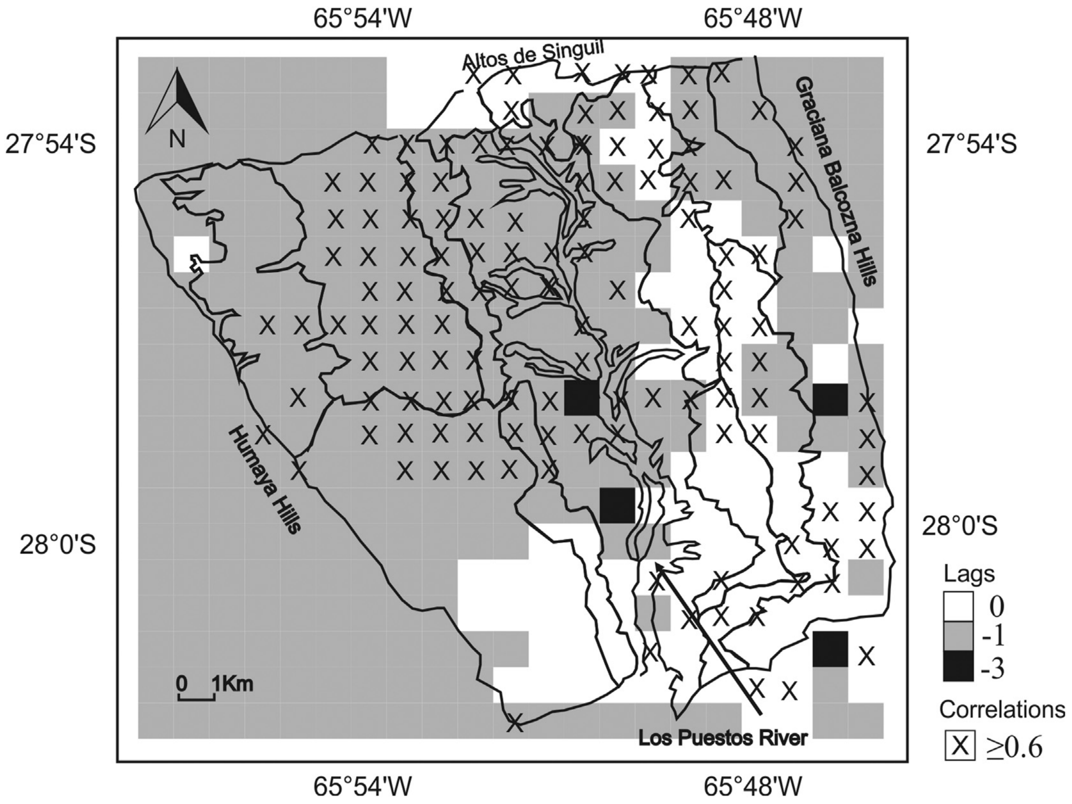

Fig. 5. Map of Valle de Ambato with the best NDVI$_a$ - precipitation correlations. Correlation with rainfall of the ongoing year (0); correlation with the previous year rainfall (− 1); correlation with the three years earlier rainfall (− 3). X indicates pixels with an NDVI$_a$ – precipitation correlation > 0.6 ($r^2 \geq 0.6$).

relationship NDVI-precipitation. On the other hand, there is a need to inquire into this relationship on different time scales.

This work on the modern NDVI dynamic and its relation to precipitation and fire will permit improving the interpretation of annual paleo-NDVI fluctuations detected along the last 1600 years in the Ambato Valley by means of the Hindcasting Ecosystem Model (Marconetto et al., 2015). Associations can be made with different local or global environmental conditions (D'Antoni et al., 2016).

This study represents a contribution to future archaeological studies for the retrodiction of the environment and fire events.

6. Conclusions

The implications of this study can be considered from two points of view: firstly, the usefulness of this kind of models to describe local ecological variables in the study area and secondly, its application to paleoenvironmental reconstructions and its use in environmental archaeology and paleoecology associated to past fire events.

In relation to the local ecological variables we can conclude that a spatial variation of the annual NDVI linked to the type of vegetation of the Ambato Valley is evidenced. Both the south western and piedmont forests, and the summit grasslands of Sierra Balcozna show the highest NDVI values; the shrub-grassland mosaic has medium values. However, the shrub-grassland mosaic characterised by cultured annual species, like soy and corn, and deciduous trees (walnut trees) shows the lowest NDVI values. This difference can be explained by the wide NDVI seasonal variations of cultures that smooth the annual NDVI of the agricultural sector.

Regarding the NDVI temporal variation, anomalies were detected during all the studied period. In 2009, extreme negative anomalies were registered, representing a particularly dry year with probable accumulation of flammable material. Coincidently, at the end of 2009 a fire of great magnitude occurred.

As for the vegetation types, the NDVI-precipitation relation evidenced the fact that some zones of the Ambato Valley are more sensitive to rainfalls of the ongoing year while others are to the previous year. On the other hand, we must emphasize the importance of fog coming from the Yungas, showing that in some areas of the valley the horizontal precipitation can make important contributions to the ecosystem humidity.

On the other hand, these models can serve to adjust the comprehension of the result of the paleaoenvironmental retrodiction. Thus this type of analysis is a good complement to the study of past fire regimens based on microcharcoal studies. This model can help us adjust the variations in the past fire regimens especially with the impossibility of radiocarbon dating all soil samples extracted in the field when studying the past wildland fire events.

Finding these associations linked with the paleoenvironmental retrodictions that stretches to archaeological epochs will permit to consider potential fire scenarios in the past that can be of interest to resolve different problems in the field of archaeology, especially related to environmental factors, which could have affected past societies.

Conflict of interests

The Authors declare that there is no conflict of interest.

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