ARTICLE IN PRESS

Journal of Archaeological Science: Reports xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Ecosystem modeling using artificial neural networks: An archaeological tool

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ARTICLE INFO

Keywords:
Paleo-NDVI
Hindcasting
Artificial Neural Network
Ecosystem modeling
Argentina

ABSTRACT

Prediction of past Normalized Difference Vegetation Index (paleo-NDVI) in Valle de Ambato (Catamarca, Argentina) in the periods of 550–650 and 1550–1650 CE was carried out to test the efficacy of Artificial Neural Network (ANN) to predict past environments for Archaeology. This work shows that both subtropical Yunga and xerophytic Chaqueña vegetations respond in contrasting fashion to changes in climate forcings. To predict the past an ANN perceptron multilayer model was used. Modern NDVI data and Tree-Ring data were obtained from NOAA-Paleoclimate, and other public sources. These data were used to train the model. Real data and predictions were close (Pearson correlation 0.83–0.90) and warranted the following step, hindcasting. Important paleo-NDVI fluctuations lasting 15 to 20 years were identified in both periods under study. The paleo-NDVI fluctuations in the earlier period were probably related to the unidentified eruption of 583. The fluctuations in the later period appear related to the eruption of 1600 of the Huaynaputina volcano (SW Peru). These findings suggest that the model accurately identified vegetation fluctuations in response to changes in the volcanic forcing. Hence, the ANNs may be considered as apt tools for modeling past environments in support of archaeology.

1. Introduction

This paper presents a hindcast of the Normalized Difference Vegetation Index (NDVI) within two periods (550–650 and 1550–1650 CE) of significant ecosystem changes in north of Valle de Catamarca (Catamarca, Argentina).

This index relates the absorbed photosynthetically active radiation (PAR) in the range of 400 to 700 nm used for photosynthesis, and the near infrared, from 700 nm up to 1100 nm, mostly reflected by the foliar structures of plants. The NDVI is a good indicator of various vegetation parameters for it provides a strong vegetation signal and a good spectral contrast of most reference materials (Tucker and Sellers, 1986). Also when training our Neural Net model, we want to have as much of historical information and observed variance as possible. This is why we use AVHRR-NDVI.

Our hindcast was performed on two pixels belonging to the Yunga plant geographical province and on one to the Chaqueña plant geographical province (Cabrera, 1976; Palmieri et al., 2014). These three pixels were selected because they (a) reflect the most contrasting environmental settings north of the Valley and are placed in the Valley's opposite slopes, (b) have the best correlation in the train step of Artificial Neuronal Network (ANN) and, (c) have the largest variability in the Valley during the periods analyzed in this work.

We are interested in further understanding the ecosystem responses on each slope of the Valley to changes in one climate forcing, and offer background to the dynamic of human settlements through time in connection with environmental changes.

The choice of these pixels was based on the relatively low human activity at the present time. Therefore, the modern data collection used to train the ANN model contains data with little human impact. This responds to a general rule in paleobiological research: first reconstruct the environmental history free of human impact in order to offer this reconstruction to comparative analysis when the reconstruction is performed in an area of human activity and hence impact.

There are a few previous works applying this approach to modeling. An ANN predictive model was used to hindcast the Sea Surface

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http://dx.doi.org/10.1016/j.jasrep.2017.07.013
Received 6 December 2016; Received in revised form 1 July 2017; Accepted 12 July 2017
2352-409X/

Please cite this article as: Burry, L.S., Journal of Archaeological Science: Reports (2017), http://dx.doi.org/10.1016/j.jasrep.2017.07.013

Temperature (SST) of the Pacific Ocean close to South America and the South Atlantic linking SST to Tree Ring widths over the period of 1246–2000 CE (D'Antoni and Mlinarevic, 2002; D´Antoni, 2008). The correlation of SST with the NDVI of South American plant communities was tested with an ANN predictive model over the period 1982–2000 CE (D'Antoni et al., 2002). Hindcasting of paleo-NDVI on eleven pixels of Valle de Ambato over the period of 442–1998 was carried out using ANN models (Marconetto et al., 2015). Further applications of this method were developed in the progress report to the NASA Astrobiology Institute (D'Antoni et al., 2008).

Other methods have been used for predicting the past, particularly those based on linear regression. These are all good and reliable for interpolation work. However, when hindcasting, the calibration dataset has necessarily a shorter timespan. Hence, a large part of the work is extrapolation where linear prediction is less reliable. Neural Network models using the sigmoid function are equally reliable in prediction and in hindcasting (Adya and Collopy, 1998; Bandyopadhyay and Chattopadhyay, 2007; Cigizoglu, 2003; Russell and Norvig, 2003). Paruelo and Tomasel (1997) predicted NDVI from time series of temperature and precipitation of the 20th century using regression models and ANN. These authors got better results with ANN because, they submit, ANNs relate temperature and precipitation data of previous years that are connected with ecosystem functioning in the following years.

In this work it was possible to demonstrate the contrasting responses of Yunga and Chaqueña vegetation to the effects of climate forcings north of Valle de Catamarca over the periods of 550–650 and 1550–1650 CE while offering further detail than in previous works (Marconetto et al., 2015).

The understanding of past environmental variations with the aim of assembling them with the dynamics of human occupations implies in turn the comprehension of climate forcings, perhaps linked to the anomalies observed in retrodictive models.

In a previous work (Marconetto et al., 2015) as a result of the ecosystemic model built for 11 pixels covering the northern Valley of Catamarca until 442 CE, two moments were particularly observed that caught our interest. They refer to two situations where the behavior of positive and negative anomalies of NDVI was substantial and complex to be explained. We then hypothetically associated the 20th century observations to global events, e.g. Little Ice Age. Nevertheless, the potential role of volcanic eruptions cannot be discarded. Volcanic eruptions are a dominant driver of naturally forced climate variability during the last millennium (Colose et al., 2016).

In this line it is suggestive the mention and description of the eruption of the Huaynaputina volcano (south of Peru) by the Mercedarian Martín de Murúa, illustrated and mentioned by the chronicler Guamán Poma de Hayala (Fig. 1) (Lavallé, 2011). The episode is narrated by chroniclers as a relevant and significant event, and studies on volcanism mention that the eruption generated recorded global events.

> LA CIVDAD DE ARIQVIPA: Rebentó el bolcán y cubrió de zeníza y arena la ciudad y su juridición, comarca; treynta días no se bido el sol ni luna, estrellas. Con la ayuda de Dios y de la uirgen Santa María sesó, aplacó.
>
> Le fue castigado por Dios cómo rreuentó el bolcán y sallió fuego y se asomó los malos espíritus y salió una llamarada y humo de senisa y arena y cubrió toda la ciudad y su comarca adonde se murieron mucha gente y se perdió todas las uiñas y agiales y sementeras.
>
> Escurició treynta días y treynta noches. Y ubo proción y penetencia y salió la Uirgen María todo cubierto de luto y ancí estancó y fue seruido Dios y su madre la Uirgen María. Aplacó y pareció el sol pero se perdió todas las haziendas de los ualles de Maxi. Con la senisa y pistelencial de ella se murieron bestias y ganados.
>
> *LA VILLA DE ARICA tanbién fue cubierto de seniza del bolcán toda la cordellera de la mar.* (Guamán Poma de Hayala, 1615).

It has been paralleled to the nineteenth century Krakatoa eruption (de Silva and Zielinski, 1998). According to Costa et al., 2003) the eruption of Huaynaputina is an example of the effectiveness of explosive silicic arc magmas at producing short term although abrupt climate changes.

Certainly, global events produce different effects on ecosystems with different limiting factors; however, we find it interesting to explore this variable in relation to our model, particularly because of the proximity at global scale of the Haynaputina volcano with the Argentine northwestern.

2. Materials and methods

2.1. Study area

The study area is the north of Valle de Catamarca, in the surroundings of Valle de Ambato (Catamarca province) (27°48′ to 28°04′S and 65°46′ to 65°56′W) in Northwestern Argentina. The area is orographically heterogeneous; therefore, it also holds diverse plant communities. The valley lies in the Sierras Pampeanas and limits with the summits of Sierra de Humaya to the west and Graciana Balcozna to the east (Fig. 2). Annual precipitation varies from 500 to 800 mm and most of the rain falls in summer. Mean temperature is 25 °C in the warmest month and 9 °C in the coldest (de la Orden and Quiroga, 1997; Palmieri et al., 2005). Elevation and exposure of the slopes give climatic peculiarities to the different sectors. Within this frame, de la Orden and Quiroga (1997) have established different vegetation units (Fig. 3).

On the Eastern and Northeastern sides of the Valley, Eastern slope of the Graciana Balcozna Hills, is the Yunga Plant Geographical Province, with montane forest and grasslands in the hill summits (Morláns, 1995). Elements of this vegetation appear on the western slopes. The climate is warm and humid with abundant rainfall in summer and frost in winter (Cabrera, 1976). The Yunga receives humidity from the low level jet of South America (Insel et al., 2010; Virji, 1981) forming the fog forest (Hunzinger, 1997). Therefore, Yunga gets water from vertical as well as horizontal precipitation. This horizontal precipitation (fog) is the one that crosses through the Graciana Balcozna Hills summits and covers the grassland area of the western side of the hills. Consistently, the east slope side pixels show NDVI annual average larger than 0.60 (Burry et al., 2017) for this environment with no restrictions for humidity.

In contrast, on the west side of the Valley, the vegetation belongs to the Chaqueña Plant Geographical Province (Chaco Serrano District) with warm and drier climate conditions (Cabrera, 1976). The Chaco Serrano covers the summit and the eastern slopes of Sierra de Humaya. Its characteristic vegetation arranges in "belts" or "levels" with particular structure and composition (Morláns, 1995). The presence of xerophytic vegetation (xerophytic forest and patches of grass and shrubs) is related to an annual NDVI average of around 0.5, reflecting an environment with moisture restriction. Also, the annual values of NDVI show a large variation range that underscore the sensitivity of grassland NDVI to the effects of drought (Zerda and Tiedemann, 2010).

Two pixels (2 and 5) belonging to the Yunga, and another one (pixel 6) from the Chaco Serrano District were selected within the study area. Pixel 2 located to the east of Sierra Graziana Balcozna has a montane forest vegetation, while pixel 5, in the eastern and western slopes show forest and grasslands upon the summit. Pixel 6 has mainly shrubby vegetation, dry forest southwest of the pixel, and grasslands upon the summit (FAO, 2014, de la Orden y Quiroga 1997, Morláns, 1995).

2.2. Materials (data)

(a) Satellite: NDVI from the Global Inventory Modeling and Mapping Studies, GIMMS (GLCF, Tucker et al., 2004) derived from satellite images AVHRR with 8 km pixels (AVHRR sensor mounted in NOAA