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Environmental changes in southeastern Amazonia during the last 25,000 yr revealed from a paleoecological record

Barbara Hermanowski [a,*], Marcondes Lima da Costa [b], Hermann Behling [a]

[a] University of Göttingen, Albrecht-von-Haller Institute for Plant Sciences, Department of Palynology and Climate Dynamics, Untere Karspüle 2, 37073 Göttingen, Germany
[b] Universidade Federal do Pará, Centro de Geociências, Departamento de Geoquímica e Petrologia, Av. Augusto Correa 1, Guamá, 66075-900 Belém, Brazil

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ABSTRACT

New pollen, micro-charcoal, sediment and mineral analyses of a radiocarbon-dated sediment core from the Serra Sul dos Carajás (southeast Amazonia) indicate changes between drier and wetter climatic conditions during the past 25,000 yr, reflected by fire events, expansion of savanna vegetation and no-analog Amazonian forest communities. A cool and dry last glacial maximum (LGM) and late glacial were followed by a wet phase in the early Holocene lasting for ca. 1200 yr, when tropical forest occurred under stable humid conditions. Subsequently, an increasingly warm, seasonal climate established. The onset of seasonality falls within the early Holocene warm period, with possibly longer dry seasons from 10,200 to 3400 cal yr BP, and an explicitly drier phase from 9000 to 3700 cal yr BP. Modern conditions with shorter dry seasons became established after 3400 cal yr BP. Taken together with paleoenvironmental evidence from elsewhere in the Amazon Basin, the observed changes in late Pleistocene and Holocene vegetation in the Serra Sul dos Carajás likely reflect large-scale shifts in precipitation patterns driven by the latitudinal displacement of the Inter-Tropical Convergence Zone and changes in sea-surface temperatures in the tropical Atlantic.

Introduction

The Amazon rainforest is one of the most species-rich regions in the world and plays a significant role in the global hydrology and climate system. About 10% of global carbon is found in Amazonian forests and soils (Melillo et al., 1993). Given the possibility of a future constriction of the Amazon rainforest due to increased fire frequency and droughts (Nobre et al., 1991; Cox et al., 2004), it is essential to understand long-term vegetation dynamics under changing climatic conditions. Paleoecological studies in particular contribute to an improved understanding of the resilience of Amazon rainforest to large-scale environmental and climate changes.

Under the dry climatic conditions during the LGM and early to mid-Holocene, the prevalence of savanna vegetation in Amazonia is suggested. But there are still questions to be addressed, including reasons for the extension of savannization during arid periods, and the complex feedbacks between climate and vegetation. Pollen records spanning the LGM have been interpreted as indicating (1) Amazonian forests were replaced by savanna (Absy et al., 1991; Van der Hammen and Absy, 1994), (2) the Amazon Basin remained forested (Haberle and Maslin, 1999; Colinvaux et al., 2000; Kastner and Goñi, 2003; Bush et al., 2004; Beerling and Mayle, 2006), and (3) Amazonia remained forested with savanna expansion at its margins (Sternberg, 2001; Mayle et al., 2009). The general consensus is that Amazonia has been forested during the late Quaternary, with the expansion of savanna at the periphery during the LGM and early Holocene. Climate was apparently drier than during the intervening periods, but ecosystems across the Amazon Basin were affected by significantly different regional precipitation patterns (Absy et al., 1991; Colinvaux et al., 2000; Behling and Hooghiemstra, 2001; Sifeddine et al., 2001; Burbridge et al., 2004; Bush et al., 2004; Irion et al., 2006; and Cordeiro et al., 2008).

The presumed climatic drivers for these different patterns are changes of the general position of the Inter-Tropical Convergence Zone (ITCZ) (Mayle et al., 2000; Haug et al., 2001; Burbridge et al., 2004; Peterson and Haug, 2006), moisture input from the tropical Atlantic, and the effects of El Niño/Southern Oscillation events (ENSO) (Liu et al., 2000; Marengo et al., 2001; Zheng et al., 2008). The southeastern part of Amazonia is of particular interest because it is especially sensitive to shifts of the ITCZ and to moisture input from the Atlantic Ocean, but few pollen records are available from this region, none has spanned the LGM, and the interpretation of the pollen data is still controversial (Absy et al., 1991).

Here, we describe a new paleoecological multiproxy record from the Serra Sul dos Carajás that provides (1) insights into the environmental history of this region including the LGM, (2) an extended taxa list to clarify previous uncertainties of interpretation, and (3) new proxy data to better understand fire history, soil dynamics and changes in hydrology. Of particular interest are the dynamics of

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* Corresponding author. Fax: +49 551/39 8449.
E-mail address: barbara.hermanowski@biologie.uni-goettingen.de (B. Hermanowski).

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edaphic savanna and forest communities and their possible connections to past climatic conditions.

Study area

Climate

The regional climate of southeast Amazonia is tropical humid (Aw, Köppen), with pronounced wet (November–May) and dry seasons (June–October) (Sifeddine et al., 2001). The average mean monthly temperature is 25°C. Mean monthly precipitation at Marabá climate station (5°37′S,49°13′W, 95 m a.s.l.) accounts for 740 mm during the wet season, and 60 mm during the dry season (INMET, 2011). The seasonality of regional precipitation is influenced by several factors including the migration of the ITCZ due to changing Atlantic sea surface temperatures (SST), moist trade winds from the tropical Atlantic, evapotranspiration from the forest itself, and the coupled onset and intensity of Amazon convection (Marengo et al., 1993, 2001; Nobre and Shukla, 1996; Fu et al., 2001; Liebmann and Marengo, 2001) (Fig. 1b). During the dry season the ITCZ is situated north of the equator and convection in eastern Amazonia is decreased. During the wet season the ITCZ moves south of the equator and convection is enhanced.

Topography and soil

The Serra Sul dos Carajás (Serra Sul) is a series of plateaus of 600–800 m a.s.l. The top of the plateaus varies from flat to slightly wavy surface. Numerous lakes and wetlands are located in interconnected depressions with gentle to steep margins. The ferruginous lateritic crusts of the plateaus are locally porous and cavernous. These rocky substrates are covered by a thin ferruginous soil layer with a silty and sandy texture. Thicker soils with a higher availability of nutrients and water accumulate at the slopes of the plateau and at rocky lake borders, depressions, and small canyons on top of the plateau.

Modern vegetation

The nutrient-poor soils of Serra Sul are associated with a xerophytic vegetation that comprises a mosaic of dense shrubby and open shrub–bush savanna called ‘Campo rupestre’ (Cleef and Silva, 1994; Silva et al., 1996; Sifeddine et al., 2001; Rayol, 2006; Nunes, 2009). Evergreen tropical rainforest occurs along slopes and in the lowlands (IBAMA, 2003) (Fig. 1b).

The most common families of the ‘Campo rupestre’ are Poaceae, Myrtaceae, and Asteraceae. *Borreria* and *Byrsonima* are also common. Typical taxa of the ‘open campo rupestre’ are several *Croton* species, *Cuphea tenella*, and *Mimosa*. ‘Dense campo rupestre’ is characterized by Mimosaceae, *Byrsonima*, *Ficus nymphaeifolia*, *Miconia*, *Tibouchina*, Myrtaceae, and Rubiaceae (Rayol, 2006; Nunes, 2009).

Typical taxa of the tropical rainforest are Melastomataceae, Anacardiaceae, Moraceae, Meliaceae, *Alchornea*, *Aparisthmium* and other Euphorbiaceae (Rayol, 2006; Nunes, 2009). The transition between forest and savanna is characterized by a successional forest dominated by *Aparisthmium* and *Erythroxylum* (Morellato and Rosa, 1991).

The dominant plant families of the tropical rainforest in the lowlands of Carajás and the surrounding region are Fabaceae, Meliaceae, Melastomataceae, Euphorbiaceae, Anacardiaceae, Bignoniaceae, Moraceae, and Combretaceae (Salomão et al., 1988; Morellato and Rosa,

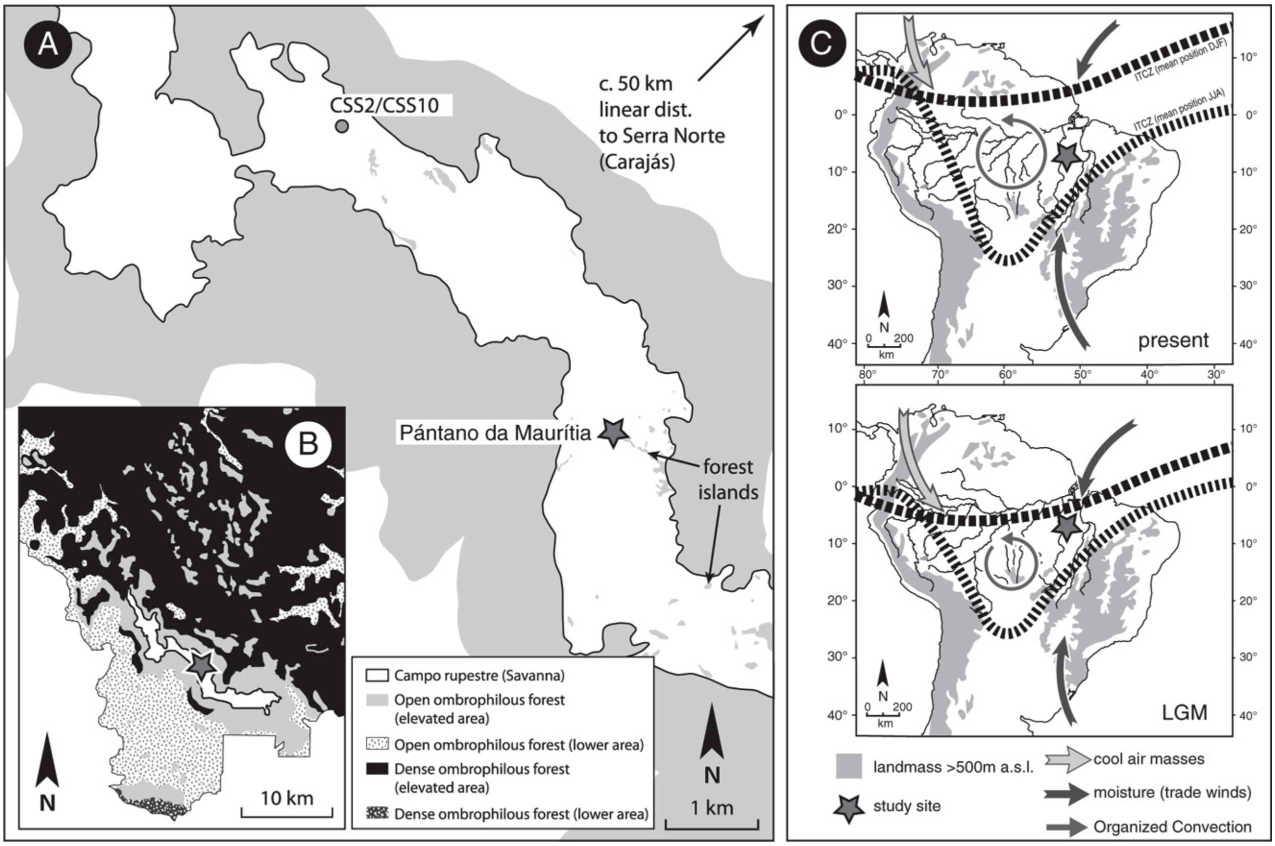

Figure 1. Location of the study site in the Serra dos Carajás and important climatic factors. (A) Position of Pántano da Maurítia in relation to former study sites in the Serra Sul dos Carajás (CSS2/CSS10), (B) Vegetation types in the southern part of the Floresta National de Carajás (after: Plano de Manejo para uso múltiple da Floresta National de Carajás, 2003), (C) Present climatic conditions (above) and suggested conditions (below) during the LGM (DJF = austral summer, JJA = austral winter); B modified after IBAMA, 2003; C modified after Maslin and Burns 2000.

1991). Islands of forest, similar in composition to the rainforest below, occur on the plateau in depressions, small canyons, and along rocky lake borders. Several *Ficus* species and two *Alchornea* species are also typical for these forest islands (Nunes, 2009).

Location of the study site

Pántano da Maurítia (6°21′6.20″S, 50°23′36.60″W, 740 m a.s.l.) is a small (surface area 100 × 200 m) wetland on a narrow plateau of Serra Sul in the southeastern Amazonian lowlands (Fig. 1). Today it is mainly covered with Cyperaceae and Juncaceae. Previous paleoecological studies were carried out at study sites on the plateau 5 km north of this wetland (Absy et al., 1991, Sifeddine et al., 2001). Pántano da Maurítia is 600 m from the edge of the rainforest.

Methods

A 466-cm-long sediment core was taken from Pántano da Maurítia in 2005 using a Russian corer (50 cm long). The core was transported to the Geoscience Institute at the Universidade Federal do Pará (UFPA) in Belém, where it was stored in darkness at 4°C. The upper 200 cm of the core were analyzed and 7 bulk sediment samples (2–3 g) were used for radiocarbon dating by the Accelerator Mass Spectrometry (AMS) Laboratory Erlangen (Table 1).

Pollen and micro-charcoal

32 sediment subsamples (0.5 cm^3) were used for pollen and micro-charcoal analysis. Pollen samples were prepared using standard methods (Faegri and Iversen, 1989) including 70% HF treatment, addition of the exotic marker *Lycopodium clavatum* (Stockmarr, 1971), and mounting in glycerine gelatin. Almost all samples were counted to a minimum of 300 terrestrial pollen grains, but where pollen concentration was very low a minimum of 200 terrestrial pollen grains was counted. Percentages of spores and aquatic taxa are calculated relative to the terrestrial pollen sum. Micro-charcoal particles were counted on the pollen slides and were divided in two size classes. Small charcoal particles (10–125 μm) are assumed to represent regional fires, whereas large particles (> 125 μm) record fires near the catchment area (Gardner and Whitlock, 2001; Sadori and Giardini, 2007). Thus, the division into size classes allows the differentiation of regional and local fire events, but given the possibility that large particles are broken into smaller pieces during laboratory processing, the smaller size class should be interpreted with caution.

The zonation of the percentage diagram was conducted with CONISS (Grimm, 1987) using Psimpoll (Bennett, 1998). All 99 identified pollen and spore taxa were included in the CONISS analysis. The AMS radiocarbon dates were calibrated with BCal (Buck et al., 1999) using the IntCal04 calibration curve (Reimer et al., 2004). The age–depth curve was calculated in Psimpoll by linear interpolation between the weighted average of calibrated ages. Pollen and spore identification was based on appropriate literature (Roubik and Moreno, 1991; Carreira et al., 1996; Colinvaux et al., 1996a, 1996b; Carreira and Barth, 2003) and a pollen reference collection held at the Department of Palynology and Climate Dynamics, University of Göttingen.

Table 1
Radiocarbon dates from Pántano da Maurítia.

Depth (cm)	^{14}C yr BP	Laboratory number	Age range (cal yr BP), 2σ	Age (cal yr BP), weighted average
48–49	2140 ± 40	Erl-12483[a]	1999–2183	2148
60–61	3373 ± 26	KIA 39910[b]	3558–3692	3616
96–97	8547 ± 51	Erl-12484[a]	9463–9601	9523
120–121	8899 ± 39	KIA 39911[b]	9898–10,189	10,034
148–149	9900 ± 54	Erl-12173[a]	11,207–11,412	11,331
160–161	10,537 ± 57	KIA 39912[b]	12,220–12,277	12,543
196–197	19,795 ± 147	Erl-12485[a]	23,230–24,166	23,646

[a] AMS-Labor Friedrich-Alexander-Universität Erlangen-Nürnberg.

[b] Leibniz Labor für Altersbestimmung und Isotopenforschung, Christian-Albrechts-Universität Kiel.

Sedimentology and mineralogy

Ten samples were selected for analyses of grain size and mineralogy. Grain-size distribution (0.3 to 400 μm) was characterized by laser particle analyzer Quantachrom-Cilas 920 at the Institute of Geosciences, Halle University. Approximately 0.5 g of each sample were disaggregated in distilled water and then introduced into the laser analyzer. Mineral identification was carried out by X-Ray Diffraction (XRD), powder method. Scanning electron microscopy with energy dispersive system (SEM/EDS) completed the mineral characterization (both analyses carried out at the Geosciences Institute, UFPA, Belém).

Results

Chronology and zonation

The chronology for the upper 200 cm of the sediment core is based on 7 AMS ^{14}C dates spanning the last 25,000 yr (Table 2). As the bedrock is not calcareous, an error by hard-water can be excluded. The age model shows uneven rates of sediment deposition, suggesting alternating phases of low and high accumulation rates (Fig. 2). No reversals in the radiocarbon data are present.

Four zones (PDM = Pántano da Maurítia) were identified based on CONISS: zone PDM 1 (200–149 cm), PDM 2 (149–123 cm), PDM 3 (123–58 cm) and PDM 4 (58–0 cm)

In the pollen diagram (Fig. 3), identified pollen taxa are grouped in five categories: tropical forest taxa (tropical rainforest and dry forest taxa), cold-adapted taxa, palms, taxa of savanna ecosystems, and aquatic taxa (Salomão et al., 1988; Morellato and Rosa, 1991; Gentry, 1993; Cleef and Silva, 1994; Silva et al., 1996; Rayol, 2006; Marchant et al., 2007; Nunes, 2009). Only the most important or representative taxa for each category are shown. Moraceae pollen was classified as a tropical forest taxon, as today the only Moraceae species at Serra Sul associated with Campo rupestre is *Ficus nymphaeifolia*, and no *Ficus* pollen grains were encountered.

Zone PDM 1 (200–149 cm; 7 samples; 25,000–11,400 cal yr BP)

The zone is characterized by high pollen frequencies of the savanna taxa Poaceae (40%), *Spermacoce* (14%), and Asteraceae (7%). *Cuphea*, Mimosaceae, *Byrsonima*, Amaranthaceae/Chenopodiaceae, and Amaranthaceae (others) are abundant (<5%). Tropical forest taxa (10–15%) are mainly represented by pollen of Moraceae/Urticaceae and Melastomataceae/Combretaceae. The latter slightly increase (max. 25%) at the end of the zone. Other tropical forest taxa include Fabaceae (max. 8%), *Celtis*-type (7%), and *Cecropia* (<5%). Cold-adapted forest taxa are represented by low frequencies of *Myrsine* (max. 11%), *Ilex*, and *Hedyosmum* (both <5%), and single pollen grains of *Euplassa*-type, *Podocarpus*, and *Styrax*, most notably at 160–149 cm core depth. Arecaceae are abundant (<10%), but absent at 174–160 cm (17,000–12,500 cal yr BP). The aquatic taxa Eriocaulaceae and Cyperaceae are frequent (ca. 8%).

A high amount of spores of the aquatic *Isoëtes* (max. 90%) is characteristic; fern spores only occur with low values (1–5%). Colonies of the alga *Botryococcus braunii* are frequent (50%, max. 78%). At the beginning of the zone the total terrestrial pollen concentration is low with mean values of 5400 grains/cm^3. Between 176 and 149 cm (17,500–11,300 cal yr BP) concentrations increase to max. 124,300 grains/cm^3. The concentration of carbonized particles is

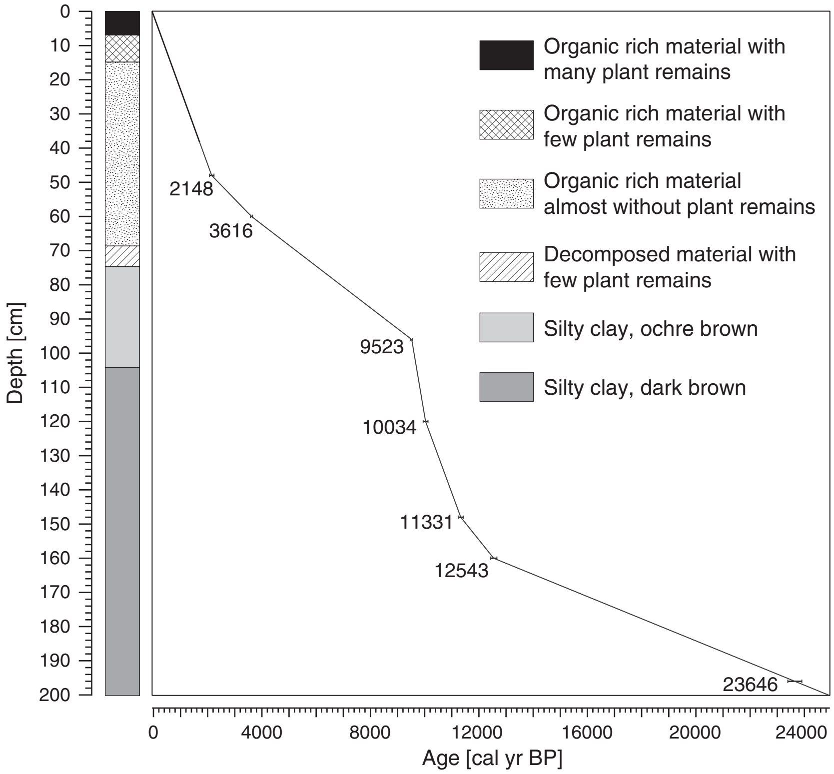

Figure 2. Age–depth curve of Pántano da Maurítia based on linear interpolation between the weighted average of calibrated ages (cal yr BP) in combination with stratigraphy of the core part from 0 to 200 cm.

low, except the high concentration of large micro-charcoal particles in one subsample (176 cm).

The zone is characterized by a brown-colored clay unit with fine micro-units of dark organic matter (OM) with a cycling structure. The grain size analyses show a silt to clay domain (Fig. 4), changing from 10 to 51 μm at 50% in frequency (35 μm in average). The sediments are composed of kaolinite, goethite, quartz, siderite, anatase, beside gibbsite, barite, talc and/or chlorite. The XRD spectrum (absence of the 20 to 22° 2Θ) shows a low structure order for kaolinite (Fig. 5). Goethite is abundant in nanocrystal scale showing an unequal distribution. Siderite is another typical mineral. It occurs with goethite, from which it has formed. Siderite forms micro- to sub-millimeter crystals, sometimes as well formed rhombohedra, which confer a friable sandy aspect to this unit. OM occurs and is strongly oxidized. A large XRD shoulder at 4.1 to 4.3 Å indicates the presence of opaline material in the sample bearing 'Cauixi' (fresh water sponges *Tubella reticulata* and *Parnula betesil*) and diatomaceous fragments. Opal changes gradually into quartz and kaolinite within this unit. Changing proportions of mineral and OM are responsible for the sediment bands of alternating color and texture.

Zone PDM 2 (149–123 cm; 3 samples; 11,400–10,200 cal yr BP)

High pollen frequencies of the rainforest taxa Moraceae/Urticaceae (max. 36%) characterize the whole zone. Melastomataceae/Combretaceae (max. 16%) and *Celtis*-type (11%) are represented by moderate values. Pollen of *Alchornea/Aparisthmium* is frequent (<10%) and the pioneer taxa *Trema* and *Cecropia* are abundant (<5%). Percentages of the cold-adapted taxon *Myrsine* decrease below 5%. *Ilex* only occurs as a single pollen grain at 145 cm (11,200 cal yr BP). Pollen of savanna taxa show a clear decline in abundance compared to PDM 1, with lower values of Poaceae (ca. 15%) and *Spermacoce*, Asteraceae, Myrtaceae, and *Byrsonima* (<5%). *Cuphea* pollen is absent, and percentages of Arecaceae decrease (<5%). Aquatic taxa are mainly represented by pollen of *Nymphaea* (3–12%), an indicator for open-water conditions.

A clear decrease in the abundance of *Isoëtes* spores is found at the beginning of this zone, together with a higher abundance of monolete verrucate fern spores (5%). High frequencies of *B. braunii* (ca. 80%) are characteristic. Pollen concentration is high with max. 285,000 grains/cm³. The concentration of micro-charcoal particles is low.

The zone occurs in a thicker gray silt to clay unit rich in OM and micro-units of brown clay material, which covers PDM 1. It shows the same grain size and mineralogy of the underlying zone: kaolinite, goethite, siderite, anatase, opal, beside gibbsite, barite, talc, and/or chlorite. Opal found at 138 cm (10,800 cal yr BP) is much more frequent. OM still occurs together with the minerals and is moderately preserved. Quartz is more abundant than in PDM 1 and is found along almost the entire zone. Most of the quartz seems to be the alteration product of organic opal mineralization (spicules and diatomaceous material) within PDM 2. Rock quartz grains are rare and primarily derive from the lateritic iron crust. Kaolinite is still frequent in the PDM 2 and shows a low structure order, too. Goethite is abundant in nanocrystal scale showing an unequal distribution (PDM 1). Anatase persists as a nanocristalline mineral dispersed in the sediment and is less frequent (0.3 to 2.4 wt.%). Together with the other minerals this confirms the persistence of lateritic source materials for the shallow lake.

Zone PDM 3 (123–58 cm; 14 samples; 10,200–3400 cal yr BP; PDM 3)

A decrease to generally low values of main tropical forest taxa (<10%) is characteristic for this zone, though slightly higher values of Anacardiaceae, Bignoniaceae, and *Zanthoxylum*, and higher values of Fabaceae (max.18%) between 123 and 96 cm (10,200–9400 cal yr BP) are recorded. Pollen of Arecaceae (ca. 8%, max. 24%) is frequent, as well as single pollen grains of *Mauritia flexuosa*-type. Only few pollen of the cold-adapted taxa *Ilex* and *Myrsine* are found in the

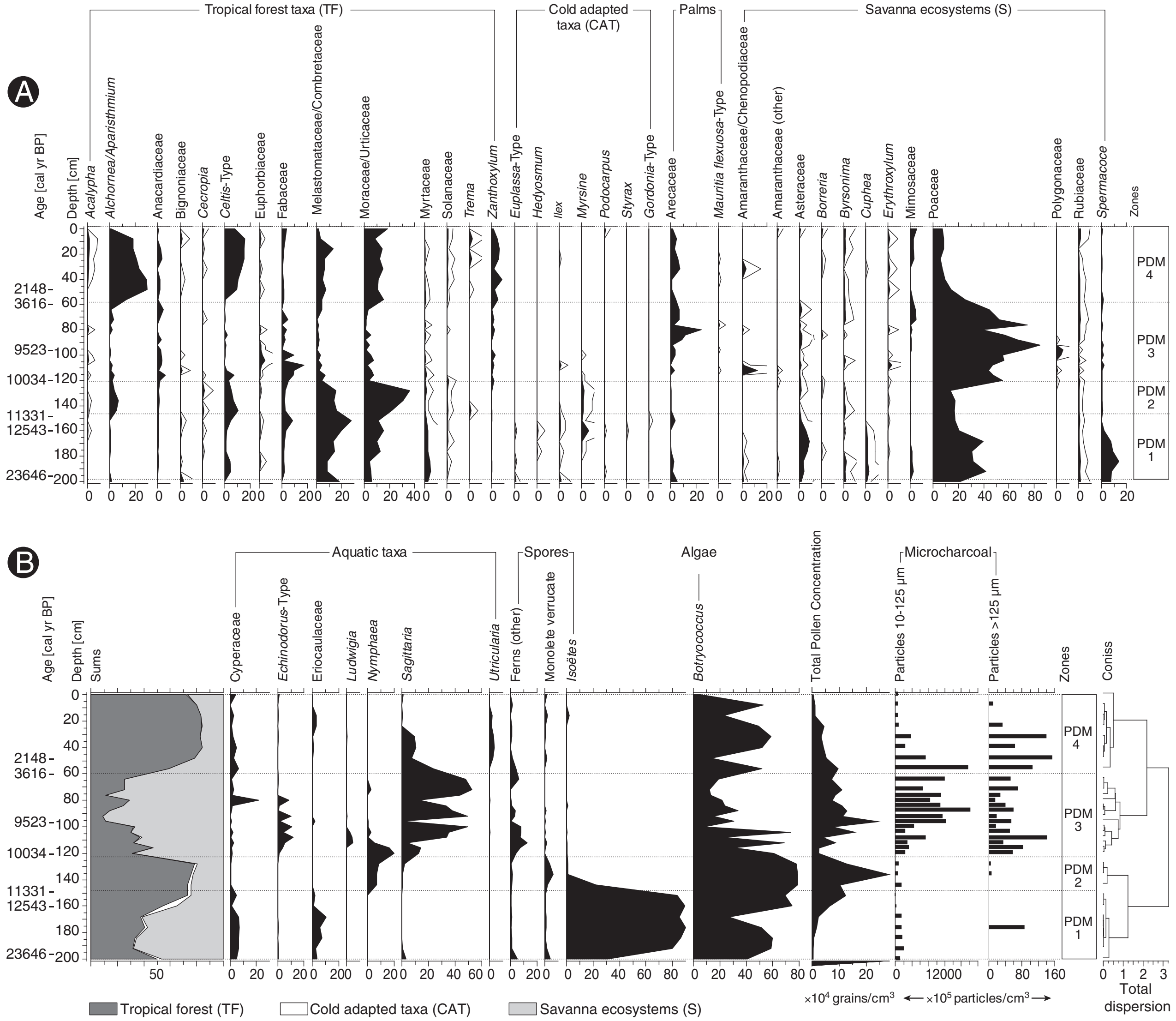

Figure 3. Pollen percentage diagram and zonation of the Pántano da Maurítia core from 0 to 200 cm core depth. (A) Most important taxa grouped in tropical forest taxa (TR), cold-adapted taxa (CAT), palms and taxa of savanna ecosystems (S), solid lines indicate 5× exaggeration, (B) Sums of TR, CAT and S together with aquatic taxa, spores and algae percentages; also shown are micro-charcoal concentrations.

lower part of the zone, and are absent above 96 cm. Poaceae reach maximum values (max. 85%), whereas other savanna-related taxa remain below 5%, except slightly higher values in Polygonaceae (123–92 cm, 10,200–8800 cal yr BP) and Mimosaceae (76–58 cm (6000–3300 cal yr BP). The zone is characterized by an increased abundance of several aquatic taxa, especially *Sagittaria* (ca. 40%) and *Echinodorus*-type (ca. 15%). At the base of the zone *Nymphaea* pollen increases to ca. 18%, but then decreases to low values or is even absent, while *Ludwigia* (5%) occurs at 116–100 cm (9900–9600 cal yr BP). Cyperaceae show maximum values (22%) at 80 cm (7000 cal yr BP).

Fern spores (ca. 8%) slightly increase at the beginning of the zone, whereas spores of the monolete verrucate type decrease to low values or are even absent. Low mean values in *B. braunii* (20%) are characteristic. In the lower part of the zone, pollen concentration increases (max. 245,000 grains/cm³) but decreases steadily between 92 and 58 cm (min. 72,540 grains/cm³). High concentrations of carbonized particles occur, with large particles at123–90 cm (10,200–8500 cal yr BP), and small particles at 90–58 cm (8500–3300 cal yr BP).

The zone is enclosed in a gray silt to clay sediment unit, rich in OM and micro-units of brown clay material. The organic debris reaches coarse silt. A clear enrichment of OM with an increased length of the debris up to the top of the zone can be observed. This suggests a change from a lake to a swamp environment. Quartz is frequent but kaolinite, goethite, siderite and anatase are rare or disappear in this zone. On the contrary, opal becomes much more frequent as a component of 'Cauixi' (fresh water sponges *T. reticulata* and *P. betesil*) and diatomaceous fragments.

Zone PDM 4 (58–0 cm; 8 samples; 3400 cal yr BP to present)

The zone is marked by distinct increases in pollen frequencies as well as pollen accumulation rates (not shown) of the tropical forest taxa *Alchornea/Aparisthmium* (max. 30%), *Celtis*-type (max. 15%), Melastomataceae/Combretaceae (max. 14%), and Moraceae/Urticaceae (max. 19%). A slight increase in frequencies of *Zanthoxylum* (<10%) occurs, as well as pollen of the pioneer *Trema* (<5%), whereas frequencies of Fabaceae (<10%) decrease. Pollen of *Acalypha* (<5%) occurs more continuously. Single pollen grains of *Ilex* (24 cm, 1000 cal yr BP) and *Podocarpus* (top sample) are recorded. As Mimosaceae pollen is scarcely present in the lower part of the zone, it increases to max. 10% from 24 cm onward. Overall low pollen frequencies of savanna taxa and a clear decrease in the abundance of Poaceae pollen (ca. 10%) occur together with a decrease of the aquatic

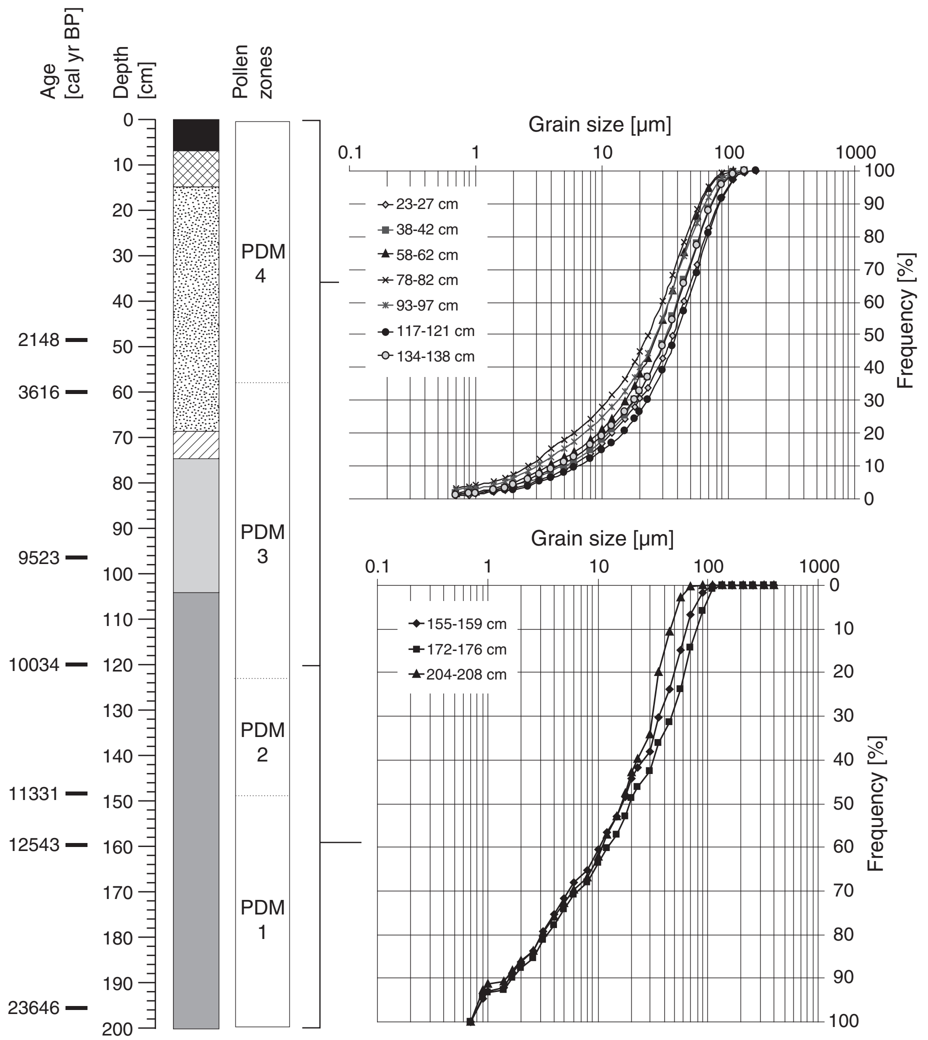

Figure 4. Distinct grain-size distribution (accumulative frequency) of sediments of Pántano da Maurítia.

taxon *Sagittaria* (ca. 10%). Other aquatic taxa such as Cyperaceae, Eriocaulaceae, and *Utricularia* occur with mean values around 5%, whereas ferns spores decrease. High frequencies of *B. braunii* with strong oscillations are characteristic.

Pollen concentration decreases markedly from a maximum of 96,800 grains/cm³ at the beginning of the zone to minimum values around 4900 grains/cm³ at the end. High micro-charcoal concentrations are recorded up to 27 cm (1200 cal yr BP), from 27 cm onward the concentrations clearly decrease.

The zone occurs in a dark gray sediment unit primarily consisting of OM, represented by fine plant debris in the middle of the zone and coarse plant debris between 15 and 0 cm (7000–0 cal yr BP). Silica-rich remnants of sponges and diatoms are very frequent. Only quartz and opal can be found as minerals in this zone, where quartz is less frequent.

Paleoenvironmental reconstruction

Analyses of pollen, charcoal, organic content, mineralogy, and grain size in the Pántano da Maurítia sediment core provide insights into the local hydrology, fire, and vegetation of Serra Sul, and the regional vegetation and climate of southeastern Amazonia over the past 25,000 yr. Pántano da Maurítia shows no sediment hiatus for the glacial period, in contrast to other records from Serra Sul and Serra Norte dos Carajás, which appear to have dried up during intervals of reduced precipitation (Absy et al., 1991; Sifeddine et al., 2001).

Characteristic color, grain size, and OM contents of the analyzed sediment units indicate cycling environmental changes in physical sedimentary conditions from a sedimentary basin into a swamp. An inorganic domain (minerals from the neighboring lateritic crust: kaolinite, goethite, anatase, ‘siderite’) changed into vegetation-based organic accumulation (very small mineral contribution) under high humidity.

The late Pleistocene (25,000–11,400 cal yr BP; PDM 1)

The occurrence of semiaquatic *Isoëtes* and *B. braunii* colonies represents continuously low water depths. Poaceae, together with *Spermacoce*, Asteraceae, *Byrsonima*, and *Cuphea*, reflect larger areas of savanna vegetation than today which indicates drier climatic conditions between 25,000 and 11,400 cal yr BP. Rare occurrence of forest taxa suggests forested areas at the plateau's slopes, where soils with higher water and nutrient availability accumulate. These forest communities were different from today, as indicated by a suite of cold-adapted taxa (Fig. 3). Even though climate was dry, the micro-charcoal data suggest low fire activity, perhaps due to cold temperatures or low biomass.

The deposition of a thick unit of inorganic, mainly lateritic material is indicative for slight weathering conditions during a long, generally dry period. The micro banding imprinted by alternation of thin gray sediment bands on the other side, may be indicative of an alternating water level of a shallow lake during short wet periods, which

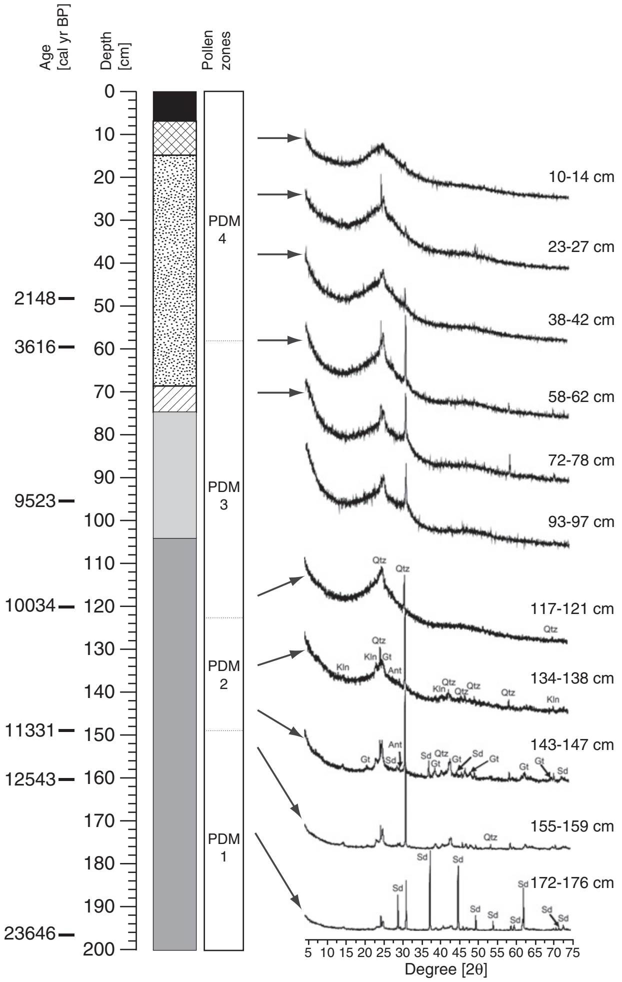

Figure 5. The XRD main minerals at 0–200 cm core depth. Quartz (Qtz); goethite (Gt); kaolinite (Kln); anatase (Ant); siderite (Sd). The shoulder at 25° 2θ may be opal.

favored the diagenesis of laterite-bearing minerals into siderite. The deposition of lateritic detritus (hematite, goethite, and anatase) was induced by detritus flow and/or run-off during dry conditions without high vegetation.

We suggest that forests were smaller in size and the slopes were mainly covered by scrub-bush savanna until 13,000 cal yr BP. Today *Euplassa*, *Hedyosmum*, *Myrsine*, *Podocarpus*, and *Styrax* are known from montane forests (>1000 m elevation) and *Ilex* is also associated with higher elevations (Marchant et al., 2002). These taxa, which are rare in modern lowlands, were mixed with lowland elements of tropical rainforests like Melastomataceae/Combretaceae and Moraceae/Urticaceae and are indicative for cooler climatic conditions. As these forest communities without modern analog show, forests in southeast Amazonia were not completely replaced by savannas as suggested by Absy et al. (1991). Likewise, a forest vegetation without a modern analog existed in northwest Amazonia during 22,000–12,000 cal yr BP (Bush et al., 2004). At the end of this period the increased occurrence of forest and decline of savanna at Pántano da Maurítia between 13,500 and 11,400 cal yr BP is in agreement with forest development in the surroundings of the plateau recorded by Sifeddine et al. (2001). The authors suggested erosion events due to intensive rainfall, indicative of wetter climatic conditions from 14,920 to 10,810 cal yr BP.

Both pollen data and paleovegetation simulations suggest that cold (Stute et al., 1995), dry climate and low atmospheric CO_2 may have resulted in low-density forests in Amazonia (Beerling and Mayle, 2006; Cowling et al., 2001).

Onset of the Holocene (11,400–10,200 cal yr BP; PDM 2)

A decline in abundance and diversity of cold-adapted taxa mark the transition from late glacial to early Holocene, and open water conditions (*Nymphaea*) occurred at the study site. High percentages of forest taxa and low micro-charcoal concentrations suggest the development of denser rainforest communities at sites where water and nutrient-rich soil accumulated, for example at the slopes but also at lake borders and depressions ontop of the plateau.

Al-goethite, gibbsite and hematite become unstable due to strong root activity of growing trees by decomposing these minerals for nutrient extraction. The decomposition rate increases under high humidity and temperature. This caused their chemical dissolution, reduction of Fe^{3+} and simultaneously OM oxidation. Consequently HCO_3^- was formed, providing the physico-chemical conditions for new mineral formations (siderite, kaolinite). Kaolinite may be a reaction product of free Al-complexes and amorphous silica (opal OM). Forest development and restarted biochemical weathering of the exposed lateritic iron crust refer to a warming trend in the early Holocene with increasing wetter conditions.

Slowed erosion at Serra Sul from 10,810 to 7930 cal yr BP was interpreted as full development of humid forest (Sifeddine et al., 2001). Absy et al. (1991) interpreted the increased abundance of Melastomataceae from 11,000 to 8320 ^{14}C yr BP (12,600–9500 cal yr BP) as forest development. Our new detailed data suggest that forest development took only about 1200 yr, with increasing abundance of various forest taxa including Moraceae/Urticaceae and Melastomataceae. Low occurrence of forest fires at Serra Norte from 11,800 to 7600 cal yr BP (Cordeiro et al., 2008) supports our interpretation. Furthermore, this corroborates paleovegetation simulations that show an increase in evergreen ombrophilous forests as a result of increased temperatures and atmospheric CO_2 levels (Cowling et al., 2001).

Early to mid-Holocene (10,200–3400 cal yr BP; PDM 3)

The most striking feature of this interval is the high abundance of Poaceae and *Sagittaria*, accompanied by generally low levels of arboreal savanna taxa and limited occurrence of tropical forest.

The existence of aquatic and semiaquatic plants in large quantity allowed a high OM accumulation. The micro-banding of brown sediments may be an indicator for conditions favoring laterite-bearing minerals coming from the swamp margins during short dry periods. The deposition of lateritic detritus (hematite, goethite, and anatase) was caused by detritus flow and/or run-off during short-term rains under generally dry conditions.

Dry conditions could cause a reduction of the wetland due to a lowered water level and pollen deriving from local and aquatic vegetation (Poaceae and *Sagittaria*) would be statistically overrepresented (Faegri and Iversen, 1989) (Fig. 3a,b). Colinvaux et al. (1999) and Bush (2004) interpreted high amounts of grass (Poaceae) pollen at Serra Sul as an overrepresentation of local vegetation (wetland grasses). As it is not possible to distinguish wetland and savanna grasses palynologically, it remains uncertain if the high abundance of Poaceae is attributable to the contribution of wetland or savanna species. Thus a clear statement about the extent of the reduction of forest and expansion of savanna is almost impossible. To test if Poaceae pollen mainly derives either from wetland or savanna grasses, we excluded Poaceae from the pollen sum (not shown). As the sum of savanna taxa increases from 20% (in the former period) to 40% of the total pollen sum, we suggest that Poaceae pollen largely reflect the vegetation around the swamp and not only wetland grasses. Today Poaceae clearly belong to the surrounding campo rupestre vegetation (Rayol, 2006), whereas swamps are mainly covered by Cyperaceae (Cleef and Silva, 1994). Thus we think that grass-dominated savanna expanded on top of the plateau, whereas forest pollen represents forest vegetation at the slopes of the plateau only 600 m from the study site.

Our data suggest a highly variable water level over a long time period, with alternating wet and dry phases rather than an overall dry period. Frequent fires may also indicate long dry phases, as well as the overall low abundance of *Botryococcus*, which could be the result of dry seasons too long for this alga to survive. A possible scenario may be the development of a seasonal climate in southeast Amazonia with dry seasons longer than today. Longer dry seasons may have been coupled with increased precipitation during the wet season, as the presence of *Sagittaria* and a peak of Arecaceae refers to the availability of moisture sufficient to support a swamp environment. Slightly lower occurrence of forest taxa after 9000 cal yr BP could indicate even drier conditions until 3700 cal yr BP. Dry seasons longer than four months are not favorable for humid tropical rainforest (Sternberg, 2001; Maslin, 2004) and could be a possible causal factor for a more open vegetation at the slopes of the plateau. The occurrence of Anacardiaceae, Bignoniaceae, Euphorbiaceae, Fabaceae, and *Zanthoxylum* may also indicate the presence of forests similar to modern semi-deciduous dry tropical forest in southwest Amazonia that are able to handle longer dry periods (Gosling, 2009).

Sifeddine et al. (2001) suggested that opening of the forest at Serra Sul was caused by alternating dry and brief humid periods since 7930–9370 cal yr BP. Likewise, Martin et al. (1993) suggested that forest regression in the Carajás region was caused by a series of dry periods alternating with slightly wetter periods, in contrast to the idea of permanent dry conditions and the widespread extension of savannas (Absy et al., 1991). Fire events at Serra Sul 7000 and 5000 yr ago (Elias et al., 2001), forest fires at Serra Norte between 7500 and 4750 cal yr BP (Cordeiro et al., 2008), and charcoal fragments in eastern Amazon soils between 6000 and 3000 ^{14}C yr BP (6850–3150 cal yr BP) (Soubiés, 1979) are thought to be climatically influenced. However, the recorded regional fire events from Pántano da Maurítia presumably derive from natural as well as anthropogenic ignitions, considering that early human occupation (hunter-and-gatherers) in the Carajás region occurred 9000 cal yr BP (Kipnis et al., 2005; Magalhães, 2009).

The late Holocene (3400 cal yr BP to present; PDM 4)

Increasing abundance of tropical forest taxa after 3400 cal yr BP suggests that modern rainforests established at this time. *Alchornea*/*Aparisthmium* clearly contributes to this increase as well as Moraceae/Urticaceae, *Celtis*, and *Trema*. Whereas forest trees of the genus *Alchornea* are known from mid-elevation sites, the pioneer taxon *Aparisthmium* contains small trees and shrubs growing chiefly on poor soils (Gentry, 1993; Colinvaux et al., 2000). Together with the increased abundance of the pioneers *Celtis* and *Trema* (Marchant et al., 2005) this suggests a successive expansion of tropical rainforest at the slopes, and the combined increase of *Alchornea*/*Aparisthmium* and Moraceae/Urticaceae indicates reduced water stress during this period due to increased precipitation. The occurrence of pioneers and high micro-charcoal concentrations between 3000 and 1400 cal yr BP could be indicative of human influence, but can also be explained by natural re-colonization of a more open habitat. Dark sediment units have been deposited at 1–1.5 m water level under aquatic vegetation and alga development. The domain of organic matter debris suggests the prevalence of a swamp.

Forest development with increased abundance of pioneers around 3140 cal yr BP at Serra Sul is documented also by Absy et al. (1991). The inferred changes in precipitation coincide with rising lake level at Serra Norte from 2800 to 1300 cal yr BP (Cordeiro et al., 2008).

Paleoclimatological context

A comparison of the record from Pántano da Maurítia with evidence from other Amazonian records is necessary to gain new insights into paleoclimatic changes in Amazonia.

Recorded dry conditions at the Carajás region from 25,000 to 11,400 cal yr BP are consistent with studies from ecotonal areas near the northern (Behling and Hooghiemstra, 2000; 2001; Behling, 2002) and southern margins (Turcq et al., 2002; Burbridge et al., 2004) of the Amazon Basin. In northeastern Amazonia, aeolian activity indicates drier or seasonal conditions from 17,000 to 15,000 cal yr BP (Teeuw and Rhodes, 2004). Bush et al. (2004) interpreted drier and cooler conditions in northwest Amazonia without an increase in dry flora indicators as a reduction of precipitation in the wet season.

The mean position of the ITCZ, intensity of moist trade winds from the Atlantic Ocean, and onset and intensity of the Amazon convection are most frequently mentioned when explaining climatically induced vegetation changes in Amazonia. A reduction in annual rainfall was possibly the result of a delayed onset of Amazon convection during austral spring (Cook, 2009) and a smaller Amazon convective center (Sylvestre, 2009).

At the transition to warmer Holocene conditions, tropical South America experienced widespread environmental changes, but differences between eastern and western parts of the Amazon Basin as well as at the southern and northern margins are evident.

Contemporaneous with the wet early Holocene phase at Pántano da Maurítia, studies from northwest Amazonia suggest increasing seasonality or decreased moisture availability after 12,000 cal yr BP (Bush et al., 2004). From 11,800 to 10,000 cal yr BP a drying trend with shorter rainy seasons in northeast Brazil was possibly linked to a southern position of the ITCZ (Jacob et al., 2007), which could be an explanation for both the recorded increase in precipitation in southeast Amazonia and a more seasonal climate in the northwestern portions of the basin.

In southeastern Amazonia our data indicate an onset of seasonal climate at 10,200 cal yr BP with drier conditions than today. Even drier conditions from 9000 to 3700 cal yr BP are possibly related to an intensified seasonality in the mid-Holocene. This coincides with a regionally widespread mid-Holocene dry episode (Mayle and Power, 2008) in tropical South America, recorded in western Amazonia (Mayle et al., 2000; de Freitas et al., 2001; Burbridge et al., 2004; Bush and Silman, 2004) as well as in the Andes (Cross et al., 2000; Baker et al., 2001; Mourguiart and Ledru, 2003; Paduano et al., 2002; Niemann and Behling, 2008; Brunschön and Behling, 2009). Replacement of forest by savannas near the northern (Behling and Hooghiemstra, 2000) and southern (De Freitas et al., 2001; Burbridge et al.; 2004) margins of the Amazon rainforest indicates drier conditions and reduced precipitation.

Overlapping with the dry period from 9000 to 3700 cal yr BP, studies from northwestern Amazonia point to wetter conditions after 6060 ^{14}C yr BP (6900 cal yr BP) (Behling and Hooghiemstra, 2000) or strong seasonal conditions between 6100 and 5800 cal yr BP (Bush et al., 2000). A northward shift of the ITCZ (Haug et al., 2001; Koutavas and Lynch-Stieglitz, 2004; Silva Dias et al., 2009) could explain these drier conditions in southeast Amazonia and coevally wetter or more seasonal conditions in the northwestern Basin.

A shifting of the ITCZ is coupled with changes in Atlantic sea surface temperatures (SSTs). Early to middle Holocene dry conditions in Carajás roughly coincide with rising SSTs in the northern tropical Atlantic, which were 1–2°C higher during the Holocene Thermal Maximum than today (Rühlemann et al., 1999). Hence, recorded vegetation changes at Serra Sul seem to be coupled with changes of Atlantic SSTs, which play a key role in modifying rainfall distribution and onset of the rainy season in central and eastern Amazonia (Fu et al., 2001; Cook, 2009). The drought in Amazonia in 2005, with delayed onset of the rainy season and occurrence of fires during the dry season, is also suggested to be linked to warming SSTs in the tropical North Atlantic (Marengo et al., 2008). Continuously increasing SSTs during the mid-Holocene possibly caused a reduced moisture transport to southern Amazonia due to reduced trade winds. It is conceivable that the influence of Atlantic conditions in southeastern

Amazonia was more intense during the mid-Holocene than today due to strengthened SST rise in the Atlantic and simultaneously weaker ENSO activity (Sandweiss et al., 1996; Keefer et al., 1998; Rodbell et al., 1999; Clement et al., 2000; Sandweiss et al., 2001; Otto-Bliesner et al., 2003).

The establishment of modern humid rainforest at Serra Sul in the late Holocene indicates increased precipitation and coincides with the expansion of modern rainforest in western Amazonia after 3000 cal yr BP in the south (Mayle et al., 2000; Burbridge et al., 2004) and around 3900 cal yr BP in the north (Behling and Hooghiemstra, 2000). Increased precipitation is also shown by records from eastern Amazonia (Behling and Costa, 2000; Bush et al., 2000), and rapid water-level rise of Lake Titicaca at this time suggests generally intensified precipitation over the Amazon Basin (Cross et al., 2000). A shift of the ITCZ is suggested as a reason for precipitation changes (Haug et al., 2001), and a greater southerly migration of the ITCZ is assumed to be linked to increased annual precipitation and shorter dry seasons in southwest Amazonia (Mayle et al., 2000; Burbridge et al., 2004). Slightly reduced SSTs in the late Holocene (Rühlemann et al., 1999) probably resulted in intensified moisture transport from the tropical Atlantic and a stronger Amazon convection.

Conclusion

New results from pollen, spore, micro-charcoal, grain size and mineralogical sediment analyses from Pántano da Maurítia at the Serra Sul dos Carajás reveal a transition from a cool, dry LGM and late glacial (25,000–11,400 cal yr BP) to a warmer, wet early Holocene (11,400–10,200 cal yr BP) and the development of a strong seasonal climate in southeastern Amazonia in the course of the early-mid-Holocene (10,200–3400 cal yr BP). Humid tropical rainforest on the slopes of Serra Sul developed during an early Holocene wet period and around 3400 cal yr BP, when modern climatic conditions established. Adapted to cooler temperatures and lower atmospheric CO_2, forested areas on the slopes could have existed during the LGM together with savanna vegetation. During the mid-Holocene, forested areas existed together with more extended savanna vegetation. These forests were possibly less dense forest communities that were able to handle long dry periods.

Several changes in precipitation patterns since the beginning of the Holocene affected environmental changes in southeast Amazonia. This region is tightly correlated to shifts of the ITCZ coupled with changing SSTs in the northern tropical Atlantic. In periods with lower SST and a southerly position of the ITCZ, southeastern Amazonia experienced wet conditions, whereas increasing SSTs and the northward shift of the ITCZ were coupled with strongly seasonal, but generally drier conditions.

Intensified fire events and the abundance of pioneer species over the past 9000 yr may be partly attributable to human disturbance. However, environmental changes across the Amazon Basin coinciding with incidents in the Carajás region, strongly suggest that vegetation changes at Serra Sul are mainly forced by large-scale climate fluctuations during the late Pleistocene and throughout the Holocene. Comparisons with data from other study sites in the Amazon Basin show a high accordance in timing and direction of recorded vegetation shifts, and therefore the results of this study allow for an integration into the current paleoclimatic discussion.

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