Quaternary Science Reviews 132 (2016) 114–128

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Long-term man–environment interactions in the Bolivian Amazon: 8000 years of vegetation dynamics

Sandra O. Brugger [a, b, *], Erika Gobet [a], Jacqueline F.N. van Leeuwen [a], Marie-Pierre Ledru [c], Daniele Colombaroli [a], W.O. van der Knaap [a], Umberto Lombardo [b], Katerine Escobar-Torrez [d], Walter Finsinger [c], Leonor Rodrigues [b], Alena Giesche [b], Modesto Zarate [e], Heinz Veit [b], Willy Tinner [a]

[a] Institute of Plant Sciences and Oeschger Centre for Climate Change Research, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland
[b] Institute of Geography, University of Bern, Hallerstrasse 12, CH-3012 Bern, Switzerland
[c] Institut des Sciences de l'Evolution, CNRS UM2 IRD EPHE, Place Eugène Bataillon, 34095 Montpellier Cedex, France
[d] Herbario Nacional de Bolivia, Unidad de Palinología, Universidad Mayor de San Andrés Instituto de Ecología Calle27, Cota Cota Campus Universitario, La Paz, Bolivia
[e] Herbário Forestal Nacional Martín Cárdenas, Centro de Biodiversidad y Genética de la Universidad Mayor de San Simón, Parque la Torre, Casilla 538, Cochabamba, Bolivia

ARTICLE INFO

Article history:
Received 14 August 2015
Received in revised form
29 October 2015
Accepted 1 November 2015
Available online xxx

Keywords:
Llanos de Moxos
Amazonia
Zea mays
Fire history
Rainforest
Palynology
European impact
Cerrado
Land use
Pre-Columbian settlements

ABSTRACT

Only few studies documenting the vegetation history of the Llanos de Moxos, one of the largest seasonally flooded wetland areas in South America, are available and little is known about the environmental impact of pre-Columbian settlements. We use radiocarbon-dated terrestrial plant macrofossils to establish a sound chronology and palynological analyses to reconstruct the vegetation and fire history of the Lago Rogaguado area. The sedimentary pollen and spore record suggests that wetland and wooded savannah (Cerrado) environments occurred around the lake between 8100 and 5800 cal BP. Fire activity was high during this period and was probably connected to the dry Cerrado environments. The pollen evidence suggests early plant cultivation (*Zea mays*, Annonaceae and Cucurbitaceae) from 6500 cal BP onwards, which is significantly earlier than hitherto assumed for Amazonia. Gallery forests expanded after 5800 cal BP, when fire activity strongly declined. Forest expansion intensified around 2800 cal BP and continued until 2000 cal BP, when forest cover reached its maximum and fire activity its minimum. The late-Holocene forest expansion to the south and the decrease of fire activity may have resulted from a climatic shift to moister conditions (possibly a shorter dry season). New crops (e.g. *Avena*-type) or adventive plants (e.g. *Rumex acetosella*-type) document the impact of European economies after ca. 500 cal BP. Land use intensity remained rather stable over the most recent centuries, arguing against a collapse of settlements in response to the arrival of Europeans, as reconstructed from other Amazonian pollen records.

1. Introduction

The Llanos de Moxos are located between the central Andes and the Brazilian Shield, and are one of the largest seasonally flooded wetlands of South America with an estimated area of about 150,000 km^2 (Hanagarth, 1993). Today, the Llanos de Moxos comprise a mosaic of different ecosystems depending on precipitation, elevation, drainage and soils (Navarro, 2011; Lombardo, 2014). Seasonal inundation patterns determine the occurrence and distribution of plants and animals and are thus important for the ecology of floodplain ecosystems (Junk, 2013). This patchwork

* Corresponding author. Institute of Plant Sciences and Oeschger Centre for Climate Change Research, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland.
E-mail addresses: sandra.bruegger@ips.unibe.ch (S.O. Brugger), erika.gobet@ips.unibe.ch (E. Gobet), jacqueline.vanleeuwen@ips.unibe.ch (J.F.N. van Leeuwen), marie-pierre.ledru@ird.fr (M.-P. Ledru), daniele.colombaroli@ips.unibe.ch (D. Colombaroli), pim.vanderknaap@ips.unibe.ch (W.O. van der Knaap), umberto.lombardo@upf.edu (U. Lombardo), kescobar.torrez@gmail.com (K. Escobar-Torrez), walter.finsinger@univ-montp2.fr (W. Finsinger), leonor.rodrigues@giub.unibe.ch (L. Rodrigues), alena.giesche@giub.unibe.ch (A. Giesche), zaratemodesto@gmail.com (M. Zarate), heinz.veit@giub.unibe.ch (H. Veit), willy.tinner@ips.unibe.ch (W. Tinner).

http://dx.doi.org/10.1016/j.quascirev.2015.11.001
0277-3791/

contributes to a high biodiversity, including rare and threatened species (Mayle et al., 2007; Olson and Dinerstein, 1998).

Recent studies demonstrate that hunter and gatherer communities inhabited the Llanos de Moxos since the beginning of the Holocene (Lombardo et al., 2013), but only little is known about how early hunter and gatherer communities dealt with the seasonal floods during the early- to mid-Holocene (Capriles and Albarracin-Jordan, 2013; Lombardo, 2014). A growing number of archaeological sites across Amazonia provide evidence of large and complex societies before the arrival of Europeans in the New World at AD 1492 (Heckenberger et al., 2008; Heckenberger and Neves, 2009; Neves, 2008; Saunaluoma, 2010). Nevertheless, it is still debated (Barlow et al., 2012; McMichael et al., 2011), whether pre-Columbian populations had a limited and mainly local influence on a so called "pristine landscape" (Denevan, 1996) or a wide impact that shaped Amazonia to a "cultural parkland" (Clement and Junqueira, 2010; Erickson, 2006, 2000; Heckenberger et al., 2003; Whitney et al., 2013). Most of the debate focused on the extent of anthropogenic impact on a primarily forested landscape as inferred from the modern distribution of rainforest (Carson et al., 2014).

The Llanos de Moxos are located at the transition between rainforest and savannah and are thus sensitive to changes caused by climate and other environmental forcing (IPCC, 2001; Magrin et al., 2014; Mayle et al., 2007). However, substantial uncertainty over the extent of evergreen rainforest during the Holocene (Beerling and Mayle, 2006; Jones et al., 2011; Mayle and Power, 2008; Pennington et al., 2000) impedes a thorough assessment of the sensitivity of tropical Amazonian vegetation to past climate change.

Our study site, Lago Rogaguado, is one of the biggest lakes in the Bolivian lowland and is located only 80 km south of today's southern Amazonian rainforest boundary (Navarro, 2011). The presence of numerous raised fields around the lake gives archaeological evidence of pre-Columbian societies in the catchment (Tyuleneva, 2010). Therefore, this site provides excellent features to study vegetation history and anthropogenic impact of pre-Columbian societies in a broad regional context.

Here we use palynological approaches to reconstruct the Holocene vegetation and fire history. Particular attention is paid to landuse and potential effects of climate change. An assessment of the role of pre-Columbian societies and the resilience of Amazonian forests to prehistoric and historic disturbances (e.g. fire) may contribute to a better understanding of the cultural legacy of the modern landscape (Beerling and Mayle, 2006; Jones et al., 2011; Lombardo et al., 2012) and to more accurate conservation policies (Bush and Lovejoy, 2007; Carson et al., 2014; Lombardo, 2014; Mayle et al., 2007; Willis and Birks, 2006). Similarly, studying the climatic sensitivity of past tropical ecosystems may contribute to refine climate-impact knowledge and mitigation strategies.

2. Study site

Lago Rogaguado is one of the biggest lakes in Bolivia. It has a surface area of 315 km^2 and is located in the Llanos de Moxos (12°59′50.60″ S, 65°59′10.10″ W) at about 125 m a.s.l. The lake was very likely formed within a river valley that became flooded about 5800 cal BP as a result of neotectonic events (Lombardo, 2014). The basin is shallow with a maximum depth of 3–4 m. At present, Lago Rogaguado has no major permanent inflows or outflows but receives floodwater during the rainy season from swamp areas located southwest of the lake.

Today's climate is characterized by a strong seasonality. The mean annual temperature is 26 °C. Temperatures are high during the whole year although from June to September cold fronts from the south (locally called "surazos") can cause sharp temperature drops (Espinoza et al., 2013). Mean annual precipitation is 2400 mm and the dry season lasts from May to September when monthly precipitation is below 50 mm (Hanagarth, 1993). In the rainy season during the South American Summer Monsoon, from October to April, monthly precipitation may reach up to 500 mm (Maslin et al., 2011), which in combination with the flat landscape and clay soils results in widespread seasonal flooding (Hamilton et al., 2004; Jones et al., 2011; Larrea-Alcázar, 2010; Melack and Hess, 2011).

Due to the large lake size, the pollen catchment includes various ecosystems such as Cerrado, seasonally inundated savannah, permanent wetlands and gallery forests, depending on soil properties and flooding regime.

Cerrado (upland wooded savannah) occurs on non-flooded nutrient-poor laterites (Simon and Pennington, 2012) in large areas west and east of the lake (Fig. 1, Table 1). Most Cerrado taxa are intolerant to waterlogging (Jones et al., 2011). Fires during the dry season are an important ecological factor and most plants are adapted to frequent fires (Simon and Pennington, 2012). Today, wide areas are frequently burned intentionally in order to alter vegetation and gain better grassland for cattle ranching. Seasonally inundated savannah refers to savannah-like grasslands and parklands that are partially flooded during the rainy season. While seasonally inundated savannahs may change their local distribution due to edaphic conditions unrelated to climate, the large-scale replacement of other vegetation types by Cerrado is usually subject to large-scale environmental changes (e.g. precipitation regime; Jones et al., 2011).

The areas north and south of the lake within the former river valley are covered by wetlands. Wetland areas comprise persistent swamps, peatlands, seasonally inundated savannahs and stands of palm trees (Table 1). Seasonal inundation and soil properties restrict gallery forests to rather narrow bands of fluvial deposits e.g. east of the lake (Fig. 1) that are mainly composed of silt and sand, and are slightly elevated above the surrounding landscape and therefore only flooded for a short period of the year (Jones et al., 2011; Lombardo et al., 2011; Mayle et al., 2007). Today, the gallery forests are used for shifting cultivation and settlements by local communities. Isla Tesoro, a small island in the northwestern part of the lake (see S7 in Fig. 1B), hosts fragmented 'terra firme' forest vegetation that differs from the surrounding gallery forests in its composition (Table 1.). Numerous raised fields (elevated earth platforms to improve cultivation conditions) give archaeological evidence of pre-Columbian societies around the lake.

3. Methods

3.1. Fieldwork

In 2012 a sediment core (C1a in Fig. 1) of 82 cm length was taken with an Uwitec gravity corer 1 km from the shoreline in the northwestern part of Lago Rogaguado at 2.55 m water depth. In addition, two sediment surface cores were taken in September 2014 with an HON-Kajak sediment corer, one at the same site (C1b) and another close to Isla Tesoro (C2 in Fig. 1). Samples of 1 cm thickness were subsampled from the two surface cores in the field. In October 2013, seven soil surface samples (S1–S7 in Fig. 1) were collected from sites hosting different vegetation types around the lake in order to estimate differences in today's pollen rain.

3.2. Terrestrial macrofossil analyses and radiocarbon dating

Macrofossil samples of 2 cm thickness were taken continuously throughout the core C1a and sieved at 0.2 mm mesh width for ^{14}C-dating. The age-depth model is based on seven radiocarbon dates