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Late Pleistocene glacial forest of Humaitá—Western Amazonia

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ABSTRACT

Glacial-aged vegetation dynamics of the Humaitá—Western Brazilian Amazonia were studied by pollen, sedimentary facies, ^{14}C dating, $\delta^{13}C_{org}$ and C/N_{molar}. Two sediment cores were taken to a depth of 10 and 8 m from areas covered by grassland and dense/open forest, respectively. The deposits represent a succession of sediment accumulation in active channel (>42,600 cal yr B.P.), abandoned channel/floodplain (>42,600 to ~39,000 cal yr B.P.), and oxbow lake sedimentary environments (~39,000 cal yr B.P. to modern). The predominance of mud sediments, depletion of $\delta^{13}C_{org}$ and decrease in C/N_{molar} values identify the lake establishment. In these settings, low energy subaqueous conditions were developed, locally favoring preservation of a pollen assemblage representing herbaceous vegetation, some modern taxa from Amazonia and cold-adapted plants from the Andes represented by *Alnus* (2–11%), *Hedyosmum* (2–17%), *Weinmannia* (0–18%), *Podocarpus* (0–4%), *Ilex* (0–4%) and *Drymis* (0–1%), at least between >42,600 and <35,200 cal yr B.P. The herbs and modern taxa from Amazonia persisted through the Holocene, while the cold pollen assemblage became absent. The co-occurrence of *Alnus* with other cold adapted plants from the Andes during the late Pleistocene indicates that *Alnus* probably penetrated the Western Amazonia lowland or was growing closer to the study site due to cooler temperatures during glacial times. The present study presents the first report of a glacial age forest containing *Alnus* in areas of the Brazilian Amazonian lowlands. In addition to its palaeogeographical importance, this work demonstrates the effectiveness of using a combination of proxies for reconstructing sedimentary environments associated with vegetation.

1. Introduction

The nature of the vegetation and climate within the Amazon basin during the Last Glacial Maximum (LGM) remains a subject of scientific debate. With regard to the humidity (e.g. Irion, 1982; Räsänen et al., 1987; Salo, 1987; Colinvaux et al., 2000), pollen studies estimate a range from invariant rainfall (Colinvaux, 1998) to a reduction of about 20–55% (Bush, 1994; van der Hammen and Absy, 1994; van der Hammen and Hooghiemstra, 2000). A biogeochemical record from Lagoa da Pata, Rio Negro basin, revealed three hydrological and climatic regimes. The first phase, between 50,000 and 26,300 cal yr BP, was characterized by a relatively wet climate. The second phase, between 26,300 and 15,300 cal yr BP, was characterized by a dry phase, and the third phase, from approximately 15,300 to 10,000 cal yr BP, was characterized by a wetter climate (Cordeiro et al., 2011). Due to this dry phase, the Amazon humid forest area probably shrank to 54% of their present-day extent during the LGM (Anhuf et al. (2006). However, speleothem oxygen isotope indicates that ecosystems in western Amazonia have not experienced prolonged drying over the past 94,000 years (Mosblech et al., 2012), and during the last glacial period, a modest increase in precipitation occurred in western Amazonia, whereas a significant drying occurred in eastern Amazonia (Cheng et al., 2013).

Unlike the paleoprecipitation records, there is greater agreement of cooler surface conditions during the LGM. Andean ice cores contain isotopic evidence that tropical late Pleistocene temperatures may have been depressed as much as 8–12 °C at high elevations (Thompson et al., 1998). Pollen records from Bolivia, Ecuador, Peru and Brazil provide evidence for cooling in glacial times (Liu and Colinvaux, 1985; Bush et al., 1990; Bush et al., 1992; De Oliveira, 1992; Ledru, 1993; Colinvaux et al., 1996a; Mourguiart and Ledru, 2003; Bush et al., 2004; Pessenda et al., 2009; Urrego et al., 2010). Also, downslope movement of montane elements such as *Podocarpus*, *Drimys*, *Hedyosmum* and *Alnus* occurred in mid-elevations in Amazonian areas during the LGM (Liu and Colinvaux, 1985; Bush et al., 1990; Colinvaux et al., 1997; Bush et al., 2004; Urrego et al., 2010).

Pollen in a sediment core sampled from Lake Consuelo (1360 m above sea-level, asl) adjacent to the Bolivian border in southeastern Peru indicates that the forest surrounding the lake was dominated

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between 43.5 and 22 kcal yr B.P. by a mixture of upper montane and lowland elements. Upper montane taxa include *Alnus*, *Vallea*, *Podocarpus*, *Myrsine* and *Symplocos*, which are virtually absent from the modern pollen assemblage (Urrego et al., 2005). Palaeoecological studies in north-eastern Bolivia (600 to 900 m asl) near the southern margin of Amazonia identify the presence of pollen of *Podocarpus*, *Alnus* and *Ilex* between 50 kcal yr B.P. and the LGM (Burbridge et al., 2004). A palaeoclimate record from a shallow lake situated along the Paraguay River indicates that between ~45.0 and 19.5 kyr B.P. the climate was colder (4 °C lower compared to modern) and drier than present (Whitney et al., 2011). This set of records contributes to expanding the paleobotanical evidence (e.g., Behling, 1996; Behling et al., 1999; Colinvaux et al., 2000; Ledru et al., 2001) for cooler temperatures (5 °C below present) (Stute et al., 1995; Burbridge et al., 2004).

The LGM pollen cores for lowland Amazonia indicate also a cooling (Behling, 1996; Colinvaux et al., 1996b; Haberle and Maslin, 1999; Mayle et al., 2000; Ledru et al., 2001; Bush et al., 2004), and the few non-plant-based estimates of lowland temperature change suggest ~6 °C decrease from present from isotopic and elemental analyses of Caribbean corals (Guilderson et al., 1994) and Brazilian groundwater noble gases (Stute et al., 1995).

According to Bush (2002), the lowland forest in Amazonia contained significant populations of plants typical of modern montane areas during the LGM. This finding suggests that during early Holocene global warming, plants intolerant to the warmer climate became extinct in the lowland forest (Colinvaux et al., 2000).

As a contribution towards further evaluation of the geographic expression of a cooler climate during the late Pleistocene and a warmer climate during the Holocene, we studied two sediment cores that accumulated during these periods on the left margin of the Madeira River, the largest tributary of the Amazon River (Fig. 1a). Based on multiple proxies, including sedimentary facies, pollen, $\delta^{13}C_{org}$, C/N_{molar} ratio, and AMS radiocarbon dating, this paper provides insight into the extent of cooler tropical temperature effects on lowlands (elevation of ~100 m) of the Western Amazon forest.

2. Study area

The study area is located between the city of Porto Velho, north of the State of Rondonia, and the town of Humaitá, south of the State of Amazonas in the Western Brazilian Amazonia (Fig. 1). It is characterized by tropical climate with a short dry season (Am in Köppen's classification), with mean annual temperature between 24 °C and 26 °C, and mean annual precipitation between 2250 and 2750 mm. The relative humidity in the region is 85%. Rainy periods begin in October, with precipitation peaks in January to February, while dry periods are between June and August (Brasil, 1978). The principal vegetation cover consists mostly of arboreal vegetation including dense and open forest and dense woodland savanna that are intermingled often in sharp contact with large patches of pioneer formations and natural grassland/shrubland savanna vegetation (Fig. 1a) (Brasil, 1978). These vegetation units are not subject to periodic flooding of fluvial waters. These areas of natural savanna vegetation around Humaitá cover 615 km^2 (Vidotto et al., 2007). In the study area, a large patch of open vegetation (mostly pioneer vegetation/grassland savanna) is present, which averages nearly 20 km in length and up to 10 km in width (Fig. 1a). The arboreal vegetation is mainly represented by Euphorbiaceae, Bignoniaceae, Fabaceae, Moraceae, Anacardiaceae, Malpighiaceae, Malvaceae, Sapotaceae, Rubiaceae and Apocynaceae, whereas herbs are mainly represented by Poaceae, Cyperaceae and Asteraceae. Near the sampling sites, 138 species and genera distributed among 37 families of arboreal and herbaceous vegetation were identified (Vidotto et al., 2007) (Table 1).

The region has a small elevation range (~100 m elevation, Fig. 1b). The Quaternary sediments (Pessenda et al., 2001; Latrubesse, 2002) occur mainly along the fluvial terraces and above the modern floodplain area with altitudinal variations ranging from 45 to 100 m. The region contains a paleomorphology recording a large riverine meander belt (Fig. 1a). This landscape consists of a semi-circular shape displaying a set of concentric lines, which is in sharp contact with surrounding areas. The geological setting of the study area is within the southwestern and southeastern part of the Solimões Basin, which is a foreland basin of

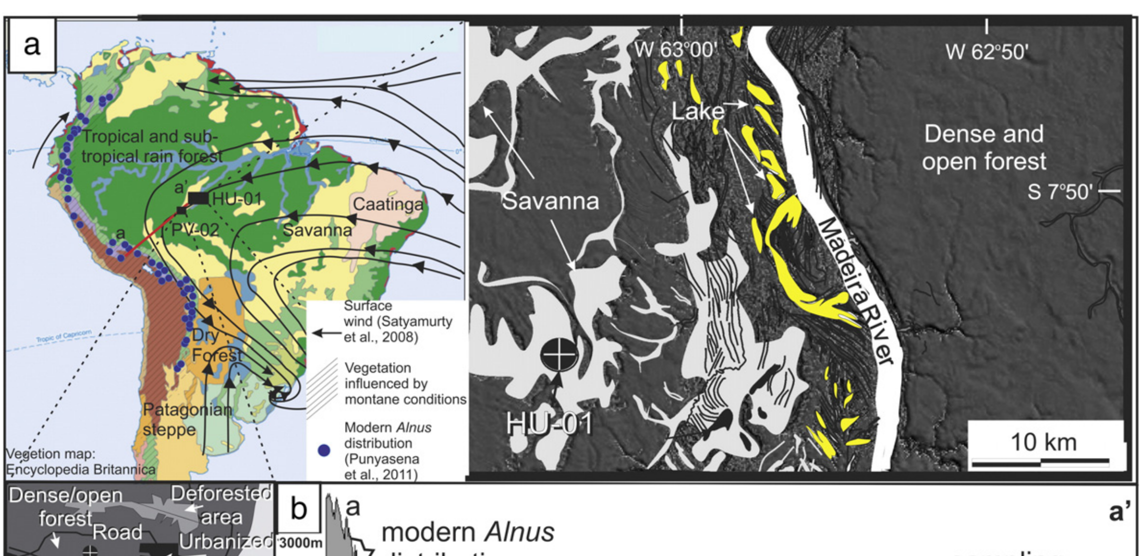

Fig. 1. a) Sediment core location, main geomorphologic features, surface wind directions, modern *Alnus* distribution, and location of vegetation units; b) topographic profile from Andes to study site.