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Salt-affected soils evolution and fluvial dynamics in the Pantanal wetland, Brazil

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ABSTRACT

In the Nhecolândia, a subregion of the Pantanal wetland, saline lakes and their associated Saline-Sodic soils have been degraded due to the atypical input of freshwater from seasonal flooding. In the present work, the soils in and around three brackish lakes that have experienced degradation (Carandazal, Cerca and Banhado lakes) were studied through a detailed morphological survey and chemical analyses to understand their genesis and establish genetic relationship with the Saline-Sodic soils of the saline lakes. The studied soils have Bnc and Bc horizons with morphological and chemical similarities to the Bnx formed around the saline lakes, presenting greenish colors, hard consistencies and, generally, the highest values of pH, exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR) and electrical conductivity in the saturated paste (EC_s) of each profile. In contrast, the near-surface horizons tend to present the lowest values of pH and the highest amounts of Al^{3+} saturation and exchangeable H + Al. These data point to the replacement of salinization/solonization around the saline lakes to the solodization process in the studied soils, with leaching of exchangeable bases, their substitution by Al^{3+} and H^+ and a consequent decrease in pH, first at shallow depths and later in the whole profile. Solodization occurs to a lower degree in the soils associated with the Carandazal lake, which has a predominance of Solonetzes and the closest water pH and electrical conductivity (EC) to the saline lakes, and to a higher degree in the soils related to the Banhado lake, which has a predominance of Solods and the most similar water pH and EC to the freshwaters of the Nhecolândia. The Cerca lake has an intermediate water geochemistry between the studied lakes and an equal prevalence of Solodized Solonetzes and Solods. Soil leaching occurs due to increasing inundation by freshwater through erosion around the saline lakes, primarily involving formation of new intermittent watercourses.

1. Introduction

Salt-affected soils are commonly defined as those containing an excess of soluble salts (Saline, Solonchaks), high amounts of Na^+ in the exchange complex (Sodic, Solonetz, Alkali), or both (Saline-Sodic or Saline-Alkali) (USSL Staff, 1954; Bohn et al., 2001; Sparks, 2003). Their classical model of genesis, initially proposed by Gedroiz (1912, 1917, 1925), is valid in many regions (Kellog, 1934; Kisel, 1981; Zaidel'man et al., 2010; Miller and Brierley, 2011), although different genetic pathways have been observed worldwide (Wilding et al., 1963; Hallsworth and Waring, 1964; Munn and Boehm, 1983; Zaidel'man et al., 2014).

Gedroiz's model and later contributions postulate that Saline, Sodic and a degraded Sodic soil originate in a sequence of soil evolution. In the first stage, Solonchaks (Saline soils) are formed from non-salt-affected soils by a process called salinization, characterized by the accumulation of salts more soluble than gypsum in the soil profile (mainly chlorides and sulfates of sodium, magnesium, calcium and potassium) and a consequent increase in mono- and divalent cations in the exchange complex (Gedroiz, 1912; USSL Staff, 1954; Fanning and Fanning, 1989; Bui et al., 1998).

Solonetzes (Sodic soils) originate in the second stage, deriving from Saline soils by the leaching of most of the soluble salts and/or the precipitation of Ca^{2+} and Mg^{2+} minerals, with a relative increase in exchangeable Na^+ and common occurrence of sodium carbonates (Gedroiz, 1912; Sumner et al., 1998; Sparks, 2003). This process, known as solonization, is generally responsible for an important increase in the soil pH, generally higher than 8.5 (USSL Staff, 1954; Fanning and Fanning, 1989; Schaetzl and Anderson, 2005), mainly because of the liberation of hydroxyls to the solution by both sodium hydrolysis[1] and the dissolution of sodium carbonates[2] (Bohn et al., 2001; McBride, 1994).

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[1] $NaX + H_2O \rightarrow HX + NaOH$, where X is the exchange complex (Bohn et al., 2001).
[2] $Na_2CO_3 \rightarrow 2Na + CO_3^{2-}$; $CO_3^{2-} + H_2O \rightarrow HCO_3^- + OH^-$ (McBride, 1994)

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Finally, the continued leaching in the environment leads to a different process called solodization, responsible for the formation of a degraded Sodic soil (Soloth) (Gedroiz, 1925; Kellog, 1934). Solodization is marked by a loss of sodium and other basic cations and an increase of H^+ in the exchange complex, first in the near-surface horizons and later in the whole profile. The soils formed in the initial stages of solodization are conventionally called Solodized Solonetz (Westin, 1953; Janzen and Moss, 1956; Whittig, 1959; Hallsworth and Waring, 1964; Miller and Pawluk, 1994; Anderson, 2010), whereas those formed in the final stages are called Soloth (Kellog, 1934), Solod (Westin, 1953; Heck and Mermut, 1992; Miller and Pawluk, 1994; Zaidel'man et al., 2010) or Solodi (Janzen and Moss, 1956; Whittig, 1959).

Typical Solonetz occurs in regions with: i) evapotranspiration higher than precipitation rates in at least part of the year, allowing for the concentration of soil solutions (Bohn et al., 2001); ii) a temporary availability of humidity, important for the instability of aggregates and subsequent colloid dispersion, especially in the natric horizon (Rengasamy and Sumner, 1998; van Breemen and Buurman, 2003); and iii) low slope gradients associated with near-impervious horizons and/or high water table levels, which restrict subsurface water flows and permit the necessary accumulation of water for high evaporation rates (Westin, 1953; USSL Staff, 1954).

The establishment and evolution of solodization and the consequent genesis of Solodized Solonetz and Solod soils are generally related to a change in one or more of these conditions, triggering an increase in soil leaching. Heck and Mermut (1992), studying salt-affected soils around a saline lake in Saskatchewan (Canada), showed that the formation of terraces due to the lake retreat produced higher topographical levels, promoting lateral leaching conditions and, consequently, the origin of Solodized Solonetzes. Whittig (1959) in California (USA) and Munn and Boehm (1983) in Montana (USA) attributed the genesis of Solodized Solonetzes to a lowering of the water table, enhancing the downward migration of ions. In Montana, specifically, the authors linked this change to a conversion from a post-glacial humid climate to a semi-arid climate 4000 years BP.

The Nhecolândia region (26,921 km^2), located in the central-southern Pantanal wetland (Fig. 1a), has hundreds of saline lakes (*salinas*) surrounded by Saline-Sodic soils (Silva and Abdon, 1998; Furquim et al., 2008; Costa et al., 2015) and thousands of freshwater lakes (*baías*) surrounded by sandy and acid soils not affected by salts (Sakamoto, 1997; Fernandes, 2000; Costa et al., 2015) (Fig. 1b). The saline lakes are on the top of elongated sand hills (*cordilheiras*), which represent the highest topographical level of the region, only 2 to 5 m higher than the surroundings. Typically, the sand hills and, consequently, the saline lakes are not reached by the freshwater that seasonally floods the wetland, allowing for the presence of forested savanna in the sand hills and in the surroundings of the saline lakes, in the outer position of a bare soil ring around the water level (Fig. 1b). In contrast, the freshwater lakes occur in the lowest areas, within long intermittent watercourses (*vazantes*) that seasonally flood, mainly during the summer (Barbiéro et al., 2002). Freshwater lakes and intermittent watercourses are typically occupied by open grass savanna and swampy grasslands (Fernandes, 2000; Evans and Costa, 2013) (Fig. 1b).

However, some lines of evidence suggest that some of the saline lakes have been converted into brackish lakes by atypical input of freshwater within the sand hills, creating new intermittent watercourses. First, the dense forested savanna that usually covers the sand hills fully surrounds the saline lakes but occurs only partially around the brackish lakes. The presence of non-forested zones and the disappearance of the bare soil ring around the saline lakes, both usually replaced by open woody savanna and grasslands, point to a partial degradation of the slightly higher and fragile sand hills, which would allow for intermittent flooding (Fernandes, 2007; Almeida et al., 2003; Evans and Costa, 2013). Second, the association of degraded natric horizons with some brackish lakes, similar to those typically created in the geochemical conditions of saline lakes, suggests a genetic relationship between them (Rezende Filho, 2006; Barbiero et al., 2008).

The destruction of the saline lakes and their replacement by brackish lakes would provoke intense transformation in the Saline-Sodic soils, especially through leaching related to the advancement of the freshwater from seasonal flooding. Although the salt-affected soils occurring around the saline lakes have been extensively studied (Furquim et al., 2008; Furquim et al., 2010a; Furquim et al., 2010b; Martins, 2012), those associated with the brackish lakes are known mainly by morphological descriptions, accompanied by a few laboratory analyses (Rezende Filho, 2006; Silva, 2007).

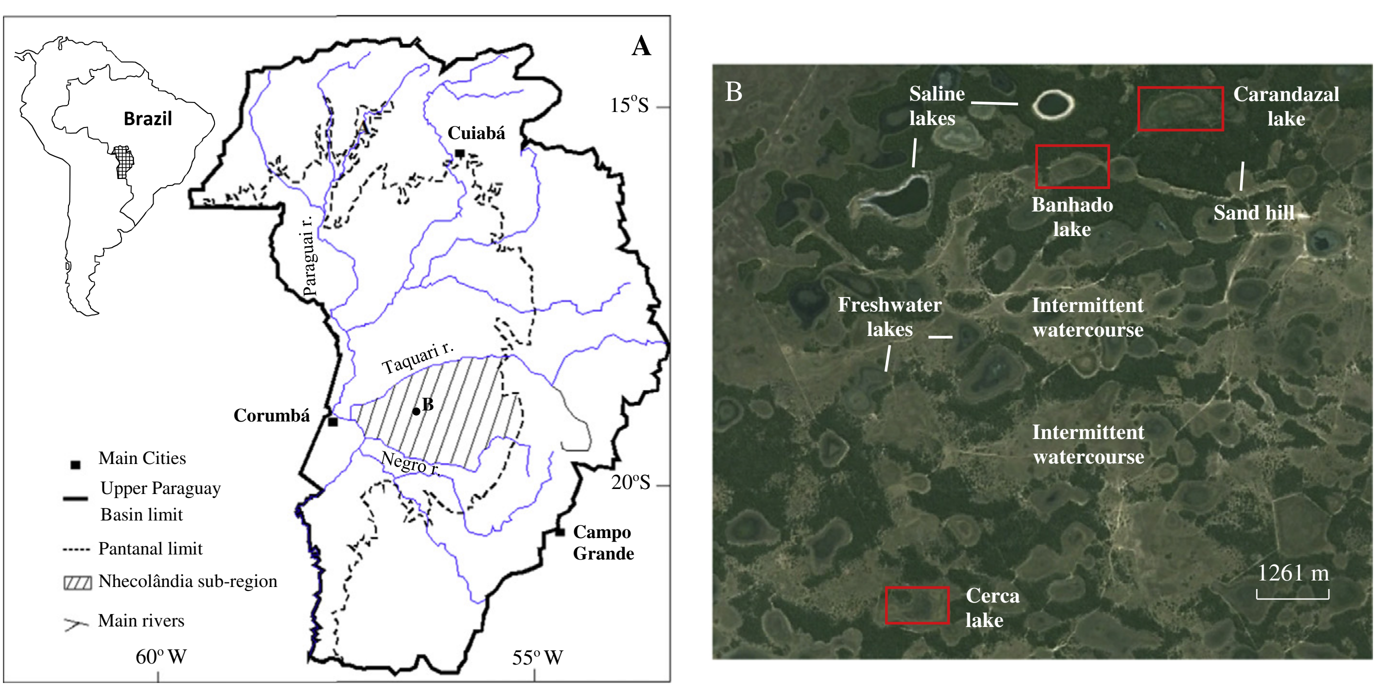

Fig. 1. A) Pantanal wetland and Nhecolândia subregion; B) Nhumirim farm: examples of the main geomorphological elements of the low Nhecolândia (sand hills, saline lakes, freshwater lakes, intermittent watercourses) and location of the studied brackish lakes (Carandazal, Cerca and Banhado).