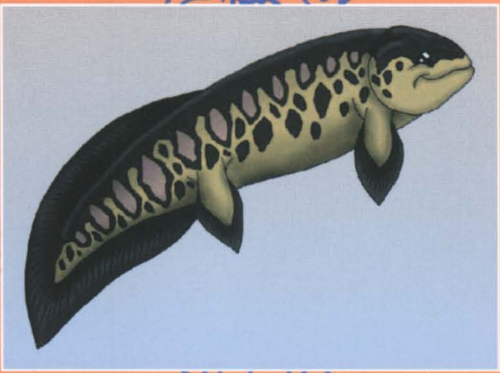

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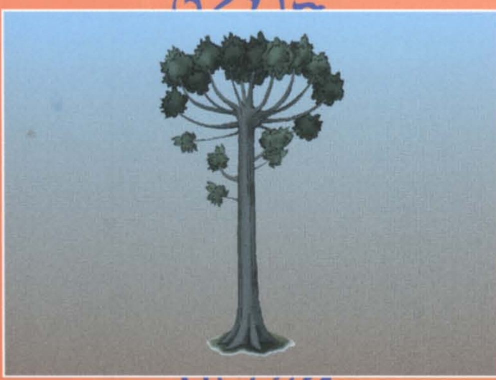

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AMAZONIAN MANGROVES DURING THE LATE PLEISTOCENE AND HOLOCENE

MANGUEZAIS DA AMAZÔNIA DURANTE O PLEISTOCENO TARDIO E HOLOCENO

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ABSTRACT

During the Last Glacial Maximum, a worldwide lowering of the eustatic sea-level occurred, and a colder and humid forest colonized sites currently occupied by mangrove vegetation. During this time, probably, the mangroves were colonizing the distal portion of the continental shelf, and they migrated upward and expanded according to the post-glacial sea-level rise and Holocene global warming. The establishment of a continuous Amazon mangrove belt occurred during the early Holocene as a direct consequence of the marine incursion caused by post-glacial sea-level rise possibly associated with tectonic subsidence. In the Late Holocene, in areas influenced by the Amazon River discharge, the mangroves were replaced by freshwater vegetation, and the coast morphology evolved from an estuarine dominated into a rectilinear coast due to coastal progradation. Nevertheless, the marine-influenced littoral, which is currently dominated by mangroves and salt-marsh vegetation, has persistently had brackish water vegetation over tidal mud flats throughout the entire Holocene. Likely, the fragmentation of this continuous mangrove line during the late Holocene was caused by the increase of river freshwater discharge associated to the change from dry into wet climates in the late Holocene. This caused a significant decrease of tidal water salinity in areas near the mouth of Amazon River. These changes in the Amazon discharge are probably associated with dry and wet periods in the northern Amazon region during the Holocene.

Keywords: Climatic changes, palynology, sea-level

RESUMO

Durante o Último Máximo Glacial ocorreu uma descida no nível eustático do mar, e florestas de clima frio e úmido ocuparam locais atualmente colonizados por manguezais. Durante este momento, provavelmente os manguezais estavam ocupando a porção distal da plataforma continental. O aumento na temperatura da atmosfera do planeta e a elevação do nível do mar pós-glacial causaram a migração e expansão dos manguezais. O estabelecimento de um contínuo cinturão de manguezais na Amazônia ocorreu durante o Holoceno inicial como uma direta consequência da incursão marinha causada pelo aumento do nível do mar pós-glacial e possivelmente associada à subsidência tectônica. No Holoceno tardio, áreas com manguezais influenciadas pela descarga do Rio Amazonas foram substituídas por vegetação de água doce, e a morfologia da costa mudou de um domínio estuarino para uma costa retilínea devido a progradação. Entretanto, o litoral de influência marinha, que atualmente é dominado por manguezais e pântanos salgados, tem permanecido colonizado por vegetação de água salobra durante todo o Holoceno. Provavelmente, a fragmentação dessa contínua linha de manguezais durante o Holoceno Tardio foi causada pelo aumento da descarga do Rio Amazonas associada às mudanças do clima de seco para úmido. Isso causou uma significativa diminuição na salinidade das águas na foz do Amazonas. Essas mudanças na descarga do Amazonas estão associadas aos períodos secos e úmido registrados na Amazônia durante o Holoceno.

Palavras-chave: mudanças climáticas, nível do mar, palinologia

1. INTRODUCTION

Approximately 75% of tropical coasts worldwide were once fringed with mangroves (Chapman, 1976). The mangroves in Brazil extend from the northern coast to the southernmost limit of the State of Santa Catarina. However, approximately 85% of Brazilian mangroves occur along 1800 km of the northern coast in the states of Amapá, Pará and Maranhão, which together contain 10,713 km^2 of these ecosystems (Schaeffer-Novelli *et al.*, 1990; Vannucci, 1999; Nascimento Jr. *et al.*, 2013), and hold one of the world's largest mangrove areas (Kjerve & Lacerda, 1993). The continuity of this mangrove littoral is interrupted by the area influenced by the Amazon River water discharge, where *várzea* (seasonally flooded) vegetation dominates (Cohen *et al.*, 2012).

Generally, mangroves are distributed parallel to the coast with some species dominating areas more exposed to the sea, and others occurring landward at higher elevations (Snedaker, 1982). Mangroves follow well-known patterns (Cohen & Lara, 2003; Cohen *et al.*, 2005a; Lara & Cohen, 2006), where salinity results in the exclusion of freshwater species and leads to characteristic patterns of species zonation (Snedaker, 1978; Menezes *et al.*, 2003). This zonation is a response of mangrove species mainly to tidal inundation frequency, nutrient availability, and porewater salinity in the intertidal zone (Hutchings & Saenger, 1987). The pore water salinity is mostly controlled by flooding frequency (Cohen & Lara, 2003) and estuarine salinity gradients (Lara & Cohen, 2006).

The relations between mangrove and sediment geochemistry have been widely investigated (Baltzer, 1970; Hesse, 1961; Walsh, 1974; Baltzer, 1975; Snedaker, 1982; McKee, 1993; Lacerda *et al.*, 1995; Clark *et al.*, 1998; Youssef & Saenger, 1999; Matthijs *et al.*, 1999; Alongi *et al.*, 1998; Alongi *et al.*, 1999; Alongi *et al.*, 2000; Mendoza *et al.*, 2012). An empirical model based on an ecohydrological approach, which allowed the integration of hydrographical, topographical and physicochemical information with vegetation characteristics of mangroves and marshes, indicates that changes in pore water salinity are displacing the vegetation boundaries (Cohen & Lara, 2003; Lara & Cohen, 2006).

Changes in mangrove distribution may also reflect changes in variables that control coastal geomorphology (e.g. Blasco *et al.*, 1996; Lara & Cohen, 2009; Fromard *et al.*, 2004). The development of mangroves is regulated by continent-ocean interactions and their expansion may be determined by the topography relative to sea-level (Gornitz, 1991; Cohen & Lara, 2003) and flow energy (Woodroffe, 1989; Chapman, 1976), where mangroves preferentially occupy mud surfaces. Thus, a rise in relative sea-level may result in mangroves migrating inland due to changes in flow energy and tidal inundation frequency. Similarly, vegetation on elevated mudflats is subject to boundary adjustments, since mangroves can migrate to higher locations and invade these areas (Cohen & Lara, 2003).

The potential of each variable to influence mangrove establishment will depend on the environmental characteristics of the given littoral. Climate, hydrology, tectonic and sea-level are the main factors controlling the modern distribution of geobotanical units along the coast of the Amazon (Cohen *et al.*, 2008, 2009, 2012), while along the southeastern Brazilian littoral the mangrove distribution might be a product of the interaction between the relative sea-level changes and the supply of fluvial muddy sediment during the late Pleistocene-Holocene (Pessenda *et al.*, 2012; Cohen *et al*, unpublished data).

Then, mangroves are considered as indicators of climatic changes and sea-level oscillations (e.g., Fromard *et al.*, 2004; Versteegh *et al.*, 2004; Alongi, 2008; Berger *et al.*, 2008, Cohen *et al.*, 2012). They have been almost continuously exposed to disturbance as a result of fluctuations in sea-level since the last glacial maximum-LGM (Gornitz, 1991; Blasco *et al.*, 1996; Sun & Li, 1999; Behling *et al.*, 2001; Alongi, 2008; Lamb *et al.*, 2006; Berger *et al.*, 2008; Cohen *et al.*, 2008; Gilman *et al.*, 2008; Pessenda *et al.*, 2012; Cohen *et al.*, 2012).

In this framework, and based on the integration of previously published studies, this chapter proposes to characterize changes in the Amazon coastal wetlands during the Late Pleistocene-Holocene according to post-glacial sea-level rise and climatic changes.

2. STUDY AREA

This study considers the Pará and Amapá littoral (Figure 1), where Calçoene-Amapá, Salinópolis, São Caetano, Soure and Bragança mangroves are part of the wetland system influenced by tidal water salinity between 30‰ and 7‰. This coastal mangrove belt is interrupted by a *várzea* vegetation area under the Amazon River influence. Lake Arari-Marajó Island and the town of Macapá are located under such conditions.

The intertidal area of the marine littoral presents 3,090 km^2 of mangroves and 90 km^2 of herbaceous flats (Cohen *et al.*, 2009). This littoral is characterized by peninsulas crossed by tidal channels that link wetlands with the estuaries, in particular of the eastern coastal region of Pará State. The main hydrodynamic features are macrotides of ~4 m range and current velocities reaching ~1.5 m s^{-1} for spring tides (Cohen *et al.*, 1999). The modern vegetation is represented by the following units: Amazon coastal forest (composed of terrestrial trees such as *Coccoloba latifolia, Himatanthus articulata, Anacardium occidentale, Protium heptaphyllum, Ouratea castanaefolia, Ouratea microdonta, Tapirira guianensis, Myrcia fallax, Myrcia sylvatica, Eugenia patrisi, Cedrela odorata, Hymenaea courbaril* and *Manilkara huberi*), elevated herbaceous flats (e.g., *Eleocharis geniculata, Fimbristylis spadicea,* *Sporobolus virginicus*, *Sesuvium portulacastrum*), mangroves (*Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa*), and restinga (*Chrysobalanus icaco*, *Anacardium ocidentale*, *Byrsonima crassifolia*) (Cohen *et al.*, 2005a; 2009).

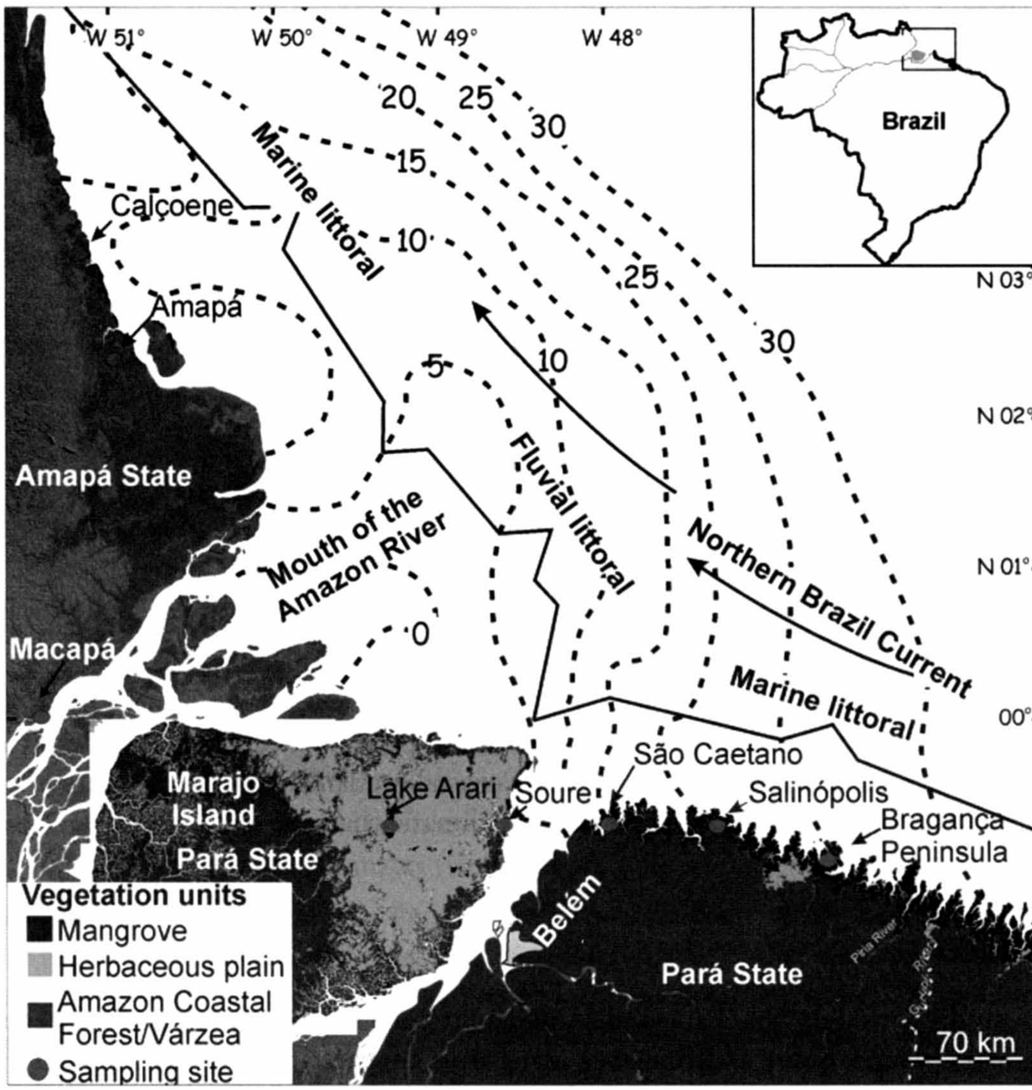

Figure 1. Location of the study areas and the sea water salinity, Amazon River plume and North Brazil Current.

The fluvial littoral is represented by part of the Amapá State and the Marajó Island. The vegetation consists of natural open areas dominated by Cyperaceae and Poaceae that widely colonize the eastern side of the Marajó island. The *várzea* vegetation (a seasonally inundated floodplain and a swamp permanently inundated by freshwater, composed of wetland species such as the palm trees *Mauritia flexuosa* and *Euterpe oleracea*, and other species such as *Hevea guianensis* (Zarin *et al.*, 2001; Junk & Piedade, 2004; McGinley, 2008)) and Amazon Coastal Forest occur on the western side of the Marajó Island (Cohen *et al.*, 2008). Mangroves are restricted to a small area (100-700 m in width) along the northeastern coastal plain of the Marajó Island (França *et al.*, 2012).

3. MANGROVES DURING THE LATE PLEISTOCENE

During the Last Glacial Maximum between ~27 and ~ 20 k cal yr BP, a worldwide lowering of the eustatic sea-level occurred, resulting from the expansion of polar ice sheets (Murray-Wallace, 2007). Evidence of the lowering of the eustatic sea-level and the resulting regression of the ocean on the southern Brazilian coast during the LGM were obtained by Corrêa (1996). From ~20 to ~19 k cal yr. BP, at ~130 m below the current mean sea-level, the southern portion of the Brazilian continental shelf was almost entirely exposed, placing the coastline at some sites more than 100 km east of its present position (Corrêa, 1996). A similar scenario should have occurred on the shallow continental shelf of Pará and Amapá State (Nittrouer *et al.*, 1996).

Pollen data in the eastern Pará State revealed *Podocarpus* trees in the coastal region during the Late-glacial that indicate wet and markedly colder conditions at that time (Behling, 2001). Palaeoecological records from southeastern littoral presented between >40,000 and ~23,000 cal yr BP *Ilex, Alchornea, Weinmannia, Myrsine, Symplocos, Drimys and Podocarpus* pollen on a site currently occupied by mangrove vegetation. These data suggest that in the past prevailed a colder and more humid climate than today, with a low relative sea-level. From ~23,000 cal yr BP to ~2,200 cal yr BP a sedimentary hiatus likely occurred, related to an erosive event associated to the post glacial sea-level rise. Since at least ~2,200 cal yr BP, isotopes and marine diatoms indicate the return of the marine coastal line to its current position, and consequently the development of mangrove (Pessenda *et al.*, 2012).

The mangrove distribution during the late Pleistocene in the northern Brazilian littoral was not yet recorded. Obviously, the evidences of mangrove migration according to the post-glacial sea-level rise may be preserved below the modern sea-level and along the submerged continental shelf. Considering that estimates of the magnitude of cooling during the LGM consistently range between 5° and 9°C (Wright *et al.*, 1989; Klein *et al.*, 1998; Mourguiart & Ledru, 2003; Paduano *et al.*, 2003; Bush *et al.*, 2004; Urrego *et al.*, 2005), probably, the mangrove development must have been harmed during glacial time, since the low temperature is widely regarded as the primary control on the latitudinal limits of mangroves globally (Lugo & Zucca, 1977; Tomlinson, 1986; Duke *et al.*, 1998). Mangrove vegetation is essentially tropical and its distribution is constrained by sensitivity to freezing temperatures (Norman *et al.*, 1984; Sherrod & McMillan, 1985; McMillan & Sherrod, 1986; Sherrod *et al.*, 1986; Schaeffer-Novelli *et al.*, 1990; Kao *et al.*, 2004; Stevens *et al.*, 2006; Stuart *et al.*, 2007). Therefore, probably, the Amazonian mangrove areas must have shrunken during the LGM.

4. MANGROVES DYNAMIC DURING THE HOLOCENE

In the early Holocene, mangroves were dominated by *Avicennia* or co-dominated by it and *Rhizophora*. Since then, a relative sea level rise of about 13.2 cm/100 year has been the most important natural disturbance suffered by the mangrove community in Venezuela (Vilarrúbia & Rull, 2002). According to Van der Hammen (1988), during the early Holocene the sea-level rise in the nearby coasts of Guyana caused the replacement of savannah by mangrove vegetation, and *Avicennia* was the first mangrove-forming tree to become established.

The Marajó Island and Macapá town present a regional low water salinity produced by the larger fresh water discharge from the Amazonas river as compared to the rivers from southeastern Pará and northwestern Amapá littoral (Kjerfve *et al.*, 2002; Santos *et al.*, 2008). This produced a fluvial sector and a marine-influenced littoral (Figure 1).

The marine littoral is mainly dominated by mangrove and herbaceous flats, typical of brackish waters, while the fluvial littoral is mainly characterized by *várzea* and herbaceous vegetation, typical of freshwaters. The mangroves are more tolerant to soil salinity than the *várzea* forest (Cohen *et al.*, 2008; Gonçalves-Alvim *et al.*, 2001), and, considering the Amazon River, the salinity is basically controlled by position along the estuarine gradient (Lara & Cohen, 2006).

4.1 Marine littoral

Considering the Amazonian mangrove belt, this wetland has occurred continually over tidal mud flats along the marine littoral of the Pará State during the Holocene and with deposition of marine organic matter during at least the late Holocene along the marine littoral of the Amapá State (Figures 1, 2d and 2h) (Cohen *et al.*, 2005b, 2009; Vedel *et al.*, 2006; Guimarães *et al.*, 2012). During the early Holocene, the mangrove establishment was marked by dominance of *Avicennia* trees in the Bragança littoral, while the *Rhizophora* expanded relative to *Avicennia* during the middle and late Holocene (Vedel *et al.*, 2006). The pollen records indicate that mangrove areas on the Bragança Peninsula have been mainly controlled by the relative sea-level during the Holocene (Cohen *et al.*, 2005a, 2005b), and the mangroves have migrated to higher elevated zones during the last decades, suggesting a relative sea-level rise (Cohen & Lara, 2003; Cohen *et al.*, 2005b).

Regarding the consequences of rainfall changes during the Holocene on the marine littoral, it should have caused changes in tidal water salinity with consequences for the mangrove structure, since the mangrove vegetation height presents an inverse relationship with substrate salinity (Lara & Cohen, 2006). In addition, the upper mudflats with porewater salinity between 90 and 50‰ consist mainly of *Avicennia* and sectors with porewater salinity around 36‰ are dominated by *Rhizophora* (Cohen & Lara, 2003).

4.2 Fluvial littoral

The Marajó Island and Macapá town present a regional low water salinity produced by the larger fresh water discharge from the Amazon River as compared to the rivers from southeastern Pará and northwestern Amapá littoral (Kjerfve *et al.*, 2002). Pollen and isotopic data from fluvial littoral indicate that marine influence and mangrove vegetation was wider than today on Marajó Island (Smith *et al.*, 2011; figures 2b and 2f) and the Macapá littoral (Guimarães *et al.*, 2012; figures 2a and 2e) between >8990-8690 and 2300-2230 and >5,560-5470 and 5290-5150 cal yr BP, respectively. In addition, recent isotopic and pollen data from Marajó Island confirm this marine influence and the presence of a tidal mud flat colonized by mangroves between >7520-7430 cal yr BP and ~3200 cal yr BP in the central area of this island (França *et al.*, 2012; figures 2c and 2g). During the last 2300-2230 cal yr BP the freshwater vegetation expanded on the Marajó Island (Smith *et al.*, 2012; figure 2b), and the mangroves were isolated in a limited area (100-700 m width) along the northeastern coastal plain of Marajó Island during the late Holocene (França *et al.*, 2012; figure 2c). Similarly, the freshwater vegetation expanded along the littoral of Macapá, on the edge of Amazon River, during the late Holocene (Guimarães *et al.*, 2012; figure 2a). Therefore, the data indicate higher marine influence near the mouth of Amazon River during the early and middle Holocene (Figures 2d and 2h). The temporal transition between the marine to fluvial littoral produced significant geomorphologic changes, such as the replacement of old lagoons by lakes (Miranda *et al.*, 2009; Smith *et al.*, 2011). The different chronology between Macapá and the Marajó Island coastline, showing the transition from brackish to freshwater vegetation may be justified by the position of sampling sites along the estuarine gradient. The littoral of Macapá, where mangroves have occurred up to 5290-5150 cal yr BP, is on the edge of the Amazon River, while Lake Arari in Marajó Island, where the mangroves resisted until 2300-2230 cal yr BP, is positioned at the mouth of the Amazon (Figure 1).

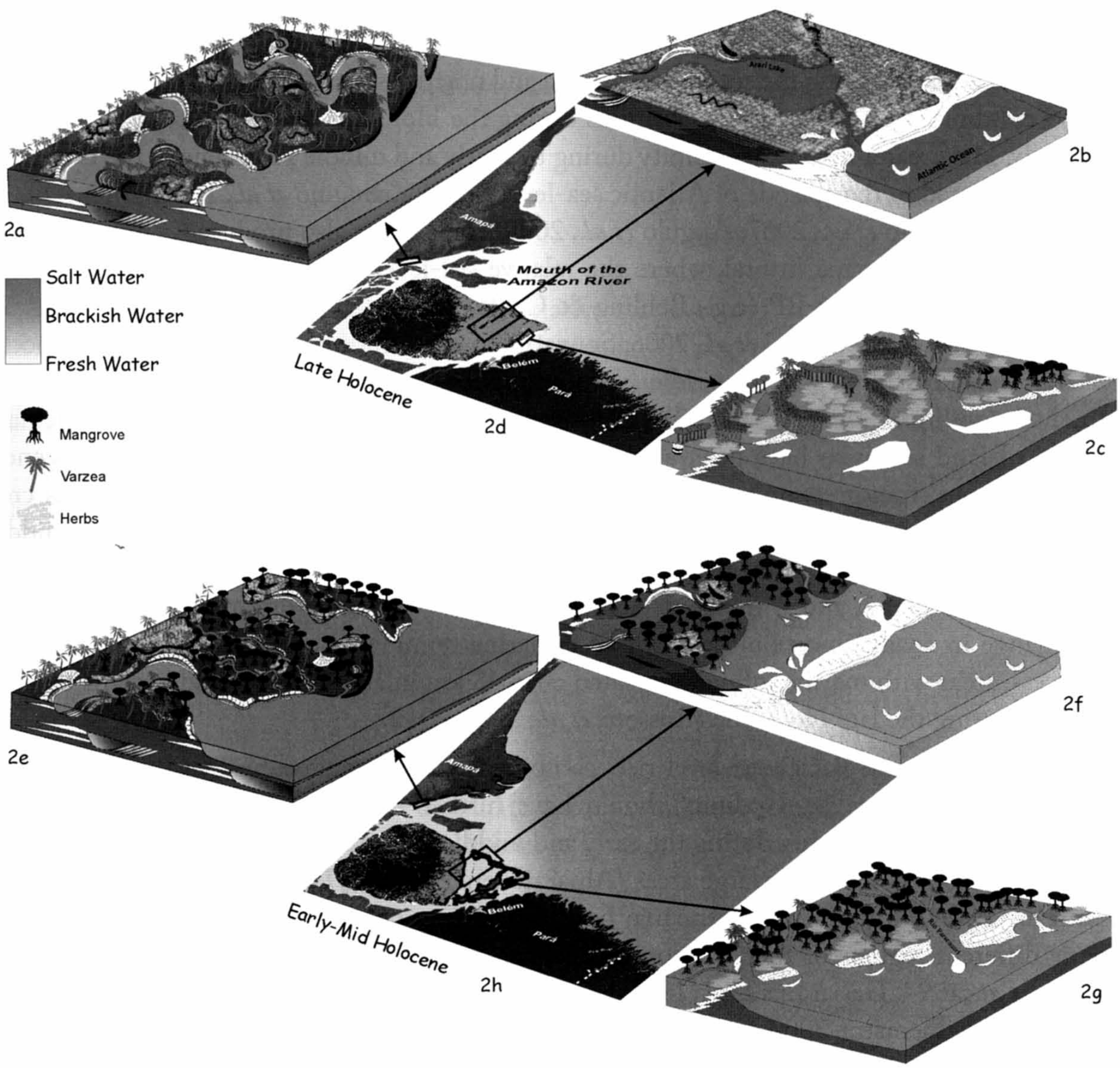

Figure 2. Model of the Amazonian mangrove development during the Holocene in the: Macapá (2a and 2e); Marajó Island (2b and 2f) and eastern Marajó Island (2c and 2g).

5. CONTROLLING FACTORS OF THE MANGROVE DYNAMIC

Understand the main factor responsible for the Amazon mangrove dynamic during the late Pleistocene and Holocene is not straightforward. This is stated particularly considering that the region might have been undergone to the complex interaction of several factors, mostly consisting of changes in sea level, subsidence rates, and climate, the latter with potential to have affected the Amazon River discharge. The most likely is that all these factors acted together and controlled the distribution of mangrove in this region over the late Pleistocene and Holocene.

During the late Pleistocene, with a low relative sea-level, palaeoecological records indicate a colder and humid forest on sites currently occupied by mangrove vegetation (Behling, 2001; Pessenda *et al.*, 2012). During this time, probably, the mangroves were colonizing the distal portion of the continental shelf, and they migrated upward according to the post-glacial sea-level rise.

The mangroves along the southeastern Pará and northwestern Amapá littoral (marine littoral) occurred continually on their current positions during the Holocene and at least the late Holocene, respectively. The greater tidal water salinity during the early and middle Holocene in the fluvial sector could be attributed to the episode of Atlantic sea-level rise (e.g., Suguio *et al.*, 1985; Tomazelli, 1990; Rull *et al.*,1999; Hesp *et al.*, 2007; Angulo *et al.*, 2008). This event also produced a marine incursion along the Pará and Amapá littoral, where the relative sea-level-RSL stabilized at its current level between 7000 and 5000 yr BP (e.g., Behling & Costa, 2001; Behling *et al.*, 2001; Behling, 2002, 2011; Cohen *et al.*, 2005a; Vedel *et al.*, 2006; Souza Filho *et al.*, 2006). A transgressive phase occurred on Marajó Island in the early to middle Holocene. Subsequently, there was a return to the more continental conditions that prevail today (Rossetti *et al.*, 2008). This history of RSL fluctuations on Marajó Island seems to have been affected by tectonic activity during the late Pleistocene and Holocene. Hence, transgression was favored during increased subsidence, when space was created to accommodate new sediments. Tectonic stability seems to have prevailed during the middle to late Holocene, leading to coastal progradation that culminated with more continental conditions prevailing on the island, and with the detachment of Marajó Island from mainland. It contributed to the change in coastal morphology from an estuarine dominated one into a rectilinear coast. In this process, areas with marine influence located circa 45 km inland in this island became freshwater dominated during the late Holocene (Rossetti *et al.*, 2008, 2012).

Hence, the post-glacial sea-level rise, combined with tectonic subsidence, caused a marine transgression. The tidal water salinity should have further increased due to low river discharge resulting from increased aridity during the early and middle Holocene. If river systems are considered to be integrators of rainfall over large areas (Amarasekera *et al.*, 1997), variations in the discharge of the Amazon River during the Holocene may be a consequence of changes in rainfall rates, as recorded in many different regions of the Amazon Basin (e.g., Bush & Colinvaux, 1988; Absy *et al.*, 1991; Sifeddine *et al.*, 1994; Desjardins *et al.*, 1996; Gouveia *et al.*, 1997; Pessenda *et al.*, 1998a, 1998b, 2001; Behling & Hooghiemstra, 2000; Freitas *et al.*, 2001; Sifeddine *et al.*, 2001; Weng *et al.*, 2002; Bush *et al.*, 2007; Guimarães *et al.*, 2012).

Climatic fluctuations in the Amazonian hydrographical region control the volume of the Amazon River's inflow (Haberle & Maslin, 1999; Harris & Mix, 1999). Consequently, during the early and middle Holocene the Amazon River's inflow was severely reduced (Maslin & Burns, 2000;

Maslin *et al.*, 2000). Irion *et al.* (2009) suggest that during the dry period, the sea level rise caused a backwater effect which reached far upstream, with the silting up of the Amazon valley and the inflow of the tributaries. This allowed the development of the Amazon River floodplain in its modern setting around ~5800 cal yr BP, when the sea level reached its present level. Afterward, with the return of a more humid climate in the region, the greater discharge of the Amazon River promoted the progressive reduction of water salinity. At present, the littoral of Macapá and Marajó Island is flooded by tidal freshwater (Santos *et al.*, 2008; Vinzon *et al.*, 2008; Rosario *et al.*, 2009) that favors the development of freshwater vegetation (Cohen *et al.*, 2012).

The modern mangrove vegetation on the fluvial sector occurs in narrow zones fed by brackish waters carried from the southeastern Pará coastline by the northern Brazil current (Figure 1). This water influx produces a relatively higher tidal water salinity, and is probably the cause for the permanence of mangroves in the fluvial littoral, for example, in a narrow zone on the northeastern part of the Marajó Island (Behling *et al.*, 2004; França *et al.*, 2012), where tidal water salinity is close to ~6 ‰ (Santos *et al.*, 2008).

6. CONCLUSIONS

During the late Pleistocene, with a low relative sea-level and the glacial period, a colder and humid forest occurred on sites currently occupied by mangrove vegetation. During this time, probably, the mangroves were colonizing the distal portion of the continental shelf, and they migrated upward and expanded according to the post-glacial sea-level rise and Holocene global warming.

The establishment of a continuous Amazon mangrove belt occurred during the early Holocene as a consequence of the post-glacial sea-level rise that was favored by tectonic subsidence. The tidal water salinity should have increased due to low river discharge resulting from increased aridity during the early and middle Holocene. However, during the late Holocene, the littoral near the Amazon River underwent a significant increase in fluvial influence that fragmented this mangrove belt. As consequence, the mangrove was replaced by *várzea* vegetation, and the marine organic matter in the sediment changed to freshwater organic matter. Likely, it was caused by the increase of river freshwater discharge during the late Holocene, which caused a significant decrease of tidal water salinity in Marajó Island and part of the Amapá coastline (Macapá). In Marajó Island, the coast morphology evolved from an estuarine dominated into a rectilinear coast due to coastal progradation. Most likely these changes in the Amazon discharge were caused by dry and wet periods recorded in the Amazon region during the Holocene.

7. ACKNOWLEDGEMENTS

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