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Methodological and environmental implications for coastal soil identification as support for land management

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ABSTRACT: Understanding methodological and environmental implications for coastal soil identification is essential for developing integrated approaches to land management that address soil physical and chemical aspects, environmental dynamics, and their importance for coastal ecosystem sustainability. In this context, a study was conducted in a natural environment, near a marine extraction reserve that was degraded by irregular urbanization and road construction in Santa Catarina Island, Florianópolis, SC, Brazil. The study focused on identifying ecological patterns and impacts associated with acid-sulfate soils. The method used consisted of: i) photointerpretation of physiographic characteristics in a historical series of aerial photos; ii) reinterpretation of historical soil data containing physical and chemical characteristics and available sulfate, and trace elements; and iii) collection, description, and analysis of the soil profile. The main pedogenetic processes affecting the area include sulfidization, paludization, gleization, salinization, and solodization. The soils were classified as Neossolos Quartzarênicos (Typic Sulfaquents and Typic Psammaquents), Gleissolos Tiomórficos (Typic Sulfaquents and Histic-Haplic Sulfaquents), and Gleissolos Háplicos (Sodic Hydraquents). The presence of materials containing reduced inorganic sulfur indicates the need to apply special procedures for the sampling, storage, and analysis of these soils to avoid misleading interpretations and conclusions about soil characteristics. The following recommendations were compiled based on the results: the inclusion of information on procedures for field analysis, sampling, and storage of soil samples in the Manual for Describing and Collecting Soil in the Field; the inclusion of analytical procedures in the Manual of Soil Analysis Methods; revisions to definitions of sulfidic materials, including hypersulfidic and hyposulfidic materials; and the inclusion of these materials as a fifth categorical level in the Brazilian Soil Classification System. Additionally, infrastructure and transport agencies should make alternatives for the total or partial replacement of soft soils in technical standards conditional on the absence of potential acid sulfate soils or on the treatment for mitigating impacts of soil disturbance. This study emphasizes the contribution of soil formation and attributes to mitigating environmental disputes. It also highlights the importance of managing acid-sulfate soils in urban planning to prevent environmental degradation and protect coastal ecosystems.

Keywords: acid sulfate soil, mangroves, sustainable territorial management.

INTRODUCTION

The efficient management of coastal natural resources has become an increasing concern, given anthropogenic pressures and global climatic changes. Accurate identification and characterization of coastal soils are essential for formulating sustainable land management strategies. However, the complexity and dynamics of coastal environments present significant challenges for implementing effective soil identification methodologies and understanding the interactions between environmental processes and soil characteristics (Rosolem et al., 2023a,b).

Coastal zones are landscapes shaped by specific dynamics and the interactions between the physical-biological medium and socioeconomic factors (Oliveira and Nicolodi, 2012). Moreover, these areas face numerous socioeconomic pressures, including accelerated and unregulated urbanization, which cause severe degradation of natural resources and pose threats to socioeconomic sustainability and environmental quality for local populations (Souza, 2009; Vikou et al., 2023).

A comprehensive understanding of the interrelations between biotic and abiotic components and human activities is necessary to analyze coastal environments better (Giménez et al., 2010). In this context, studies on coastal soils are crucial for understanding these systems, as their formation is connected to local topography, vegetation, hydrology, maritime climate, sediment composition, biochemical weathering of marine coastal landscapes (Finkl, 2019) and anthropogenic actions. Consequently, soil formation and properties in coastal zones are critical for sustainable land management, particularly in wetland areas of these environments.

Mangroves are unique ecosystems found in coastal tropical and subtropical areas, where soils are regularly flooded by tides and exhibit salinity and high organic matter content. Additionally, various plant species have adapted to conditions of flooding, salinity, sodicity, and thiomorphism (Schaeffer-Novelli et al., 2005; Bomfim et al., 2015; Gomes et al., 2016; Kitagami et al., 2023).

Most studies on the soils of coastal mangroves in Brazil described them simply as mapping units, identified as indiscriminate mangrove soils (Prada-Gamero et al., 2004). The primary pedogenetic processes of these soils include gleyzation, sulfidization, paludization, salinization, and solodization (Ferreira et al., 2007; Bomfim et al., 2015; Gomes et al., 2016; Sartor et al., 2018; Ferreira et al., 2023). The intensity of these processes is influenced by local factors, such as the physiographic position within the estuary (Ferreira et al., 2010; Gomes et al., 2016), and regional factors, such as geology and climate (Ferreira et al., 2022). In Brazil, research on these soils is concentrated in the southeast (Ferreira et al., 2007, 2010, 2022) and Northeast (Bomfim et al., 2015; Gomes et al., 2016; Sartor et al., 2018) regions.

Acid sulfate soils are associated with current and former coastal wetland areas; these soils have had, currently have, or will have their main characteristics influenced by sulfuric acid production, which results in the oxidation of sulfides (Pons, 1972). The oxidation of materials with reduced inorganic sulfur in these soils when exposed to air can lead to severe soil and water acidification and metal mobilization, resulting in the death of plants and animals, contamination of soil and water bodies with trace elements, as well as corrosion of concrete and steel structures (Grealish and Fitpatrick, 2013; Karimian et al., 2018). Therefore, the management priority should be to avoid disturbances to these materials; when disturbances are unavoidable, soil use should be minimized, and acidification and its consequences must be neutralized (Dent, 1986; Fanning and Burch, 2000).

Despite the many ecosystem services that mangroves provide, they are threatened worldwide by economic and social pressures (Bomfim et al., 2015; Kitagami et al., 2023), primarily for real estate development (Vikou et al., 2023). It is estimated that approximately 25 % of this ecosystem has been lost in Brazil, mainly due to shrimp farming and inappropriate coastal development (ICMBio, 2018). In the state of Santa Catarina, Brazil, mangroves have been degraded primarily by suppression and conversion of areas for urban activities, as well as by pollution from effluents and solid waste disposal (Souza, 1991; Lopes, 1999; Oliveira, 2001).

Although mangroves are ecosystems protected by legislation (Brasil, 2012; Matsumi and Freitas, 2018) and most remnants are currently located within preserved areas, the effectiveness of their protection is hindered by bureaucracy, a lack of conservation policies, and economic interests (Ferreira and Lacerda, 2016). The Federal Public Ministry of Florianópolis, SC, Brazil, initiated a Public Civil Action to recovery permanent preservation areas with *restinga* (a type of coastal sandbank vegetation) and mangroves affected by the irregular expansion of a real estate development (Ministério Público Federal, 2002) near the Marine Extraction Reserve of Pirajubaé, in Florianópolis, aiming to protect and ensure environmental restoration.

A soil survey conducted by Uberti et al. (2016) investigated whether the degraded portion of the study area was originally covered by mangroves before anthropogenic actions. Additionally, technical studies were subsequently conducted within the scope of the Public Civil Action, primarily involving forensic investigations (Dinslaken and Villela, 2019). However, extensive soil movement occurred in the area during the construction of large-scale roads (Prosul, 2018).

This study analyzed coastal soil-landscape relationships to support the mitigation of environmental disputes and impacts resulting from the urban management of these soils. Historical soil data were reinterpreted using advances in technical-scientific information of the study area, including remote sensing data, and new soil collections and analyses. This study aimed to significantly contribute to coastal land management, by offering a detailed analysis of soils and their environmental implications, with a focus on identifying ecological patterns and mitigating impacts associated with acid sulfate soils.

MATERIALS AND METHODS

Characterization of the study area

The municipality of Florianópolis encompasses both a continental and an insular portion, primarily consisting of Santa Catarina Island (Figure 1b). The region's climate is classified as Cfa, mesothermal humid with a hot summer, according to the Köppen climate classification system. This climate class is characterized by hot summers, a low frequency of frosts, and rainfall concentrated in the summer, but without a well-defined dry season (Pandolfo et al., 2002). According to the latest climatological normals for Florianópolis (Inmet, 2023), rainfall is well-distributed throughout the year, with an annual mean of 766 mm, ranging from 86 to 241 mm, and a trend of lower rainfall in winter and higher in summer. The mean monthly temperature in Florianópolis ranges from 16.5 °C in July (winter) to 25.3 °C in February (summer), with mean maximum temperatures ranging from 21.1 to 29.5 °C and mean minimum temperatures from 12.9 to 21.7 °C (Inmet, 2023).

Santa Catarina Island features coastal areas with varying exposures to wave action, including protected, semi-exposed, and exposed areas, which are subject to sea level variations of up to 1.4 m caused by astronomical tides (Felix, 2020). These variations (<2.0 m) classify the region as a microtidal area with a semidiurnal regime (Heidrich and Horn Filho, 2014). The study area comprised a portion of the Coastal Flat Land sector of Santa Catarina Island, located within the Carianos neighborhood and encompassing part of the Santos Dumont real estate subdivision. This area is adjacent to the Tavares River mangrove, the largest on Santa Catarina Island, which forms part of the Marine Extraction

Reserve of Pirajubaé. The study area (Figure 1c) has approximately 30 ha, measuring about 800 by 400 m, with altitudes ranging from 1.2 m along the eastern boundary near the mangrove to 1.8 m in the west near an anthropized area (Dinslaken and Villela, 2019). Two distinct stages of occupation characterize the area and its surroundings. The first stage dates back to the 17th century and is documented through Sesmarias (a colonial land grant system) and Hereditary Captaincies (hereditary administrative divisions), characterized by the occupation of small agricultural properties and fishing villages (Reis, 2010; Lins, 2023). The second stage of occupation is recent, beginning in 1950 and intensifying from 1970 onwards, involving the development of simple and orderly urban parcels (*sensu* Reis, 2002), predominantly for residential use.

The study area presents different physiographic characteristics depending on the mapping of Santa Catarina Island, mainly regarding geology. The area consists of surface paludal deposits associated with fresh to brackish water swamps near mangroves and bay deposits formed by sandy and sandy-silty-clayey sediments (Felix, 2020). The geomorphology of the study area predominantly consists of low marine terraces or low fluvial-lagoonal terraces, with part of the southern area falling within a tidal flat (Cruz, 1998). The vegetation exhibits two predominant *restinga* phytophysiognomies: arboreal *restinga* and lagoonal herbaceous sub-shrubby *restinga*, occurring in wetlands and lowlands influenced by seawater (Dinslaken and Villela, 2019). *Restinga* is a type of coastal ecosystem found in Brazil, typically located in transition zones between beaches and inland forests, and characterized by sandy, nutrient-poor soils with herbaceous, shrubby, and arboreal vegetation adapted to salty, low-fertility conditions. Soils of the study area are within a composite mapping unit (Sommer and Rosatelli, 1991); using the current Brazilian Soil Classification System (Santos et al., 2018), they would be classified as an association between Neossolo Quartzarênico Hidromórfico (Typic Psammaquents) and Organossolo Háplico (Typic Haplowassists).

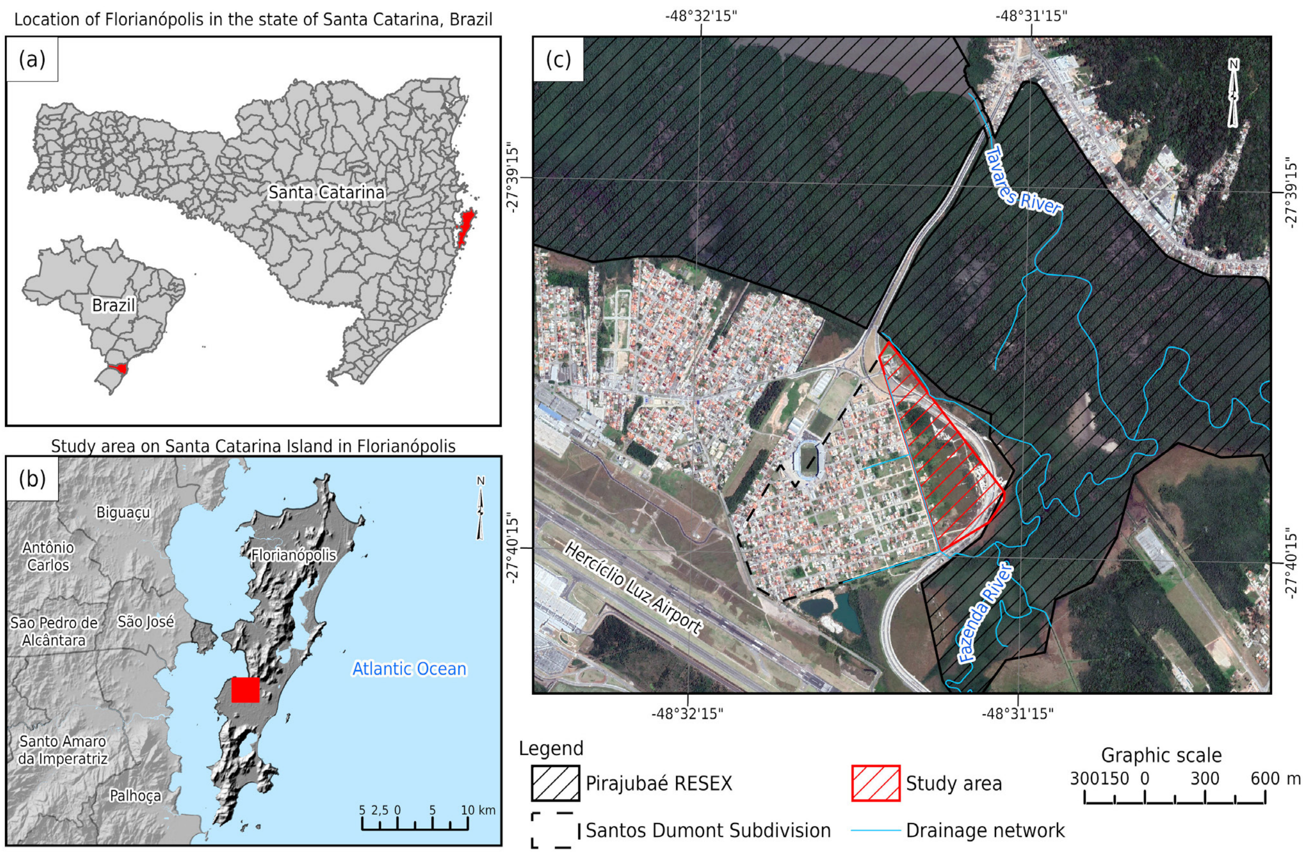

Figure 1. Location of the study area. (a) Location of Florianópolis in Santa Catarina, Brazil; (b) Location of the study area on Santa Catarina Island in Florianópolis; (c) Study area and its surroundings.

Landscape recognition and analysis

Landscape recognition and analysis began with the collection of technical-scientific information (e.g., Prosul, 2006, 2018; Panitz, 2016; Dinslaken and Villela, 2019) and thematic cartographic data available for the study area (Sommer and Rosatelli, 1991; Caruso Jr and Awdiej, 1993; Rosa and Justus, 1997; Coura Neto, 1997; Cruz, 1998; Horn Filho and Livi, 2013; Tomazzoli and Pellerin, 2014; Uberti et al., 2016; Felix, 2020). The following products were obtained: i) Aerial surveying photos from 1938, with a mean scale of 1:25,000, conducted by the American Aerial Force and provided by the Santa Catarina State Secretariat for Sustainable Economic Development (SDS/SC) and the Florianópolis Urban Planning Institute (IPUF); ii) Aerial surveying photos from 1957, with a mean scale of 1:25,000, conducted by the Cruzeiro do Sul Aerolevantamentos company and provided by SDS/SC; iii) Panchromatic aerial surveying photos from 1977 to 1979, with a mean scale of 1:25,000, conducted by the Cruzeiro do Sul Aerolevantamentos company and provided by SDS/SC; iv) Aerial surveying photos from May 1994, with a mean scale of 1:8,000, conducted by the Esteio company and provided by IPUF; v) Aerial surveying orthophotos and photogrammetric restitution letters from 2001, with a scale of 1:2,000, in SAD-69, provided by IPUF; vi) Aerial surveying orthophotos from 2002, with a scale of 1:5,000, in SAD-69, provided by IPUF; vii) Aerial surveying infrared orthophotos from 2007, with a scale of 1:5.000, in SAD-69, provided by IPUF; viii) Aerial surveying RGB and infrared orthophotos, land digital models, and vectors from 2010 and 2012, with a scale of 1:10,000, in SIRGAS 2000, provided by SDS/SC; ix) Aerial surveying mosaic orthophotos from 2015, with a scale of 1:1,000, in SIRGAS 2000, provided by IPUF; and x) Satellite images from May 22, 2016, and February 11, 2024, obtained from Google Earth Pro software, with an altitude (software parameter) of 1,000 m and image parameters collected using the software.

Orthophotos and photogrammetric restitutions from 2001, provided by the reference geodesic system SAD69, were transformed into SIRGAS 2000 system through the NTV2 method in the Geographical Information System (GIS) software, using the grid provided by the Brazilian Institute of Geography and Statistics. Aerial photos from 1938, 1957, 1965, 1977-78, and 1994, satellite images from 2016 and 2024, and other scanned thematic maps were georeferenced by associating homologous points with the cartographic bases of the Florianópolis City Hall (2001 orthophotos), in SIRGAS 2000, following a regressive order, i.e., first the most recent photos and last the oldest ones. Anaglyphs for photo pairs from 1938, 1957, and 1977-78 were produced using Stereo Photo Maker Pro software (Santos and Dias, 2011) to proceed with stereoscopic photointerpretation and analyze the landscape and physiographic elements in three dimensions. These anaglyphs were also georeferenced using the same procedure applied to the other photographs. A digital elevation model with a resolution of 1 m was produced using contour lines and points described by the photogrammetric restitution.

Obtained and generated data in GIS were integrated to conduct the photointerpretation. This step involved analyzing the color and hue, texture, size, form, pattern, shadow, position, situation, and association of the images using the convergence of evidence method (Jensen, 2015). Thus, photos from the historical series were analyzed to identify land use and cover and manually segment areas with homogeneous physiographic characteristics, including different vegetation types and phytophysiognomies, landforms such as plains and terraces, water bodies, and anthropogenic features. A field exploratory recognition through free walking was conducted for the preliminary landscape physiographic compartmentalization.

Soil collection and characterization

Six complete profiles were collected and described based on the photointerpretation of the historical series of aerial photos from June 2016. These profiles represented the different physiographic compartments identified by photointerpretation, which were preserved from intense anthropogenic actions, such as reclamation fills, soil disturbance, and drainage canals. Morphological, chemical, and physical characterization, followed by soil classification, were performed according to the recommendations by Tedesco et al. (1995), Santos et al. (2013) and Santos et al. (2015).

The soil profiles were collected using a PVC pipe with 50-mm diameter and 1.2-meter length, which was inserted into the soil until it encountered resistance that made manual insertion impossible or the length of the pipe, as the water table is near the surface or above it throughout the year. A pipe reducer from 50 to 25 mm in diameter was placed on the pipe before removing it, and a 60-kg beach sandbag was used to remove the air and create negative pressure inside the pipe to retain the soil after removal. The vacuum created by this rudimentary adaptation was sufficient to retain a soil layer more than 0.60 m deep. The soil was then extruded for separation, and the description of horizons and layers was carried out according to Santos et al. (2015), with samples being stored in plastic bags.

Collected soil horizons samples were evaluated to determine their texture, pH, sorption complex (Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+} and H^+), organic carbon via organic matter oxidation with sulfochromic solution, electrical conductivity, extractable sulfate (SO_4^{2-}), and micronutrients (Cu, Zn, B and Mn), according to Tedesco et al. (1995). Granulometry (clay content) was determined using the densimeter method; pH(H_2O) (soil:solution ratio equal to 1:1) was measured; phosphorus (P), potassium (K), and sodium (Na^+) were extracted using Mehlich-I; organic carbon was determined by conversion of oxidized organic matter using sulfochromic solution; exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), aluminum (Al^{3+}), and manganese (Mn) were extracted with KCl 1 mol L^{-1}; sulfate (SO_4^{2-}) was extracted with $CaHPO_4$ (500 mg L^{-1} of P); zinc (Zn) and copper (Cu) were extracted with HCl 0.1 mol L^{-1}; boron (B) was extracted with hot water; electrical conductivity was measured in a soil-water extract (1:5); and macro and micronutrients were determined using the soil volume. Samples were sent to the Soil Analyses Laboratory of the Federal University of Rio Grande do Sul (UFRGS), and analyses were conducted in September 2016. The period between soil collection and analysis was approximately 11 weeks. The samples were kept in closed plastic bags under field conditions and ambient temperature during this period. Samples were then dried in the laboratory in a forced-air oven at 40 °C for subsequent analysis.

A complementary soil profile was collected in 2023 from an area that has remained without direct anthropogenic intervention, to confirm the interpretations of samples collected in 2016. The soil profile, which had a depth of 3.00 m, was collected using a Russian peat borer, following the collection and storage procedures described by Sullivan et al. (2018a) for acid-sulfate soils. Samples from the layers or horizons of this profile were collected, each not exceeding 0.25 m in depth. For instance, when a horizon or layer had a depth of 0.50 m, two 0.25-m samples were collected. These samples were placed in polyethylene plastic bags (≥10 µm thick) with minimal air, sealed, labeled, and stored at temperatures below 4 °C (Sullivan et al., 2018b). The samples were stored in the extra-cold compartment of the laboratory refrigerators until analysis to prevent freezing of samples intended for pH incubation analysis.

Samples were homogenized, and an aliquot was taken to evaluate pH(H_2O) using a soil-water proportion of 1:1 (pH_a) and pH after treatment with 30 % hydrogen peroxide (adjusted to pH 5-5.5) at a proportion of 1:1 (pH_{ox}), both following the procedures described by Jayalath (2012). The reaction of hydrogen peroxide with the soil was also evaluated (Ahern et al., 2004). Another aliquot was used for pH incubation readings (pH_{inc}) following the procedure described by Creeper et al. (2012). Two sterile 50 mL universal collectors were used: one filled up to 1/3 with soil for pH readings and the other filled up to 2/3 for archiving. The pH_{inc} readings were conducted within 24 h of collection, using a soil-water proportion of 1:1 or the minimum water volume required to conduct the reading with a spear-tip electrode for semisolids. The collectors were sealed after the readings if no excess water was observed in the samples. Soil was kept moist and incubated for at least nine weeks for a second pH reading; samples with 4≤ pH_{inc} ≤6.5 during the second reading remained incubated for at least 19 weeks for a third reading. The covers of collectors containing samples with excess water after the pH reading were left open overnight or until the soil reached a moist condition (field capacity) and were then closed to continue incubation.

Soil classification and mapping

The classification of the complete soil profiles described, as confirmed by the complementary profile analysis, aligned with the current edition of the Brazilian Soil Classification System (Santos et al., 2018) and Soil Taxonomy (Soil Survey Staff, 2022). The reinterpretation of soil mapping units, using aerial photos and cartographic bases of Florianópolis, was conducted through a geomorphic approach (Zinck et al., 2016; Schoeneberger et al., 2017) complemented by vegetation analysis (Dent, 2008; Mulders, 1987), based on soil analyses from 2016, technical-scientific studies (e.g., Dinslaken and Villela, 2019), and a complementary profile analysis in 2023. Additionally, the distinction of acid sulfate soils into hypersulfidic and hyposulfidic materials was carried out using the attribute definitions from the Australian Soil Classification System (Isbell and NCST, 2021), as this system was one of the first to adopt these attributes and the Brazilian Soil Classification System does not distinguish them. Hypersulfidic materials cause severe acidification due to sulfide oxidation. They exhibit a pH (1:1) ≥4.0 in the field and show a decrease of at least 0.5 for pH (1:1) <4 when a 2–10 mm layer is incubated aerobically under field capacity (Isbell and NCST, 2021). The incubation time extends until the soil shows a variation of 0.5 units for pH <4 or until the pH level stabilizes after at least 8 weeks. In contrast, hyposulfidic materials exhibit intermediate or weak acidification due to sulfide oxidation. They also exhibit a pH (1:1) ≥4.0 in the field; however, they do not show a decrease of at least 0.5 units for pH (1:1) <4.0 after incubation (Isbell and NCST, 2021). Furthermore, hypersulfidic and hyposulfidic materials can be classified based on their net acidity, derived from the acid-base accounting approach, as hypersulfidic materials exhibit positive net acidity, whereas hyposulfidic materials show null or negative net acidity (Isbell and NCST, 2021). However, net acidity quantification was not performed.

The procedures of intermediate phases of data processing and map development were conducted in GIS. All resulting cartographic products were adapted to the Brazilian Geodesic System SIRGAS 2000 and the Universal Transverse Mercator (UTM) projection system, zone 22, South hemisphere.

RESULTS AND DISCUSSION

Land use and cover

Georeferencing and integration of geospatial data in GIS were used for the photo interpretation of land use and cover in the historical series of photos and aerial images through the convergence of evidence method. The evolution of land use and cover in the real estate subdivision and its surroundings over approximately 86 years is shown in figure 2.

In an aerial photograph of the study area from 1938, the area delimited by a red polygon in figure 2a was predominantly covered by herbaceous and sub-shrubby vegetation in wetlands, mainly in southern-southeastern and northern portions, and by shrubby and arboreal vegetation in the higher and central areas. Consequently, more than half of the arboreal and shrubby vegetation was deforested in 1957 (Figure 2b), compared to previous years, while the herbaceous and sub-shrubby vegetation remained stable.

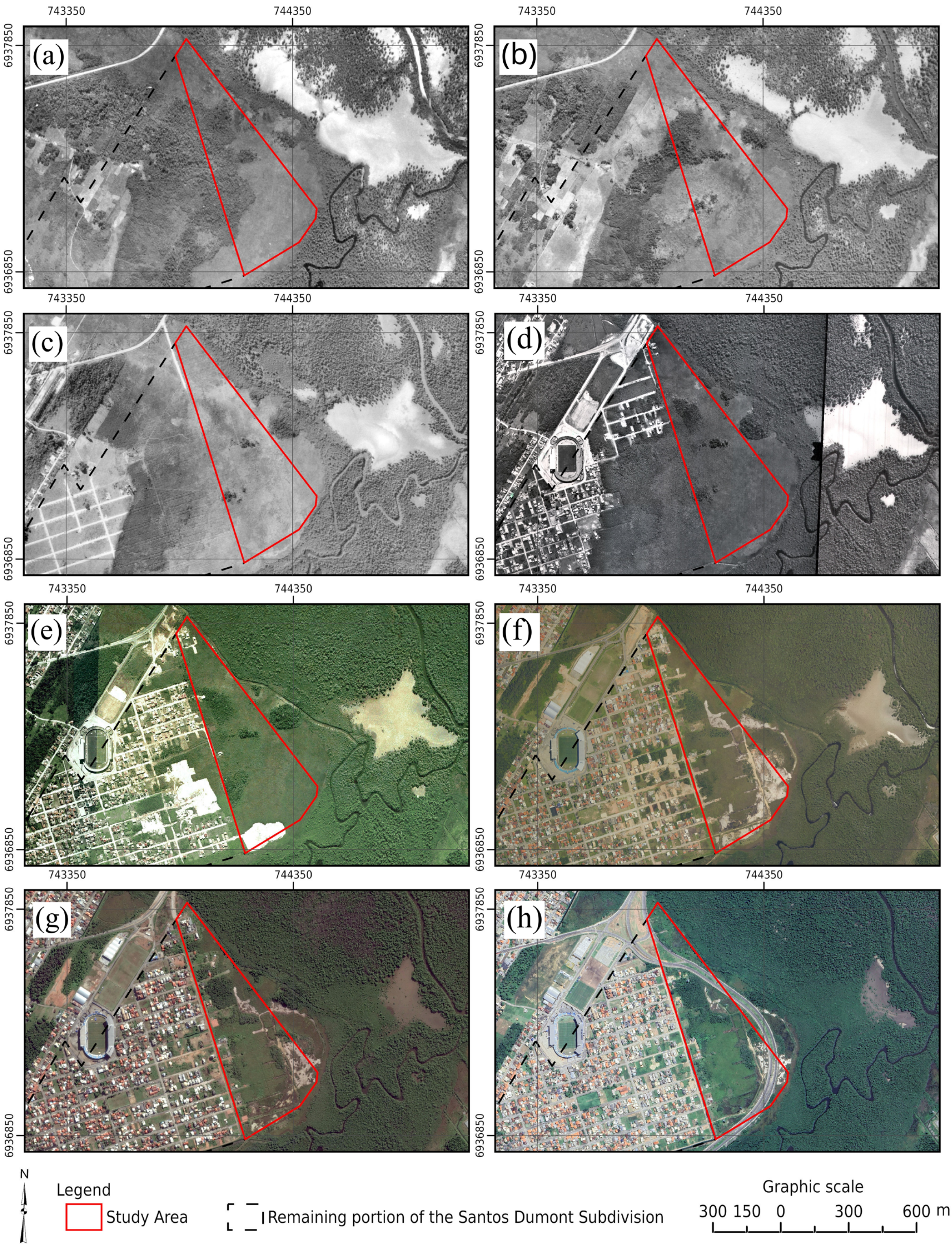

Figure 2. Historical series of aerial images. (a) Aerial photograph from 1938; (b) Aerial photograph from 1957; (c) Aerial photograph from the 1977-1979 period; (d) Aerial photograph from 1994; (e) Orthophoto from 2002; (f) Orthomosaic from the 2010-2012 period; (g) Orbital image from May 2016; (h) Orbital image from February 2024.

Conversion of land use from rural to urban began between 1957 and 1979 (Figure 2c). The real estate subdivision was partially implemented in the western part of the area, with the opening of access roads delimiting regular lots in higher areas, where rural land had predominated since 1938. During this period, arboreal *restinga* was almost entirely suppressed, remaining only small fragments within the study area.

The photograph from the 1977-1979 period illustrates the opening of parallel and perpendicular access roads to those already implemented, leading towards deforested and natural areas with herbaceous and sub-shrubby vegetation in wetlands within the study area (Figure 2c). The arrangement of these access roads indicates an alignment of pathways for continuing the implementation of the real estate subdivision throughout the entire study area, marking the first directly visible anthropogenic intervention in this phytophysiognomy since 1938.

Urbanization intensified and consolidated the implemented area as a residential urban real estate subdivision in 1994 (Figure 2d). The study area experienced a small advance in *restinga* regeneration, while the wetland herbaceous and sub-shrubby vegetation covered the previous access road arrangement. However, urbanization advanced into the study area with occupations in the northern portion, including opening a drainage canal.

This expansion intensified from 1994 to 2002 (Figure 2e), with the opening of new canals and increased urban density in the northern portion, as well as the establishment of a large reclamation fill area over herbaceous and sub-shrubby wetland vegetation in the southern portion. The embankment area expanded within the study area from 2002 to 2012 (Figure 2f), covering herbaceous vegetation and adopting a pattern and arrangement indicative of new pathways for the real estate subdivision. This period also showed growth and densification of built-up areas and the suppression of arboreal *restinga* remnants within the study area.

The expansion of the real estate subdivision within the study area was halted from 2012 to 2016 (Figure 2g) due to ongoing Public Civil Action decisions (Process 2005.72.00.0011558-0/SC) and demarcation studies on the 1831 mean high tide line. These events culminated in the prohibition of new construction licenses for areas with contour lines up to 1.00 m, in accordance with Complementary Law 482/2014. Subsequently, various *restinga* phytophysiognomies were suppressed to implement a new access route to Hercílio Luz Airport, which was consolidated, as shown in the 2024 image (Figure 2h).

In the historical series of aerial photos (Figure 2), the photograph from 1938 illustrates a more preserved natural system within the analyzed period for the study area, with no drainage canals inside or immediately outside the area and arboreal and/or shrubby *restinga* at the highest successional stage, exhibiting lower spatial fragmentation. Oliveira (2001) analyzed the evolution of the Tavares River mangrove and its immediate surroundings through the interpretation of photos from 1938 to 1998 and identified arboreal and/or shrubby *restinga* at different successional stages, including young, medium, and advanced secondary growth (*capoeira, capoeirinha,* and *capoeirões*), along with a range of herbaceous vegetation around the mangrove influenced by fluvio-marine conditions. Additionally, remote sensing and field evaluations conducted by Panitz (2016) and Dinslaken and Villela (2019) indicate that this range of herbaceous and sub-shrubby vegetation in wetland areas has a fluvio-marine influence and represents transitional environments between mangrove and *restinga*.

Although the historical series shows that arboreal and/or shrubby phytophysiognomies have been totally or selectively deforested, changes in their characteristics are observed in the images during ecological succession processes, whereas herbaceous and sub-shrubby vegetation in wetlands remains unchanged. This supports the stability of this phytophysiognomy in the study area and confirms the edaphic climax (primary vegetation) of herbaceous and sub-shrubby *restinga*, as already recognized in legislation (Brasil, 1999, 2009). Similarly, mangrove vegetation tended to regenerate in the surroundings of the study area over the historical series; however, the geographical delimitation of its arboreal and/or shrubby phytophysiognomy remained unchanged.

The conceptual model proposed by Rosolem et al. (2023a) and Nogueira (2024) was applied using a west-east transversal transect from the study area to the Marine Extraction

Reserve of Pirajubaé. The results indicated that arboreal *restinga* in higher positions transitioned into herbaceous and/or sub-shrubby *restinga* as altitude and phreatic levels decreased. The phytophysiognomy transitioned again into shrubby to arboreal mangrove as the distance from the sea decreased under the periodic influence of tides. The intensity of this change, represented by the ecotone width, varied across the study area: it was wider (indicating a gradual transition) in the South-Southeast, narrow in the North, and more abrupt in the central region. Therefore, prior to the reclamation fill deposits between 2002 and 2012 (Figures 2e and 2f), the area was not covered by mangrove but was characterized by a mangrove-*restinga* ecotone.

The points for soil description, sampling, and analysis, based on the interpretation of vegetation characteristics and other physiographic elements, were selected in more preserved locations. The objective was first to confirm the indications of remote sensing analyses regarding the compatibility of soil characteristics with the mangrove and, subsequently, to assess the implications of soil attributes, particularly concerning urbanization in the study area in recent decades (Figure 3).

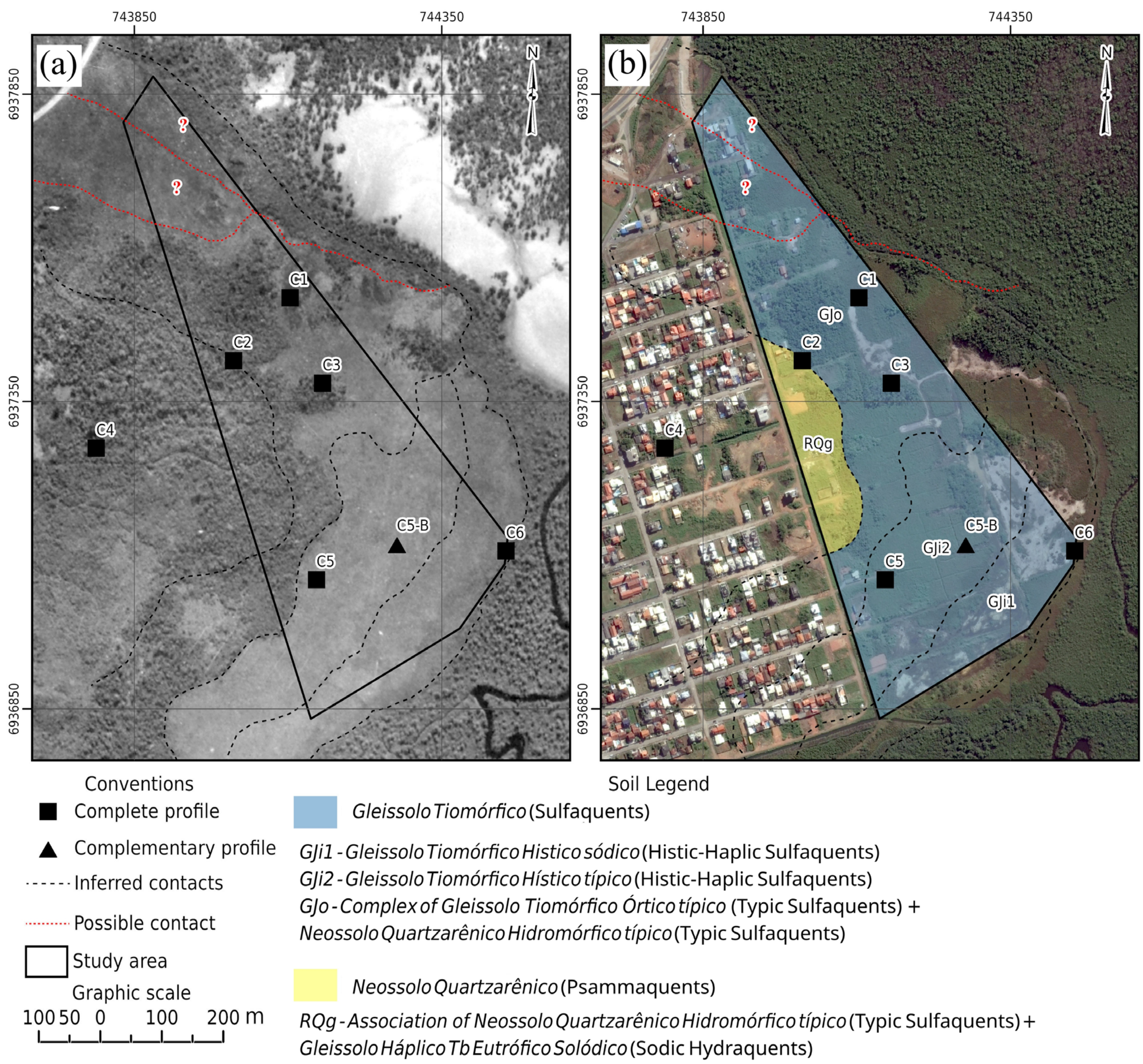

Figure 3. Semi-detailed soil map with a simplified representation of the study area. (a) Limits of inferred contacts and complete and complementary profiles on the 1938 aerial photograph. (b) Soil mapping unit on the orbital image from May 22, 2016, obtained using Google Earth Pro software.

Morphological, physical, and chemical characteristics of soils

The selection of points in 2016 (Figure 3b) was hindered by the presence of reclamation fill areas and the challenging access and logistics in the preserved areas due to dense vegetation and the high water level. Six complete profiles were collected: four were classified as Gleissolos (Hydraquents and Sulfaquents) and two as Neossolos (Sulfaquents and Psammaquents). The soil's morphological, chemical, and physical characteristics are described in tables 1, 2, and 3. A complementary soil profile was collected in 2023 and classified as Gleissolo (Histic-Haplic Sulfaquents) to confirm the pH analyses, with results shown in table 4.

The semi-detailed soil map of the study area was reinterpreted using these data, the characteristics identified by Dinslaken and Villela (2019) from other observation points of surface horizons within the study area, and hydro-sequence soil models from other sectors of the Santa Catarina Island coastal flatland (Rosolem et al., 2023a,b), as shown in figure 3. The reinterpretation resulted in two composite mapping units and two simple mapping units.

Table 1. Morphological and physical data of soil profiles collected and described in 2016

Horizon	Layer	Color		Sand	Silt	Clay	Textural Class[(1)]	Structure[(2)]	Wet Consistency[(3)]
		Wet	Dry						
	m			g kg⁻¹					
C1 - Neossolo Quartzarênico Hidromórfico típíco (Typic Sulfaquents)									
A	0.00-0.20	2.5Y 2.5/1	2.5Y 4/1	880	30	90	S	sg	LP, LPG
C_g	0.20-0.47	10YR 3/2		840	40	120	LS	sg	NP, NPG
C_{gj}	0.47-0.62⁺	2.5Y 4/2		810	80	130	LS	sg	LP, LPG
C2 - Gleissolo Háplico Tb Eutrófico solódico (Sodic Hydraquents)									
A_n	0.00-0.14	10YR 2/1	10YR 4/1	690	150	160	SL	gr, sab	P, LPG
$C_{gn\ 1}$	0.14-0.21	2.5Y 4/1		760	60	180	SL	m	LP, LPG
$C_{gn\ 2}$	0.21-0.39⁺	2.5Y 6/2		760	50	190	SL	m	LP, LPG
C3 - Gleissolo Tiomórfico *Órtico típíco (Typic Sulfaquents)*									
A	0.00-0.27	2.5Y 3/2	2.5Y 4/2	750	150	100	SL	sab	LP, LPG
C_g	0.27-0.40	10YR 3/2		750	90	160	SL	m	LP, LPG
C_{gj}	0.40-0.50⁺	2.5Y 5/1		750	110	140	SL	m	LP, LPG
C4 - Neossolo Quartzarênico Hidromórfico típíco (Typic Psammaquents)									
A	0.00-0.13	10YR 2/2	10YR, 4/1	830	80	90	S	sg	NP, NPG
C_1	0.13-0.22	10YR 3/2		810	60	130	LS	sg	LP, LPG
C_2	0.22–0.45	10YR 3/2		870	10	120	LS	sg	NP, NPG
C_3	0.45–0.50⁺	10YR 5/3		-	-	-	S	sg	NP, NPG
C5 - Gleissolo Tiomórfico Hístico típíco (Histic-Haplic Sulfaquents)									
H	0.00-0.20	10YR 2/1	10YR 3/1	40	770	190	SiL	gr	P, LPG
C_g	0.20-0.42	5Y 3/1		40	560	400	SiC	m	MP, MPG
C_{gj}	0.42-0.52⁺	5B 6/1		50	420	530	SiC	m	MP, MPG
C6 - Gleissolo Tiomórfico Hístico sódico (Histic-Haplic Sulfaquents)									
H_n	0.00-0.30	10YR 2/1	10YR 3/1	190	630	180	SiL	gr	P, LPG
C_{zgn}	0.30-0.45	5Y 3/1		200	440	360	SiCL	m	P, PG
C_{jgnz}	0.45-0.65⁺	N 5/		250	330	420	C	m	MP, MPG

[(1)] Textural Class - S: sand; LS: loamy sand; SL: sandy loam; SiL: silt loam; SiCL: silt clay loam; SiC: silt clay; C: clay. [(2)] Structure types – sg: simple grain; m: massive; gr: granular; sab: subangular block. [(3)] Wet consistency – NP: non-plastic; LP: slightly plastic; P: plastic; MP: very plastic; NPG: non-sticky; LPG: slightly sticky; PG: sticky; MPG: very sticky.

Table 2. Chemical data of soil profiles collected and described in 2016

Horizon	Layer	pH(H_2O)	$EC_{1:5}$	TOC	Ca^{2+}	Mg^{2+}	K^+	Na^+	H	Al^{3+}	SB	CEC	BS	m	SS	P
	m		dS m^{-1}	g kg^{-1}				$cmol_c$ dm^{-3}						%		mg dm^{-3}
					C1 - Neossolo Quartzarênico Hidromórfico típíco (Typic Sulfaquents)											
A	0.00-0.20	5.2	0.1	19	1.7	1	0.13	0.23	1.3	1.8	3.1	6.2	50	37	3.7	1.4
C_g	0.20-0.47	4.8	0.2	13	1	1.9	0.15	0.14	1.5	1.3	3.2	6.0	53	29	2.3	0.9
C_{gj}	0.47-0.62+	3.1	1.1	7	0.7	1.8	0.07	0.10	6.5	2.2	2.7	11.4	23	45	0.9	0.7
					C2 - Gleissolo Háplico Tb Eutrófico solódico (Sodic Hydraquents)											
A_n	0.00-0.14	5.6	0.4	36	9.5	3.6	0.62	1.10	0.1	3	14.8	17.9	83	17	6.1	3.1
$C_{gn\ 1}$	0.14-0.21	5	0.1	5	2.1	2.2	0.35	0.69	2.1	1	5.3	8.1	66	12	8.5	0.4
$C_{gn\ 2}$	0.21-0.39+	4.8	0.1	2	0.7	1.1	0.15	0.51	1.4	0	2.5	4.1	61	8	12.6	0.6
					C3 - Gleissolo Tiomórfico Órtico típíco (Typic Sulfaquent)											
A	0.00-0.27	4.5	0.1	38	1.0	0.9	0.2	0.2	4.6	4.1	2.2	10.9	20	65	1.6	3.1
C_g	0.27-0.40	4.6	0.1	28	0.9	1.3	0.1	0.2	6.1	2.6	2.5	11.2	22	51	1.7	1.2
C_{gj}	0.40-0.50+	3.9	0.4	12	1.2	2.9	0.2	0.2	6.7	2	4.5	13.2	34	31	1.5	0.9
					C4 - Neossolo Quartzarênico Hidromórfico típíco (Typic Psammaquents)											
A	0.00-0.13	5.4	0.4	25	5.6	1.3	0.4	0.4	0.7	2	7.7	10.5	73	21	4.1	8
C_1	0.13-0.22	5.4	0.2	17	3.1	1.4	0.4	0.3	0.3	1	5.2	6.9	75	21	3.7	6.6
C_2	0.22-0.45	5.4	0.2	5	2.7	1.3	0.4	0.2	1	1	4.6	6.2	74	12	3.1	5
					C5 - Gleissolo Tiomórfico Hístico típíco (Histic-Haplic Sulfaquents)											
H	0.00-0.20	5.4	0.4	87	9.0	4.4	0.6	0.3	0	4.2	14.3	18.5	77	23	1.7	3.6
C_g	0.20-0.42	4.7	0.5	35	3.9	6.9	0.7	0.6	7.0	3.9	12.1	23.0	53	24	2.5	0.4
C_{gj}	0.42-0.52+	3.9	1.2	29	4.5	9.7	0.8	0.8	14.6	4.8	15.8	35.2	45	23	2.2	0.1
					C6 - Gleissolo Tiomórfico Hístico sódico (Histic-Haplic Sulfaquents)											
H_n	0.00-0.30	4.5	-	93	6.5	10.6	0.9	7.2	5.4	7	25	38	67	22	19.2	3.8
C_{zgn}	0.30-0.45	4.2	-	45	5.8	16.4	2.1	8.2	7.8	5	33	45	73	12	18.4	6.8
C_{jgnz}	0.45-0.65+	3.5	6.5	37	4.7	14.8	2.1	8.1	13	4	30	47	63	13	17.3	10

pH: pH in water (1:1); $EC_{1:5}$: electrical conductivity in a 1:5 soil-water extract (w w^{-1}); TOC: total organic carbon; SB: Sum of bases; CEC: cation exchange capacity (S_b + H + Al); BS: base saturation (SB × 100/CEC); m: aluminum saturation [(Al × 100/ (SB + Al)]; SS: sodium saturation (Na × 100/ CEC).

Typically, Neossolos Quartzarênicos - Sulfaquents (C1) and (C4) - are hydromorphic soils with an A-C horizon sequence, a moderate A horizon, sandy texture, simple grain structure, and no plasticity or stickiness. Their colors range from 10YR to 2.5Y, and they are found on plain topography under herbaceous and/or sub-shrubby *restinga*, or even arboreal *restinga*. In contrast, Gleissolos (Sulfaquents or Hydraquents) exhibit greater variation, ranging from eutrophic (C2 and C6)) to dystrophic (C3 and C5), varying from Gleissolos Tiomórficos (Sulfaquents) to Gleissolos Háplicos (Hydraquents). They show a H-C_{gj} or A-C_g horizon sequence, a histic H horizon, and a humic or prominent A horizon. These soils have a sandy-loam to clayey texture, with a predominance of massive structure in the C_g horizon, and occur on plain topography under herbaceous and sub-shrubby *restinga* and marshy arboreal *restinga* (Tables 1 and 2; Figure 3). All soils are associated with Quaternary sediment deposited during the Holocene marine transgression and regression period.

The gray, bluish, or neutral colors in the profiles of Gleissolos (Sulfaquents or Hydraquents), combined with the presence of a massive structure (Table 1), indicate a gleyzation process in this permanently hydromorphic environment. Additionally, profiles C5 and C6 (Gleissolos Tiomórficos Hísticos - Histic-Haplic Sulfaquents) exhibit an organic surface horizon with sufficient thickness and organic carbon content to identify the histic H horizon; however, the horizon does not meet the thickness criteria to classify it as an Organossolo (Histosols) (Santos et al., 2018). The high organic carbon content in these profiles is due to the anaerobic environment, which is associated with constant deposition of plant material and, in this case, finer texture. These two profiles reflect the paludization pedogenetic process due to the accumulation of organic matter under anaerobic conditions (Schaetzl and Anderson, 2005).

In the complementary profile C5-B (Table 4) of the Gleissolo Tiomórfico Hístico típico - Histic-Haplic Sulfaquents, the pH(H_2O) (1:1) under field conditions (pH_a) ranged from slightly alkaline to alkaline, except for the histic horizon, which was slightly acidic. The pH of all samples after the 30 % hydrogen peroxide reaction (pH_{ox}) became extremely acidic, with values between 1.54 and 2.89, and exhibited strong to extreme reactions, except for the histic horizon, which showed a low reaction. The difference of more than 03 units between pH_a and pH_{ox}, and the pH_{ox} <3, with very strong reactions, indicated the presence of acid sulfate soils (Sullivan et al., 2018a), which was confirmed after the incubation period for most samples. The initial pH_{inc} values ranged from 5.7 to 8.0, and the final values after nine weeks were lower than 3.3, with decreases of 3.6 to 4.3 pH units in the samples from depths between 14 and 1.50 m.

Samples from other depths (C5-B, 1.50 to 3.00 m) showed decreases predominantly greater than 2.0 units, but with the presence of seashells (mainly consisting of calcium carbonate) and/or finer texture, which could have caused a buffering effect and/or hindered oxygen diffusion in the incubated soil layer. These samples also exhibited decreases in pH_{inc} to values lower than 4.0 after more than 19 weeks of incubation, except for samples from depths between 2.75 and 3.00 m and the upper histic horizon.

Table 3. Chemical data focused on micronutrients and sulfates of soil profiles collected and described in 2016

Horizon	Layer	pH(H_2O)	$EC_{1:5}$	EC_{SP}	TOC	B	Zn	Mn	Cu	SO_4^{2-}	
	m		—— dS m^{-1} ——		g kg^{-1}	—— mg dm^{-3} ——				g dm^{-3}	%
C1 - Neossolo Quartzarênico Hidromórfico típico (Typic Sulfaquents)											
A	0.00-0.20	5.2	0.1	1.7	19	0.3	0.5	1	0.2	0.01	0.00
C_{1g}	0.20-0.47	4.8	0.2	3.4	13	0.3	0.4	1	0.1	0.06	0.01
C_{2gj}	0.47-0.62+	3.1	1.1	18.7	7	1.9	4.4	2	0.2	0.61	0.06
C2 - Gleissolo Háplico Tb Eutrófico solódico (Sodic Hydraquents)											
A_n	0.00-0.14	5.6	0.4	5.52	36.5	0.7	1.6	5	0.3	0.08	0.01
$C_{gn\,1}$	0.14-0.21	5	0.1	1.38	5	0.6	0.5	4	0.3	0.04	0.00
$C_{gn\,2}$	0.21-0.39+	4.8	0.1	1.38	2	1.1	0.2	1	0.6	0.04	0.00
C3 - Gleissolo Tiomórfico Órtico típico (Typic Sulfaquent)											
A	0.00-0.27	4.5	0.1	1.38	38	0.8	1.4	2	0.3	0.01	0.00
C_g	0.27-0.40	4.6	0.1	1.38	28	0.6	1.1	2	0.2	0.03	0.00
C_{gj}	0.40-0.50+	3.9	0.4	5.52	12	0.7	1.5	3	0.2	0.22	0.02
C4 - Neossolo Quartzarênico Hidromórfico típico (Typic Psammaquents)											
A	0.00-0.13	5.4	0.4	6.8	25	1	0.9	7	0.1	0.13	0.01
C_1	0.13-0.22	5.4	0.2	3.4	17	0	0.4	5	0.1	0.05	0.01
C_2	0.22-0.45	5.4	0.2	3.4	5	0	0.6	4	0.2	0.07	0.01
C5 - Gleissolo Tiomórfico Hístico típico (Histic-Haplic Sulfaquents)											
H	0.00-0.20	5.4	0.4	3.8	87	0.7	1.5	10	0.4	0.07	0.01
C_g	0.20-0.42	4.7	0.5	4.3	35	0.5	1.6	11	0.4	0.15	0.01
C_{gj}	0.42-0.52+	3.9	1.2	8.4	29	2.1	8.7	53	0.2	0.67	0.07
C6 - Gleissolo Tiomórfico Hístico sódico (Histic-Haplic Sulfaquents)											
H_n	0.00-0.30	4.5	-	1.4(*)	93	0.2	2.2	7	0.3	0.00	0.00
C_{zgn}	0.30-0.45	4.2	-	-	45	6.7	11	23	0.2	1.44	0.14
C_{jgnz}	0.45-0.65+	3.5	6.5	55.9	37	6.8	10	57	0.1	1.61	0.16

pH(H_2O): pH in water (1:1); $EC_{1:5}$: electrical conductivity in a 1:5 soil-water extract (w w^{-1}); EC_{SP}: electrical conductivity of the saturated paste, $EC_{1:5}$ × conversion factor of Gibbs (2000) based on soil texture; TOC: total organic carbon; SO_4^{2-}: extractable sulfate (Tedesco et al., 1995); (*) quantity of soil insufficient for the test, value obtained by direct method for the same mapping unit, based on Dinslaken and Villela (2019).

Table 4. Chemical data of the complementary soil profile C5-B collected and described in 2023

Layer	Tactile texture	Seashells[(1)]	pH_w	pH_{ox}	Reaction[(2)] pH_{ox}	ΔpH	pH_{inc}			
							$pH_{inc\ t=0}$	$pH_{inc\ t>9}$	$pH_{inc\ t>19}$	ΔpH_{inc}
m										
0.00-0.14	organic fibric	-	5.77	1.95	Low	-3.82	5.73	4.28	4.10	-1.63
0.14-0.27	clayey silty	-	7.31	1.55	Extreme	-5.76	6.85	3.24	-	-3.61
0.27-0.50	clayey silty	-	7.77	1.54	Extreme	-6.23	6.89	2.92	-	-3.97
0.50-0.65	clayey silty	-	7.74	1.54	Extreme	-6.20	6.93	2.73	-	-4.20
0.65-0.88	clayey silty	-	7.53	1.55	Extreme	-5.98	6.97	2.66	-	-4.31
0.88-1.00	clayey silty	-	7.62	1.98	Extreme	-5.64	6.93	3.07	-	-3.86
1.00-1.25	clayey silty	-	7.86	1.95	Extreme	-5.91	7.25	2.89	-	-4.36
1.25-1.50	clayey silty	-	7.94	1.96	Extreme	-5.98	7.39	3.28	-	-4.11
1.50-1.75	clay	Few	8.57	2.18	Extreme	-6.39	7.45	4.07	3.25	-4.20
1.75-2.00	clay	Common	8.37	2.24	Strong	-6.13	7.45	4.54	3.75	-3.70
2.00-2.25	clay	Common	8.20	2.30	Strong	-5.90	7.40	5.83	3.59	-3.81
2.25-2.50	clay	Common	8.27	2.43	Strong	-5.84	7.44	4.82	3.42	-4.02
2.50-2.75	loamy clay silty	Common	8.39	2.47	Strong	-5.92	7.81	6.24	3.70	-4.11
2.75-2.88	loamy clay silty	Common	8.76	2.89	Strong	-5.87	7.99	6.92	5.62	-2.37
2.88-3.00	loamy clay silty	Common	8.63	2.89	Strong	-5.74	7.98	7.03	5.64	-2.34

Tactile texture: determined in the field; [(1)] Seashells: fragments or whole seashells, estimated by visual comparison similarly to redox features as described by [(2)] Reaction pH_{ox}: soil reaction intensity to H_2O_2 30 %; $\Delta pH = pH_{ox} - pH_a$; pH_{inc} = pH in water:soil ≤1:1 after incubation, t = 0: beginning of incubation; t >9: 9 weeks; t >19: 19 or more weeks.

Based on the pH_{inc} dynamics of the samples, profile C5-B (Table 4) predominantly contained hypersulfidic material throughout most of the profile, from depths of 0.14 to 2.75 m. This quantity of reduced inorganic sulfur was sufficient to induce extreme soil acidification upon oxidation. Additionally, the horizons that did not contain hypersulfidic materials, including the surface horizon and the C horizon at the profile base, exhibited hyposulfidic materials. These materials contain reduced inorganic sulfur but not in sufficient quantities to cause extreme acidification and/or include neutralizing materials.

The pH under field conditions was analyzed following the appropriate procedure for acid sulfate soils (Ahern et al., 2004; Sullivan et al., 2018a) to reinterpret the analytical data of profiles collected in 2016 (C1, C2, C3, C4, C5, and C6). Profiles C1, C3, C5, and C6 contained hypersulfidic material according to the criteria described by Isbell and NCST (2021) and sulfidic material by Santos et al. (2018), classifying them as potential acid sulfate soils (Fanning, 2017). This occurred because the samples from these profiles were stored wet in sealed plastic bags for 11 weeks after field collection. This incubation period is similar to the method proposed by Creeper et al. (2012), though the soil layer was considerably thicker than recommended by them. Moreover, the samples were collected under a surface water table and typical wetland vegetation (Dinslaken and Villela, 2019), and the saturation conditions were prolonged, as corroborated by morphological characteristics of gleization and/or paludization processes. Therefore, although the pH was not measured during field collection, it would be near neutral, as found in profile C5-B.

Further, TOC decreased with depth, whereas extractable sulfate (SO_4^{2-}) considerably increased (Table 3). Hydrogen content increased as the pH decreased, but aluminum content remained lower than that of horizons with pH >4.0. Melo et al. (2014) indicate that the oxidation process of pyrite may present a molar ratio between sulfates and generated protons of up to 1:8. Therefore, decreases in pH are attributed to the oxidation of reduced inorganic sulfur. However, despite horizons of profiles C1, C2, C3, C4, C5, and C6 not reaching pH <4.0, they possibly contain hypersulfidic material because they lacked sufficient time for oxidation or hyposulfidic due to the presence of neutralizing compounds, often associated with calcium carbonates (IUSS Working Group WRB, 2022).

In this context, profile C3 (Gleissolo Tiomórfico Órtico Típico - Typic Sulfaquent), collected at the edge of arboreal *restinga*, presented a pH of 3.9 in the deepest layer after 11 weeks. It also exhibited an increase in sulfate as the pH decreased, but proportionally lower than that observed in profile C1 (Neossolo Quartzarênico Hidromórfico Típico - Typic Sulfaquents), resulting in a higher pH for profile C3 (Table 2). Although these profiles were within the same mapping unit and had similar morphological characteristics, this difference may be attributed to variations in the thickness and moisture of the samples during storage until analysis. The presence of sulfidic material is not a qualifier in the subgroup of Neossolos in the Brazilian Soil Classification System (Santos et al., 2018). Thus, sulfidic material was used for identifying the soil phase of Typic Sulfaquents (Neossolo Quartzarênico Hidromórfico Típico) in the GJo unit (Figure 3) due to its importance for soil management (IBGE, 2015) and its differentiation from the *Neossolo* (Aquents) of the RQg unit.

Despite also being Gleissolos Tiomórficos (Histic-Haplic Sulfaquents), profile C5 and C6 differed from profile C3 (Histic-Haplic Sulfaquents) mainly in texture, presenting a finer texture that varied from silt loam to clay loam, with a predominance of clay fraction compared to the sand fraction (Table 1). Consequently, they showed higher pH values than the Typic Sulfaquents (C1), despite their similar (C5) or higher (C6) SO_4^{2-} concentrations compared to profile C1 (Table 2). Sandy textures allow better oxygen diffusion in the soil matrix, accelerating the oxidation of pyrite, which contrasts with the clayey texture (and massive structure) of Gleissolos. Moreover, storing soil samples in large volumes may have contributed to this difference, particularly in more clayey horizons, which were incorrectly stored in plastic bags using very thick layers (Ward et al., 2004; Sullivan et al., 2009).

Soil exchangeable bases rapidly neutralize part of the soil acidity, while another portion reacts with clay minerals (Dent, 1986), which contributes to the higher pH of Gleissolos Tiomórficos Hísticos - Histic-Haplic Sulfaquents (C5 and C6) compared to that of the Neossolo Quartzarênico Hidromórfico - Typic Sulfaquents or Psammaquents, despite having higher extractable sulfate content and theoretically higher amount of pyrite.

However, the determination of extractable sulfate in these improperly stored soils incorporates sulfate, which is a product of pyrite oxidation and fractions that do not originate from acidity. Consequently, sulfate derived from salts and/or brackish waters may have been accounted for in locations with marine influence. This appears to be the case of profile C6 (Gleissolo Tiomórfico Hístico sódico - Histic-Haplic Sulfaquents), which contained hypersulfidic material and, based on the electrical conductivity in the 1:5 extract, would exhibit a saline character (4< electrical conductivity <7 dS m^{-1}) at depth and sodium saturation (exchangeable sodium percentage >15 %) at the surface (Table 3), indicating a marine influence in which sulfate is one of the most abundant anions.

Sulfuricization process that occurred in profile samples between collection and analysis can increase the sample salinity (Fanning, 1993; Souza Junior et al., 2001). However, the effect of high concentrations of sodium chloride (1 mol L^{-1}), the main salt in seawater, is twice as significant on electrical conductivity compared to ferrous sulfate, a salt produced by sulfuricization (Fanning, 1993). The determination of electrical conductivity in the

1:5 extract ($EC_{1:5}$) is a fast and practical method for evaluating soil salinity (Hardie and Doyle, 2012), but it is not the standard method adopted by soil classification systems.

The conversion of $EC_{1:5}$ to the electrical conductivity of a saturated paste extract (EC_{SP}) using conversion factors (Table 3) indicates that practically all horizons with pH lower than 4.0 would have EC_{SP} >7, characterizing a possible salic character, whereas the surface horizons of profiles C2 and C4 were characterized as saline. However, the conversion of $EC_{1:5}$ presents complications due to the different solubility and concentrations of salts and their relationships with dilutions (Queensland, 2011). Thus, proportions of water and salt compositions need to be known for an accurate estimate of this conversion (Shawn, 1999), but these were not determined. Therefore, electrical conductivity-related attributes were not used in the soil taxonomic classifications due to the overestimation of electrical conductivity caused by the sulfurization process and the unavailability of parameters for an accurate estimate.

Sulfurization process alters electrical conductivity and, consequently, may change the sorption complex through aluminum solubilization and hydrolysis (Dent, 1992). It can also cause an increase in calcium content due to the dissolution of carbonates when neutralization occurs (Van Breemen, 1982). These alterations may affect cation exchange capacity (CEC) and, consequently, some diagnostic attributes; for example, increases in CEC due to increases in potential acidity and decreases in sodium saturation due to increases in CEC, respectively. However, the low sulfate concentration in most horizons that did not show significant decreases in pH indicates minimal interference of CEC under these conditions.

The presence of a sodic character in all horizons of profile C6 in these conditions, including its spatial proximity to the mangrove and the extremely high electrical conductivity ($EC_{1:5}$ and EC_{SP}), confirms the influence of salt or brackish waters on the profile. Thus, profile C6 exhibits a sulfidization pedogenetic process as well as salinization and solodization processes, both associated with the presence of salts.

Contents of available trace elements (B, Zn, Mn, and Cu) increased with depth. The highest values were found in horizons with hypersulfidic material, where the lowest pH values were observed, being more pronounced in profiles C5 and C6 (Table 3). These two profiles are Gleissolos Tiomórficos - Histic-Haplic Sulfaquents - and the only ones with clayey texture and an organic surface horizon (histic H) compared to the others (Tables 1 and 2). Additionally, the combination of low pH, high SO_4^{2-} contents, and high available micronutrient contents in the horizons of profiles C5 and C6, mainly manganese, are consistent with the hypothesis that these trace elements were immobilized in the soil under reduced conditions, including in sulfides, and became more available after oxidation. The phosphorus content was proportionally higher in profile C6, especially in the deepest horizon (Table 2).

Soils and coastal environments

Although the historical series of aerial images (Figure 2) showed no mangrove vegetation in the study area, analyses of soil characteristics, compared to those observed in the ecosystem, helped clarify the absence or degradation of this vegetation in the area. The profile analysis results showed that gleization pedogenetic processes were similar across four mapping units (Figure 2), sulfidation in three (GJi1, GJi2, GJo), paludization in two (GJi1, GJi2), solodization in two (GJi1 and RQg), and salinization in one (GJi1) mapping unit. Thus, among the four mapping units, GJi1 was the only one affected by all pedogenetic processes identified.

Bomfim et al. (2014) and Gomes et al. (2016) evaluated the relationships between soil characteristics and pedogenetic processes in a mangrove environment in the Northeast region of Brazil and found a predominance of gleization, sulfidation, paludization, salinization, and solodization processes in the soils, as well as predominance of the sand fraction and a lower proportion of soils with finer textures, with increases in the clay fraction. Andrade (2015) found significant variation in granulometry among mangrove soils along the Brazilian coast, with high silt and clay contents in most of the analyzed points, except for mangroves in the Brazilian Northeast region and the São Paulo coastal region, which had predominance of sand. Thus, although the legislation describes mangroves as ecosystems typically with *limosos* (silty) soils (Brasil, 2012), soil texture in Brazilian mangroves is diverse and should not be used as the sole soil proxy for these ecosystems.

Andrade (2015) evaluated a soil profile in the Tavares River mangrove, in the Marine Extraction Reserve of Pirajubaé, and found low sand concentrations (27 to 114.5 g kg^{-1}) and varying silt (27 to 114.5 g kg^{-1}) and clay (298.2 to 475.6 g kg^{-1}) contents, resulting in clayey silty and loamy clayey silty textures. They also found that the CEC at pH 7 was high (29.0 to 35.7 $cmol_c$ kg^{-1}), mostly composed of sodium (Na saturation of 54.6 to 60.2 %), despite the samples being washed with 60 % ethanol to remove excess salts in the solution before chemical analyses.

Although Andrade (2015) did not specify the exact soil sampling location in the mangrove, the soil physical characteristics were similar to those of profiles C5 and C6 in units GJi2 and GJ1, respectively. Furthermore, although the CEC values found in profiles C5 and C6 in the present study were similar to those reported by Andrade (2015), they found significantly lower potential acidity (H+Al). This suggests that these characteristics may have been overestimated in profiles C5 and C6 due to oxidation of sulfides. However, sodium contents in profile C6 (7.2 to 8.1 7 $cmol_c$ kg^{-1}) are approximately half of those reported by Andrade (2015) (17.5 to 19.5 7 $cmol_c$ kg^{-1}).

In this context, the mapping unit with soil characteristics more similar to those of mangrove soils within the study area are GJi1 and GJi2. The correlation between soils and land use and cover showed a constancy of herbaceous and/or sub-shrubby *restinga* wetlands in mapping units GJi1 and GJi2, as well as surrounding mangrove boundary stability, with regeneration over the years. Although topographic variation is subtle and difficult to distinguish in the photographs, the vegetation's responses to hydrology, salinity, and sedimentation conditions were used to indicate the separation of these units (Dent, 2008).

The GJi1 unit in the study area coincides with the mangrove-*restinga* ecotone boundary established by Nogueira et al. (2023), following the construction of the new airport access road. Therefore, the interpretation of vegetation characteristics in the historical series of aerial photos and literature data confirms that the soils of the study area are not compatible with mangrove soils. However, the similarity in morphological characteristics and pedogenetic processes, particularly when comparing profiles C5 and C6 (units GJi2 and GJi1), indicates transitional environments.

These transitional characteristics in the soils of the mangrove-*restinga* ecotone were observed by Rosolem et al. (2023a) and Nogueira (2024) in the Ratones River basin, northern Santa Catarina Island. These studies found an increasing gradient in soil salinity and sodium adsorption ratio from the non-floodable *restinga* forest to the mangrove, which were associated with changes in topography and vegetation over the gradient. The soils in these transition areas exhibited paludization and gleization, and accumulated the processes of sulfidation, salinization, and solodization, which were intensified as they approached the mangrove (Rosolem et al., 2023a; Nogueira, 2024).

Therefore, based on sea level dynamics during the Holocene on the Brazilian coast (Angulo et al., 2006) and the coastal flatland formation process in the South region of Brazil (Willwock et al., 1986; Horn Filho et al., 2014), the soils of the study area show characteristics and genesis similar to those of acid sulfate soils in the humid tropics described by Dent and Pons (1995). Sea level significantly increased by the end of the last glaciation, exceeding the current level by 2 to 3 meters (Angulo et al., 2006), forming new barriers (Willwock et al., 1986). This advance of salt and brackish waters towards the continent resulted in the formation of new coastal plains, intra-lagoonal deltas, salt marshes, and mangroves in interior locations relative to the current coastline (Suguio et al., 2005), along with the sedimentation of variable quantities of sulfidic materials.

The concentration of these materials, primarily pyrite, deposited during this sequence of events is higher in slowly deposited sediments and under dense vegetation compared to those in rapidly accumulated sediments (van Mensvoort and Dent, 1998). The mangrove ecosystems gradually transitioned into freshwater wetlands and swamps with the low sea level (Dent and Pons, 1995). Sediments containing reduced inorganic sulfur were buried by alluvial deposits near watercourses or by thick layers of organic material (peat) without sulfides, keeping sulfidic materials submerged by the water table (Diemont et al., 1993).

However, conditions for the current development of the sulfidation process return when saline or brackish waters reach these non-sulfidic horizons. According to Dinslaken and Villela (2019), the conditions in the study area are typically freshwater, but during spring tide, the saline wedge advances, bringing brackish waters into the area.

Thus, a continuous three-dimensional variation in soil attributes occurs in ecotones under very dynamic conditions, making bidimensional generalizations, such as maps, difficult to represent the reality of these environments accurately. Therefore, more investigation profiles are needed to better understand these coastal areas, even in homogeneous physiographical zones identified through photointerpretation, such as the mangrove-*restinga* transition. In the study area, this is particularly significant for unit GJo, which may include soils affected by salinization and solodization, especially at the eastern boundary of the study area (Figure 3). Furthermore, according to the genesis of surface deposits identified by Felix (2020), subsoils and deeper layers than those sampled may contain acid-sulfate soil materials, even in profiles with non-sulfidic topsoils. This highlights the importance of a control section depth of at least 2 m (Santos et al., 2018) for accurately identifying potential acid sulfate soils. Identifying such soils within the two-meter control section is essential for urban applications, as soil disturbances in these environments are often significant due to activities such as excavations, soil mobilization, or lowering of the water table.

Potential of pedology for coastal management

Results from four of the six evaluated profiles showed the presence of acid sulfate soils across nearly the entire study area (Unit GJi1, GJi2, and GJo; Figure 3), primarily composed of hypersulfidic materials. Consequently, improper management of these soils, mainly through exposure to oxidizing conditions, can represent environmental risks, especially because of their upstream location and proximity to the federal conservation unit (Natural Resource Extraction Reserve of Pirajubáe).

The construction of the new access road to Hercílio Luz International Airport significantly affected the study area between 2018 and 2021 (Figure 1). From a soil mechanics perspective, portions of the area showed low bearing capacity for engineering works, necessitating reinforcements. Among the alternatives permitted by the Brazilian National Road Department (DNER, 1998) and Brazilian National Department of Transport Infrastructure (DNIT, 2009), the replacement of soft soil with inert material possessing higher load-bearing capacity was selected. Soft soils are fine-texture sedimentary soils characterized by high plasticity and compressibility, low strength, and permeability, with the clay fraction being responsible for their cohesive and compressive properties (DNIT, 2022).

Thus, the construction of the airport access road involved completely removing the soft soil layer, approximately four meters thick, subgrade needling, and filling gullies with rock fill (Prosul, 2018). This procedure was carried out over nearly the entire extent within the study area, as predicted in the construction executive project, covering the segments from profile C3 to C5 and beyond, i.e., the whole extent of acid sulfate soils, represented by units GJi1, GJi2, and GJo (Figure 3).

These soils, referred to as unserviceable in the project, were excavated and initially deposited in side gullies before being transferred to a temporary storage site, known as "bota-espera" (Prosul, 2018). This site, located in the northern region of the study area, allowed the soil to dry and gain sufficient serviceability for transportation and compaction. The materials were then relocated to a disposal site, referred to as "bota-fora", used for excavated material unsuitable for fill due to poor quality, excessive quantity, or transport distance (DNIT, 2009). This disposal site was located outside the study area, near the Fazenda River, a tributary of the Tavares River, which runs along the Marine Extraction Reserve of Pirajubaé.

The executive project did not mention the presence of sulfidic materials in the soils, nor was this addressed in the Environmental Impact Report (Prosul, 2006). According to the Prosul company, the soil in the construction segment that intersected the study area is "[...] *basically composed of an association of humic quartz sands with the presence of organic soils of silty texture and mangrove soils*" (Prosul, 2018; p. 2; c. 8). In addition, the Environmental Impact Report describes it as "*a complex association of alic hydromorphic quartz sands, with a prominent A horizon + hydromorphic podzol, with a moderate A horizon of sandy texture + little humic eutrophic gley of medium texture, and plain topography*" (Prosul, 2006; p. 55). Therefore, the construction of the road embankment may have caused environmental impacts due to improper management of acid sulfate soils in the study area and the disposal site ("bota-fora").

The values of 0.06 % SO_4^{2-} in profile C1 (loamy sand texture) and 0.16 % SO_4^{2-} in profile C6 (clayey texture) (Table 3) represent soil oxidation values resulting from improper storage in 2016. According to Sullivan et al. (2018b), the action criteria for the development of detailed management plans for acid sulfate soils in Australia are 0.03 % for coarse textures (sandy and organic) and 0.1 % for fine textures (clayey), with net acidity (the sum of potential sulfidic acidity, actual acidity and retained acidity minus acid-neutralizing capacity, including the latter when confirmed by more than one analytical method) equivalent to reduced inorganic sulfur (S_{eq}). This applies to the mobilization of up to 1000 Mg of disturbed soil or 0.03 % S_{eq} for higher weights.

The construction segment intersecting the study area required the removal of approximately 98.000 m^3 of unserviceable soil (Prosul, 2018), corresponding to an estimated 147,000 Mg of disturbed soil, assuming an apparent soil density of 1.5 Mg m^{-3}. Based on sulfate (SO_4^{2-}) concentration as the sole indicator of potential sulfidic acidity and the established action criterion (≥0.03 % S_{eq}) values highlighted the need for a management plan for acid-sulfate soils. However, the measured SO_4^{2-} may have included contributions from various inorganic sources other than pyrite oxidation, probably overestimating the predicted potential sulfidic acidity. Moreover, as these soils were already oxidized, they may have included significant actual and retained acidity values that were not accounted for in the estimation, further increasing the net acidity values.

Therefore, the deposition of these soils on the temporary storage site ("bota-espera") and disposal site ("bota-fora") (Figure 1) may have caused an environmental impact in the area due to the oxidation of materials containing reduced inorganic sulfur. Additionally, adverse effects such as acidification and the mobilization of metals and metalloids may have reached watercourses and, consequently, the conservation unit due to the proximity of these soil sites to the marine extraction reserve. High concentrations of trace elements, mainly Mn (11 to 57 mg dm^{-3}) and Zn (1.6 to 11 mg dm^{-3}), were found, particularly in mapping units GJi 1 and 2. The acidification of these soils can increase the solubility of metals through the dissolution of minerals (Sullivan et al., 2018b).

CONSEMA Resolution No. 181 (Santa Catarina, 2021) establishes standards for the discharge of effluents not regulated by sewage management agencies, stating that effluents can only be released if they meet, among other parameters, a pH between 6.0 and 9.0, maximum concentrations of 1.0 mg dm^{-3} of total Zn and 1.0 mg dm^{-3} of soluble Mn^{2+}. The comparison of the pH incubation values of profiles C5, C6 (Table 3), and C5-B (Table 4) with those of trace elements (Table 3) revealed that the waters drained by these oxidized soils may be sources of contamination to water bodies, as these soils become highly acidic when exposed to the air, increasing the availability trace elements, especially manganese. These results are concerning, particularly considering that Brazilian water quality standards (Brasil, 2005) establish restrictions for these parameters in Class I water (for aquaculture and fishing activities), which is relevant for natural resource extraction activities, such as those in the Marine Extraction Reserve of Pirajubáe.

According to Dinslaken and Vilella (2019), fill materials deposited on the soils previous to the opening of access roads were causing a lowering effect of approximately 0.10 m in the water table beneath these deposits. This lowering can also expose hyposulfidic materials in surface horizons (such as in profile C5-B) to oxygen. Although it does not cause extreme acidification, the oxidation of sulfidic minerals can release metals that become mobilized in acidic conditions, including aluminum, representing a source of environmental contamination.

Future studies can corroborate these findings by quantifying net acidity using the acid-base balance approach, which includes different acidity fractions and the neutralizing capacity in soils with potential and active acid sulfate, as well as quantifying the threat of metal and metalloid mobilization (Sullivan et al., 2018b) to remnant areas and the disposal site (“bota-fora”).

Proposal for the improvement of manuals, soil classification system, and technical standards

Based on the results presented in this study on potential acid sulfate soils (Sullivan et al., 2018a; Isbell and NCST, 2021), methods for collection and storage, and adequate preparation of samples containing materials with reduced inorganic sulfur should be included in the Brazilian Soil Classification System (Santos et al., 2018), Manual of Soil Analysis Methods (Teixeira et al., 2017), and in the Manual for Describing and Collecting Soil in the Field (Santos et al., 2015), as already included in other international soil classification systems (Soil Survey Staff, 2014; Sullivan et al., 2018a). Making this information explicit is primarily important for pedologists less experienced in coastal soils and professionals of other areas that search interdisciplinarity.

Similar to the recommendations for soils with high organic matter content, the Manual for Describing and Collecting Soil in the Field (Santos et al., 2015) should include a specific item for the collection of soils containing sulfidic materials, which should include: i) pH_a and pH_{ox} readings in the field (Sullivan et al., 2018a), or alternatively, in the laboratory, preferably within 24 hours of collection (Jayalath, 2012; Rosolem, 2024); ii) immediate placement of collected samples in leak-proof containers that minimize contact with air, such as thick plastic bags, which should be sealed after air extrusion (Sullivan et al., 2018a); and iii) maintenance and transport of samples at temperatures ≤4 °C from collection to laboratory preparation to preserve sample integrity, ensuring that incubated samples do not freeze (Sullivan et al, 2018b).

Soils of coastal plains, mainly the saturated horizons, should be treated as potential acid sulfate soils in terms of collection, storage, and preparation procedures (Sullivan et al., 2018a) until proven otherwise, as soil characteristics may change. In this context, the use of pH_a, pH_{ox}, and the hydrogen peroxide reaction (Western Australia, 2015; Sullivan et al., 2018a; Isbell and NCST, 2021;IUSS Working Group WRB, 2022) are effective indicators for screening analyses to confirm the presence of acid sulfate soils. This screening may also include the effervescence test (Ahern et al., 2004) to assess the presence of carbonates and, consequently, their potential neutralizing capacity.

In the case of a positive indication of acid sulfate soils, further chemical characterization analyses should be conducted as soon as possible, with samples evaluated for the degree of sulfide influence, as occurs using methods such as the determination by organic carbon on wet oxidation with dichromate (Dent, 1986). Electrical conductivity should be evaluated first using a 1:5 soil-to-water ratio (v v^{-1}), measured in the supernatant and prepared with a chilled sample maintained under field conditions, as recommended for subaquatic soils (Soil Survey Staff, 2014). The drying process for other analyses should be carried out in forced-air oven, with samples no larger than three centimeters in height to ensure a rapid drying. Therefore, the Manual of Soil Analysis Methods (Teixeira et al., 2017) should include the description of analytical methods for pH_a, pH_{ox}, and effervescence tests (Ahern et al., 2004; Sullivan et al., 2018a), as well as pH after incubation, which is already cited in the Brazilian Soil Classification System (Santos et al., 2018), but without adequate guidance or standardization of the processes.

Regarding taxonomy, the Brazilian Soil Classification System (Santos et al., 2018) should revise the definition of sulfidic material to include the terms hypersulfidic material and hyposulfidic material, as already adopted in international systems (Isbell and NCST, 2021; IUSS Working Group WRB, 2022; Soil Survey Staff, 2022). Additionally, hypersulfidic and hyposulfidic materials should be incorporated into the fifth categorical level of the Brazilian Soil Classification System, particularly for the classes Gleissolos, Organossolos, Neossolos, and Espodossolos, as they describe crucial characteristics for Soil Use Manage.

These terms can be included for soils where the content of these materials at depth is sufficiently high to meet the thiomorphic (Tiomórfico) criterion of the suborders, the thionic (tiônico) criterion of subgroups, or, in any depth, for other soils, primarily contributing to urban applications. Furthermore, the fourth categorical level of Neossolos Quartzarênicos Hidromórficos should include hypersulfidic and hyposulfidic subgroups when these materials are within 1.00 m of the surface, as in the case of profile C1. Results from further studies on coastal soils could corroborate the recurrence of these materials in these soils and recommend changes to the fourth categorical level of the Brazilian Soil Classification System for other classes of Neossolos and Espodossolos commonly found in coastal flatlands.

Regrading urban and geotechnical applications, the Brazilian National Department of Transport Infrastructure (DNIT) and the State Department of Infrastructure and Mobility of Santa Catarina (SIE/SC) should develop alternatives for the total or partial replacement of soft soils in technical standards, conditional on the absence of material containing reduced inorganic sulfur or on the treatment of disturbed acid sulfate soils. Thus, soil information is essential for supporting ecosystem studies and territorial planning by existing agencies and policies to ensure sustainable land management.

CONCLUSIONS

Analysis of the historical series of land use and cover indicates a significant transformation over the last 86 years, reflecting the transition from a natural to a predominantly urbanized environment. The area was initially dominated by herbaceous and/or sub-shrubby native vegetation (*restinga*) in wetlands with fluvio-marine interference and, to a lesser extent, by arboreal and/or shrubby *restinga* in the higher portions. Over the decades, progressive deforestation and intense urbanization altered the landscape by replacing native vegetation with drainage canals, reclamation fill areas, buildings, and roads.

The soils in the study area were formed from sedimentary and pedogenetic processes associated with the last marine transgression and regression during the Holocene. The potential presence of materials containing reduced inorganic sulfur and the salinity of soils in the coastal plains suggest the need for special procedures in the collection, storage, and analysis of these soils. Improper packaging and treatment of coastal soil samples, particularly acid sulfate soils, may alter essential parameters for soil characterization and classification, resulting in misleading interpretations and conclusions from the analyses.

Information on field analysis procedures and sample collection and storage should be included in the Manual for Describing and Collecting Soil in the Field. Analytical procedures should be included in the Manual of Soil Analysis Methods. Additionally, the definitions of sulfidic materials should be revised to specify hypersulfidic and hyposulfidic materials as classification criteria, and these terms should be incorporated into the fifth categorical level in the Brazilian Soil Classification System. Furthermore, infrastructure and transport agencies should develop alternatives for the total or partial replacement of soft soils in technical standards, conditional on the absence of potential acid sulfate soils or the implementation of treatments to mitigate the impacts of soil disturbance. Our results also highlight the need for urban planning that not only focuses on preserving remnant natural ecosystems but also emphasizes careful soil management to reduce environmental impacts caused by urban development. Identifying and characterizing acid sulfate soils are essential for preventing environmental degradation and protecting adjacent ecosystems and water bodies.

DATA AVAILABILITY

The data will be provided upon request.

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