Araguaia River Floodplain: Size, Age, and Mineral Composition of a Large Tropical Savanna Wetland

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ORIGINAL RESEARCH

Araguaia River Floodplain: Size, Age, and Mineral Composition of a Large Tropical Savanna Wetland

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Abstract The Araguaia River floodplain is a large wetland in the tropical savanna belt (*cerrado*) in the southern Amazon basin. Studies using multitemporal satellite Landsat 5 TM images with a spatial resolution of 30 m indicate a surface area at maximum flood level of 88,119 km^2. During the low-water period, only 3.3 % of the area is covered by water. Flooding is the result of the annual rise in the water level of the Araguaia River and of local rainfall and insufficient drainage during the rainy season. Sedimentology studies have distinguished between an active recent and sub-recent floodplain, which covers ~20 % of the area, and a paleo-floodplain probably several hundreds of thousand years in age. Paleo-floodplain sediments are strongly weathered and marked by the clay mineral association of kaolinite, gibbsite, goethite, and Al-chlorite, predominantly formed from feldspars and micas. The active paleo-floodplain participates in the hydrological cycle but does not receive recent sediments from the river. Higher-lying, not flooded areas (inactive paleo-floodplain) are probably the remnants of paleo-levees, now in an advanced stage of erosion. A hypothesis to explain the genesis of the floodplain is proposed herein.

Keywords Araguaia floodplain · Wetland area · Mineralogy · Hydrochemistry · Remote sensing · Paleo-floodplain

Introduction

The Araguaia River floodplain belongs to a group of three very large savanna (Brazilian *cerrado*) wetland systems in the southern Amazon basin. Of these, the Pantanal, at the upper Paraguay River, is the most well-known and best examined (summarized in Junk et al. 2011). The Llanos de Moxos, at the Mamore/Guapore and Madre de Dios Rivers, located at the frontier area between Brazil and Bolivia, has also been studied (summarized in Pouilly et al. 2004), whereas little is known about the floodplain of the middle Araguaia River. Moreover, the scant scientific information is often scattered in difficult to access reports (Brasil 1981; Brasil et al. 2001). In recent years, the hydrogeomorphologic aspects of the middle Araguaia River floodplain have been the focus of several investigations (Latrubesse and Stevaux 2002; Latrubesse 2003; Aquino et al. 2009; Latrubesse et al. 2009; Valente and Latrubesse 2012).

Like most large floodplains in the tropics and sub-tropics, the Araguaia River floodplain is composed of sediments that were deposited during different climatic periods. Paleo-sediments are strongly weathered and they differ from the sediments of the recent river floodplain in terms of grain size and fertility. Differences in mineral composition can be used to differentiate between recent sediments and paleo-sediments and provide hints on the age of the paleo-floodplain. However, these facts have been largely disregarded in the ecological

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differentiation of macrohabitats and in land-use planning of river floodplain systems.

Worldwide, wetlands, despite their importance for the hydrological cycle and for species diversity, are under heavy pressure by agroindustry. In Brazil, the establishment of the New Forest Code (Federal Law no. 12.561/12) dramatically reduced wetland protection favoring agriculture and animal ranching (Piedade et al. 2012). Floodplains in savannas are at particular risk, because of their pronounced dry season and their shallow flooding, which is mainly the result of local precipitation. Furthermore, vegetation cover differs between the paleo-floodplain and the recent river floodplain. Agrobusiness has failed to recognize the wetland character of paleo-floodplains and has invested heavily in the transformation into pasture or agricultural land. A determination of the size of the periodically flooded area is therefore essential for land-use planning, land management, and environmental protection. Data on water chemistry and mineral composition provide information on the fertility and carrying capacity of the different floodplain areas. This article presents new information, collected by the authors during several field trips over the last 3 years, on the size, age, water chemistry, and mineral composition of the Araguaia River wetlands. The data contribute to the scientific basis for future studies on the ecology and sustainable management of these wetlands.

Material and Methods

Study Area

Geological and Geographic Aspects of the Upper and Middle Araguaia River Basin Most of the wetlands of the Araguaia River are situated in the Bananal Basin, a large depression in the middle Araguaia River. The basin is covered by Quaternary deposits of the Araguaia Formation, which reach a maximum thickness of 170–320 m and are composed of unconsolidated to consolidated, yellowish to brownish, ferruginous silts and sands (Araújo and Carneiro 1977). According to Hales (1981), Paleozoic sediments may underlie Pleistocene deposits, such that the total sediment layer has a depth of about 2000 m in the deepest part of the Bananal Basin, located between the city of Luiz Alves and the southern part of Bananal Island.

The Araguaia River enters the Bananal Basin at Arunã, after the river has coursed for about 600 km, corresponding to a linear distance of 400 km from its source, 850 m above mean sea level (Fig. 1). The linear distance from Arunã to the northern end of the basin at the junction of the Araguaia and Javaé Rivers is 570 km. Only the Araguaia River has a large drainage system outside the Bananal Basin. Along its first 600 km, it passes through Jurassic sandstones and Permian, Permian/Carbon, and Devonian sand/siltstones and shale. Further along, the river crosses Silurian/Devonian siltstones and, again, Carbon/Permian sandstones. In the upper catchment, sand/siltstones dominate, resulting in a sand- and silt-rich sediment load. More than half of the drainages areas of the Formosa, Pium, and Javaé Rivers, on the eastern side of the basin, and the Das Mortes River are inside the Bananal Basin. In addition, many small rivers and creeks drain exclusively within the basin. In total, the drainage areas of the small tributaries in the Precambrian rock east of the Araguaia plain are small and in the west they are negligible with respect to the sediment budget. The sediment load of the Araguaia River's main stem is much larger than that of the lowland tributaries of the Bananal Basin (Aquino et al. 2009).

Today's Araguaia wetland extends over Tertiary and Quaternary sediments (Fig. 1). At the northern end of the basin, the fluvial Bananal Island has a surface area of ~20,000 km^2. In this article, we differentiate between the *active-recent floodplain*, the *active paleo-floodplain*, and the *inactive paleo-floodplain* (sensu Irion 1976), based on their mineralogical and hydrological peculiarities, discussed herein. Holocene deposits form the *active-recent floodplain* and accompany the channels of the Araguaia River and its major tributaries. The characteristic hydro-geomorphologic features of these deposits include ridges, swales, abandoned channels, and oxbows, with a relatively high relief-energy (Latrubesse et al. 2009). The *active paleo-floodplain* is covered by much older sediments and has not been involved in major processes of recent sediment deposition. However, it does serve as a hydrological buffer and participates in many ecological processes affecting the entire river-floodplain system. In some places the river directly erodes the old sediments. The height differences of former hydro-geomorphic units in the active paleo-floodplain have mostly been leveled off, resulting in a planar surface with a low relief-energy. The characteristic geomorphologic features of this area are referred to by specific local names: (1) *Ipucas* or *impucas* are small circular or elongated depressions that are periodically flooded or waterlogged, sometimes with a permanent lake in their centers. The depressions are covered with shrubs and trees. (2) *Esgotos* are seasonal drainage channels that transport water from the surrounding grasslands to small rivers that are the remnants of old drainage systems. (3) *Murunduns* (termite mounds), found in the seasonally flooded grassland, are earth mounds up to 1.20 m high and with a surface area of 1–15 m^2 that reach above the mean high-water level. The mounds were built by termites to escape flooding during flood periods. (4) *Monchões* extend 1–1.5 m above the maximum flood level and are the remnants of paleo-fluvial terraces and paleo-levees. We refer to *monchões* as the *inactive paleo-floodplain* because they consist of paleo-sediments but are not flooded, thus providing permanently terrestrial macrohabitats inside the floodplain. The total area of the *monchões* inside the active

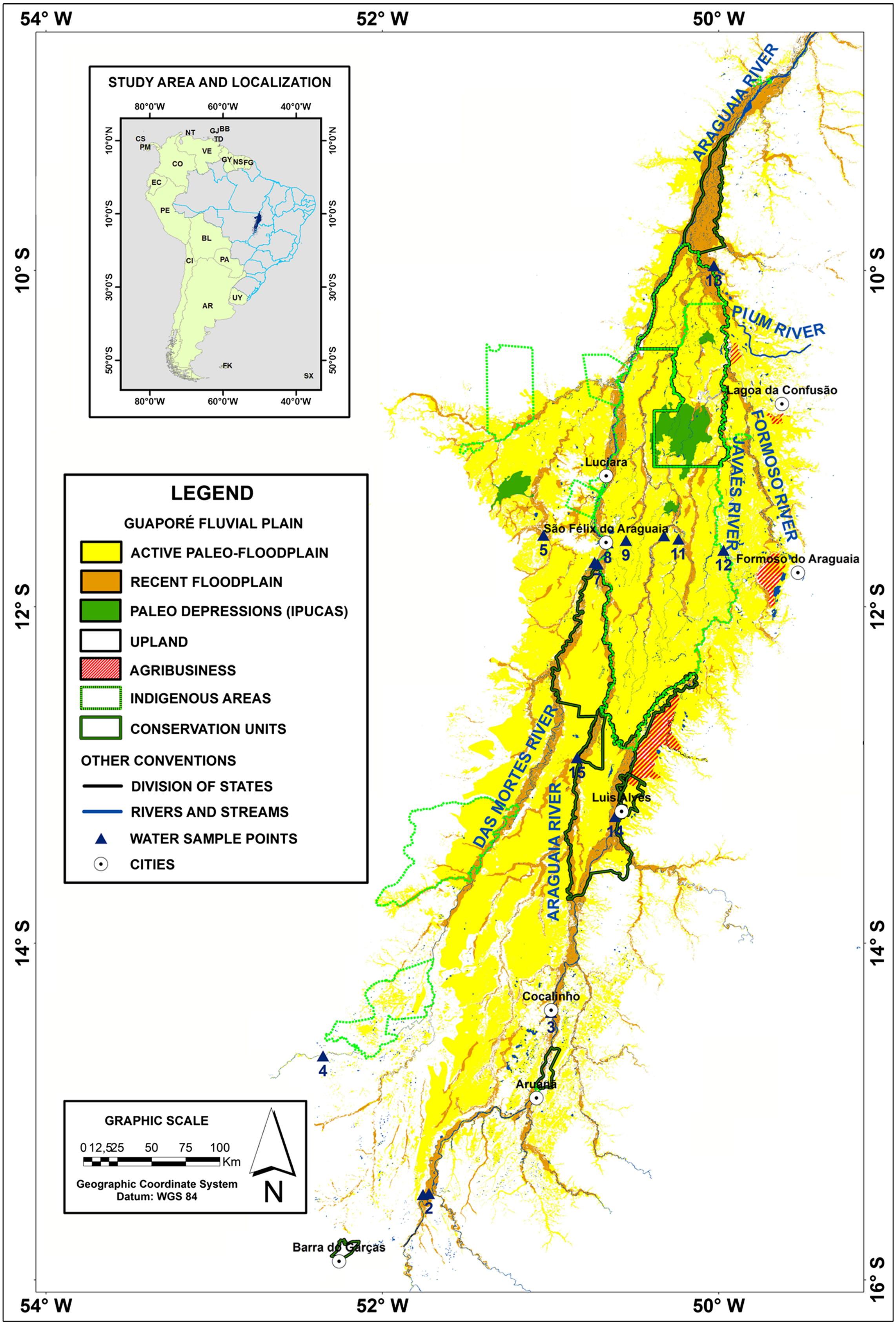

Fig. 1 Floodplain of the middle Araguaia River, indicating the active-recent floodplain and the active paleo-floodplain. Patches of inactive paleo-floodplain inside the active paleo-floodplain area are too small to be distinguished. The numbers indicate the water-sampling points of this study

paleo-floodplain is small. Remnants of the inactive paleo-floodplain occur also at the edges of the floodplain area.

Neo-tectonic uplift and subsidence favored the development of denudation and aggradation systems. As proposed by Valente and Latrubesse (2012), the neo-tectonic events were associated with the Goiás-Tocantins seismogenic zone and occurred mainly in the Middle Pleniglacial, between 56.6 ± 5.9 and 34.0 ± 2.3 k-annum before present (kaBP), and in the Upper Pleniglacial, between 24.5 ± 3.1 and 17.2 ± 2.3 kaBP. Seismic activity in recent times has had a magnitude of 2.9–4.1 on the Richter scale, as reported by Veloso (1997). Earthquakes are indicators of neo-tectonic activities but as long as tectonic faults cannot be demonstrated their impact on specific geomorphic surface structures, such as river courses inside a large river floodplain, is unclear. Little is known about the paleo-climatic history, but data indicate cold and relative wet conditions during 26–22 kaBP and dryer and colder climate between 22 and 13 kaBP (Salgado-Laboriau 1997; Salgado-Laboriau et al. 1997). These changes in paleo-climate have certainly affected the dynamics and sedimentation of the Araguaia River floodplain as well as erosion processes.

Climate and Hydrology The climate of the Araguaia River floodplain is tropical, with pronounced rainy and dry seasons. Precipitation varies between 1200 and 1900 mm annually and occurs mainly between September and May (Fig. 2). The mean annual temperature is 22–26 °C. At Sao Felix de Araguaia city, the Araguaia River has a mean annual discharge of about 2700 $m^3 sec^{-1}$. Minimum and maximum discharges of 493 and 9126 $m^3 sec^{-1}$ have been recorded (Latrubesse et al. 2009). The river level begins to rise in December, reaches a maximum in February/March, and then falls quickly thereafter (Figs. 2 and 3). The low-water period is from September to November. The flood amplitude varies between 4 and 7 m, with a mean of about 6 m. The flood curve often shows two peaks at high water.

The rise and fall of the floods are steep, resulting in an active recent floodplain near the river channels in a rather short flood period of only 1–3 months. This pattern, however, does not reflect the hydrological conditions in major parts of the active paleo-floodplain. Rather, during the rainy season, the high-lying parts of the active paleo-floodplain are covered for several months by a shallow (0.2–1 m) layer of water because flooding is induced mostly by local rainfall, which evaporates or drains slowly into the Araguaia River by the internal drainage system. During the dry season, there is intense drought stress in most of the Araguaia River floodplain, as shown by the extended areas of drought-tolerant vegetation types, e.g., termite savannas, single-tree savannas, and savanna forest (*cerradão*). These cover about 60 % of the total wetland area. Longer flood periods occur in low-lying parts of the active floodplain along the main river channels, in low-lying areas along the internal drainage system connected with the main river, and in paleo-depressions (*ipucas*). Low-water levels in the river channel are generally uniform and fluctuate by only about 0.5 m, although in extreme cases they may differ by about 1 m.

Data Collection

Determination of the Floodplain Area The floodplain area was taken as the maximum extent of flooding of the Middle Araguaia Basin during January to April, using data from 1986 to 2011. In that study, digital processing was applied to multitemporal satellite Landsat 5 TM images (Table 1) with a spatial resolution of 30 m and six spectral bands between the intervals of the visible, near-infrared, and short-wave infrared, compatible with analyses of the periods of maximum flooding. Indexes were generated by the Tasseled Cap transformation and training samples were selected from landscape elements, including vegetation, soil, water, and wetlands. From these training sample sets, a supervised classification was obtained using the Support Vector Machine

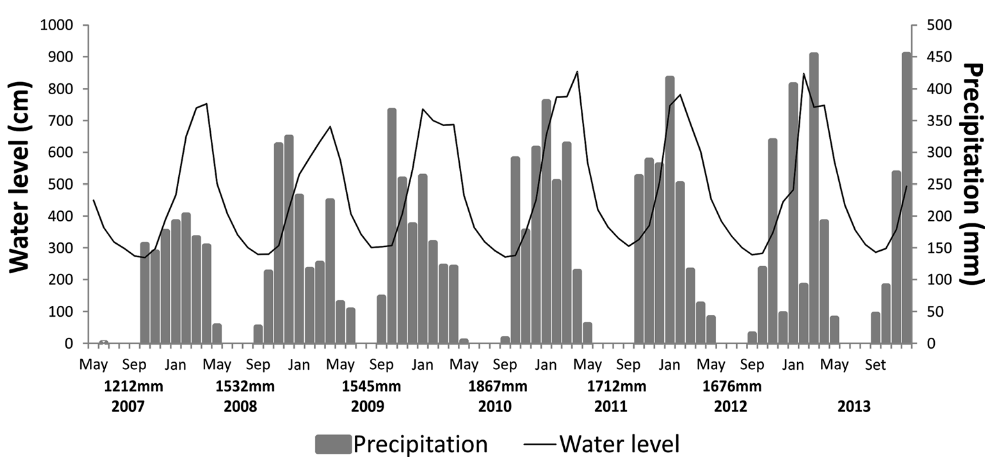

Fig. 2 Water-level fluctuations of the Araguaia River from 2007 to 2013, determined at Sao Felix de Araguaia. Monthly precipitation is also shown. (Data from the National Water Agency, ANA)

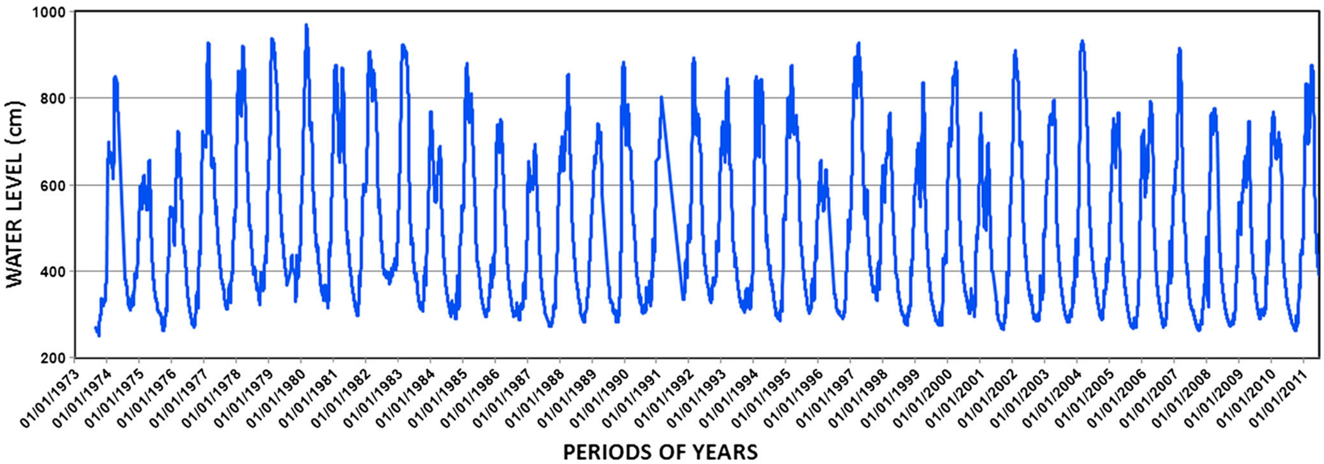

Fig. 3 Water-level fluctuations of the Araguaia River from 1973 to 2011, determined at Sao Felix de Araguaia. (Data from the National Water Agency, ANA)

(SVM) algorithm. In addition, a Height Above the Nearest Drainage (HAND) model was created using the Shuttle Radar Topography Mission (SRTM) digital elevation model. The classes associated with humidity, determined from the digital classification, correlated with the altimetric classes obtained from the hydrologically consistent HAND-SRTM. This approach allowed delineation of the maximum area likely to be inundated during flood seasons.

A geomorphologic map on a scale of 1:250,000 was then generated using vector databases of geomorphology and pedology obtained from the State Agencies of Mato Grosso, Goiás, Tocantins, and Pará. With these tools and the Geographic Information System the active paleo-floodplain, the recent floodplain, and major paleo-depressions could be distinguished (Fig. 1). To complement the analysis and to obtain geomorphologic classes mapped in greater detail, digital processing was carried out using data acquired by the operational land imager (OLI) sensor (onboard instrument of the Landsat 8 satellite) in August and September of 2013. The spectral bands of the OLI sensor used in the digital processing are associated with intervals of the visible, near-infrared, and short-wave infrared (bands 1–7), all having a spatial resolution of 30 m.

Table 1 Locations to multitemporal Landsat 5 TM images overlying the floodplain of the Middle-Araguaia basin

Orbit	Point	Dates
223	66	02/11/1999 01/29/2000
223	67	02/23/1986 01/29/2000
223	68	03/20/1995 04/23/1996
223	69	04/17/2011
223	70	03/23/1995
223	71	04/14/2010
224	67	04/25/1987
224	68	04/25/1994
224	69	02/12/1991 04/12/2001
224	70	04/13/1984 04/12/2001
224	71	01/24/1990

For the pre-processing of the sensor data from the OLI, radiometric and atmospheric corrections were made. Subsequently, the SVM algorithm was used, mainly to discriminate the paleo-depressions (*ipucas*), together with the collection of training samples and implementation of the supervised classification.

The SVM algorithm used the radial basis kernel functions, which achieved better results and can be described by the mathematical formula:

$$K\ (xi, xj) = \exp(-\gamma\|xi{-}xj\|2), \gamma > 0$$

where x is the sample and γ is the penalty parameter, which are controlled by the user.

The interval value of the probability of constraint was set at zero (default value). This value defines the required probability that the algorithm will classify a given pixel (classification probability threshold). Thus, the pixels in which all the probability rules are smaller than the constraint value are considered as unclassified. In the determination of the permanently flooded area, data from the OLI sensor covering the region during the dry period of August–October 2013 were used.

The accuracy of the map was evaluated using a confusion matrix, which are typically used to assess digital image classification. It consists of a comparison between number of sample units assigned into a class by, the classification approach employed, and the number of sample units that actually belong to that class, based on field data (Congalton 1991). The overall concordance of the statistical classification with the field data classification is based on the kappa coefficient (a by-product of the confusion matrix that varies from 0 to 1). An advantage of the kappa coefficient is that it takes into account all pixels, rather than just the pixels classified correctly. Values of kappa values above 0.75 are considered very good to excellent (Mather 1999).

We used a confusion matrix to assess the accuracy of the classification of Floodplain and Non-Floodplain Areas. We recognized four distinct classes for Floodplain Areas: Water, Flooded Area, Wet Soil and Flooded Vegetation. Similarly, three distinct classes were recognized for Non-Floodplain Areas: Dry Soil, Secondary Vegetation and Vegetation. We validated these classes using 100-control field sites randomly distributed within each class for a, total of 700 sampling points. Reference data and validation was based on photographs obtained during field campaigns, GPS coordinates, SPOT mosaics of high-resolution images, and georeferenced aerial photographs acquired in 2010 and 2011.

Hydrochemistry Water samples were taken at 15 localities, mostly on or near Bananal Island. The samples were stored on ice and analyzed for Ca, Mg, Na, K, HCO_{3-}, and P_{tot} using standard methods. The analyses were carried out by the water and soil laboratory Agro Analise-Souza Neto & Souza LTDA, in Cuiabá. Transparency, temperature, pH, and electrical conductivity were measured in situ.

Mineralogy A motor-driven steel sounding device was used to collect samples up to a depth of 6 m. The hard soils of the Araguaia plain were such that iron bars 2.2 cm in diameter were the only tools able to penetrate the subsurface. The most appropriate method to determine the mineral composition in the <20-μm fractions is X-ray diffractometry. This method is based on the similarity of the wavelength of X-rays and the lattice distances along the repeating chains of atoms in the minerals. The X-rays are deflected at specific angles characteristic of each mineral. The different grain sizes were separated by means of settling tubes, which yielded fractions of <2 μm, 2–6 μm, 6–20 μm, 20–63 μm, and >63 μm. From the <2-μm fraction, a smear slide was prepared and an X-ray diagram was obtained using Philips PW1729 equipment. X-ray data were recovered from Mg-acetate-, K-acetate-, and ethylene glycol-treated specimens.

Results

Determination of the Floodplain Area

The maximum total floodplain area covers 88,119 km^2, corresponding to ~23 % of the Araguaia Basin (Fig. 1). This is considerably larger than the 58,550 km^2 estimated by Hamilton et al. (2002). The active paleo-floodplain covers 70,588 km^2, corresponding to 80 % of the total floodplain area. Here, about 1678 km^2 (1.9 % of the total area) consist of major paleo-depressions (*ipucas*). The recent floodplain covers 17,535 km^2 (20 % of the total floodplain area). Only 2930 km^2 of the wetland are covered by water during the dry period, corresponding to only 3.3 % of the floodplain system of the Araguaia River (Dias 2014).

The confusion matrix yielded 77 % of global with a kappa coefficient of 0.73 (Table 2).

Hydrochemistry

The sampling locations are shown in Fig. 1, and the data are provided in Table 3. The pH and electrical conductivity values were 7.6–9.1 and 5.9–32.8 uS_{20}, respectively. In the Araguaia River, the corresponding mean values of three samples at different river stretches were 8.1 and 22.3 uS_{20}. At some of the sampling locations, water transparency was greater than water depth, as indicated in Table 3 by, e.g., >70 cm. Monthly measurements carried out by the National Water Agency (ANA) at the Araguaia River (Sao Felix de Araguaia city) and at the Das Mortes River yielded pH values of 5.9–7.3 and 6.2–7.5 and conductivity values of 15–45 and 3–50 uS_{20}, respectively. Limnological data are also given in Brasil et al. (2001).

Mineralogical Aspects of Recent and Paleo-Sediments

River sediments show a characteristic mineralogical composition. The >20-μm fraction is generally made up of quartz, whereas the fine fraction consist of various clay minerals, mainly smectite, chlorite, illite, and kaolinite, as well as quartz. Tropical sediments also contain neo-formatted

Table 2 Confusion matrix results

CLASS	Vegetation	Water	Secondary Vegetation	Flooded Area	Dry Soil	Wet Soil	Flooded Vegetation
Vegetation	41	0	1	0	0	0	74
Water	0	100	0	16	0	0	0
Secondary Vegetation	0	0	92	0	0	0	0
Flooded Area	0	0	0	84	0	0	1
Dry Soil	0	0	7	0	97	0	0
Wet Soil	0	0	0	0	3	100	0
Flooded Vegetation	59	0	0	0	0	0	25

Table 3 Hydrochemical data from rivers and lakes in the Araguaia River floodplain collected during the sampling period of July 30–August 8, 2011

Place	Locality	Hour	pH	Conductivity (μS. cm^{-1})	Water temperature (°C)	Water transparency (cm)	Ca (mgL^{-1})	Mg (mgL^{-1})	K (mgL^{-1})	Na (mgL^{-1})	HCO_3 (mgL^{-1})	P total (mgL^{-1})
Place 1	Mimoso Lake	10:13	9.0	9.43	29.0	50	2.0	0.8	0.7	0.4	6.0	0.11
Place 2	4 Bocas Pond	15:25	8.6	11.64	30.5	210	1.6	0.6	1.3	0.9	8.0	0.09
Place 3	Araguaia River	16:32	8.3	23.08	31.0	50	3.8	1.4	0.9	0.9	8.0	0.09
Place 4	Das Mortes River	05:30	9.2	7.68	25.0	-	1.8	0.6	0.4	0	4.0	0.07
Place 5	Xavantinho River	10:15	9.1	11.71	29.5	60	1.8	0.6	0.7	0.8	8.0	0.11
Place 6	Das Mortes River	16:00	8.4	8.69	29.5	70	2.0	0.6	0.4	0	6.0	0.2
Place 7	Araguaia River	16:14	8.3	28.00	30.5	50	4.0	1.6	0.9	1.0	14.0	0.08
Place 8	Araguaia River	22:55	7.6	15.78	28.5	-	3.0	1.0	0.7	0.5	8.0	0.06
Place 9	Vinte e Três River	09:15	7.9	11.02	27.0	40	1.4	0.4	1.2	0.6	4.0	0.16
Place 10	Jaburu River	10:35	7.9	15.45	27.5	>80	2.2	1.0	1.0	0.8	6.0	0.08
Place 11	Riozinho	11:22	8.1	9.68	28.5	>70	1.8	0.4	0.8	0.7	4.0	0.1
Place 12	Javaés River	12:40	8.2	32.8	32.5	>50	4.6	2.6	1.0	1.6	14.0	0.09
Place 13	Lago Mato Verde	15:00	8.5	5.86	31.0	>100	1.6	0.4	0.3	0.4	4.0	0.11
Place 14	Km Pond	09:56	8.2	23.18	27.0	25	3.0	1.4	1.7	1.5	16.0	0.16
Place 15	Cristalino River	15:16	8.9	8.78	29.5	100	1.6	0.8	0.6	0.3	2.0	0.03

minerals, such as gibbsite and Al-chlorite. The mineralogical composition of the Araguaia sediments indicates a large difference between active-recent and paleo-floodplains, but not between active and inactive paleo-floodplains. The clay mineral association of the Araguaia River and its active-recent floodplain is characterized by the sequence smectite, illite, and kaolinite. The paleo-floodplain is marked by the clay mineral association of kaolinite, gibbsite, goethite, and Al-chlorite.

Three profiles (1, 17, and 16) from the floodplain are shown as examples in Fig. 4. Profile 1 was taken from the sub-recent floodplain near Cocalinho city, profile 17 about 10 km northeast of São Felix do Araguaia city, in the old active paleo-floodplain, and profile 16 near a *monchão*, representing the inactive paleo-floodplain. The sub-recent floodplain shows the expected pattern. In the upper meters, the smectite peak has been reduced due to weathering, but the sediment below is perfectly preserved. The old sediments of the active and inactive paleo-floodplains are strongly weathered and modified. Illite has been transformed into Al-chlorite. A widespread neo-formation of Al-chlorite and traces of gibbsite, goethite, and haematite are evident. Kaolinite is largely preserved but the upper meter contains a disordered kaolinite.

The present-day clay mineral associations of Araguaia River sediments change along its fluvial course. The content of minerals formed during weathering (gibbsite and goethite) increases in sediments transported by the river as it flows through the Araguaia plain, whereas the proportion of minerals that are unstable during tropical weathering (smectite) decreases. This relationship shows that the sediment load carried from the upper drainage area, above Barra do Garças city, is of the same magnitude as that eroded from the Araguaia plain (Fig. 5). This is in contrast to most of the world's rivers, whose sediment characteristics generally do not change after the rivers have entered lowland plains. For example, there is only a small change in the illite content of Amazon River sediments along the 4000-km course of the river through the lowland (Irion 1991).

Small, recently active floodplains develop along internal drainage systems, e.g., along the small rivers of Bananal Island. Their sediments consist of old, eroded, and re-deposited material from the active paleo-floodplain and do not contain recent sediments from the Araguaia River, as indicated by the absence of smectite and the presence of Al-chlorite (Fig. 6).

The Das Mortes and Cristalino Rivers and the many small rivers of the Araguaia plain drain the sediments of the plain, either mostly or exclusively. The fine-grained suspended load of these rivers is predominantly or completely made up of minerals generated in the paleo-floodplain, such as kaolinite, gibbsite, goethite, and Al-chlorite. With the exception of the active sub-recent Araguaia floodplain, where no or only a very

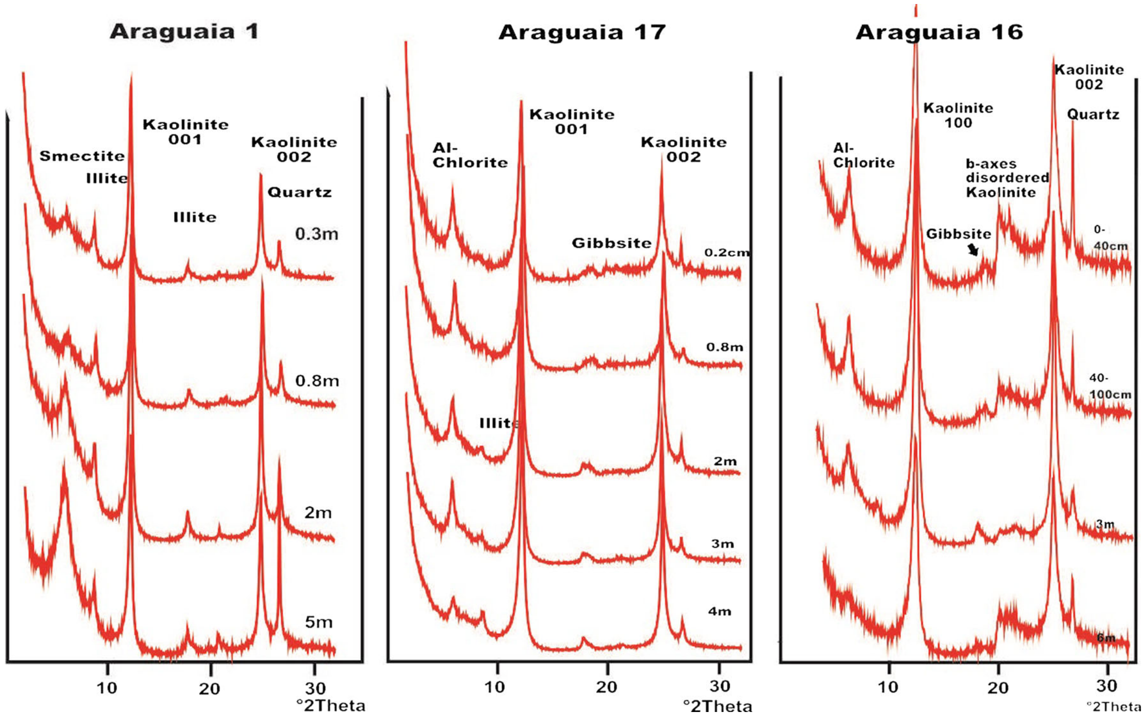

Fig. 4 X-ray diffraction of <2-µm samples from a 5-m sediment profile of the sub-recent sediments of the Araguaia River near Cocalinho city (Araguaia 1, left), a 4-m profile in the active paleo-floodplain south of São Felix do Araguaia city (Araguaia 17, middle), and a 6-m profile on a *monchão* (Araguaia 16, right)

small amount of new minerals is delivered from the catchment outside the Araguaia depression to the active paleo-floodplain. The sediments become lixiviated by the rains and thus bioelement-poor. This eluviation occurs in parallel with an alteration of grain size, determined by means of settling tubes. Separation of the fractions allowed a determination of their clay mineral contents. This method (Atterberg 1912) yielded similar data for the >20-µm fractions and those obtained from sieves, whereas for smaller grain sizes there were large differences. Clay mineral particles with diameters of, e.g., 5 µm settle in water due to their foliaceous character, as is the case for quartz spheres <2 µm.

Sediments in the recent or sub-recent Araguaia floodplain are more or less sandy and typically become increasingly coarser with increasing depth (Fig. 7a). By contrast, those of the much older active paleo-floodplain are characterized by a high clay fraction (Fig. 7b), due to changes in former mineral associations and to the neo-formation of clay minerals. All minerals of the active paleo-floodplain, except quartz and kaolinite, have disappeared. Because of its higher disposition in the uppermost layers, kaolinite has recrystallized to a disordered, extremely fine-grained form.

Discussion and Conclusions

The Araguaia River floodplain is one of the largest floodplains in South America. The maximum size of the flooded area as determined in this study, 88,119 km^2, is considerably larger than estimated by Hamilton et al. (2002). Using long-term hydrological annual series and sensor data obtained with passive microwave from SMMR Satellite Nimbus-7, those authors estimated that the Araguaia wetlands extend for 58,550 km^2 between the latitudes 9°S and 15°S. However, the spatial resolution of the SMMR sensor data was 27 km, which prevented the detection of flooded areas with smaller dimensions. Hamilton et al. (2002) thus pointed out the need for data collection using sensor systems with higher spatial resolution and for statistically based validations, as realized in this study.

Among the Brazilian wetlands, the Araguaia River floodplain has one of the largest fluctuations in size between the rainy and dry seasons. During the dry season, only 2930 km^2, corresponding to 3.3 % of the entire river floodplain system, are covered by water. This reflects the dramatic impact of the flood pulse on the entire region. The tremendous periodic drought stress is evidenced by the vegetation. Thus, there is the characteristic dynamic floodplain vegetation, with small-scale patches of forests and grasslands of different successional stages in the active-recent floodplain, and a rather static drought-tolerant *cerrado* vegetation interspersed with small communities of flood-tolerant herbaceous plants, shrubs, and trees in the depressions and around permanent water bodies in the active paleo-floodplain (Veloso et al. 1974; Valente et al. 2013; Junk et al. unpublished data).

Our hydrochemical data and data from the literature show that the waters of the Araguaia River and its tributaries belong

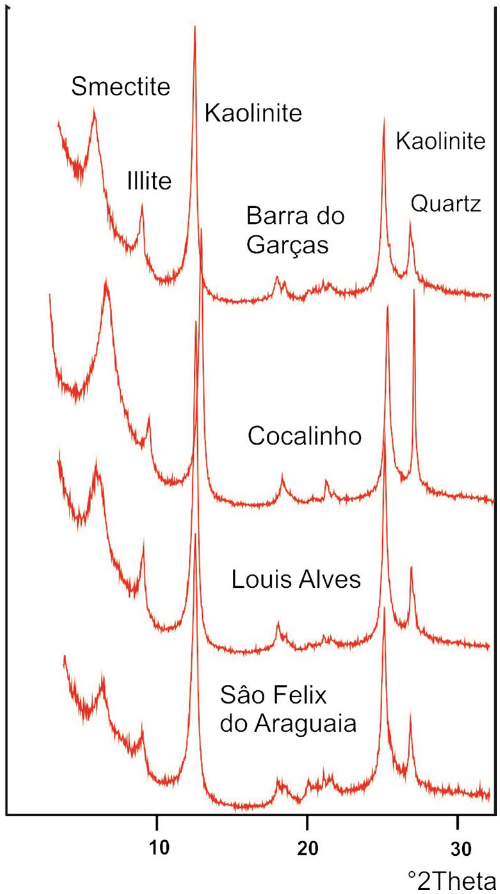

Fig. 5 Comparison of the clay fractions of the suspended matter of Araguaia River between Barra do Garças and São Felix do Araguaia cities, where sediments of the paleo-floodplain contribute to the river's sediments. There is a strong reduction in the smectite content between the cities of Luiz Alves and São Felix do Araguaia

to Sioli's "clear water" category, characterized by near-neutral pH, low electrical conductivity, relatively high transparency, and a greenish color (Sioli 1956; Villamizar 2013). The comparatively low transparency of the Araguaia River's water may be the result of increased sediment input from the extended agro-industries in the catchment (Aquino et al. 2009; Latrubesse et al. 2009). Major cations are the alkali-earth metals Ca and Mg, which represent about 75 % of the metallic cations in the Araguaia River. The hydrochemical variability in smaller tributaries and standing water-bodies is relatively large. For example, the percentage of alkali earth metals is smaller in water bodies inside the floodplain, fed mostly by rainwater, than in the Tocantins River, whereas in streams draining carboniferous outcrops the percentages are higher, with Mg concentrations that may exceed those of Ca (Brasil et al. 2001). Comparisons of the bioelement levels with the Amazon River (Furch and Junk 1997) reveal the low to intermediate productivity of the Araguaia River water bodies. The fine-grained sediment fraction of the paleo-floodplain mainly consists of the clay mineral association kaolinite, gibbsite,

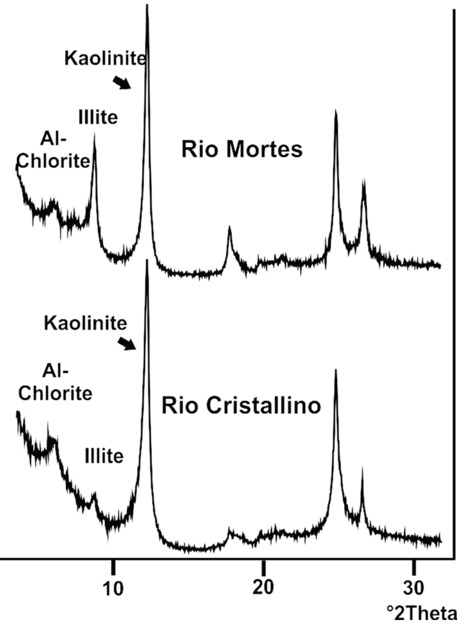

Fig. 6 X-ray diffraction of <2-μm samples of suspended matter from the Das Mortes and Cristalino Rivers, both of which drain the Araguaia plain, either mostly or exclusively

goethite, and Al-chlorite, all of which are poor in Mg, Ca, and K. This indicates the low soil fertility of the paleo-floodplain. The low nutrient status of water and soils and the heavy drought and flood stress make the Araguaia River wetlands very vulnerable to the impact of human use.

The complexity of the Araguaia River floodplain sediments is characteristic of many tropical and sub-tropical wetlands and distinguishes them from wetlands in northern and southern temperate regions. River floodplains in temperate regions are young, dynamic hydromorphologic landscapes that developed after the last glacial period. In the tropics and sub-tropics, however, parts of the river floodplains are likely to differ considerably in age, as is the case in the Araguaia River floodplain. Mineralogical data indicate that only ~20 % of this large, periodically flooded savanna is covered by a recent to sub-recent active floodplain whereas ~80 % of the floodplain is a much older paleo-floodplain. The term "active paleo-floodplain" reflects the fact that during high-water periods this part of the floodplain participates directly in the hydrological cycle, by retaining, storing, and delivering flood- and rainwater. It also plays a significant role in biogeochemical cycles and in the maintenance of the biodiversity of the river-floodplain system. By contrast, it does not participate to a major extent in the sedimentation and erosion processes that characterize the active recent to sub-recent floodplain (Latrubesse et al. 2009). Exceptions are areas of the paleo-floodplain directly bordered by river channels, where the erosion of paleo-sediments influences the composition of sediments transported by the Araguaia River. These areas of the paleo-floodplain

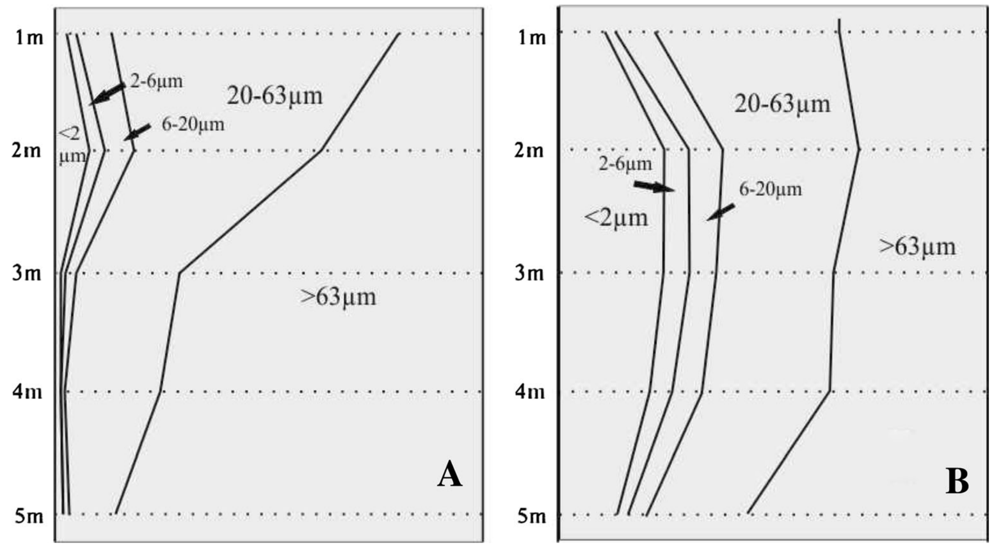

Fig. 7 Grain size (in µm) of sediments in (**a**) the active-recent floodplain of the Araguaia River near Luiz Alves city and (**b**) the active paleo-floodplain of the river ~10 km east of São Felix do Araguaia city (**b**). Note the large difference in the <2-µm fraction between (**a**) and (**b**)

clearly lie somewhat higher than the active-recent floodplain, because during peak floods they are not the sites of new sediment deposition by the river. Indeed, the river channel is bordered directly byxerophytic cerrado vegetation.

The minerals of the strongly weathered paleo-floodplain (kaolinite, gibbsite, goethite, and Al-chlorite) are predominantly formed from other minerals present in the coarser fraction of the Araguaia River, especially feldspars and micas. Consequently, there is a major difference between the clay fraction of Araguaia River sediments and that of its paleo-floodplain. In central Amazonia, sediments with a clay mineral sequence similar to that of the paleo-floodplain reflect a generation period of far greater than 100,000 years (Irion 1981, 1984; Irion and Kalliola 2010).

Our hypothesis regarding the genesis of the paleo-sediment in the Araguaia plain is as follows: The Araguaia paleo-floodplain was formed during the early Pleistocene, about one million years ago, or earlier. Parts of the hydromorphologic structures of the floodplain were higher than today's surface, as shown by the small remnants inside the active paleo-floodplain (*monchões*), which rise about 1 m above the actual active paleo-floodplain level. We refer to these areas as the inactive paleo-floodplain. The similar mineralogical composition of the sediments of the active and inactive paleo-floodplains indicates their similar ages. Later, the fluvial system lowered and dissected the pre-existing floodplain. The visible remnants of this period are the internal drainage system and the roundish and elongated depressions inside the active paleo-floodplain (*ipucas*).

In the subsequent period, the mineral association in at least the upper 6 m of the paleo-floodplain was greatly altered, resulting in the formation of kaolinite, gibbsite, goethite, and Al-chlorite. The hydrological conditions required for weathering include a mainly downward directed interstitial water movement in the upper horizons of the sediments. Hence, the water table in the paleo-floodplain must have been lower during the formation of the above-mentioned minerals than when the sediments were deposited. Weathering of the sediments also resulted in a decrease in particle size, as evidenced by paleo-sediments that are much finer than the original sediments in the active recent to sub-recent floodplain. Valente (2007) determined ages of up to 240 kaBP for the paleo-floodplain, although this is probably an underestimate and the true age of the sediments may be beyond the limits of determination of the physical methods (thermoluminescence and optically stimulated luminescence) used in that study.

Later, during a late period of the Pleistocene, the water tables of the Araguaia and Das Mortes River systems rose to their present levels, because of a shift to a wetter climate and/or a tectonically downward movement of the Araguaia plain, or a backwater effect caused by a tectonic uplift in the area north of the Araguaia plain. Major erosion and sedimentation processes occurred only along the river shores forming the active-recent to sub-recent floodplain, which now covers about 20 % of the area and is composed of recent and sub-recent sediments. This area shows the characteristic dynamic features of swales, riches, lakes, and abandoned channels (Latrubesse et al. 2009). The interfluvial paleo-sediments were not affected by these processes. Height differences in the interfluvial areas were leveled by the small-scale local translocation of sediments, such that a flat landscape with shallow depressions (*ipucas*) and elevations (*monchões*) was formed. Our equipment allowed only the penetration of the subsurface to a depth of 6 m. Deeper penetration will be necessary to better understand the genesis of the floodplain.

The new Brazilian Forest Code mandates the protection of wetlands along rivers and streams according to the width of the river bed during the "regular water level," which means during the low-water period. The outer border of the adjacent wetland to be protected is determined at each site according to about half of the width of the river bed. Consequently, only narrow strips along the river channels of the Araguaia floodplain and other Brazilian floodplains are protected; most of the paleo-floodplain of the Araguaia River will lose its protection status. Considering the natural large annual water-level fluctuations and associated changes in wetland extent, Brazilian scientists have proposed that the outer wetland borders be defined based on the mean maximum flood level (Junk et al. 2014). Therefore, the extent of the Araguaia River floodplain as determined in this study corresponds to the area inundated at the high-water level.

The active paleo-river floodplain does not receive new sediments and nutrients from the parent rivers and is accordingly nutrient-poor, as shown by the water-chemical and mineralogical data reported in this study. Both the natural productivity and the carrying capacity for cattle are low. Deforestation and the substitution of natural herbaceous vegetation by exotic grasses strongly modify the vegetation cover but, in the long run, do little to improve the carrying capacity of the system for cattle. Increased fire frequency destroys shrub and tree communities and diminishes habitat diversity. Agriculture is possible only with large investments in flood control and intensive applications of agrochemicals and pesticides, as demonstrated by the crop plantations in polders, already established in some areas of Bananal Island. Data on the agrochemical load in the affected water and the release of those chemicals from the polders to the river channel are lacking. Nonetheless, local people refer to periodic, unusual fish mortality and to water-quality problems down-river from the plantations. We argue that management planning has to consider that the entire floodplain is essential both for the water balance of the river-floodplain system and the maintenance of biodiversity in the area as a whole, because of the permanent exchange of organisms between the upland, the river channel, and the different sections of the floodplain.

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