

Comissão 1.2 - Levantamento e classificação do solo

CHARACTERIZATION AND CLASSIFICATION OF SOILS IN THE TAQUARI RIVER BASIN - PANTANAL REGION, STATE OF MATO GROSSO DO SUL, BRAZIL⁽¹⁾

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SUMMARY

Among the soils in the Mato Grosso do Sul, stand out in the Pantanal biome, the Spodosols. Despite being recorded in considerable extensions, few studies aiming to characterize and classify these soils were performed. The purpose of this study was to characterize and classify soils in three areas of two physiographic types in the Taquari river basin: bay and flooded fields. Two trenches were opened in the bay area (P1 and P2) and two in the flooded field (P3 and P4). The third area (saline) with high sodium levels was sampled for further studies. In the soils in both areas the sand fraction was predominant and the texture from sand to sandy loam, with the main constituent quartz. In the bay area, the soil organic carbon in the surface layer (P1) was (OC) > 80 g kg⁻¹, being diagnosed as Histic epipedon. In the other profiles the surface horizons had low OC levels which, associated with other properties, classified them as Ochric epipedons. In the soils of the bay area (P1 and P2), the pH ranged from 5.0 to 7.5, associated with dominance of Ca²⁺ and Mg²⁺, with base saturation above 50 % in some horizons. In the flooded fields (P3 and P4) the soil pH ranged from 4.9 to 5.9, H⁺ contents were high in the surface horizons (0.8–10.5 cmol_c kg⁻¹), Ca²⁺ and Mg²⁺ contents ranged from 0.4 to 0.8 cmol_c kg⁻¹ and base saturation was < 50 %. In the soils of the bay area (P1 and P2) iron was accumulated (extracted by dithionite - Fed) and OC in the spodic horizon; in the P3 and P4 soils only Fed was accumulated (in the subsurface layers). According to the criteria adopted by the Brazilian System of Soil Classification (SiBCS) at the subgroup level, the soils were classified as: P1: Organic Hydromorphic Ferrohumiluvic Spodosol. P2:

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Typical Orthic Ferrohumiluvic Spodosol. P3: Typical Hydromorphic Ferroluvic Spodosol. P4: Arenic Orthic Ferroluvic Spodosol.

Index Terms index: Spodosols, Quaternary sediments, soil taxonomy, SiBCS.

RESUMO: CARACTERIZAÇÃO E CLASSIFICAÇÃO DE SOLOS DA BACIA DO RIO TAQUARI NO PANTANAL SUL-MATO-GROSSENSE

Dentre os solos existentes no Mato Grosso do Sul, destacam-se no Bioma Pantanal, os Espodossolos. Apesar de serem verificados em extensões consideráveis, poucos estudos com objetivo de caracterização e classificação desses solos foram realizados. Objetivou-se caracterizar e classificar solos de três feições fisiográficas da bacia do rio Taquari: baía e campos de inundação. Foram abertas duas trincheiras na área de baía (P1 e P2) e duas na de campos de inundação (P3 e P4). A terceira feição (salinas) foi amostrada para estudos posteriores, por apresentar altos teores de sódio. Nos solos estudados, nas duas áreas houve predomínio da fração areia, com textura variando de areia a franco-arenosa, sendo o principal constituinte o quartzo. Na área de baía o horizonte superficial (P1) apresentou teor de carbono orgânico (CO) maior que 80 g kg⁻¹, sendo diagnosticado como H hístico. Para os demais perfis, os horizontes superficiais apresentaram baixos teores de CO, o que, em associação com outros atributos, fez com que eles fossem diagnosticados como A moderado. Nos solos da área de baía (P1 e P2) os valores de pH variaram de 5,0 a 7,5, associados à dominância dos íons Ca²⁺ e Mg²⁺, com saturação por bases, em alguns horizontes, maior que 50 %. Na área de campos de inundação, os solos (P3 e P4) mostraram valores de pH variando de 4,9 a 5,9, elevados valores de H⁺ nos horizontes superficiais (0,8 a 10,5 cmol_c kg⁻¹), valores de Ca²⁺ + Mg²⁺ variando de 0,4 a 0,8 cmol_c kg⁻¹ e saturação por bases maior que 50 %. Nos solos da área de baía (P1 e P2) ocorreu acúmulo de Fe, extraído por ditionito (Fed), e CO no horizonte espódico; e nos solos de campos de inundação (P3 e P4) houve acúmulo somente de Fed (nos horizontes subsuperficiais). De acordo com critérios adotados pelo Sistema Brasileiro de Classificação de Solos (SiBCS), em nível de subgrupo os solos foram classificados como: P1: Espodossolo Ferri-humilúvico hidromórfico organossólico, P2: Espodossolo Ferri-humilúvico órtico típico, P3: Espodossolo Ferrilúvico hidromórfico típico e P4: Espodossolo Ferrilúvico órtico espessarênico.

Termos de indexação: Espodossolos, sedimentos quaternários, taxonomia de solos, SiBCS.

INTRODUCTION

The Brazilian Pantanal, in the Upper Paraguay River Basin, covers approximately 138,183 km², distributed in the states of Mato Grosso and Mato Grosso do Sul. Its northern limit is the river Itiquira, in the South the river Apa, in the East the western border of the Paraná river basin and in the West the borders of Bolivia and Paraguay. The region has a complex drainage network and is often periodically flooded. The main axis of the drain region is the Paraguay River, with several marginal alluvial fans. The most important among these is the Taquari river is, with a collecting area covering about 36 % of the wetland.

The marsh plain is formed by recent, still active sediments of the Quaternary period, composed primarily of sand with predominantly small and medium grain size. The altitude varies from 80 to 190 m (Assine, 2003). In this sedimentary, periodically flooded environment, the large

oscillations in the groundwater level can be considered one of the main factors responsible for changes in soil characteristics, e.g., in color and chemical properties, such as those related to exchangeable cations and organic carbon content. In this environment, RADAMBRASIL (1982) identified Planosols, Plinthosols and Spodosols.

In Brazil, Spodosols are typically related to coastal environments and restinga vegetation (Oliveira et al., 2010; Coelho et al., 2010), but also occur in large areas in the Amazon on lower slopes with shrub vegetation and sediments with high sand content, as observed in the region of Rio Negro (Klinge, 1965; Lucas et al., 1984, 1987; Bravard & Righi, 1989; Righi et al., 1990).

The Brazilian System of Soil Classification - SiBCS (Embrapa, 2006) divides the order of Spodosols into Espodossolo Humilúvicos, when there is a predominance of organic carbon (OC) accumulated in the spodic horizon (Bh and/or Bhm); Espodossolos Ferrilúvicos, with accumulation of

aluminum (Al) that may or may not contain iron (Fe) in the spodic horizon (Bs and/or Bsm) and Espodosolos Ferrihumilúvicos with accumulation of OC, Fe and Al in the spodic horizon (Bhs and/or Bhsm). More detailed research, addressing what forms of Fe and Al would be complexed by organic matter in the spodic B horizon, to generate more information for the structuring of the lower hierarchical levels of the SiBCS, was carried out by Oliveira et al. (2010) and Coelho et al. (2010) for the coastal region of Brazil. However, in the Pantanal region, although the conditions are favorable for the formation of Spodosols, there is still a lack of research on this soil type, compared to the number of studies in the coastal region of Brazil. Moreover, in some areas of the Pantanal region, the formation of spodic horizons associated with high levels of sodium (Na^+) is observed, which is uncommon for most Spodosols classified in Brazil.

In this context, the purpose of this study was the characterization and classification of some Spodosols of the Upper Paraguay River Basin in the Pantanal.

MATERIALS AND METHODS

The study was conducted in the Upper Paraguay River Basin (UPB) which is part of the Bacia do Prata, located in the Pantanal of Mato Grosso do Sul, in the Midwest region of Brazil (lat 16–22° South; long 55–58° West; 80–190 m). The characteristic climate of the region according to Köppen is Aw (tropical megathermic), with 1,433 mm annual rainfall, and maximum and minimum temperatures of 40.0 and 20.3 °C, respectively (Soriano & Galdino, 2002). The source material of the soils were sediments from the Taquari Basin dating back to the Quaternary Period (Assine, 2003).

One of the 11 subregions of the Pantanal, Nhecolândia, was selected. This 26,921 km² area located in the central region of the Pantanal, is largely covered by sediments of the river Taquari. Its soils are sandy, deep and hydromorphic, located on the floodplain subject to periodic flooding for 3-4 months a year (Sousa, 2003). The predominant Spodosols are covered by deciduous tropical cerrado (woodland savanna) and tropical cerrado (open shrub); Natraqualfs (Planossolos Nátricos) were observed in areas of cerrado and tropical Quartzipsamments on the banks and near the river Taquari, associated with tropical cerrado and deciduous tropical cerrado (RADAMBRASIL, 1982).

The subregion Nhecolândia has different environments, mainly due to the relief variations,

namely: a) bays: depressed areas flooded most of the year, b) flooded fields: periodically flooded areas, and c) saline areas, where ponds of brackish water appear that are rarely flooded by the rivers. Four trenches were opened in two areas, which are described below: a) Bay: profiles P1 and P2 (coordinates 18° 59' 34" S and 56° 36' 15" W, 97 m) and b) flooded fields: Profile P3 (coordinates 19° 09' 39" S and 55° 17' 32" W, 290 m) and profile P4 (coordinates 18° 58' 49" S and 56° 39' 08" W, 100 m). Profiles from the saline physiographic area were also sampled. The colors of the subsurface layers of these profiles have low values and chromas, indicating reductomorphic environments. The presence of a strongly cemented spodic B horizon called "ortstein" was also observed. The pH values determined in the field were high (9.9–10.0), and may be due to the high levels of exchangeable sodium. These profiles will be the subject of future studies.

The profiles were morphologically described according to Santos et al. (2005), based on samples collected from all horizons. The samples were dried and sieved (2 mm mesh) to obtain air-dried fine earth (ADFE). Undisturbed soil from the profiles was sampled with a volumetric ring (73.5 cm³) to determine bulk density (BD), according to Embrapa (1997).

The chemical and physical analyses were performed using air-dried fine earth (ADFE). The particle size was determined by dispersion, using 0.1 mol L⁻¹ sodium hydroxide and sodium hexametaphosphate ($\text{NaPO}_3 + \text{Na}_2\text{CO}_3$). The particle density was determined by the volumetric flask method. The exchangeable cations Ca^{2+} , Mg^{2+} and Al^{3+} were extracted with 1 mol L⁻¹ KCl, and H + Al with a solution of 0.5 mol L⁻¹ calcium acetate, at pH 7.0. The levels of P, Na^+ and K^+ were extracted with 0.0125 mol L⁻¹ H₂SO₄ solution + 0.05 mol L⁻¹ HCl. The Ca^{2+} and Mg^{2+} contents were determined by titration with 0.0125 mol L⁻¹ EDTA solution, Na^+ and K, by flame photometry, P by colorimetry, and Al^{3+} and H + Al, by titration with 0.025 mol L⁻¹ NaOH. The pH in water and KCl (weight 1:2.5) was determined by a potentiometer, and from the data the delta pH (ΔpH) was calculated. Organic carbon (OC) was determined according to Yeomans & Bremner (1988). From these data, the aluminum saturation (m); S value (sum of exchangeable bases); T value (soil CEC), and V % value of sodium saturation (Na/T) were calculated. The above procedures were performed as proposed by Embrapa (1997).

The total contents of Si, Al, Fe, and Ti were determined after acid digestion (sulfuric acid) according to Camargo et al. (2009). The Fe forms, in their different crystallinity degrees, were evaluated

using sodium dithionite-citrate-bicarbonate (DCB) (Mehra & Jackson, 1960) and 0.2 mol L⁻¹ ammonium oxalate, at pH 3.0, in the dark (McKeague & Day, 1966).

Mineralogical analysis was carried out in the subsurface horizons, by X-ray diffraction of the sand fraction in a Philips PW 2400 diffractometer with a copper anode (Cu K_α) and Ni filter at 40 kV and 40 mA, at 1.2 two-Theta (degrees) per minute. Samples were prepared as described by Witthig & Allardice (1986).

From the morphological descriptions and analytical (physical, chemical and mineralogical)

data, the soils were classified according to the Brazilian System of Soil Classification (SiBCS) (Embrapa, 2006).

RESULTS AND DISCUSSION

Soil morphology

The area described in the two environments (bay and flood fields) differed with regard to soil color, structure, consistency, and thickness of the horizons and their transitions (Table 1).

Table 1. Morphological properties of soils developed from sediments of the river Taquari watershed in the Pantanal of Mato Grosso do Sul

Horiz.	Depth	Munsell color ⁽¹⁾		Structure ⁽²⁾	Consistence			Transition ⁽⁶⁾
		Matriz	Mottled		Dry ⁽³⁾	Moist ⁽⁴⁾	Wet ⁽⁵⁾	
Bay area P1 - Altitude 97 m								
H	0-20	5Y 2.5/1		M, M, G	H	Fir	PL and SSt	PA
E	20-42	2.5Y 7/3		SG	L	L	NPL and NSt	PA
Bhs1	42-60	2.5Y 3/2		SG	L	L	NPL and NSt	PC
Bhs2	60-78	2.5Y 4/3		SG	L	L	NPL and NSt	PC
Bhs3	78-101	2.5Y 4/3		SG	L	L	NPL and NSt	PC
Bhs4	101-120	2.5Y 4/3		SG	L	L	NPL and NSt	-
Bay profile P2 - Altitude 97 m								
A1	0-12	5Y 2.5/1		M, M, G	H	Fir	SPL and SSt	PA
A2	12-17	2.5Y 3/2		M, M, G	H	Fir	SPL and SSt	PA
E	17-32	2.5Y 7/2		SG	L	L	NPL and NSt	DA
Bhs1	32-53	2.5Y 3/2		SG	L	L	NPL and NSt	DA
Bhs2	53-66	2.5Y 3/2		SG	L	L	NPL and NSt	DA
Bh	66-82	2.5Y 5/3		SG	L	L	NPL and NSt	DA
2Bhs3	82-100	2.5Y 3/2		SG	L	L	NPL and NSt	DA
2Bhs4	100-120 ⁺	2.5Y 4/2		SG	L	L	NPL and NSt	-
Flooded field profile P3 - Altitude 290 m								
A1	0-22	10YR 3/2		M, M, G	H	Fr	SPL and SSt	PG
A2	22-31	10YR 4/4		W, P, SB	H	VF	SPL and SSt	PA
E	31-50	10YR 7/6		SG	L	L	NPL and Npe	PG
Bs1	50-56	10YR 6/8	10YR 5/2 Ab, Sm, Dist,	M, P/M, AB	H	Fr	SPL and Lpe	PG
Bs2	56-70 ⁺	10YR 6/8		M, M, AB	H	Fir	SPL and Lpe	-
Flooded field profile P4 - Altitude 100 m								
A	0-10	10YR 3/3		SG	L	L	NPL and NSt	PA
E	10-35	10YR 8/6		SG	L	L	NPL and NSt	PA
Bhs1	35-54	10YR 4/4		SG	L	L	NPL and NSt	PA
Bhs2	54-69	10YR 4/6		SG	L	L	NPL and NSt	PA
Bs2	69-80	10YR 4/6		SG	L	L	NPL and NSt	PA
C	80-110 ⁺	10YR 5/4		SG	L	L	NPL and NSt	-

⁽¹⁾ Ab: abundant; Sm: small; Dis: distinct. ⁽²⁾ Structure: degree of development: (W: weak, M: Moderate), size (S: small and M: medium), shape (G: Granular, SB: Subangular blocks, AB: Angular blocks and SG: single grains). ⁽³⁾ Dry consistence: (L: loose and H: hard). ⁽⁴⁾ Moist consistence: (L: loose, VF: very friable, Fr: friable and Fir: Firm). ⁽⁵⁾ Wet consistence: (NPL: not plastic, PL: plastic, SPL: slightly plastic, NSt: not sticky, SSt: slightly sticky and St: sticky). ⁽⁶⁾ Transition: (PA: Plain and Abrupt, PC: Plain and Clear, PG: Plain and Gradual and DA: Discontinued and Abrupt).

In the bay area, the horizon sequence of the soils (P1 and P2) was H, E and A, E, respectively, both presenting uncemented spodic horizons. The surface horizon H of profile P1 had hue 5Y, granular structure; hard and firm consistence when dry and moist, respectively, and plastic and slightly sticky when wet. Profile P2 contained a horizon with morphological characteristics similar to the H horizon of P1, except for the slightly plastic wet consistence. The subsurface horizons (E and B) had hue 2.5 Y, simple grain structure, loose consistence when dry and moist, not sticky and not plastic when wet. The transition between the surface and E horizons was sharp and plain; and in the subsurface layers ranged from clear and plain in P1 to abrupt and discontinuous in P2.

In the flooded field the soil horizon sequence was A, E, followed by uncemented spodic B. In all horizons of the soils in this environment, yellowish colors with hue 10YR were observed, and in the subsurface horizon (Bs1) of profile P3 the presence of abundant small to medium-sized, contrasting speckles, with hue 10YR. In general, the aggregate shapes ranged from granular in the surface horizons to angular and subangular blocks in the subsurface. Specifically in all P4 horizons, simple grain structure without aggregation was observed. The transition between horizons in P4 was abrupt and plain, while in P3, the topography is flat, and differentiation ranged from abrupt to gradual.

In both areas studied, a marked influence of the podzolization process was observed, by which organic compounds in solution that complex metal ions such as Fe and/or Al or not, were translocated into subsurface layers, due to variations in the water table (Andriessse, 1969; Mokma & Evans, 1999; Dias et al., 2003; Oliveira et al., 2010; Coelho et al., 2010). The soils studied were characterized by an albic E horizon (Embrapa, 2006), suggesting an intense podzolization process.

In the environments under study, the oscillation of the water table can be considered primarily responsible for the morphological differences of the soils. In the bay area, where the water table is closer to the surface for most of the year, the soil colors ranged from dark gray to dark olive (low value and chroma), indicating hydromorphism. This environment is favorable for organic matter accumulation at the surface, as observed in the surface horizon of profile P1 in the bay area. On the other hand, in the flooded field areas the water table is below 1 m soil depth for most of the year, resulting in more oxidized colors (brown, dark brown and yellowish brown). Also, in this environment where the water table is high for a short period only, mottled colors were observed, as well as the

possibility of formation of aggregate structures with angular block shape in the subsurface horizons.

Physical properties

In the two studied areas, the sand fraction was predominant in terms of granulometric composition, reflecting higher values of bulk and particle density (Table 2). In the bay area, the sand content ranged from 617 to 904 g kg⁻¹ and in the flooded fields from 677 to 973 g kg⁻¹. Due to the high sand content in both environments, the soil texture ranged from loamy sand to sandy loam. In all soils, except for profile P3 in the flooded field, the fine sand fraction was highest.

Most commonly, based on the criteria adopted by SiBCS (Embrapa, 2006), the texture of Spodosols is described as predominantly sandy, so particle size is variable but always essentially sandy (Dias et al., 2003; Oliveira et al., 2010), and the fine sand fraction may be predominant (Coelho et al., 2010).

The particle size can be used to draw conclusions on the dynamics of sedimentation. For the study environment in the Taquari river basin, variations in size, according to Assine (2003) indicate closeness to the river bed. In profile P3 (Flooded field), with greater sand particle size, the environment was characterized by higher altitude (290 m) and proximity to the Taquari riverbed. The other profiles were farther away from the riverbed, at lower altitudes, and the sediments were brought from a greater distance during the flood period, consisting mostly of fine sand.

Except for the surface horizon H in profile P1 (0.86 Mg m⁻³) in the bay area, the values of bulk density were high (1.37–1.93 Mg m⁻³). The latter was associated with particle density, ranging from 2.65 to 2.95 Mg m⁻³. The pattern observed for the mineral horizons, both for bulk and for particle density, may be due to the predominance of the sand fraction, whose main constituent is mineral quartz (Figure 1), with a density of about 2,65 Mg m⁻³.

Chemical properties

In the bay area, the OC levels were high (110.5 g kg⁻¹) in the surface horizon of profile P1. Also, in this area, OC is accumulated in the subsurface horizons, by a characteristic eluviation process of organic matter.

The water pH in the A1 horizon in Bh (P2) was 5.0 to 7.5; the profiles were classified as moderately acidic to neutral. Particularly, in the surface horizons of profiles P1 and P2, a highly acidic water pH was observed, while in the subsurface layers the water pH values were close to neutral.

Table 2. Bulk density, particle size and texture of soils developed from sediments of the river Taquari watershed in the Pantanal of Mato Grosso do Sul

Horiz.	Depth cm	Bulk density		Particle size				Texture
		Soil	Particle dens. Mg m ⁻³	Coarse sand	Fine sand	Silt	Clay	
Bay profile P1 - Altitude 97 m								
H	0-20	0.86	0.76	135	516	182	167	-
E	20-42	1.73	2.61	167	731	78	24	Sand
Bhs1	42-60	1.72	2.72	173	647	121	59	Sand
Bhs2	60-78	nm	2.69	177	680	121	22	Sand
Bhs3	78-101	1.85	2.64	167	673	109	51	Sand
Bhs4	101-120	nm	2.70	161	634	95	110	Loamy sand
Bay profile P2 - Altitude 97 m								
A1	0-12	1.61	2.46	86	531	184	200	-
A2	12-17	nm	2.63	162	630	135	74	Loamy sand
E	17-32	1.68	2.65	155	749	75	21	Sand
Bhs1	32-53	1.74	2.75	194	653	49	104	Loamy sand
Bhs2	53-66	nm	2.73	164	665	76	95	Loamy sand
Bh	66-82	nm	2.63	157	729	80	34	Sand
2Bhs3	82-100	1.81	2.71	137	703	92	68	Sand
2Bhs4	100-120 ⁺	nm	2.70	166	627	104	104	Loamy sand
Flooded field profile P3 - Altitude 290 m								
A1	0-22	1.37	2.85	343	334	138	185	-
A2	22-31	1.71	2.71	445	458	29	68	Sand
E	31-50	1.79	2.63	481	461	34	24	Sand
Bs1	50-56	1.93	2.66	585	254	87	74	Sand
Bs2	56-70 ⁺	1.88	2.73	535	286	72	106	Loamy sand
Flooded field profile P4 - Altitude 100 m								
A	0-10	nm	2.68	167	806	25	2	Sand
E	10-35	nm	2.68	132	719	95	54	Sand
Bhs1	35-54	nm	2.68	142	808	7	43	Sand
Bhs2	54-69	1.57	2.70	151	771	16	62	Sand
Bs2	69-80	1.60	2.65	119	798	17	66	Sand
C	80-110 ⁺	nm	2.66	122	823	4	51	Sand

nm: not measured.

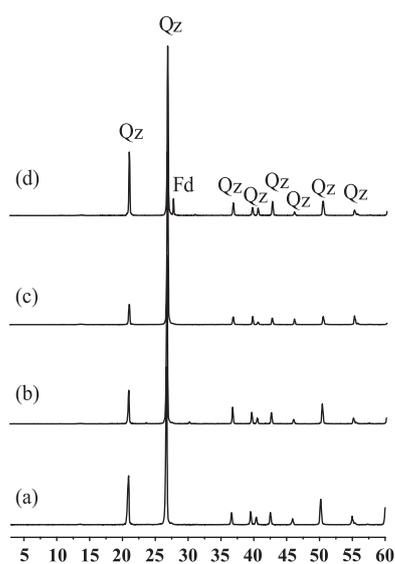


Figure 1. X-ray diffractometry of the sand fraction of soils developed from sediments of the river Taquari watershed in the Pantanal of Mato Grosso do Sul. A: bay area P1 (Bhs2 60–78 cm); B: bay area P2 (Bh 66–82 cm); C: flooded field P3 (Bs1 50–56 cm); D: flooded field P4 (Bhs2 54–69 cm); Qz: quartz; Fd: feldspar.

In the bay area, the pH in KCl was lower than in water, resulting in a negative ΔpH . The P concentrations were low and quite similar to the profiles of the bay area (0.02–0.03 mg kg⁻¹). In the surface horizons (H, A1 and A2) of the two profiles, the highest levels of Ca²⁺, Mg²⁺ and H⁺ were observed, reflecting higher values of sum of bases (SB) and cation exchange capacity (CEC). The highest CEC in the surface horizons was associated with organic matter, primarily responsible for the cation exchange capacity in sandy soils (Embrapa, 2006), as well as in Spodosols (Dias et al., 2003; Oliveira et al., 2010; Coelho et al., 2010). In this environment, the occurrence of Ca²⁺ and Mg²⁺ accumulation in subsurface horizons Bhs3 and Bhs4 (P1) and Bhs1, Bhs2, 2Bhs3 and 2Bhs4 (P2) is noteworthy, resulting in base saturation values of > 50 %. Also, high levels of sodium (Na⁺) were detected, contributing to increased Na⁺ saturation (Na/Tx100). According to a class-defining control section based on sodium saturation (Na/Tx100) of the SiBCS (Embrapa, 2006), soils can have a sodic (Na/Tx100 ≥ 15 %) or solodic character (Na/Tx100 between 6 and 15 %) for some subsurface horizons of P1 and P2). In some horizons, Al³⁺ contents

were high (0.50 cmol_c kg⁻¹), but not enough for an aluminate character.

In the flooded fields, surface horizons had low OC levels (13.11–8.13 g kg⁻¹ in P3 and P4, respectively). Differing from the bay area, the OC in flooded field soils decreased gradually with depth, and no podzolization was observed. The soils had low water and KCl pH, ranging from moderately to strongly acidic. In this environment, similarly to the bay area, the pH in KCl was lower than in water, making ΔpH negative. The P concentrations were also low, with little variation between profiles. Similarly as observed for P, the content of exchangeable cations was low (0.2–0.9 cmol_c kg⁻¹), decreasing slightly with depth. The highest values of exchangeable bases in the upper horizons followed the OC levels, and the values of H⁺ and CEC of these horizons were also highest. Despite the low values of sum of bases, base

saturation was ≥ 50 % in the E horizon of profile P3, a fact attributed to very low Na⁺ values in the exchange complex. Specifically, H⁺ values increased in depth in profile P4, indicating high CEC values. In the soils of this area, no high Al³⁺ concentrations were observed in the exchange complex; the highest content was found in the surface A1 horizon profile P3 (0.8 cmol_c kg⁻¹).

The contents of SiO₂, Al₂O₃, Fe₂O₃, Fe extracted with dithionite-citrate (Fed), Fe extracted with oxalate (Feo) and their molecular relationships differed between the sampled soils (Table 4).

The SiO₂ contents were highest in the surface horizons of the bay area (profile P1 and P2) and flooded field (profile P3) (104.7, 119.7 and 97.3 g kg⁻¹, respectively). Additionally, SiO₂ were highest in the subsurface layers of all studied profiles. Al₂O₃

Table 3. Chemical properties of soils developed from sediments of the river Taquari watershed in the Pantanal of Mato Grosso do Sul

Horiz.	Depth	TOC	pH		Δ pH	P	K	Na	Ca	Mg	Ca + Mg	H	Al	H + Al	SB	T	Na/T	V
			Water	KCl														
	cm	g kg ⁻¹				mg kg ⁻¹	cmol _c kg ⁻¹											%
Bay profile P1 - Altitude 97 m																		
H	0-20	110.5	5.2	4.3	-1.0	0.02	0.26	0.25	7.20	2.80	10.00	14.00	0.40	14.40	10.51	24.91	1	42
E	20-42	3.8	6.5	5.1	-1.4	0.02	0.02	0.00	0.50	1.00	1.50	8.20	0.20	8.40	1.52	9.92	0	15
Bhs1	42-60	3.3	6.4	5.0	-1.4	0.02	0.07	0.29	0.80	0.40	1.20	9.20	0.10	9.30	1.56	10.86	3	14
Bhs2	60-78	5.5	7.0	6.1	-1.0	0.02	0.05	0.29	1.00	0.30	1.30	5.60	0.10	5.70	1.64	7.34	4	22
Bhs3	78-101	3.7	7.4	6.0	-1.4	0.02	0.05	0.31	0.90	0.80	1.70	0.90	0.10	1.00	2.06	3.06	10	67
Bhs4	101-120	1.9	7.2	5.8	-1.4	0.03	0.11	0.29	1.80	2.30	4.10	0.50	0.10	0.60	4.50	5.10	6	88
Bay profile P2 - Altitude 97 m																		
A1	0-12	11.8	5.0	4.1	-0.9	0.02	0.20	0.26	7.60	2.90	10.50	23.20	0.50	23.70	10.96	34.66	1	32
A2	12-17	5.5	6.3	4.9	-1.3	0.02	0.07	0.30	0.80	1.60	2.40	9.40	0.10	9.50	2.76	12.26	2	23
E	17-32	0.4	6.8	5.7	-1.2	0.02	0.01	0.00	0.50	0.20	0.70	0.40	0.10	0.50	0.71	1.21	0	59
Bhs1	32-53	1.5	6.5	5.0	-1.5	0.02	0.08	0.30	1.70	1.60	3.30	1.10	0.10	1.20	3.67	4.87	6	75
Bhs2	53-66	5.2	6.9	5.6	-1.4	0.02	0.10	0.29	2.00	1.20	3.20	1.40	0.10	1.50	3.59	5.09	6	71
Bh	66-82	5.5	7.5	6.4	-1.1	0.02	0.02	0.00	0.50	0.30	0.80	0.40	0.10	0.50	0.82	1.32	0	62
2Bhs3	82-100	4.7	6.7	5.3	-1.4	0.02	0.06	0.30	1.10	0.90	2.00	1.00	0.10	1.10	2.36	3.46	9	68
2Bhs4	100-120 ⁺	4.3	7.0	5.5	-1.5	0.02	0.10	0.29	1.40	1.10	2.50	0.90	0.10	1.00	2.89	3.89	7	74
Flooded field profile P3 - Altitude 290 m																		
A1	0-22	13.1	4.9	3.9	-1.0	0.33	0.06	0.14	0.50	0.30	0.80	10.50	0.80	11.30	0.99	12.29	1	8
A2	22-31	2.9	5.2	4.0	-1.2	0.11	0.04	0.05	0.30	0.30	0.60	3.30	0.30	3.60	0.69	4.29	1	16
E	31-50	0.1	6.0	4.7	-1.3	0.09	0.04	0.03	0.30	0.20	0.50	0.50	0.00	0.50	0.57	1.07	2	53
Bs1	50-56	1.0	5.5	4.2	-1.4	0.07	0.06	0.06	0.50	0.20	0.70	0.80	0.20	1.00	0.82	1.82	3	45
Bs2	56-70 ⁺	0.6	5.5	4.1	-1.4	0.04	0.06	0.08	0.40	0.30	0.70	0.60	0.20	0.80	0.84	1.64	5	51
Flooded field profile P4 - Altitude 100 m																		
A	0-10	8.1	5.5	4.1	-1.4	0.03	0.01	0.00	0.30	0.10	0.40	0.80	0.40	1.20	0.41	1.61	0	25
E	10-35	1.3	5.4	4.3	-1.1	0.02	0.00	0.00	0.10	0.10	0.20	0.90	0.30	1.20	0.20	1.40	0	14
Bhs1	35-54	1.9	5.5	4.3	-1.2	0.02	0.00	0.00	0.10	0.10	0.20	8.70	0.30	9.00	0.20	9.20	0	2
Bhs2	54-69	1.3	5.4	4.4	-1.0	0.02	0.00	0.00	0.20	0.10	0.30	8.50	0.30	8.80	0.30	9.10	0	3
Bs2	69-80	0.4	5.6	4.4	-1.2	0.02	0.00	0.00	0.20	0.10	0.30	8.60	0.20	8.80	0.30	9.10	0	3
C	80-110 ⁺	0.4	5.9	4.4	-1.5	0.02	0.00	0.00	0.10	0.10	0.20	8.60	0.20	8.80	0.20	9.00	0	2

Table 4. Contents of SiO₂, Al₂O₃, Fe₂O₃, TiO₂, Fed, Feo and molecular ratios Feo/Fed and Al₂O₃/Fe₂O₃ of soils developed from sediments of the river Taquari watershed in the Pantanal of Mato Grosso do Sul

Horizon	Depth	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	Fed	FeO	Feo/Fed	Al ₂ O ₃ /Fe ₂ O ₃
	cm	g kg ⁻¹							
Bay profile P1 - Altitude 97 m									
H	0-20	104.7	26.5	18.7	2.8	4.7	2.3	0.5	2.2
E	20-42	12.0	2.6	5.0	2.4	1.3	0.3	0.2	0.8
Bhs1	42-60	47.2	23.2	19.2	4.4	11.7	3.1	0.3	1.9
Bhs2	60-78	30.1	20.5	13.1	3.4	6.8	2.0	0.3	2.5
Bhs3	78-101	28.9	25.6	9.0	5.7	2.4	0.6	0.3	4.5
Bhs4	101-120	52.3	7.7	14.1	4.4	2.5	0.9	0.4	0.9
Bay profile P2 - Altitude 97 m									
A1	0-12	119.7	42.5	20.9	3.5	9.8	4.7	0.5	3.2
A2	12-17	30.0	23.1	8.1	2.7	2.5	1.4	0.6	4.5
E	17-32	12.6	12.8	3.0	2.4	0.7	0.3	0.4	6.7
Bhs1	32-53	42.4	18.0	17.1	3.7	8.1	3.1	0.4	1.7
Bhs2	53-66	52.8	36.1	23.2	4.4	9.5	4.5	0.5	2.7
Bh	66-82	14.0	5.1	6.0	3.3	0.9	0.4	0.4	1.3
2Bhs3	82-100	27.3	17.9	8.0	3.4	2.5	0.9	0.4	3.5
2Bhs4	100-120 ⁺	48.8	20.6	11.1	4.0	2.9	1.5	0.5	2.9
Flooded field profile P3 - Altitude 290 m									
A1	0-22	97.3	88.6	18.4	5.5	19.5	4.4	0.2	7.6
A2	22-31	21.5	5.1	10.0	4.0	6.5	2.0	0.3	0.8
E	31-50	4.8	12.8	5.0	2.1	2.6	0.3	0.1	4.0
Bs1	50-56	23.3	25.6	19.1	4.3	23.9	0.9	0.0	2.1
Bs2	56-70 ⁺	28.1	38.3	32.1	4.0	38.8	1.0	0.0	1.9
Flooded field profile P4 - Altitude 100 m									
A	0-10	9.4	12.8	4.0	2.4	1.9	0.6	0.3	5.0
E	10-35	9.0	12.8	10.0	2.7	2.2	0.4	0.2	2.0
Bhs1	35-54	8.0	20.5	8.0	3.0	6.1	0.4	0.1	4.0
Bhs2	54-69	14.2	20.5	2.0	4.3	9.3	0.4	0.0	16.0
Bs2	69-80	17.2	12.8	5.0	3.7	6.4	0.4	0.1	4.0
C	80-110 ⁺	7.6	12.8	5.0	4.0	1.3	0.2	0.2	4.0

and Fe₂O₃ contents behaved similarly, ie, tended to accumulate in the deeper soil layers. On the other hand, the TiO₂ levels were low (2.1 kg to 5.7 g kg⁻¹) with little variation in depth.

In both areas, the Fed were higher than the Feo contents. In the bay area, a tendency to accumulate OC, Al³⁺, Fed and FeO in illuvial horizons (B horizon) was observed, more than in the horizons

A and E of each profile. The levels of OC and Al (p = 0.0023 profile P1 and p = 0.0056 profile P2) were correlated (Figure 2a,b). On the other hand, only Fed was accumulated in the flooded field soil; the levels of OC and Al were correlated with Fed (p = 0.0027 profile P3 and p = 0.0134 profile P4) (Figure 3a) and with Feo (p = 0.0018 and p = 0.0205 profile P3 and P4) (Figure 3b). The translocation of Fe and Al occurred due to the complexation

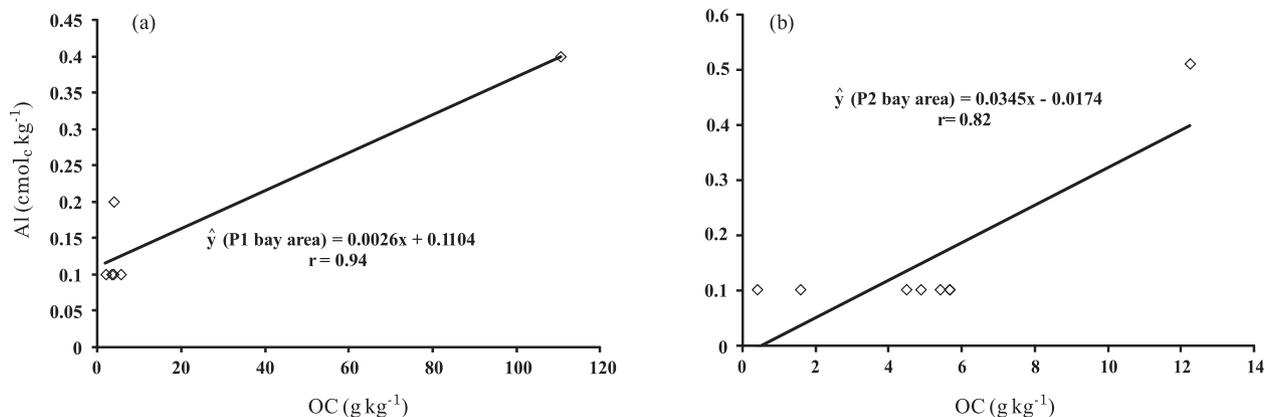


Figure 2. Pearson correlation between carbon and aluminium. A: bay profile P1 (p = 0.0023); B: bay profile P2 (p = 0.0056).

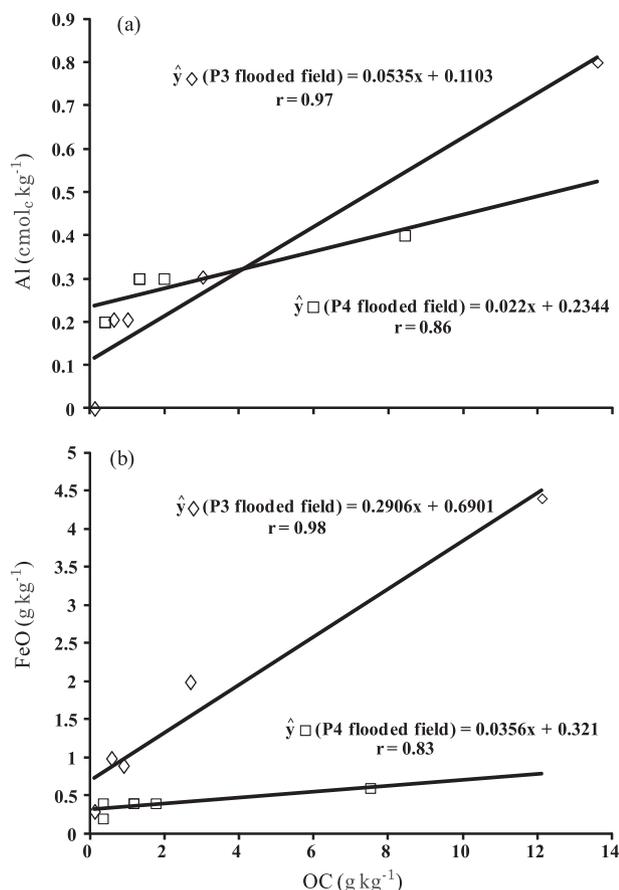


Figure 3. Pearson correlation between carbon and aluminium (a). P3 ($p = 0.0027$), P4 ($p = 0.0134$); and between carbon and iron oxalate (b). P3 ($p = 0.0018$), P4 ($p = 0.0205$).

of these elements with organic compounds (van Wambeke, 1992; van Breemen & Buurman, 1998; Mokma & Evans, 1999; Dias et al., 2003; Oliveira et al., 2010). In view thereof, we suggest the participation of OC, Fe and Al in the genesis of the spodic horizon B in the bay soils, while in the flooded fields only of Fe not complexed by organic matter (Fed), as corroborated by SiBCS (Embrapa, 2006). This pattern was reported elsewhere for areas with restinga (sparse herbaceous vegetation on sandy soil) (Moura Filho, 1998; Moreau et al., 2006; Gomes et al., 2007; Oliveira et al., 2010) and also for highland regions, (Dias et al., 2003), with participation of Fe and Al in the genesis of the spodic B horizon, or only with greater participation of Al in the podzolization process (Coelho et al., 2010).

The minor contribution of Fe complexed with organic acids can be attributed to the presence of a high water table in the soil profile, promoting Fe reduction and removal from the system (Anderson et al., 1982; Farmer et al., 1983; Oliveira et al., 2010) independently, which is intensified by the sandy texture (Andriessse, 1969).

Soil classification

Due to the high levels of OC ($> 80 \text{ g kg}^{-1}$) and horizon thickness, the surface of the profile P1 (bay area) was identified as Histic epipedon, while the surface horizons of the other three areas did not fit in any other surface diagnostic horizons and were therefore classified as Ochric epipedons (Embrapa, 2006). In all studied profiles, spodic B horizons were observed, which were classified by SiBCS in the 1st category level as Spodosols (Embrapa, 2006).

In the bay areas, the profiles P1 (horizon sequence H-E- Bhs) and P2 (A-E-Bhs), with hue 2.5Y and 5Y, respectively, and Fe and OC accumulation in the subsurface horizons, were classified as Ferrohumiluvic Spodosol. Profile P1 fits into the 3rd level as hydromorphic, and Organic at the 4th level, as it remains water-saturated in one or more horizons down to 100 cm beneath the soil surface and has a histic H horizon; it was therefore classified as Organic Hydromorphic Ferrohumiluvic Spodosol. Profile P2 had no additional differentiating property towards a major group or subgroup and was classified as Typical Orthic Ferrohumiluvic Spodosol.

In P3 and P4 of the flooded field soils, with horizon sequence A-E-Bs and hue 10 YR, Fe was predominant in the spodic horizon, leading to the classification Ferroluvic Spodosol. Profile P3, due to the presence of speckles and water saturation down to 100 cm beneath the soil surface, was classified as hydromorphic and at the subgroup level, in view of the absence of any differentiating property, as a Typical Hydromorphic Ferroluvic Spodosol. Profile P4, with sandy texture from the surface to below 100 cm, was classified as Arenic Orthic Ferroluvic Spodosol.

CONCLUSIONS

1. The main morphological and physical properties in the bay area were colors ranging from brown – light– grayish, black to gray – olive – dark, due to the extremely poor drainage, and yellowish and mottled in the flooded fields with slightly better drainage. In all profiles, the sand fraction texture ranged from sand to sandy loam mostly.
2. The chemical and mineralogical properties differed in the studied soils. Acid soils were found in the flooded fields, with low base saturation and Fe and Al accumulation in the spodic horizon.
3. The influence of topography and source material associated with the process of podzolization was observed in both environments, playing a major role in the genesis of these soils.

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