Remote sensing and geology in the Bojuru region, middle portion of the Coastal Plain of Rio Grande do Sul State, Brazil: Boundaries of the Pleistocene and Holocene barriers and the forms of land use.

Sensoriamento remoto e geologia na região de Bojuru, porção média da Planície Costeira do Estado do Rio Grande do Sul, Brasil: Limites das barreiras pleistocênica e holocênica e as formas de uso do solo.

Marco Antonio Fontoura Hansen[a][d], José Pedro Rebés Lima[a][e], Jair Weschenfelder[b][f], Nelson Luis Sambaqui Gruber[b][g], Cesar Augusto Moreira[c][h]

[a]Universidade Federal do Pampa-UNIPAMPA, [b]Universidade Federal do Rio Grande do Sul, [c]Universidade Estadual de São Paulo, [d]marcohansen@unipampa.edu.br, [e]jprebes@unipampa.edu.br, [f]jair.weschenfelder@ufrgs.br, [g]nelson.gruber@ufrgs.br, [h]cesar.a.moreira@unesp.br

Abstract

In the locality of Bojuru, the middle portion of Rio Grande do Sul coastal plain (Southern Brazil) the research was carried out with the purpose of a better understanding the geology, geomorphology, recognition of the sedimentary facies of this coastal area, and ways of land use and occupation. This region has active coastal sedimentation, with several occurrences and research for heavy minerals, mainly ilmenite ($FeTiO_3$). For the stage of digital processing of satellite images, generation of databases, and crossing of information, the software SPRING 5.2.7-INPE, was used. The objective of this study aimed to verify how coastal sedimentary environments, due to their morphology and associated facies, directly or indirectly influence land use and occupation of the locality of Bojuru, on the middle coast of Rio Grande do Sul State. The techniques used in the digital image processing of the 1 MSS, 2 MSS, 7 ETM+, and three 8 OLI Landsat satellites, orbit 221/82, with their passage years being 1973, 1980, 2002, 2016, and 2019. The result of this processing with the field truths resulted in the delimitation of the main features related to coastal evolution, based on the spectral combination of the bands 742-RGB of the Landsat 8 OLI of 2019. In this way, it was possible to delimit the features of the Pleistocene, Lagoon, and Holocene barriers in the evolution of coastal and sedimentation dynamics. The highlights made, in the false color, were through the arrangement of the bands 543-RGB on the satellite image which favored the identification of the forms of land use and occupation and highlighted the morphostratigraphic changes of the Pleistocene and Holocene barriers deposits. Therefore, the greatest contrast was observed between the emerged and submerged portion, highlighting the sand/sea limit, the limit between the Pleistocene and Holocene barriers. The forms of use and occupation were also highlighted, enhancing the vegetation on the dunes and cultivation areas, with a loss of 61.2% in the dune area in 46 years.

Keywords: remote sensing; coastal plain; morphostratigraphy; coastal evolution

Resumo

Na localidade de Bojuru, porção média da Planície Costeira do Rio Grande do Sul (Sul do Brasil), foi realizada a pesquisa com a finalidade do melhor entendimento da geologia, geomorfologia, reconhecimento das fácies sedimentares dessa área costeira e formas de uso e ocupação da terra. Esta região possui sedimentação costeira ativa, com diversas ocorrências e pesquisas para minerais pesados, principalmente, ilmenita ($FeTiO_3$). Para a etapa de processamento digital de imagens de satélite, geração do banco de dados e cruzamento de informações, foi utilizado o *software* SPRING 5.2.7-INPE. O objetivo deste estudo foi verificar como os ambientes sedimentares costeiros, devido à sua morfologia e fácies associadas, influenciam direta ou indiretamente o uso e ocupação do solo na localidade de Bojuru, no litoral médio do estado do Rio Grande do Sul. As técnicas empregadas no processamento digital de imagens dos satélites Landsat 1 MSS, 2 MSS, 7 ETM+ e duas 8 OLI, órbita 221/82, sendo seus anos de passagens 1973, 1980, 2002, 2016 e 2019. O resultado desse processamento, com as verdades de campo, resultou na delimitação das principais feições relacionadas com a evolução costeira, com base na combinação espectral das bandas RGB-742 do Landsat 8 OLI, de 2019.

Desta maneira, foi possível delimitar as feições relativas aos depósitos de barreiras pleistocênica, holocênica e Lagunar, na evolução da dinâmica costeira e de sedimentação. Os realces efetuados, na falsa cor, foram através do arranjo das bandas RGB-543 sobre as imagens de satélite, o que favoreceu a identificação das formas de uso e ocupação dos solos e, ressaltou as mudanças morfo-estratigráficas dos depósitos de barreiras pleistocênica e holocênica. Portanto, o maior contraste foi observado entre a porção emersa e submersa, destacando limite areia/mar, limite entre as barreiras pleistocênica e holocênica. As formas de uso e ocupação também foram realçadas, destacando a vegetação sobre as dunas e áreas de cultivo, com perda de 61,2% na área das dunas em 46 anos.

Palavras-chave: sensoriamento remoto; planície costeira; morfo-estratigrafia; evolução costeira

1. Introduction

The locality of Bojuru, the middle portion of the Coastal Plain of Rio Grande do Sul State, south of Brazil, has as its economic base the agriculture, cattle raising, vegetal extraction (*Pinus* and *Eucalyptus*), and fishing. The region is also a target for heavy minerals used by industry, such as ilmenite ($FeTiO_3$), rutile (TiO_2), zircon ($ZrSiO_4$), and other heavy minerals deposited in fixed or mobile coastal dune ridges (figure 1).
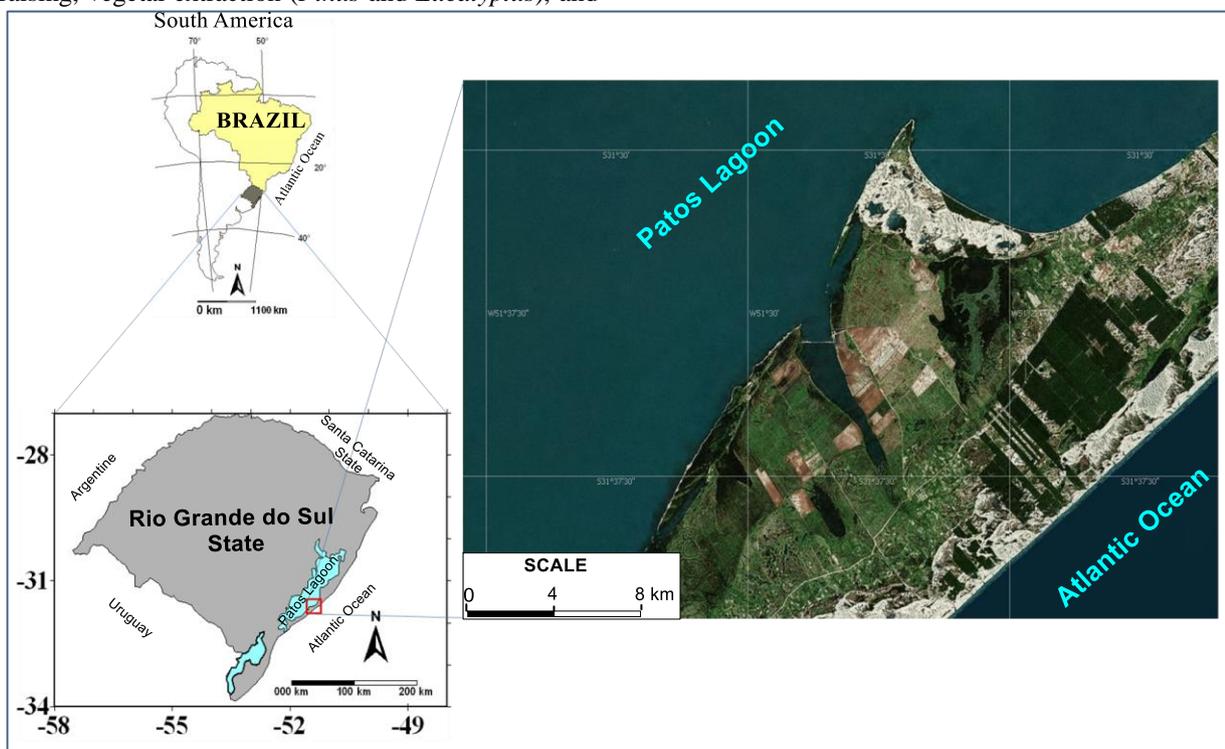

Figure 1: Situation and location of the study area in Bojuru, São José do Norte, Rio Grande do Sul State. Google (2019).

Many economic resources (heavy mineral placers, oil, gas, water, and sand for construction) have been exploited from deposits accumulated in this type of system in many places in the world (Arejano, 2006). Considering the mineral importance of the region, the works of Villwock et al. 1979, Munaro 1994, Tagliani 1997, 2002, Dillenburg et al. 2003 should be mentioned.

From the geological, stratigraphic recording, coastal evolution and sedimentation point of view, the lagoon/barrier type systems have outstanding importance among the coastal depositional systems. Such thematic has been considered by several works in the coastal region of Rio Grande do Sul State (Villwock 1978, Villwock 1984, Villwock et al. 1986, Tomazelli & Villwock 1992, Calliari & Klein 1993, Weschenfelder et al. 1997, Calliari 1998, Corrêa et al. 2004, Villwock et al. 2007), some of these with a focus on geological mapping (Horn Filho et al. 1984, Tomazelli et al. 1988, Villwock & Tomazelli 1995, Villwock & Tomazelli 1998, Tomazelli & Villwock 2005) and some scientific papers describing aspects related to aeolian deposits of coastal dunes (Martins 1967, Cordazzo & Seeliger 1987, Tomazelli 1993, 1994, Calliari et al. 2005).

Due to the dynamic conditions of the coastal deposits, as a function of the wind transport processes, the previous geological maps have their different limits, especially when there is interference through reforestation and forms of land use and occupation (Tagliani 1995).

The remote sensing technique is applicable for the correct positioning and updating of geological contacts between the Pleistocene and Holocene formations (aeolian deposits), as well as delimiting the forms of land use and occupation. Such a technique was used by De Lopes (2011) working in the coastal region of Bojuru.

This study aimed to verify how coastal sedimentary environments, due to their morphology and associated facies, directly or indirectly influence land use and occupation of the locality of Bojuru, on the middle coast of Rio Grande do Sul State.

2. Materials and methods

The thematic map elaboration, treatment, and digital processing of remote orbital satellite images for the construction of a georeferenced database were performed with SPRING's Geographic Information System of the National Institute of Space Research - INPE (Camara et al. 1996).

The techniques of digital processing were applied in images obtained from the satellites and their respective dates passed through orbit 221/82 Landsat 1 MSS of December 3, 1973, Landsat 2 MSS of September 4, 1980, Landsat 7 ETM++ of November 12, 2002, Landsat 8 OLI of August 22, 2016, Landsat 8 OLI of March 24, 2019, and Landsat OLI of November 19, 2019, for the lowest cloud coverage.

The technique used was the traditional false color for the 1973, 1980, 2002, 2016, and 2019 images, after other combinations were tested. This was obtained by the NRG crossing of the near-infrared, red and green bands aiming the colored infrared to highlight the vegetation and coastal dunes around the small town of Bojuru. This is a combination of bands useful for vegetation studies, with the purpose of monitoring drainage and soil patterns in various stages of crop growth (Jensen 1996, Florenzano 2007, USGS 2019, Souza et al. 2019). Generally, dark red colors indicate broad-leaf or healthy vegetation, while lighter reds mean plains or rare vegetation.

The result of processing with the field truths allowed the areas to be extracted. The study area has a total of 748 km^2 of the image, considering the emerged and submerged areas of the Patos Lagoon and the Atlantic Ocean.

To delimit the main geological features of the emerged area, the combination of spectral bands was used, which highlighted the morphostratigraphic units on the image Landsat 8 OLI, November 19, 2019, with bands 742-RGB to assist in understanding the coastal evolution of this sector of the middle coast of Rio Grande do Sul State.

The data presented in the geological map (CPRM 2008) have been synthesized according to spectral responses.

Historical rainfall (mm) and wind speed (m/s) data were acquired from (BDMEP-INMET 2019).

3. Results

Surface and subsurface geology data supported by field surveys define the evolutionary systems of the Lagoon-barrier type Pleistocene III and Holocene IV, and the CPRM geological map (Villwock et al. 1986, Tomazelli et al. 1988, Dillenburg et al. 2003, CPRM 2008).

Based on the colorful spectral imaging channels combination of the November 2019 Landsat 8 OLI, it was possible to delimit the features of the Pleistocene barrier III, Lagoon III, and Holocene barrier IV deposits in the evolution of coastal dynamics and local geology (figure 2).

Pleistocene barrier III deposits are represented in the study area by two morphostratigraphic units: the lagoon plain and aeolian deposits (adapted from CPRM 2008).

The lagoon plain deposit is constituted by silty clay sand, poorly selected, and with incipient parallel plane lamination.

The aeolian deposit has fine, well-selected quartz sand, parallel plane, and crossed lamination.

The deposits of the Holocene barrier IV have three morphostratigraphic units with deposits of peat, lagoon plain, and aeolian, lagoon ridges, and beach (adapted from CPRM 2008).

It is noteworthy that the aeolian reworked deposits were not considered as a separate unit, since, in addition to having the same description as the aeolian deposit, they have similar spectral responses.

The peat deposit is homogeneous, interspersed, or mixed with clay, silt and sand and, locally, with diatomite and the presence of shells closer to the sea (figures 3a, b).

The lagoon plain deposit consists of silty clay sand, poorly selected with incipient parallel plane stratification.

The beach deposits and lagoon ridges present fine quartz sand, well selected, with the morphology of ridges parallel to the lagoon margins.

The aeolian deposit varies in the region of Bojuru from 0.5 m to 5.2 m in height and is characterized by presenting fine to medium quartz sand, well rounded and selected, rare parallel plane lamination, or cross-stratification (figures 3c, d).
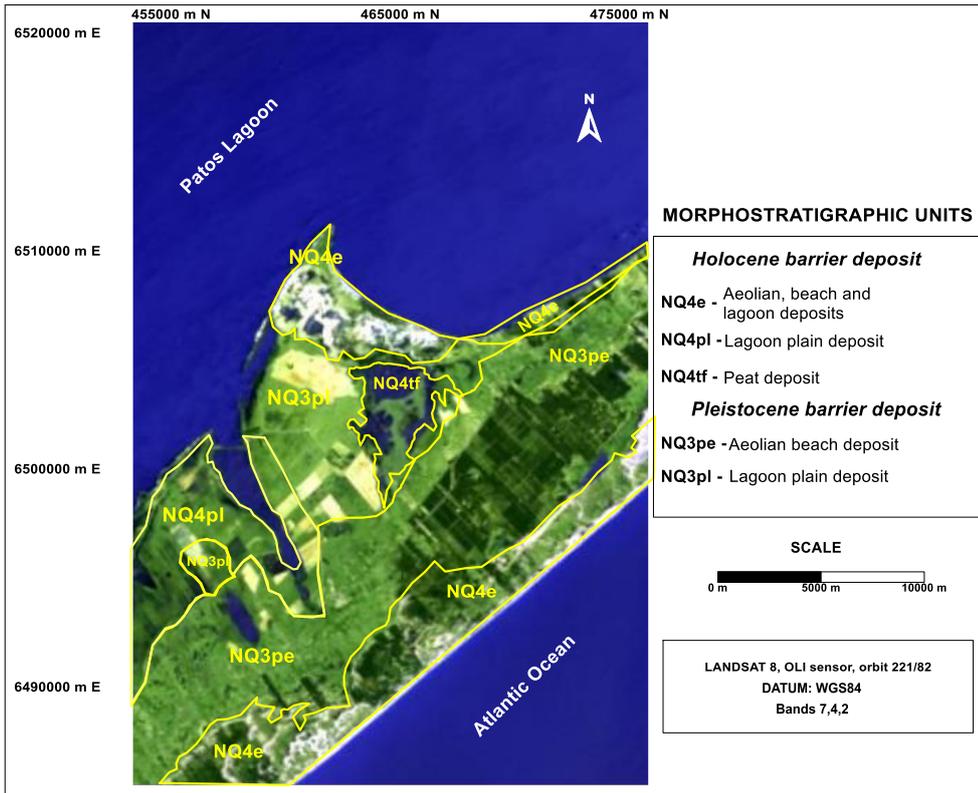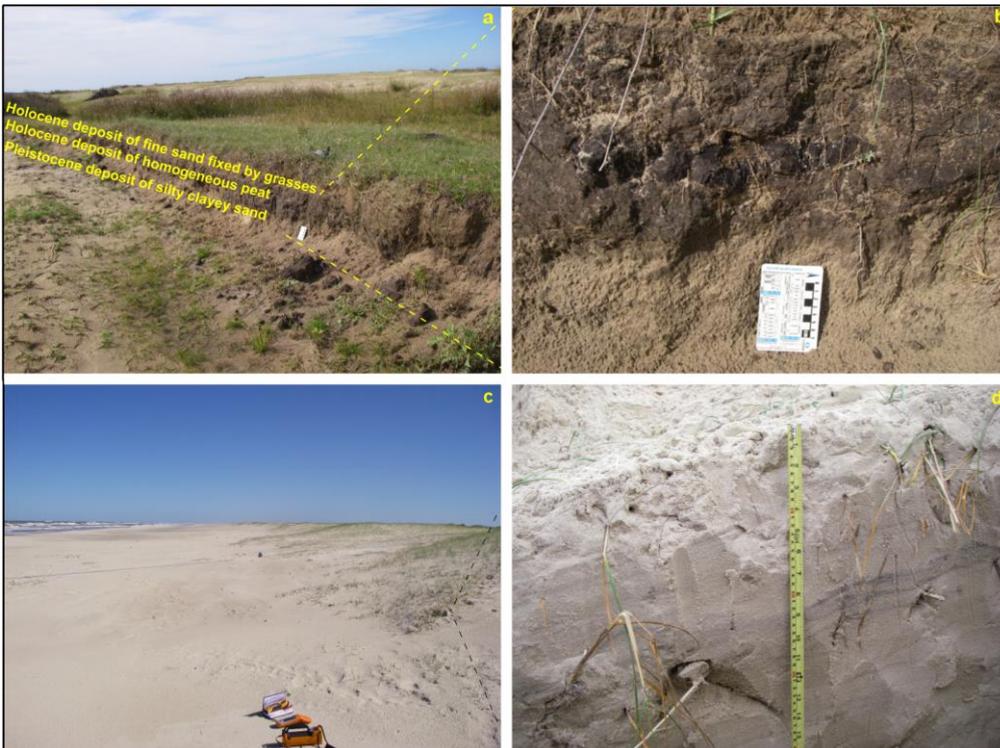
Figure 2: Boundaries of the morphostratigraphic units of the emerged area near Bojuru, São José do Norte, RS.

Figures 3a, b, c, d: View of the layers, (a) of the Pleistocene and Holocene deposits; (b) detail of the homogeneous peat interspersed with Pleistocene deposits at the base and Holocene at the top. Peat thickness 27 cm. Scale 7 cm. Frontal dunes are partially fixed by vegetation (c) stage 4, morphology according to Hesp (2000); (d) incipient parallel plane stratification with heavy mineral laminations.

The highlights on the satellite image were three: the composition of the bands 543-RGB favored the identification of the forms of land use and occupation.

The bands 742-RGB emphasized the morphostratigraphic changes of the Pleistocene barrier III deposits, and the Holocene barrier IV deposits (figures 4a, b, c, d, e).

The vegetation appears in red, the soils from dark brown to light, and the sands of the dunes and clouds are white or light cyan.

According to the morphological stage classification, described by Hesp (2000), the frontal dunes present in the study area are in stage 4, with the presence of embryonic dunes (Short & Hesp 1982; Hesp 1988).

The Holocene transgressive aeolian dunes present in the study area resemble those described by Tomazelli et al. (2005).

In figure 4a, the image of the 1973 Landsat 1 MSS satellite, the largest area with the presence of dunes equivalent to 138.34 km^2 is observed (figure 5).

In figure 4b, image from the 1980 Landsat 1 MSS satellite, aeolian deflation is observed in the portion characterized by the geological map as an aeolian reworked deposit.

In figure 4c, the image of the Landsat 7 ETM+ satellite from 2002, an extensive area of pine, reforestation can be verified on aeolian and dune reworked deposits.
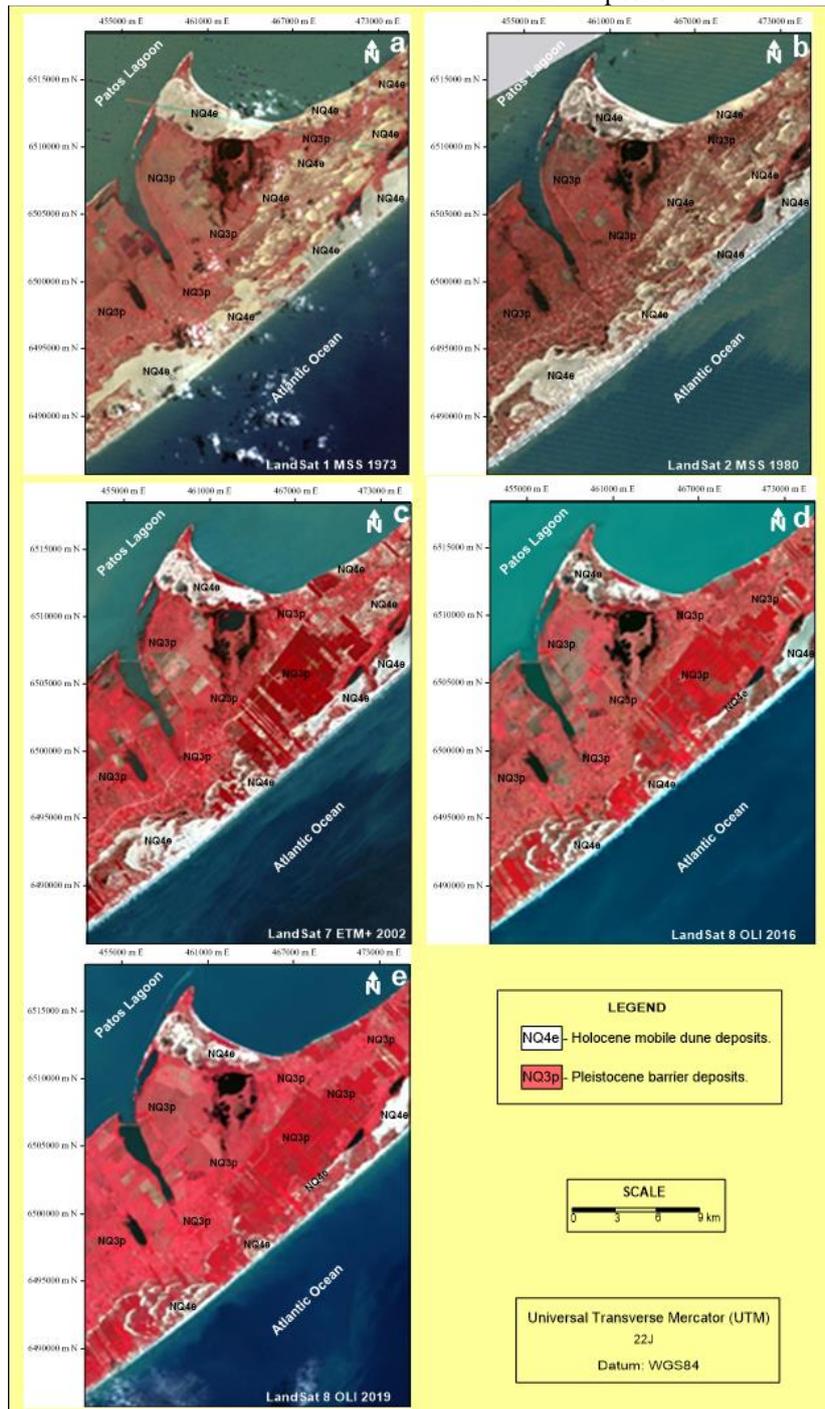
Figures 4 a, b, c, d, e: Analysis of the space-time variation at the limits of the Holocene mobile dune deposits (a) image Landsat 1, 1973; (b) image Landsat 2, 1980; (c) image Landsat 7, 2002; (d) image Landsat 8, 2016; (e) image Landsat 8, 2019.
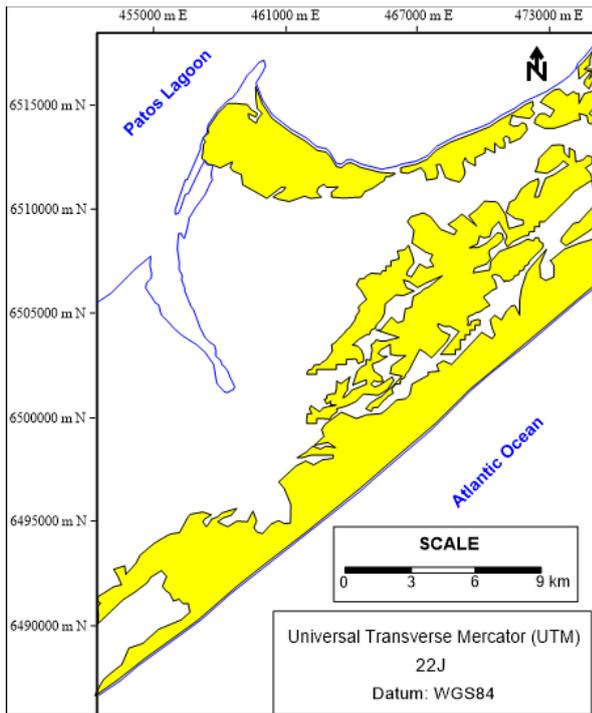
Figure 5: Extraction of the dune area from the 1973 Landsat 1 MSS satellite image.

In figure 4d, satellite image Landsat 8 OLI, 2016, the aeolian reworked deposits practically disappear.

From the limits of the morphostratigraphic units of the geological map of the Geological Survey of Brazil (CPRM, 2008) there is mainly the complete disappearance of the aeolian reworked deposit (figure 6).
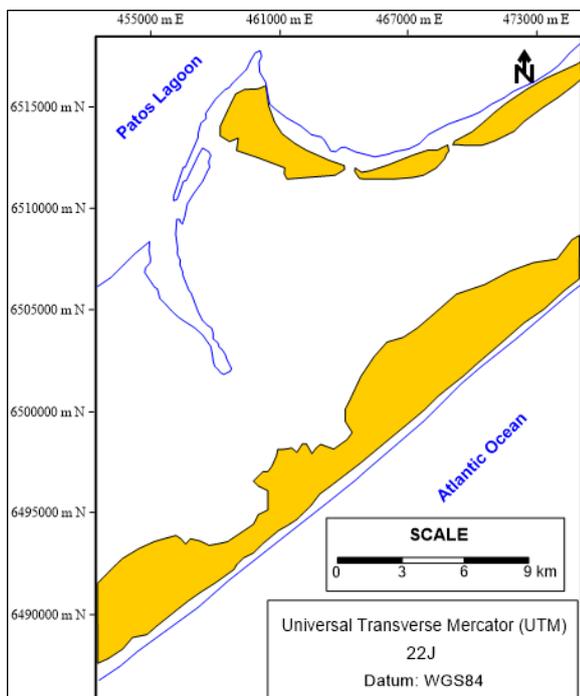

Figure 6: Extraction of the dune area from the Geological Map adapted from CPRM (2008).

The total area of aeolian deposits in the geological map (CPRM 2008) corresponds to 94.67 km^2.

In figure 4e, Landsat 8 OLI satellite image from 2019, there is a drastic decrease in dune and aeolian deposits. The extraction area can be observed with an area of 49.54 km^2 (figure 7).
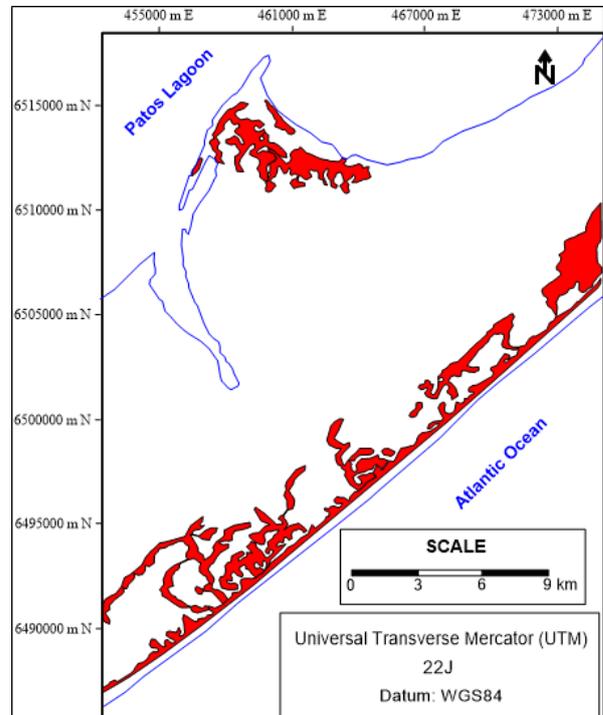

Figure 7: Extraction of the dune area from the 2019 Landsat 8 OLI satellite image.

After 46 years, from 1973, 2008 and 2019 images, the overlapping of the dune extraction areas can be observed in figure 8.

These space-time data show that from 1973 to 2008 there was a 31.6% loss in the aeolian deposit area.

Considering the period from 1973 to 2019, the loss reached 61.2%.

This reinforces that the *Pinus elliottii*, known as slash pine, predominant in the study area, appears in the composition of the images in the darker red color. It is used for reforestation and functions as an anthropic barrier for the migration of transgressive dunes and wind blankets, corroborating Seeliger & Costa (1998).
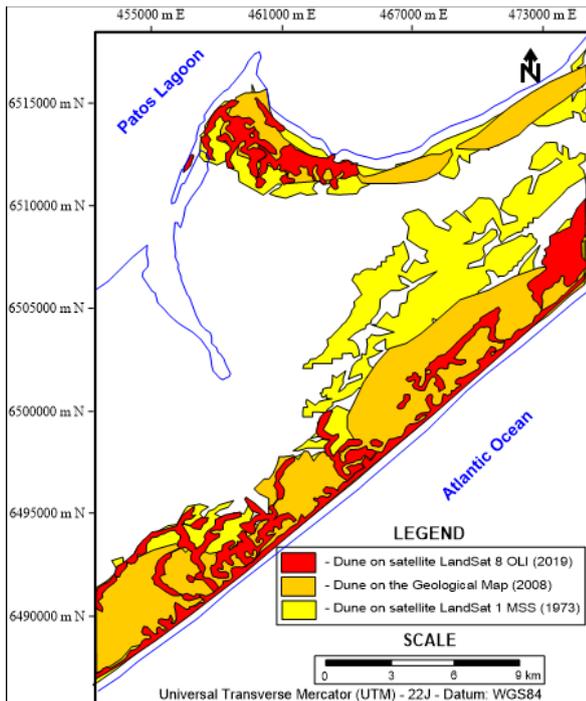
Figure 8: Overlay of the occurrence of aeolian dunes on the Landsat 1 image, MSS sensor from 1973, adapted from Geological Map CPRM (2008), and Landsat 8 OLI sensor image from 2019.

The most intense northeast winds are responsible for the mobilization of the dunes in the area.

Calliari et al. (2005), further south of the study area, in the Estreito region, points out that the coastline is practically parallel to the prevailing NE wind. In this area, there are reduced dunes with a height of 0.5 to 1.0 meters, with medium to large blowouts, besides sandy plains and deflation basins.

The intensity of the winds for the month preceding the 1973 image varied, according to the Beaufort Scale (WMO, 1970), from light air (0.5 m/s) to gentle breeze (5 m/s) with the capacity to transport, according to the scale of Wentworth (1922), coarse silt to medium sand (figure 9a).

For the 1980 image, it varied with minimum light air (0.7 m/s) to moderate breeze (6 m/s) carrying coarse silt to coarse sand (figure 9b) like the 2002 image (figure 9c), which varied from light air (0.6 m/s) to fresh breeze (9 m/s).

For the 2016 image, it went from light air (1 m/s) to moderate breeze (6 m/s) with the transport of very fine to coarse sand (figure 9d).

For image 2019 from light air (1.5 m/s) to gentle breeze (4 m/s), from coarse silt to very fine sand (figure 9e). The grain size fraction of very fine sand (0.062 mm) corroborates as described by Munaro (1994).

According to Seeliger et al. (1998) and reinforced by Figueiredo & Calliari (2005), surface and subsurface water resources are altered as a function of the variation in the water table caused by the *Pinus* plantations near the beach.

Historical rainfall data of one month before the imaging was taken (figures 10a, b, c, d, e).

In one month before the 1973 satellite image was obtained, it rained a total of 14.3 mm (below the monthly average for the period), with a minimum of 0.1 mm and a maximum of 10.4 mm. It represented 13 previous days without rain, with a small rainfall of 0.9 mm (figure 10a).

For the 1980 satellite image, it rained a total of 19.8 mm (below the monthly average for the period) having a minimum of 3.3 mm and a maximum of 13.2 mm. It represented 17 previous days without rain, with a small rainfall of 3.3 mm (figure 10b).

For the 2002 image, it rained a total of 85.3 mm, with a minimum of 0.3 mm and a maximum of 25.5 mm. It represented two previous days without rain, with a small rainfall of 2.0 mm (figure 10c).

For the 2016 satellite image, it rained a total of 75.5 mm, with a minimum of 0.6 mm and a maximum of 23 mm. It represented one previous day without rain, with a small rainfall of 0.6 mm (figure 10d).

For the 2019 satellite image, it rained a total of 28.8 mm (below the monthly average for the period) having a minimum of 0.5 mm and a maximum of 8.3 mm. It represented five previous days without rain, with small precipitation of 7.8 mm (figure 10e).

These pluviometric data serve to demonstrate how high spatial resolution images, drainage, and water bodies become more prominent. Due to their good porosity and permeability, dunes are important water reservoirs.

According to Clark (1977), the dunes act as a barrier against the penetration of saline wedges at the water table, due to the pressure of freshwater in their reservoir.

In the study area, on the coast of the Atlantic Ocean, it was observed 26 kilometric length and 44 intermittent and ephemeral streams and anthropic channels. Eight of them are anthropic channels, corroborating with Figueiredo & Calliari (2005). The distances between the outlets of the channels vary from 182 m to 955 m, representing an average distance of 590 m.

Drainage from the reforestation of the Pinus area leads to the occurrence of permanent artificial channels, observed in the localities of Bojuru.

The number of anthropic channels in the cutout of the analyzed image represents 22.2% concerning the number of channels. This represents a change in the way the waters flow into the Atlantic Ocean.

Although the national tax policy incentives to the reforestation activity began in the 1970s and 1980s, reforestation in the study area occurred only after 1980.

4. Conclusions

Through the combinations of bands 742-RGB of the Landsat 8 OLI, aiming to highlight the geological aspects and treatment of the images, it was possible to superimpose and update the lateral limits of the morphostratigraphic coastal units around Bojuru.

The greatest contrast observed in the infrared false color compositions was between the submerged and emerged portion, highlighting the sand/sea limit, as well as the boundaries between the Pleistocene barrier III, and the Holocene barrier IV.

The forms of use and occupation highlight the reforestation over the dunes and cultivation areas.

The reforestation areas constitute anthropic barriers, decreasing the mobility of available sediments, causing a loss of dunes in the order of 61.2%, in 46 years of monitoring.

It is verified by the existence of eight anthropogenic channels about the natural streams, on the side of the Atlantic Ocean, a modification in the order of 22% in the hydrodynamics of the natural stream and the subsurface flow due to the ways of use and occupation of the soils, mainly by pine reforestation.
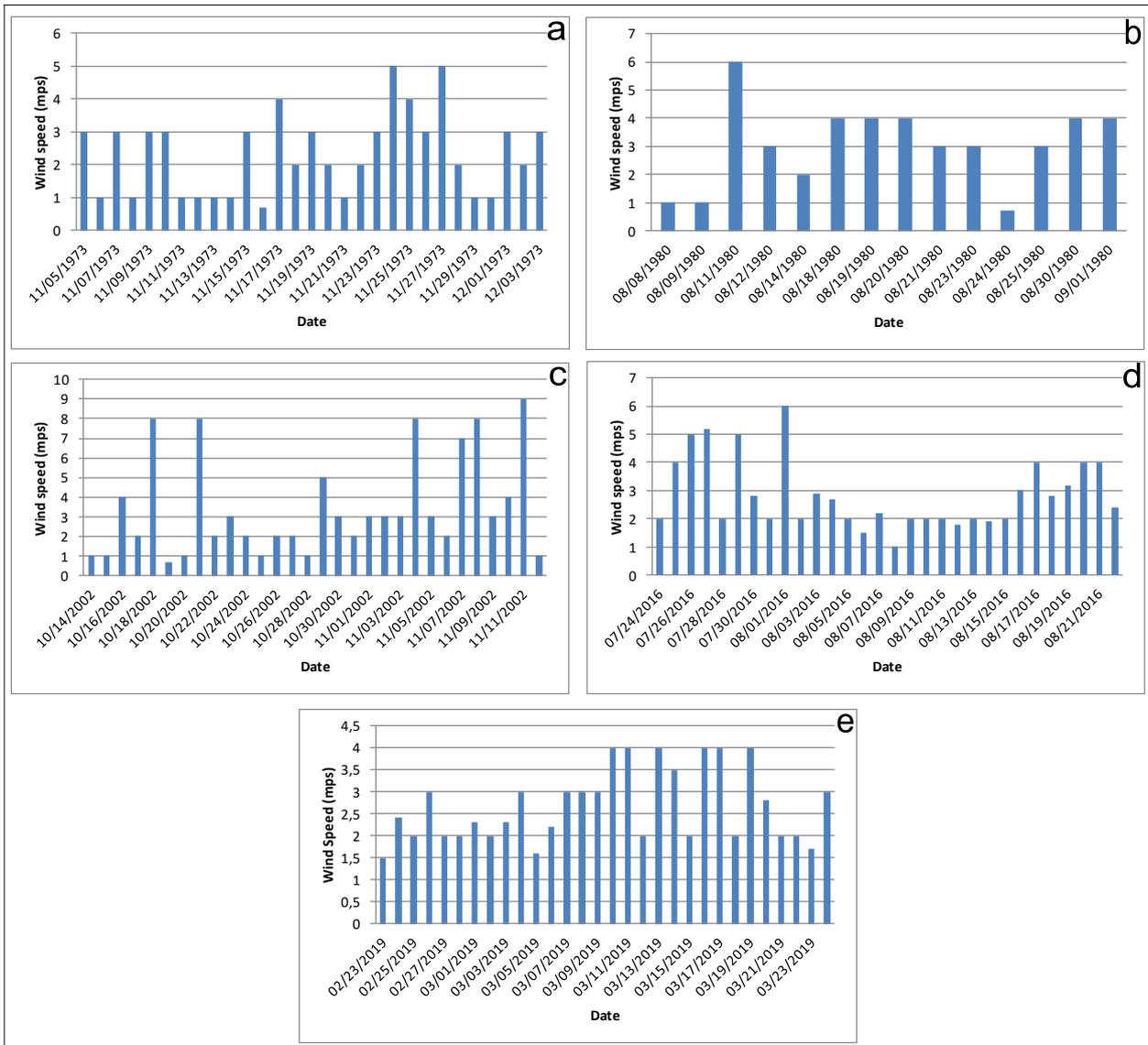
Figures 9a, b, c, d, e: Wind speed column graphics in (mps), 30 days before the images: (a) Landsat 1, 1973; (b) image Landsat 2, 1980; (c) image Landsat 7, 2002; (d) image Landsat 8, 2016; (e) image Landsat 8, 2019.
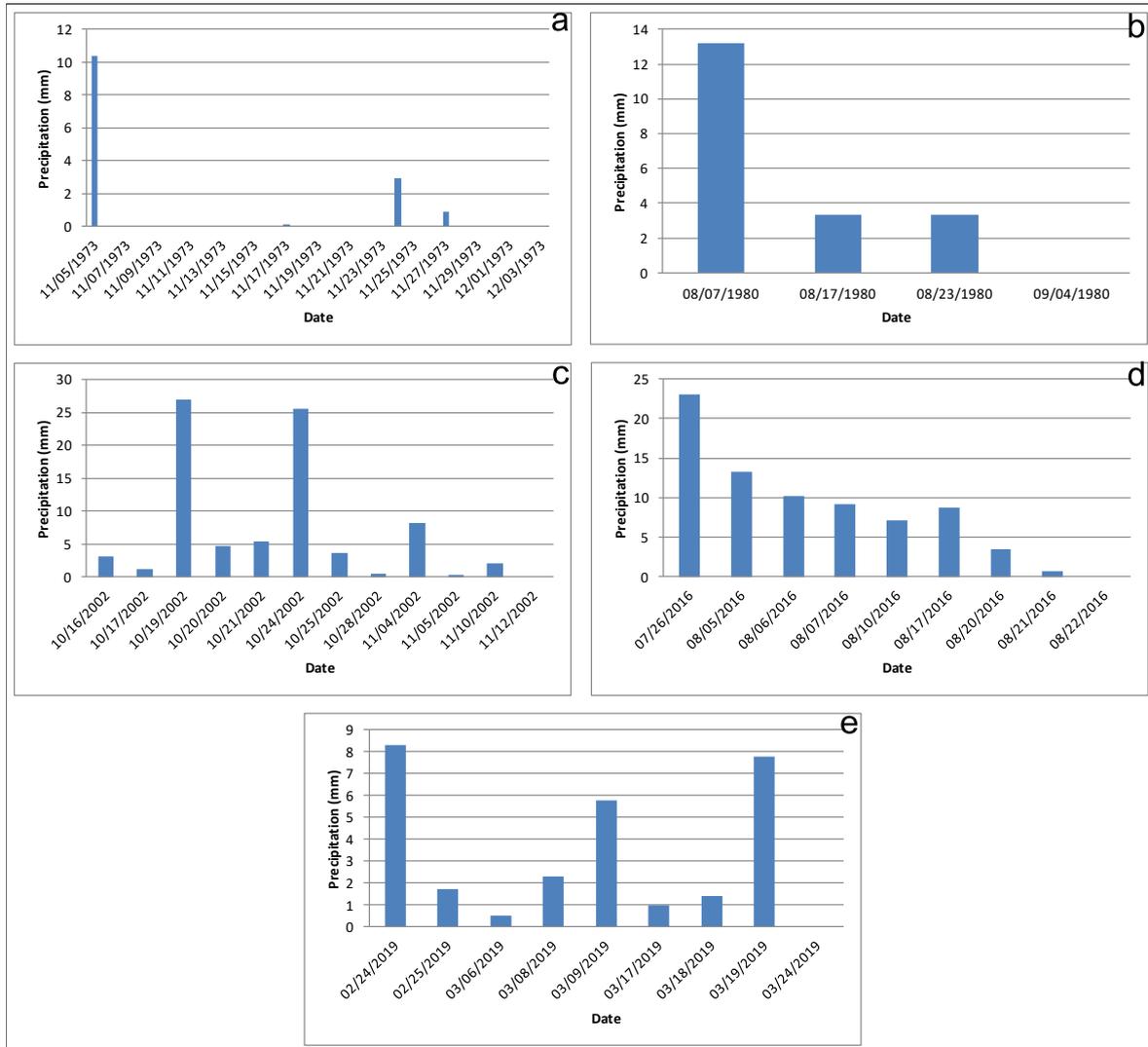
Figures 10a, b, c, d, e: Column graphics of precipitation in (mm), 30 days before the images: (a) Landsat 1, 1973; (b) image Landsat 2, 1980; (c) image Landsat 7, 2002; (d) image Landsat 8, 2016; (e) image Landsat 8, 2019.

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