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Southward migration of the austral limit of mangroves in South America

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ABSTRACT

Temperature influences the global distribution of mangroves, and global warming may be causing a poleward mangrove expansion. Sedimentary features, pollen, and isotopes data from six sediment cores, as well as ¹⁴C datings, indicated a marine transgression during the Holocene, and it contributed to the expansion of tidal flats occupied by saltmarshes. Environmental conditions suitable for mangroves development occurred on the study site during the Holocene, but, according to ²¹⁰Pb and ¹⁴C dating, the establishment of mangroves mainly represented by *Laguncularia* trees only began between ~1957 and ~1986 (AD) on the studied tidal flats. Spatial-temporal analysis, based on satellite and drone images, revealed a mangrove expansion of ~10 ha in the study area between 2003 (96.1 ha) and 2019 (106.1 ha). Nowadays, in the study area, saltmarshes, mainly characterized by *Spartina* and *Acrostichum*, are sharing tidal flats with mangroves, represented by *Laguncularia* (≤ 5 m tall) and *Avicennia* (≤ 11 m tall). Probably, the absence of mangroves during the Holocene, followed by their establishment and expansion during the Anthropocene in the subtropical zone, is associated with a migration of the austral mangrove limit into the temperate zone, caused by the gradual increase in winter temperatures. This process may be related to a poleward mangrove migration since the late Holocene, caused by a natural Holocene global warming. However, the industrial-era warming must have intensified the mangrove expansion into temperate zones.

1. Introduction

Global warming has been controversial during the last decades, mainly about human influence on climate (Keller, 2003). However, stronger recent warming trends indicated that human influence is dominant in long-term warming (Medhaug et al., 2017). For instance, human-induced warming reached approximately 1 °C above pre-industrial levels in 2017, increasing at 0.2 °C per decade (Allen et al., 2018), and minimum temperatures globally are rising at twice the rate of maximum temperatures (Easterling et al., 2000; Walther et al., 2002). Global warming is causing a poleward migration of isotherms at rates averaging 27 km/decade (Burrows et al., 2011), and pushing tropical species to become more abundant in temperate areas (Parmesan and Yohe, 2003; Poloczanska et al., 2010), butterfly species (Parmesan et al., 1999), birds (Thomas and Lennon, 1999) and modern corals (Yamano et al., 2011) have advanced poleward.

In this context, mangroves may also be used as indicators of climate change (Alongi, 2008; Blasco et al., 1996; Fromard et al., 2004), since they are strongly susceptible to cold temperatures. For this reason, mangroves are restricted to latitudes where the coldest monthly mean temperature is above 20 °C, and the annual thermal amplitude is less than 5 °C (Chapman, 1976; Giri et al., 2011; Walsh, 1974). Then, cold temperatures have limited the northern and southern limits for mangroves to around 30°N (Kangas et al., 1961) and 28°S (França et al., 2019; Soares et al., 2012). However, saltmarshes are dominated by freeze-tolerant herbs that are most abundant along temperate and arctic coasts (Ibáñez et al., 2012). Probably, under global warming influence, mangroves will migrate to higher latitudes, replacing salt marsh (Field, 1995; Gilman et al., 2008; Woodroffe and Grindrod, 1991).

Mangrove contraction and expansion in North America occurred during the Quaternary in response to changes in temperatures (Osland

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et al., 2017; Saintilan et al., 2014; Sandoval-Castro et al., 2012; Sherrod and McMillan, 1985; Woodroffe and Grindrod, 1991). Mangroves occupied areas north of their current limits in Texas, Louisiana, Mississippi, Alabama, and Georgia before the Quaternary (Gee, 2001; Sherrod and McMillan, 1985; Westgate and Gee, 1990). In contrast, during the Pleistocene, the northern limit of mangroves retreated to more equatorial zones in the Caribbean (Sherrod and McMillan, 1985). Regarding the Last Glacial Maximum (LGM), mangrove limits migrated to more tropical zones, followed by an expansion poleward after the LGM (Kennedy et al., 2016; Sandoval-Castro et al., 2012). During the early and mid Holocene, the global mean surface temperature increased (Kaufman et al., 2020), causing a sea-level rise (Angulo et al., 2016; Cohen et al., 2020), and the establishment of tropical mangroves along the Brazilian coast at ~7000 cal yrs BP (Cohen et al., 2020, 2014, 2012; Fontes et al., 2017; França et al., 2015, 2013; Ribeiro et al., 2018). This Holocene warming may have caused a mangrove expansion from tropical to subtropical zones during the late Holocene (França et al., 2019; Pessenda et al., 2012). According to Alongi (2008), the mangrove dynamics in the northern hemisphere is related to global climate and sealevel changes since the LGM.

Regarding the industrial-era warming, some studies have indicated a tropicalization of coastal wetlands ecosystems, for instance, by the poleward mangrove expansion along Mexico (Saintilan et al., 2014) and United States (Cavanaugh et al., 2014; Osland et al., 2018; Perry and Mendelssohn, 2009). In the hypothesis of the poleward expansion of mangroves in North America is being caused by the modern global warming, the southern boundary of the Southern American mangroves must also be migrating poleward. In this context, the warming for Southern Brazil between 1960 and 2002 was stronger in the minimum temperature range at annual timescales (+0.5 °C per decade) and in winter (+0.4 °C per decade) as compared to the smaller warming trends in maximum temperatures at annual and summer timescales (+0.2 °C per decade) (Marengo and Camargo, 2008). Marengo (2006) estimated an increase between 3 and 5 °C by 2080 for the Brazilian territory. If this recent rise in temperature is inducing such poleward mangrove migration, this ecosystem should be absent along its modern austral limit during the Holocene, since the industrial-era warming has led to a modern climate that is unprecedented in the Holocene context (Porter et al., 2019). Then, to test the relationship between latitudinal mangrove expansion and global warming, this work aims to develop a paleoenvironmental reconstruction on a millennial and decadal-scale based on satellite/drone images and pollen, geochemical (δ^{13} C, δ^{15} N and C\N) and sedimentary data, as well as ¹⁴C and ²¹⁰Pb datings along six cores sampled from tidal flats occupied by mangroves in their austral limit.

2. Study site

2.1. Geomorphological settings

The study site is at Santo Antônio Lagoon, near the city of Laguna in the State of Santa Catarina (Fig. 1). The lagoon complex, formed by the Imaruí, Mirim, and Santo Antônio lagoon, has approximately 40 km in length (Eichler et al., 2006). The Santa Catarina coastal plain is subdivided mainly into four depositional systems: Holocene regressive barrier, strand-plain, dune fields, and Holocene lagoonal system. The Holocene regressive barrier system occurs in the south of Laguna and is associated with back-barrier lagoonal and paleo-lagoonal deposits. The strand plain system is composed of, at least, a late Pleistocene and a Holocene section. The strand plain is distinguished from the barrier system by the absence of a contiguous back-barrier lagoon. The Imaruí and Mirim lagoons, which occur behind the Pleistocene strand plains, are drowned river valleys (Angulo et al., 1999).

2.2. Climate

The climate is subtropical humid without a dry season. In the state of Santa Catarina, the highest temperature in summer at Laguna reaches 30 °C, and the minimum in winter is 6 °C. The humidity is around 85%, and the annual average precipitation is between 1250 mm (Imbituba) and 1400 mm (Laguna) (INMET, 2017). The climate is controlled by South Atlantic Tropical Anticyclone, related to trade winds from the NE, and Polar Migratory Anticyclone (PMA). The migration of the PMA to the north can generate cold fronts with increases in precipitation rates (Carvalho do Amaral et al., 2013).

2.3. Vegetation

The native vegetation of east Santa Catarina is subdivided into five main zones: The Coastal vegetation, Atlantic pluvial forest, Cloud forest zone, Araucaria forest, and the Grassland. Coastal vegetation consists of mangrove, and plants communities occupying beaches and dunes directly or indirectly influenced by the ocean (Behling, 1995). The foredune vegetation is mainly characterized by a low diversity of herbaceous species that occurs under variable temperature, with low soil humidity and constant sand movements (Cordazzo and Seeliger, 1995). The dominant families are Poaceae, Amaranthaceae, Asteraceae, and Apiaceae. The vegetation surrounding the lagoons, swamps, and peat bogs are mainly represented by Lentibulariaceae, Cyperaceae, and Poaceae families. The lowland forest is characterized by a high diversity of species, with a large number of epiphytes, lianes, and several types of ferns. The dominant trees are Euphorbiaceae, Moraceae, Fabaceae, Malpighiaceae, Aquifoliaceae, Urticaceae, and Myrtaceae families (Carvalho do Amaral et al., 2013).

3. Material and methods

The materials used involved spatial-temporal analysis based on satellite/drone images and digital elevation models obtained by drone data. Field investigation allowed validation of the results through the acquisition of topographic data, vegetation height, and vegetation types. Sedimentary features, isotopic and elemental laboratory analysis on six sediment cores, with temporal control obtained by ^{14}C (AMS) and ^{210}Pb dating, were developed, following a pre-designed methodology flow chart (Fig. 2).

3.1. Data sources

3.1.1. Satellite data

According to the availability and quality of QuickBird satellite images obtained from Google Earth Pro, seven dates (Aug/2003, Jun/ 2009, Jan/2012, Jul/2013, May/2016, Jul/2017, and Jul/2018) were chosen for the identification and quantification of mangrove areas. These images present a spatial resolution of 2.44 m (multispectral) and three bands (blue, green, red). All images were imported in GeoTIFF format into the Agisoft Metashape Professional version 1.6.2 software and orthorectified according to high-resolution orthoimages of drone, with a spatial accuracy of 10 cm. The drone images were orthorectified based on 102 ground control points (GCPs). All images were exported in GeoTIFF format into the Global Mapper version 18 software for analysis. Human interventions in the study area, such as houses and roads, were used to define reference points for spatial–temporal analysis.

3.1.2. Drone data

High-resolution images obtained by a Drone Phantom 4 Advanced DJI completed the spatial-temporal analysis. It is a battery-powered quadricopter, equipped with GPS and inertial measurement. It has a FC 6310 digital 4 K/20MP (RGB) camera with focal length and sensor width of 8.8 mm and 12.8 mm, respectively. It generated image width with 5472 pixels. This camera positioned on a motion-compensated



Fig. 1. Location of the study area, mangrove distribution in the sectors 1, 2 and 3, and sampling core sites; (a–c) Ground photos showing *Avicennia* and *Laguncularia* trees, as well as *Acrostichum* and *Spartina* along a channel in the sector 2; (d) Ground photo exhibiting clusters of *Laguncularia* shrubs surrounded by Spartina in the sector 3.

gimbal and calibrated by the DJI Assistant 2 Software obtained high spatial resolution images of 2.6 cm/pixel (flight height of 100 m) and 1.6 cm/pixel (60 m) for the study area. The drone mapped at 60 m altitude specific zones to identify the mangrove type. This spatial resolution was calculated using the following Eq. (1):

$$GSD = (Sw * H * 100/60) / (Fr * imH),$$
(1)

where GSD = Ground Sampling Distance (centimeters/pixel), Sw = sensor width of the camera (millimeters), H = the flight height (meters), Fr = the focal length of the camera (millimeters) and

imH = the image width (pixels) (PIX4D, 2013).

The drone surveying was carried out using the DJI Ground Station Pro Software installed in an IPad Air tablet with predefined missions implemented autonomously to follow a route defined by several navigation way-points with 90° camera angle, 90% frontal and 75% lateral overlay. A total of ten missions (4632 images) were flown in Sep/2017, Oct/2019 (spring) at Santa Catarina, and covered 434 ha. A single mission was performed in each target mangrove area, with interruptions for drone battery replacements. Each battery allowed scanning \sim 48 ha (15–18 min).



Fig. 2. Methodology flow chart modified from Cohen et al. (2018).

The major limitation of the drone survey is related to the incidence of sunlight during the flights. Data quality decreases significantly in low light, for instance, during sunrise, sunset, and when there are visibility constraints in the area, which can be caused by seasonal occurrences like fog, snowfall or rainfall. Then, it is recommended that such surveys occur during the summer and without clouds. Besides, the accuracy of the measurements depends on the flight height.

3.1.3. Ground control points

We carried out field trips in Oct/2015, Sep/2017, and Oct/2019. During these campaigns, planialtimetric data were obtained using an Antenna Trimble Catalyst with a differential Global Navigation Satellite System (GNSS). A sub-metric correction was applied to the GNSS data. After 30 min counting, the altimetric accuracy of the GCPs was in the order of \pm 10 cm with the Real-Time Kinematic correction. This margin of error was calculated by comparing the data obtained by the Antenna Catalyst with the IBGE geodetic benchmarks. Physical obstacles such as buildings, tree canopy, and powerlines may affect the GNSS signals and reduce the accuracy of the planialtimetric data. Due to the long stabilization period of the Antenna Catalyst, the planialtimetric data, obtained with the Catalyst, were used as reference points for the topographic survey developed by an electronic theodolite (model CST Berger DGT10). Once a certain planialtimetric reference point based on the Catalyst was established, the theodolite was installed on that point to determine the relative topography of other Ground Control Points (GCPs). The planimetric (\pm 30 cm) and altimetric (\pm 10) data obtained for that GCPs were based on the Catalyst and theodolite, respectively. These data were used as GCPs (102 points) to calibrate the DEM obtained by photogrammetry.

Vegetation heights (VH) were calculated for mangrove and saltmarsh vegetation using a ruler of 4 m. These data were used to validate the vegetation height model obtained by photogrammetry. Visual observation and photographic documentation were used to confirm the key vegetation units.

3.1.4. Sediment cores

Cores LAG-3 (28°29'42.9"S/48°47'43.1"W), LAG-4 (28°29'34.0"S/ 48°47′49.6″W), LAG-5 (28°29'34.9"S/48°47'50.7"W), LAG-6 (28°29′37.5″S/48°0.47′57.2″W), RP-4 (28°29'14.6022"S/ 48°50′31.4710″W) and RP-3 (28°29′35.2333″S/48°50′52.9254″W) were collected during the spring season in October 2015, using Russian type sampling equipment. The sediment cores were taken from area colonized by mangroves mainly characterized by genus Laguncularia, and salt marsh characterized by Spartina densiflora and Spartina alterninflora. The cores were subsampled every 5 cm for grain-size, organic geochemistry, and pollen analysis. The geographical positions were determined by the Global Position System (GPS).

3.2. Methods used

3.2.1. Image classification

The categorization of vegetation cover was developed mainly under a visual classification by the Global Mapper Software, where a data set of locations with known land cover was used to determine the images features of each land cover type. The data collection for training and testing was based mainly on a range of image features (multispectral digital numbers) associated with the texture of a Quickbird image of 2018. The Create Area Features from the Equal Values tool allows for raster to vector or elevation grid to vector conversion of data based on the pixel values. The image was segmented based on spectral, physical, and geometric parameters. Regarding the multispectral digital numbers that best represented the mangroves, it was specified how close to an exact match a set of spectral values must be to match another set of spectral values, where the value of zero requires an exact match and 256 covers all valid spectral range. After the evaluation of the color fuzziness, the mangrove limits were adequately represented in the value 20. This set of information allowed us to individualize objects and compare them with a visual classification of drone orthoimages obtained in 2019 with spectral information between 380 and 710 nm. Drone images with a spatial resolution between 2.6 and 1.6 cm/pixel were able to individualize Avicennia and Laguncularia trees among the saltmarsh. These images were used as a reliable reference base to validate the classification developed on the Quickbird images. Ground photos were also used to facilitate the identification of vegetation units (Fig. 1a-d). The parameters that best represented the boundaries between the mangroves and saltmarshes were used to classify the Quickbird images of previous years. This procedure was followed by a visual check of each mangrove unit classified in the Quickbird images. This cross-validation data generated the highest accuracy for the identification of vegetation units. More details about the drone image processing may be obtained in Cohen et al. (2020, 2018).

3.2.2. 3D models generation and validation

Agisoft Metashape Professional version 1.6.2 software was used to process the drone images. This software develops photogrammetric processing based on digital images. It produced 3D spatial data and



Fig. 3. (a) Vegetation map of the study area; (b) Digital elevation model, (c) Vegetation height model; (d) Terrain elevation model, (e) and a-b transect exhibiting the substrate topography and vegetation height.

orthomosaics with the support of ground control points (www.agisoft. com) (Figs. 3 and 4). The developed orthomosaic images of 2019 were used in the time series analysis.

A dense point cloud (spacing points from 3 to 5 cm) was executed in high resolution to obtain digital models of surface, terrain, and vegetation. Initially, this process generated a digital surface model (DSM) that represented the natural (trees, herbs, sediments, soils, and water) and built (power lines, buildings, and towers) features on the Earth's surface. A dense point cloud classification was developed to identify the terrain elevation. The digital terrain model (DTM) considers only the substrate surface without the vegetal covering and built features. The dense point clouds were split into cells, and the points in each cell were identified. Triangulation of these points allowed the first estimate of the DTM. Then, new points were added to the DTM, following these criteria: they occurred within a certain distance from the terrain model, and the angle between the terrain model and a line connecting the new points was less than a certain angle. For nearly flat terrain, it is recommended to use a default value of 15 deg. It is reasonable to set a higher value if the terrain contains steep slopes (Agisoft, 2018).

This procedure was applied in tidal flats without vegetation and in flats occupied by mangrove and marsh vegetation. The sharp differences in the elevations of point clouds enabled individualizing the points representing the vegetation cover and that reflecting the soil surface. Then a mesh of the soil surface was built based only on the points representing the topographic surface of the soil. This procedure extrapolated the topographic gradients of tidal flats without vegetation cover or with sparse vegetation to substrates with dense vegetation cover. This model was adjusted to the GCP obtained by the Antenna Catalyst and theodolite in areas under dense vegetation cover. Therefore, the digital terrain model below vegetation cover was a product of the combination of GCP interpolation from flats covered by vegetation with the topographic gradients of tidal flats without vegetation extrapolated to flats below vegetation cover. Tidal flats occupied by dense mangroves hinder an accurate topographic survey.

The vector data containing an elevation component were able to create an elevation grid based on the Triangulation. This setting uses a triangulated irregular network connecting the known elevation values. The vegetation height model was obtained by the Combine/Compare Terrain Layers tool. This command permits the generation of a new gridded elevation layer by combining and/or comparing the elevation values from two other loaded layers. For instance, this method was used to subtract the gridded elevation layer that represented the DSM from the DTM to obtain the digital vegetation height model (DVHM) of the sector 2 (Fig. 3c).

A quantitative analysis based on the vertical differences between check points and the DTM and DVHM of 2019 were obtained using the following Eq. (2), as suggested by Cohen et al. (2018):

$$Z_{dif} = Z_{DEM} - Z_{grd} \tag{2}$$

where Z_{dif} = the vertical differences, Z_{DEM} = the Z value of the 3D dense point cloud, and Z_{grd} = the Z value of the Antenna Catalyst/ theodolite checkpoint. The Z_{dif} values were lower than 10 cm. Considering that Antenna Catalyst data have an error of ± 10 cm, a vertical margin of error of ± 10 cm was admitted for the 3D models. The final digital terrain model was adjusted using the Z_{dif} values.

3.2.3. Facies analysis

The cores were X-rayed to identify internal sedimentary structures. Grain size was determined by laser diffraction using a Laser Particle Size SHIMADZU SALD 2101 laser particle size analyzer in the Laboratory of Chemical Oceanography at UFPA. Around 0.5 g of each sample was rinsed with H_2O_2 to remove the organic matter, and the remaining sediments were disaggregated by ultrasound (França, 2010). The grain-size scale with sand (2–0.0625 mm), silt (62.5–3.9 µm), and clay fraction (3.9–0.12 µm) was considered for this work (Wentworth, 1922).



Fig. 4. Vegetation map highlighting the mangrove type location and the digital elevation model.

Following the methods of Harper (1984) and Walker (1992), facies analysis included a description of color (Color, 2009), lithology, texture, and structure. The sedimentary facies were codified following Miall (1978).

3.2.4. Pollen analysis

The sediment cores were sub-sampled (1 cm³) at 5 cm intervals with 125 total samples. All samples were prepared using standard analytical techniques for pollen, including acetolysis (Faegri and Iversen, 1989). Reference morphological descriptions (Colinvaux et al., 1999; Herrera and Urrego, 1996; Roubik and Moreno, 1991) were consulted for the identification of pollen grains and spores. A minimum of 300 pollen grains was counted for the muddy samples. Sandy samples presented a lower amount of pollen grains, since the sandy sediments are not favorable to pollen preservation (Havinga, 1967), then a minimum of 100 pollen grains were counted for sandy samples. Considering the objective of this work was to identify the mangrove presence in the study area, such samples (< 300 pollen grains) were also presented in the pollen diagrams. Software packages TILIA and TILIAGRAPH were used to calculate and plot pollen diagrams (Grimm, 1990). CONISS was used for cluster analysis of pollen taxa, permitting the zonation of the pollen diagram (Grimm, 1987).

We consider important to mention that the spatial representativeness of pollen records obtained from lagoons or lakes depends on the winds blow and extension of its drainage system, in which the proportion of the pollen signal provided by each vegetation type is distance-weighted (e.g. Davis, 2000; Xu et al., 2012). However, preserved pollen in tidal flats and flood plain sediments present smaller spatial representativeness. Pollen traps from tidal flats occupied by herbaceous vegetation, which were located ~1.5 km distant from *Rhizophora* trees and 100 m distant from *Avicennia*, recorded an average of 410 *Rhizophora* grains/cm²/yr and 8 *Avicennia* grains/cm²/yr. This indicates that the dispersion of *Rhizophora* pollen grains, transported by wind, is wider than *Avicennia* pollen (Behling et al., 2001).

3.2.5. Organic geochemistry

A total of 100 samples (6-50 mg) were collected at 5 cm intervals from sediment cores to associate the vegetation changes and to understand the variations in organic matter source. Sediments were treated with 4% hydrochloric acid (HCl) to remove carbonate, washed with distilled water until the pH reached 6, dried at 50 °C, and finally homogenized. The samples were analyzed for total organic carbon (TOC) and total nitrogen (TN) at the Stable Isotope Laboratory of the CENA/USP. The results were expressed as a percentage of dry weight, with analytical precision of 0.09% (TOC) and 0.07% (TN), respectively. The δ^{13} C and δ^{15} N were expressed in per mille (‰) with respect to the VPDB and N₂ standards, respectively, with a precision of 0.2‰. Elemental results were used to calculate the C/N (weight/weight) for all samples. The determination of organic matter source will be environmental-dependent with $\delta^{13}C,\;\delta^{15}N$ and C/N composition (Lamb et al., 2006), as follows: the C₃ terrestrial plants show δ^{13} C values between -32% and -21% and C/N ratio > 12, while C₄ plants have δ^{13} C values ranging from -17% to -9% and C/N ratio > 20 (Deines, 1980; Meyers, 1994, 1997). Freshwater algae have δ^{13} C values between -25% and -30% (Meyers, 1997) and marine algae around -24% to -16‰ (Meyers, 1997, 2003). Meyers (1997) and Thornton and McManus(1994) used δ^{15} N values to differentiate organic matter from aquatic (> 10.0%) and terrestrial plants (\sim 0%). The main limitation of the isotopic method is the eventual isotopic fractionation that can alter the original isotopic ratios, mainly of the $\delta^{15}N$ in anaerobic environments by denitrification. The fractionation can impair paleoenvironmental interpretations as the sedimentary organic matter becomes older (White, 2015).

3.2.6. Radiocarbon dating

The events chronology was based on 12 radiocarbon dates by

 Table 1

 Mangrove area (ha) between 2003 and 2019 based on satellite/drone images.

Time (month/yr)	Sector 1 (ha)	Sector 2 (ha)	Sector 3 (ha)	Total (ha)
08/2003	23.27	72.6	0.2377	96.1077
06/2009	25.68	73.6	0.2474	99.5274
01/2012	25.8	74.3	0.2424	100.3424
07/2013	25.79	74.3	0.3188	100.4088
05/2016	25.82	75.9	0.3131	102.0331
07/2017	26.83	77.2	0.3112	104.3412
07/2018	28	77.2	0.3112	105.5112
06/2019	28.77	77	0.3131	106.0831
Expansion (ha)	5.5	4.4	0.0754	9.9754

accelerator mass spectrometer (AMS) (Table 2). The sedimentary samples were checked and physically cleaned under a stereomicroscope to avoid natural contamination. The organic matter was chemically treated to remove any more recent organic material such as fulvic and/ or humic acids and carbonates. This process consisted of extracting residual material with 2% HCl at 60 °C for 4 h, washing with distilled water to neutralize the pH, and drying at 50 °C (Pessenda et al., 2012). Sedimentation rates were based on the relationship between depth and time intervals. Samples were analyzed at the ¹⁴C Laboratory of Radiocarbon at UGAMS (University of Georgia-Center for Applied Isotope Studies). Radiocarbon ages were normalized to a δ^{13} C of -25% VPDB and reported as calibrated years (cal yr BP) (20) using CALIB 6.0 (Stuiver et al., 2017). The dates are presented along the text as the median of the range of calibrated ages (Table 2). This technique may be used to date anything that was alive during the last 60,000 years, such as charcoal from ancient fires, wood used in construction or tools, cloth, bones, seeds, and leather (Plastino et al., 2001).

3.2.7. Pb-210 dating

Pb-210 dating was conducted at UNESP-São Paulo State University, UNESPetro-Geosciences Center Applied to Petroleum, IGCE-Geosciences and Exacts Sciences Institute, Rio Claro, São Paulo State, Brazil. The sediment cores were analyzed by gamma spectrometry using a coaxial hyper-pure germanium gamma rays detector (HPGe). ²¹⁰Pb readings in the 46.54 keV photopeak provided data of the total ²¹⁰Pb (210PbT) activity in the sediment slices, whereas 226Ra readings in the 186.21 keV photopeak provided data of the in situ (supported) ²¹⁰Pb (210Pbs) activity. The excess (unsupported) 210 Pb (210Pbs) activity aliquots were obtained by the difference 210 PbT – 210 Pbs. Plots of the In ²¹⁰Pbxs against the cumulative dry weight/area allowed to construct straight lines required by the application of the Constant Flux: Constant Sedimentation (CF:CS) ²¹⁰Pb chronological model. The slopes of the straight lines permitted determine sedimentation rates of 5.3 mm/yr (Lag-6) and 16.1 mm/yr (Lag-3) for the cores analyzed. Then, deposition ages were estimated from these rates. This method is suitable for dating approximately 100 years back (Jia et al., 2018).

4. Results

4.1. Geomorphology and vegetation

The study site was carried out on tidal flats at the margin of the São Francisco Lagoon (Fig. 1). The tidal flats in the western sector are under the influence of a channel with a high sinuosity. Lateral migration may be recorded with erosion of the outer channel margins and sedimentation in its inner margins (Fig. 3a and b). Noteworthy is the presence of channel segments on the verge of being abandoned. (Fig. 4d). Such abandoned channels form stagnant zones favorable to the gradual accumulation of muddy sediments. Later, these muddy surfaces emerge to form tidal flats suitable for the establishment of mangroves and/or saltmarshes. The channel sediments are comprised of moderately sorted, medium- to very coarse-grained sands, which extend from

Table 2

Laboratory (UGAMS)	Sample\Depth (cm)	¹⁴ C age yr, BP	pMC (\pm error)	Calibrated (Cal yr BP)	Mean (calyr BP)
27,333	LAG3\60-65 cm	361 ± 23		313-459	385
34,672	LAG3\90-95 cm	960 ± 26		766–916	840
34,673	LAG4\20-25 cm		103.819 (0.322)	1957 CE	
34,674	LAG4\60-65 cm	589 ± 23		519–560	540
34,675	LAG5\52-55 cm		104.329 (0.302)	1957 CE	
26,627	LAG5\90-95 cm	1019 ± 24		913–971	940
34,676	LAG6\35-40 cm	51 ± 23			50
34,680	RP4\30-32 cm		100.036 (0.298)	1956 CE	
34,681	RP4\60-65 cm	359 ± 23		312-455	380
34,682	RP4\170-175 cm	8130 ± 30		8974–9128	9050
34,677	RP3\32-35 cm		104.64 (0.302)	1957 CE	
34,679	RP3 100–105	$685 ~\pm~ 24$		559–617	585

mountainous areas and tablelands. Muddy silt sediments characterize the tidal flats. The eastern area (sector 3) is characterized by islands formed from sandy bars with central depressions that favor the accumulation of muddy sediments (Figs. 1 and 4c).

Mangroves, represented by Laguncularia and Avicennia trees with a stature < 11 m, are distributed on $\sim 1 \text{ km}^2$ of tidal flats (10-60 cm above mean sea level) and as fringe along the channel under brackish water influence (\sim 15‰). Avicennia (< 11 m tall) represents the highest mangrove trees, surrounded by Laguncularia shrubs (< 2 m) in the northern area (sector 2, Fig. 4b). The tallest Laguncularia trees (~5 m) occur along the channels (Fig. 4a and d), while the lowest (< 4 m) are concentrated on small islands on sandy bars (Fig. 4c). Saltmarshes, mainly represented by Spartina and Acrostichum, occupy a significant part of the tidal flats. Sandy tidal flats (~10-50 cm amsl) and dunes may be colonized by restinga vegetation, mainly represented by Ipomoea, Cereus, Sporobolus, Spartina ciliate and Alternanthera. Dense ombrophylous forest, with trees between 5 and 11 m height, occurs upstream, mainly represented by Arecacea on floodplain under freshwater influence (Fig. 4d). Tidal flats, positioned on topographically lowest part (~0 cm amsl) and near the margin of the lagoon, are almost permanently flooded and without vegetation cover (Fig. 3).

4.2. Spatial-temporal analysis

Spatial-temporal analysis, based on satellite and drone images, indicated an expansion of mangrove forests in the study site between 2003 (96.1 ha of mangrove area) and 2019 (106 ha), mainly represented by *Laguncularia* trees (Fig. 5 and Table 1). Mangroves invaded tidal flats previously occupied by *Spartina* and *Acrostichum*. The migration of mangroves into marshes was progressive during that time. Satellite images obtained in 2009 recorded 99.52 ha of mangroves, a gain of 3.42 ha (3.5%) compared to 2003, followed by an expansion of 0.81 ha (2009–2012), 0.07 ha (2012–2013), 1.62 ha (2013–2016) and 2.3 ha (2016–2017), 1.17 ha (2017–2018), and 0.57 ha (2018–2019), representing a mangrove expansion of 0.62 ha/yr (Table 1). Proportionally, the sector 3 had the most extensive mangrove area gains between 2003 and 2019 (0.07 ha, 31.7%), followed by the sector 1 (5.5 ha, 23.6%) and 2 (4.4 ha, 6.1%) (Figs. 1 and 5).

4.3. ¹⁴C, ²¹⁰Pb dates, and sedimentation rates

The ¹⁴C and ²¹⁰Pb data are shown in Tables 2 and 3, respectively. Regarding the radiocarbon dates, the sedimentation rates estimated for the upper part of the core RP-4 was 5.1 mm/yr (30–0 cm) (Fig. 7). The Lag-4, Lag-5, Lag 6 and RP-3 presented 4.2 mm/yr (25–0 cm), 9.2 mm/ yr (55–0 cm), 3.5 (40–0 cm) and 6.0 mm/yr (35–0 cm), respectively (Figs. 6–9 and 11). All the five samples dated by ¹⁴C indicated that upper parts (< 100 cm) of the studied cores, interpreted as tidal flats, were formed over the past 120 years (Figs. 6–9, 11, and Table 2). The sedimentation rates (5.3 mm/yr and 16.1) obtained by ²¹⁰Pb for the

cores Lag 3 (0-60 cm), and Lag 6 (0-50 cm) corroborate for that deposition ages (Tables 2 and 3, and Figs. 9 and 10). The use of multiple dating has allowed a corroboration between methods that would support one another in providing accurate chronologies (Piotrowska et al., 2010b). Age-depth models using the combined results of ²¹⁰Pb and ¹⁴C dating may be obtained in De Vleeschouwer et al. (2009) and Piotrowska et al. (2010a). It should be highlighted the ¹⁴C dating of the Lag 6 (40 cm) indicated an age 1922–1876 CE, while the ²¹⁰Pb revealed an age around 1943 CE, then 21 years younger than the margin of error of the ¹⁴C dating. This chronological difference between the two methods can be considered acceptable because bioturbation caused by soil fauna can mix locally sedimentary organic matter of different stratigraphic levels (Boulet et al., 1995; Gouveia and Pessenda, 2000). Besides, considering the radiocarbon dating by AMS, small carbon content (< 0.5 g) in a small sample mass can contain a high concentration of young/old contaminants coming from the shallow/bottom soil horizons, even after the physical and chemical pretreatments. These procedures remove only the adsorbed contaminants, whereas, in some cases, the absorbed ones can keep preserved in the residual organic matter (humin fraction) (Pessenda et al., 1996).

4.4. Facies description

The studied cores are mainly characterized by olive-gray coarse sand (45–90%) and silt (10–55%) sediments with a small fraction of olive-brown clay (0–8%) sediments. The bottom of sedimentary deposits is predominantly formed by massive sands, while the top presents lenticular and wavy heterolithic bedding. Plant remains, roots, and roots marks evidenced bioturbation along the studied cores. The integration of sedimentary facies, pollen data, and geochemical records allowed to define three facies associations: (A) Herbaceous flood plain, (B) Sandy bar, and (C) Tidal flat (Table 4).

4.4.1. Facies association (A) herbaceous flood plain

This facies association was evidenced in the RP4 between 200 and 100 cm depth (Fig. 7). Sand, silt, and clay sediments oscillated between 2 and 50%, 15 and 80%, and 5-30%, respectively. Sedimentary successions with wavy (facies Hw)/lenticular (Hl)/flaser (Hf) heterolithic bedding characterize this facies association. These sediments began to accumulate at least 9050 cal yrs BP. Pollen analysis indicated four ecologic groups characterized by herbs (70-25%), trees, and shrubs (15-37%), palms (0-15%), and aquatic plants (0-8%). Herbs pollen are represented mainly by Poaceae (5-55%), Myrsinaceae (0-15%), Cyperaceae (0-10%) and Asteraceae (0-10%), while the arboreal group is represented by Euphorbiacea (0-18%), Myrtaceae (0-25%), Sapindaceae (0-10%) and Fabaceae (0-7%), followed by Cannabaceae (Trema), Araucariaceae, Cunoniaceae, Moraceae, Podocarpus, and Mimosa ranging from 0 to 10%. Anacardiaceae, Melastomataceae/Combretaceae, Salicaceae, Solanaceae, Annonaceae, Cletraceae, Podocarpus, and Piperaceae ranged from 0 to 5%. Aquatic plants were represented by



Fig. 5. Spatial-temporal analysis of the austral limit of mangroves in South America based on satellite and drone images between 2003 and 2019.

Table 3

Stratigraphic	depth	selected	for	identification	of	sedimenta
tion rates bas	ed on	²¹⁰ Pb da	ting			

Sample/Depth (cm)	²¹⁰ Pb (AD) age		
LAG3/0 cm	2015		
LAG3/10 cm	2012		
LAG3/20 cm	2008		
LAG3/30 cm	2004		
LAG3/40 cm	2000		
LAG3/50 cm	1996		
LAG3/58 cm	1993		
LAG6/ 0 cm	2015		
LAG 6/7 cm	2009		
LAG 6/14 cm	1998		
LAG 6/21 cm	1986		
LAG 6/28 cm	1974		
LAG 6/35 cm	1961		
LAG6/42 cm	1943		
LAG6/ 50 cm	1921		

Alismataceae (0–8%), Typhaceae (0–2%) and Plantaginaceae (0–5%). The ferns are represented mainly by Polypodiaceae (Fig. 1, supplementary material). The δ^{13} C values presented an upward increase trend from –23 to –21‰, while the C/N of sedimentary organic matter presented an upward decrease trend from 28 to 8 (Fig. 7).

4.4.2. Facies association (B) sandy bar

This facies association is represented by the sedimentary units between 120 and 100 cm, 100 and 65 cm, 100 and 60 cm, 70 and 43 cm, and 100 and 55 cm depth in the cores RP-3, RP-4, Lag-3, Lag-4, and Lag-5, respectively, accumulated between ~940 and ~385 cal yr BP (Figs. 6-8, 10, and 11). It presents massive coarse-medium sand sediments (facies Sm) exhibiting a fining upward sandy deposit. The pollen data indicated four ecologic groups characterized by herbs, trees and shrubs, palms, and ferns. The herbs are represented by Poaceae (0-90%), Asteraceae (0-10%), Apiaceae (0-6%), Cyperaceae (0-10%), Myrsinaceae (5-10%), Amaranthaceae (0-10%), Araceae (0-10%), Apocynaceae (< 5%), and Loranthaceae (< 5%). The trees and shrubs are characterized by Mimosa (0-20%), Malpighiaceae (0-9%), Ericaceae (0-8%), Euphorbiaceae (0-5%), Cunoniaceae (0-5%), Podocarpus (0-2%), Fabaceae (0-5%), Moraceae (0-6%), Myrtaceae (0-8%), Rubiaceae (0-2%), Melastomataceae (0-5%), Anacardiaceae (0-5%) e Matayba (0-10%). Arecaceae pollen occur with a small percentage (0–11%) (Figs. 1, 2, 4, and 5, Supplementary material).

The δ^{13} C values presented an increasing trend, especially the core Lag-3 that increased from -26 to -15% (mean -20%, Fig. 10), while the δ^{15} N oscillated from 5 to 8% (mean 7.75%) (Figs. 7, 8, and 10). The TOC results presented stable values around 1.5%, TN values show a slightly increasing trend from 0.01 to 0.15% (mean 0.08%), and C/N values presented also increased trends, mainly to the RP-4 and LAG-5 (Figs. 7, 8, and Table 4).



Fig. 6. Lithostratigraphic profile of the core RP-3 with sedimentary features and pollen diagram exhibiting percentages of the ecological groups and zones.

4.4.3. Facies association (C) tidal flat

Facies association C is present as the upper sedimentary unit of the cores Lag-3 (60-0 cm), Lag-4 (43-0 cm), Lag-5 (55-0 cm), Lag-6 (50-0 cm), RP-3 (100-0 cm) and RP-4 (65-0 cm) accumulated during the last decades (Figs. 6-11). It is characterized by lenticular (HI) and wavy heterolithics (Hw) bedding and massive mud (Mm) with roots, root marks, and leaves. The radiocarbon dates indicated ages between ~50 cal yr BP and 1957 CE, while the ²¹⁰Pb suggest that sediments were accumulated during the last century under sedimentation rates between 5.3 mm/yr (Lag-6, Fig. 9) and 16.1 mm/yr (Lag-3, Fig. 10, Tables 2 and 3). The palynology shows five ecologic groups represented by herbs, trees, and shrubs, mangroves, palms, and ferns. Besides the pollen types found in the Facies Association A and B, it was possible to identify herbs pollen of Lentibulariaceae (0-20%) and Aizoaceae (0-2%) families, as well as trees and shrubs pollen of *Ílex* (0-5%), Sebastiana (0-5%), Boraginaceae (0-2%), Annonaceae (0-3%), Sapotaceae (0-2%), Alnus (0-5%), Byrsonimia (0-8%), Sapindaceae (0-5%), Borreria (0-10%), Myrcinaceae (0-5%) and Anacardiaceae (0-4%). Mangrove pollen are represented by Laguncularia (0-20%) and Avicennia (0-3%) (Figs. 1-5, Supplementary material). Mangrove pollen were not recorded in the RP-3 (Fig. 6).

Geochemical records indicate values of δ^{13} C, δ^{15} N e C/N oscillating from -24 to -17% (mean -20%), 4 to 7% (mean 5.5%) and 7 to 29 (mean 18) respectively. The C_{org} and N_{total} presented values varying between 1.2 and 4.5% (mean 2.85%) and 0.05 and 0.25% (mean 0.3%), respectively (Figs. 9–12, Table 4). The RP-4 exhibited an upward

increase trend for the δ^{13} C values, while the C/N presented a decreased trend (Fig. 7).

5. Interpretation and discussion

5.1. Holocene

Along the south-northeastern Brazilian coast occurred a relative sealevel rise mainly during the early Holocene, and a mid Holocene highstand between 1 and 5 m above the modern sea-level at about 5500 cal yrs BP. During the mid and late Holocene occurred a gradual relative sea-level fall (Angulo et al., 2016, 2006; Caldas et al., 2006; Cohen et al., 2020). The stabilization or low rates of sea-level rise/fall around the mid Holocene allowed the establishment only of tropical mangroves at ~7000 cal yr BP along the coast of Espírito Santo (19°S), Bahia (17°S), Rio Grande do Norte (5°S), Pará (1°S), and Amapá (2°N) (Cohen et al., 2020, 2014, 2012; Fontes et al., 2017; França et al., 2015, 2013; Ribeiro et al., 2018). Although the trends of relative sea-level changes are the same for the tropical and subtropical Brazilian coast, the subtropical mangroves were established only at ~2200 cal yr BP (São Paulo, 25°S) and ~1630 cal yr BP (Santa Catarina-Brazil, 26°S) (França et al., 2019; Pessenda et al., 2012), suggesting that natural global warming during the Holocene (Kaufman et al., 2020) may have caused the mangrove expansion from tropical to subtropical areas during the late Holocene.

In the study area, the early-mid Holocene sea-level rise caused



Fig. 7. Summary of the core RP-4, showing sedimentary features, pollen data, and geochemical results.



Fig. 8. Summary of the core LAG-5, showing sedimentary features, pollen data, and geochemical results.

erosion of the coastline, invasion of coastal depressions, and fluvial valleys along the southern Brazilian littoral (Cooper et al., 2018). During this time, lagoons and tidal channels were formed. The flood-plains at the margin of fluvial valleys were filled by muddy and sandy sediments, as recorded at the base of the core RP-4 (~9000 cal yrs BP). It is characterized by lenticular, wavy, and flaser heterolithic bedding (Facies Association A) (Fig. 7). The marine transgression contributed to the expansion of tide-influenced environments, as indicated by massive mud and heterolithic beds. Also, the binary δ^{13} C and C/N showed an upward increase trend of marine influence along the Facies Association A (Fig. 12). The increased trend of herbs pollen percentage associated to the enrichment of δ^{13} C and decrease of C/N values from the base to the top of the core RP-4 suggests a transition of a fluvial floodplain dominated by a mixture of grasses, trees, shrubs and ferns (200–100 cm) to a tidal flat (65–0 cm, < ~380 cal yrs BP) dominated

by herbs with a substantial contribution of sedimentary organic matter from estuarine origin (Figs. 7 and 12).

Considering the last 1000 years, the sandy bars deposits were accumulated between at least 940 and ~385 cal yrs BP (Figs. 6–8, 10, and 11). The δ^{13} C and C/N values revealed an increasing trend of estuarine influence during this time interval (Figs. 8, 10, 11, and 12). Probably, after the RSL stabilization, sandy bars deposits emerged isolated in the lagoon and allowed the establishment of muddy tidal flats. Such environmental conditions favor the establishment and expansion of mangroves. The temporal differences between the top of the Facies Association B (~380 cal yr BP, Figs. 7 and 10) and the base of the A (1921–1993 CE, Figs. 8–10) can be attributed to erosive events that preceded the deposition of that tidal flats.



Fig. 9. Summary of the core LAG-6, showing sedimentary features, pollen data and geochemical results.



Fig. 10. Summary of the core LAG-3, showing sedimentary features, pollen data and geochemical results.

5.2. Anthropocene

The term Anthropocene, launched into public debate by Nobel Prize winner Paul Crutzen, has been used informally to describe the period during which human actions have had a drastic effect on the Earth and its ecosystems. The ratification process of the Anthropocene as a geological time unit is ongoing. Several start dates for the Anthropocene have been proposed, but the atomic bomb testing during the 1950s has been more favored than others (Zalasiewicz et al., 2018).

Our work revealed that mangrove pollen in the study area occurred only during the last decades. Regarding the Holocene, mangrove pollen were not recorded along the stratigraphic record of the RP-4



Fig. 11. Summary of the core LAG-4, showing sedimentary features, pollen data and geochemical results.

Table 4

Summary of facies association with sedimentary characteristics, predominance of pollen groups and geochemical data.

Facies association	Facies descripition	Polen predominance	Geochemical data	Interpretation
A	Wavy (Hw), flaser (Hf) and lenticular heterolitic bedding (facies Hl), with fine sand, silt and clay	Herbs, trees, shrubs and palmss	$\begin{array}{l} \delta^{13} C: \ -23 \ to \ -21 \% \\ C_{total}: 0.5 - 2 \% \\ N_{total}: 0.01 - 0.15 \% \\ C / N: \ 10 - 30 \end{array}$	Herbaceous floodplain
В	Massive sand (facies Sm) with medium–coarse sand	Trees, shrubs palms and herbs	$\begin{array}{l} \delta^{13} C: \ -24 - 15 \% \\ \delta^{15} N: \ 6 - 9.5 \% \\ C_{total} \cdot 0.5 - 2 \% \\ N_{total} \cdot 0.01 - 0.15 \% \\ C/N: \ 6 - 30 \end{array}$	Sandbar
С	Wavy (Hw) and Lenticular heterolitic bedding (facies Hl), with fine sand, silt and clay	Trees, shrubs, herbs, palms and mangroves	$\begin{array}{l} \delta^{13}C:\ -24\ to\ -17\% \\ \delta^{15}N:\ 4-7\% \\ C_{total}:\ 1.2-4.5\% \\ N_{total}:\ 0.05-0.25\% \\ C/N:\ 7-22 \end{array}$	Tidal flat

accumulated since 9000 cal yr BP (Fig. 7), although the sampling site, located in the modern southern limit of American mangroves (28°29'S), presents dense Avicennia and Laguncularia trees nowadays, with stature between 2 and 11 m (Fig. 4d). From the physicochemical and hydrodynamic point of view, environmental conditions were favorable for the establishment and expansion of mangroves since the mid Holocene, as it occurred along the Brazilian coast between latitudes of 25°S and 2°N (Cohen et al., 2020, 2014, 2012; França et al., 2015, 2013; Ribeiro et al., 2018; França et al., 2019; Pessenda et al., 2012). During this time occurred a significant contribution of organic matter sourced from estuary on tidal flats occupied by saltmarshes. As revealed by the spatial-temporal analysis (Fig. 5 and Table 1), the mangrove expansion in the study site has occurred at least between 2003 and 2019. Considering this period and a rate of continuous sedimentation of 6.0 mm/ vr along the interval 35–0 cm in the RP-3, mangrove pollen should be preserved in the last 7 cm of this core (Fig. 6). Unfortunately, the samples from this interval did not record mangrove pollen, probably due to a loss of sediments from the upper part of this stratigraphic section at the time to remove the core from the substrate.

The cores Lag-3, Lag-5, Lag-6, Lag-4, and RP-4 indicated mangrove presence along 52 cm (sedimentation rate of 16.1 mm/yr), 17 cm (9.2 mm/yr), 20 cm (5.3 mm/yr), 22 cm (4.2 mm/yr), and 6 cm depth (5.1 mm/yr) (Figs. 7–11) respectively. Higher sedimentation rates for

the core Lag-3 produced a longer stratigraphic section to preserve mangrove pollen for the last decades. In addition, these cores (Lag-3, Lag-4, Lag-5, Lag-6, and RP-4) were sampled during the low tide, which facilitated the removal of the upper section of the stratigraphic column. Based on these pollen profiles and ¹⁴C and ²¹⁰Pb dates, mangrove vegetation mainly represented by *Laguncularia* trees was established on studied tidal flats under the estuarine influence between ~1957 and 1986 CE. Today, these areas are occupied by *Laguncularia* and *Avicennia* shrubs/trees (Figs. 1, 3, and 4).

The mangroves in the sector 2 show Avicennia and Laguncularia trees with stature up to 11 and 5 m, respectively (Figs. 1, 3, 4b, and d). In comparison, the sector 1 exhibits mainly Laguncularia trees with a maximum height of 5 m (Fig. 4a). The sector 3 presents small groups of Laguncularia shrubs with < 2 m tall (Fig. 4c). Probably, the difference in the mangrove structure can be attributed to the microclimate. Microclimate refers to climatic conditions in a reduced spatial scale (i.e., < 100 m horizontally and < 10 m vertically) (Geiger et al., 2012). It may be regulated by local factors, such as proximity to vegetation, soil, and water. Regarding the impacts of low winter temperatures on mangroves, Osland et al. (2019) proposed six microclimatic factors that may produce air temperature gradients and modulate mangrove responses to winter temperature extremes: (1) distance from the ocean; (2) distance from wind buffers; (3) mangrove canopy cover; (4) height



Fig. 12. Binary diagram illustrating the relationship between δ^{13} C and C/N for the different sedimentary facies association.

above the soil surface; (5) local slope concavity; and (6) tidal inundation. Regarding the study sites, the wind effects and mangrove canopy may have significant influences on mangrove structure. Sectors 2 and 3 are located in internal parts of the studied lagoon (Fig. 1), which offers some protection against the winter wind. In contrast, the sector 3 is isolated on an island, then more exposed to the winter winds than the sectors 1 and 2. Considering this hypothesis, some geomorphological characteristics of the studied lagoon could be more favorable for mangrove development. The gradual mangrove expansion could produce natural protection against the low winter temperatures, because mangrove canopy can reduce wind speeds and produce warmer winter temperatures into mangroves, causing temperature variations within the mangroves and impact gradients from the edge to the innermost sector of these forests (Devaney et al., 2017; Geiger et al., 2012; Guo et al., 2017).

Considering the macroclimate, Spartina dominates saltmarshes mainly along the south of the Santa Catarina littoral. This genus has a higher tolerance to low winter temperatures than mangrove trees, which occur predominantly in tropical regions (Idaszkin and Bortolus, 2011; Soares et al., 2012). The coast of Joinville, northern Santa Catarina littoral, mangroves exhibit Rhizophora, Avicennia, and Laguncularia trees, while the southern littoral presents a decreasing trend of Rhizophora trees density until its absence along the studied littoral (Soares et al., 2012). The study area presents mangroves represented only by Lagungularia with a few Avicennia shrubs/trees. This distribution of mangrove genus along the Santa Catarina coast should reveal its gradual intolerance to low winter temperatures, where Lagungularia and Avicennia are more tolerant to low temperatures than Rhizophora (Duke et al., 1998; Quisthoudt et al., 2012). A palynological study carried out in Babitonga Bay-northern littoral of Santa Catarina, 250 km distant from the study site, revealed the establishment of mangroves represented only by Laguncularia between ~1629 and ~853 cal. yr BP. After ~853 cal. vr BP occurred an increase of Laguncularia and the establishment of Avicennia (Franca et al., 2019). Probably, this mangrove succession was caused by a warming trend in South America during the late Holocene (Baker and Fritz, 2015). Rhizophora trees have arisen in Babitonga Bay only during the last decades (França et al., 2019), probably caused by warming during the Anthropocene (Bernardino et al., 2015).

Therefore, considering four relevant issues discussed in this work: (1) the stabilization or low rates of sea-level rise/fall around the mid Holocene that allowed the establishment of Brazilian tropical mangroves since \sim 7000 cal yr BP; (2) the mangroves expansion from tropical to subtropical zones along the Brazilian coast during the late Holocene; (3) the mangrove succession during the last 1600 years in Babitonga Bay (250 km north of the study area), and (4) the establishment of mangroves in Laguna de Santo Antônio only over the last decades, would be reasonable to propose that the gradual increase in winter temperatures (+0.4 °C per decade) at least between 1960 and 2002 (Marengo and Camargo, 2008) contributed significantly to the expansion of the austral limit of American mangroves into the temperate zone during the Anthropocene. Probably, the poleward mangrove migration since the late Holocene was caused by a natural Holocene global warming, but the industrial-era warming must have accentuated such mangrove expansion.

6. Conclusions

Sedimentary features, pollen, and isotopes data from six sediment cores, as well as geomorphological and vegetation analyses indicated a marine transgression during the Holocene, and it contributed to the expansion of tide-influenced environments and development of saltmarshes. From the physicochemical and hydrodynamic point of view, environmental conditions were favorable for the establishment and expansion of mangroves in the studied area during the mid and late Holocene, when mangroves were established along the tropical (2°N-19°S) and subtropical (25°-26°S) Brazilian coast, as a consequence of the stabilization or low rates of sea-level rise/fall around the mid Holocene, and the Holocene warming, respectively. However, the establishment of mangroves mainly represented by Laguncularia trees on the studied tidal flats (28°29'S) only began between ~1957 and ~1986 CE. Spatial-temporal analysis, based on satellite and drone images, revealed a mangrove expansion of ~ 10 ha in the study area between 2003 (96.1 ha) and 2019 (106.1 ha). Nowadays, in the study area, saltmarshes, mainly characterized by Spartina and Acrostichum are sharing tidal flats with mangroves, represented by Laguncularia ($\leq 5 \text{ m}$ tall) and *Avicennia* (≤ 11 m tall). Probably, the Anthropocene mangrove establishment and expansion are associated with a migration of the austral mangrove limit into the temperate zone, caused by the gradual increase in winter temperatures. This process may be related to a poleward mangrove migration since the late Holocene, caused by a natural Holocene global warming. However, the industrial-era warming must have accentuated the mangrove expansion into temperate zones.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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