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Forest-savanna boundary shift on the plateau of Serra Sul dos Carajás (southeastern Amazonia) since the mid-Holocene; driving forces and limiting factors

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A B S T R A C T

The vegetation history of the savanna on the plateau of Serra Sul dos Carajás (PSSC) is well studied by three palynological records. Nonetheless there is no record from the forests around this plateau so that the long term forest-savanna boundary shift can be investigated. In this study, a sediment core taken from the forests on the slopes of the plateau is studied using a multi-proxy analysis. The palynological result is compared with the records from adjacent savanna. This study reveals that well-established forests have been present around the plateau during the last 6600 cal yr BP. Since the mid-Holocene owing to a change to favorable climatic conditions, forests started to move toward the savanna and after 3400–4000 years reached their modern borders in the savanna region. Because during this long period forest borders moved horizontally a relatively short distance (ca. 250 m), we concluded that there might be limiting factors that delayed forest expansion. Among different possible factors, fire and human may play an important role. However, the evidence suggests that the slow process of soil formation to produce a soil layer with sufficient depth is the main limiting factor that delayed the forest expansion. According to the previous hydroclimatic and palaeo-ecological studies, the southward displacement of Inter Tropical Convergence Zone (ITCZ) is more likely the trigger of forest expansion in the area since the mid-Holocene.

1. Introduction

The amount of atmospheric CO_2 that is absorbed, processed and stored by Amazon forests each year is more than twice the CO_2 emitted from fossil fuel combustion (Malhi and Grace, 2000). Therefore the role that Amazon forests plays to control the concentration of atmospheric CO_2 and thus offset the effect of climate change is critical. This huge carbon sink however, is vulnerable to marked climatic events like the severe drought occurred in 2005 that hampered trees growth and killed the trees selectively (Phillips et al., 2009). Hence investigating the long-term dynamics of Amazon forests, especially the shift in savanna-forest boundaries under substantial climate changes, affords an applicable way to understand the future of these forests under the upcoming climate changes.

During the last two decades, the PSSC has been a key area for such long-term palaeoecological studies. The reasons why this plateau is interesting for scientists are: i) it is located in "Amazonian Dry Corridor" (Bush, 1994; van der Hammen and Absy, 1994) that receives less rainfall compared to other regions in Amazon (Absy et al., 1991) and so it is vulnerable to position of ITCZ (Peterson and Haug, 2006), moisture input from Atlantic Ocean and the surface temperature of Pacific Ocean (Liu et al., 2000; Marengo et al., 2001; Zheng et al., 2008), ii) it is developed upon "banded iron formation" that causes some restrictions on the establishment of vegetation (Absy et al., 1991) and iii) this region has accommodated human beings since ca. 10,000 cal yr BP (Kipnis et al., 2005; Magalhães, 2009) and therefore is suitable to detect the long

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term effects of human activities on the natural landscapes.

These factors explain that the PSSC was subjected to several environmental changes through the Holocene. Two important changes in the time frame of this study are the early to mid-Holocene savanna expansion and the late Holocene forest expansion. The first change, with some temporal variations among different records, is agreed to be caused by periods of dry climatic condition alternating with slightly wetter conditions. During this interval the repeated failed forest expansion into the savanna is evident implying that the wet periods were not long enough to support forest expansion. The second environmental change that occurred at ca. 4500-3500 cal yr BP is characterized by return to wetter climatic conditions and forests boundary shift toward the savanna (Absy et al., 1991; Hermanowski et al., 2012; Martin et al., 1993; Sifeddine et al., 2001).

These environmental changes have been revealed through the studies carried out on the savanna of PSSC. So far the dynamics of the forest fringe on the slopes of the plateau have not been directly investigated using a sediment core taken from forested area. Therefore we do not know how far the forest margins from their modern borders were and with which rate did forests move toward the savanna. Also factors promoting/hampering the forest expansion are not clear. This study using multi-proxy analyses (pollen, charcoal, lithology, soil Fe and radiocarbon dating) on a sediment core retrieved from forests surrounding the plateau aims to answer these questions.

2. Study area

2.1. Climate

The regional climate of southeast Amazon is tropical wet and dry (type “Aw” in the Köppen system) or savanna climate (McKnight and Hess, 2000) with pronounced wet (November–May) and dry seasons (end of June–early October) (Lopes et al., 2013; Sifeddine et al., 2001). The average annual rainfall in Carajás is 2126 mm that increases with elevation so that lowlands receive 1500 mm and higher altitudes receive 1900 mm rainfall per year (IBAMA, 2003). The mean annual temperature ranges from 23.5 °C at 835 m a.s.l. to 26.2 °C at 203 m a.s.l. (Silva et al., 1996). The main drivers of seasonal precipitation are the position of the ITCZ and the coupled onset and intensity of convection in the Amazon. During the austral summer, warmer southern Atlantic sea surface temperature (SST) causes southward movement of the ITCZ and intensifies the convection, causing higher rainfall rates. Other factors influencing the regional rainfall are moist trade winds from the tropical Atlantic and evapotranspiration from the forests itself (Fu et al., 2001; Liebmann and Marengo, 2001; Marengo et al., 2001, 1993; Nobre and Srukla, 1996) (Fig. 1a).

2.2. Topography and soil

The PSSC, is a narrow plateau located in the southeastern region of Amazonia and is comprised of several hilly plateaus ranging from 600 to 900 m in elevation (Fig. 1a and b). The plateau is developed upon a banded iron formation (Absy et al., 1991) which is covered by a thin layer of lateritic soil with low water content and high concentrations of iron oxyhydroxides and relatively low amounts of aluminum. A thicker soil horizon with higher water content provides habitats for arboreal vegetation on the slopes around the plateau and in the depressions (Absy et al., 1991; Hermanowski et al., 2014, 2012; Nunes et al., 2015; Sifeddine et al., 2001; Soubiès et al., 1991).

2.3. Modern vegetation

The lateritic substrate underlying the superficial soil horizon causes a series of restrictions on establishment of vegetation, such as forming shallow and patchy infertile soils with low water content, high energy absorption from sunshine, raised temperatures, and soil poisoning (Meirelles et al., 1991). Four different vegetation units present in the study area are separated according to the soil depth gradient whereby herbaceous *campo rupestre*, shrubby *campo rupestre*, *capão* forests and upland forests grow in shallower to the deeper soils, respectively (Nunes et al., 2015). In *campo rupestre*, Poaceae, Myrtaceae, and Asteraceae are the most common families and the genera *Borreria* and *Byrsonima* are also frequent. Herbaceous *campo rupestre* is an open vegetation covered by small shrubs, with *Vellozia glochidea* (Velloziaceae) growing on the grassy layer. Taxa such as several *Croton* species, *Cuphea tenella*, and *Mimosa* are also common. Dense or shrubby *campo rupestre* is supported on more fragmented ironstone cap (canga) that provides a softer medium for root development. Vegetation is composed of tall shrubs and herbaceous plants with dominance of Mimosaceae, *Byrsonima*, *Ficus nymphaeifolia*, *Miconia*, *Tibouchina*, Myrtaceae and Rubiaceae. *Capão* forests form repetitive small islands of semi-deciduous forest within *campo rupestre* vegetation. Upland forests are dense ombrophilous forest established on the margin of plateau in the transition (ecotone) between *campo rupestre* and the forests of the lower slopes of the plateau (Nunes et al., 2015).

2.4. Location of the coring site

The studied core is called Buriti (BRT) and was collected from a small depression (5 × 10 m, 6°23′28.95″ S, 50°22′18.29″ W, 710 m a.s.l.) in a narrow U shaped forest hollow (80 × 900 m) surrounded by upland forests. The site is 250 m distant from the modern forest-savanna boundary. The core name is taken from the local name for *Mauritia* palm (Buriti) that occurred in a small population at the location.

Former palaeoecological records from PSSC (Fig. 1c and d) are i) Pântano de Mauritia (PDM, (Hermanowski et al., 2012)), a swamp located in the savanna area at 740 m a.s.l, with 700 m mean distance from the forest borders on both the eastern and western sides, ii) Lagoa da Cachoeira (LDC, (Hermanowski et al., 2014)) at 705 m a.s.l., that is today connected to forests on the eastern side and is surrounded by a broad area of savanna from the other 3 sides with 1 km mean distance from the forest borders on the western side, and iii) CSS2 and CSS10 (Absy et al., 1991; Sifeddine et al., 2001) are located about 9 km to the northwest of BRT; Only the pollen records from Hermanowski et al. (2012, 2014) were available to be discussed and compared with the record BRT in this manuscript.

3. Material and methods

3.1. Coring, lithology and Fe measurement

For this study in 2005, a core with a length of 93 cm was collected using a Russian corer. Sediments were transported to the Geoscience Institute at the Federal University of Pará (UFPA) in Belém and stored in dark and cold (4 °C) conditions.

Lithological description was done based on the color and texture of the sediment core. To measure amount of soil extractable Fe, 19 sediment subsamples were taken in intervals of 5 cm along the core plus one additional subsample at 93 cm. Subsamples were dried for 48 h in 70 °C and 100 mg dry weight of each subsamples were treated through digestion in HNO_3 acid 65%. Digestion was carried out in closed vessels for 12 h at 195 °C (modified protocol from