Degradation of a transgressive coastal Dunefield by pines plantation and strategies for recuperation (Lagoa Do Peixe National Park, Southern Brazil)

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ABSTRACT

The transgressive dunefield of the Lagoa de Peixe Natural Park was modified drastically due to intensive pine plantation and the leeward development of the associated degraded areas. The present study analyzed the disturbances in the dunefield of the Lagoa do Peixe Natural Park due to pine tree plantation and the impact of the subsequent deforestation program conducted in the region. Aerial photographs, satellite images, and DGPS topographic data collected over a 70-year-long period were retrieved, analyzed, and compared, which allowed the observation of the geomorphological evolution of the dunefield. In addition, a profile of GPR on the inlet (during a period with the channel closed) was analyzed. In 1948, the surface of the sand barrier was occupied by high transverse dunes and low barchan dunes. Pine tree plantation on the inner side fixed the transgressive dunes and, consequently, avoided the filling of the shallow lagoon, although degraded areas were generated on the lee side of the pines. Simultaneous pine plantations in the backshore avoided the aeolian sediment input to the dunefield, generating a large interdune area along with the development of a few parabolic dunes, which resulted in cannibalization of the transgressive dunes. In 2001, pine trees occupied 15.03% of the total area analyzed in the present study, while the degraded area accounted for 10.81% of the total area. Progressive deforestation was performed (ring bound technique for tree gradual death), maintaining three lines of pines in contact with the dunes, to promote autochthonous vegetation growth, thereby preventing the filling of the adjacent lagoon with aeolian sediments. By the year 2018, the pine tree plantation area reduced to 3.25%, the dunefield area was 79.03%, and the extension of the degraded areas had increased and reached 17.71% of the total area. The pine tree plantation and the deforestation for conservation purposes are the main factors explaining the degradation of the dunefield during the period between 1948 and 2018, while regional climatic oscillations contributed as the secondary factor. Although internationally controversial, the present case study demonstrates that the removal of this exotic vegetation, through dune vegetation recovery programs, is often unsuccessful and may generate more degraded areas. However, in the case presented here, it was essential to remove the forest to ensure the dune field geodynamics and, therefore, the base (biotope) of the natural system (maintenance of the lagoon and the dunefield).

1. Introduction

Coastal Zone (CZ) has great strategic importance due to the great biodiversity and fragility of their ecosystems and the divergent and conflicting economic interests. The CZ is often subject to development actions vectors in the process of expansion, such as tourism, aquaculture, forestry, installation of wind farms, and large structures (industrial, logistical and/or port) (Esteves et al., 2003; MMA, 2018; Portz et al., 2011a, 2016). These anthropic actions produce major changes in the landscape and loss of biodiversity (Cristiano et al, 2016, 2018, 2016; Diegues, 1999; Ferreira et al., 2009; Rockett et al., 2018), increasing the vulnerability of the coastal ecosystems (Brown and

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McLachlan, 2002; Martínez et al., 2006; Portz et al., 2016).

The coastal dune ecosystem is a highly dynamic habitat representing critical environments from both ecological and landscape perspectives. These ecosystems are not significant producers and exporters of nutrients like many other coastal environments; however, they act as sediment reserves, stabilize coastlines, are recreation areas, and provide breeding and feeding sites for seabirds and other coastal species (Van der Biest et al., 2017). The main actors benefited by the use or impacted by the decrease in the quality of ecosystem services offered by the dunes are the local community and the tourist sector (inns, hotels, restaurants, and ecotourism companies) (Veiga Lima et al., 2016).

Many scientific articles have focused on human impacts on beaches and coastal dunes like tourism and recreational activities, marine litter, the expansion of urban areas and infrastructures and vehicular and pedestrian traffic (Fantinato, 2019; Ivar do Sul and Costa, 2007; Kutiel et al., 1999; Malavasi et al., 2016; de Oliveira et al., 2020; Pinna et al., 2015; Portz et al., 2016; Provoost et al., 2011; Rickard et al., 1994; Schlacher et al., 2011; Thompson and Schlacher, 2008; Villate et al., 2020). However, the study of the impact of introducing exotic vegetation is still scarce (e.g. Alberio and Comparatore, 2014; Campos et al., 2004; Fischer et al., 2014; Kim, 2005; Marchante et al., 2008; Mason et al., 2007; Matthews, 2005; Portz et al., 2011b).

In the last centuries, many countries planted exotic vegetation in coastal dune areas to develop foredunes, stop the migration of transgressive dunes, control coastal erosion, or other economic goals (Choi et al., 2013; Del Vecchio et al., 2013; Hill and Wallace, 1989; Martinez and García-Franco, 2008; Snowdon, 2002; Manríquez-Tirado, 2021; Latorre and Canavero, 2014). In Portugal, for example, *Pinus* sp were planted for timber extraction and to prevent the advancement of dunes inland (Costa et al., 2000). In South Korea, coastal forests were created to protect villages and farmlands against strong winds and sand blowing from the beaches (Kim et al., 2014a). Pine plantation in the LPNP and other coastal dune fields of Brazil was carried out in the 70′ and 80′ decades, promoted by the Brazilian Federal Government, with the purpose of developing wood exploitations. Similarly, in other countries of Southern South America (Uruguay and Argentina) similar projects have been developed (Latorre et al., 2013; Latorre and Canavero, 2014; Rodrigues Capítulo et al., 2018). However, at the time of plantation, the negative impacts of the exotic species due to competition with natural vegetation were not considered (Burgueño et al., 2013).

Pine trees can easily proliferate in areas with high insolation and are independent of soil fertility (Lamprecht, 1990; Moran et al., 2000). They produce shadow areas and chemical alterations of the soil, which prevents the development of native vegetation (Tilman, 1985; Ziller, 2001) and, therefore, affects the natural stabilization of coastal dunes (Kim, 2005). For example, *Acacia longifolia* planted in Mediterranean coastal dunes has spread to new areas, displacing the native vegetation and significantly altering the ecosystems and soil properties (Marchante et al., 2008). In South Korea, invasive plants partially replaced native plants of high reproductive potential, thereby reducing the role of native species on the overall stabilization of sand dunes (Kim, 2005). As a result of these processes, there is a reduction in the populations of native vegetation and the risk of their disappearance (Ziller, 2001).

In the southern hemisphere, the success of *Pinus* sp. dispersion/invasion process in coastal areas is related to its ability to colonize marginal and nutrient-poor habitats (Moran et al., 2000). The rapid growth, the high competitiveness in relation to grasses and woody shrubs (Lamprecht, 1990), and the large reservoir of seeds from the pine plantations maybe explaining the extent of the invasion. On the other hand, dunes's vegetational species generally present characteristics of early succession stages, such as rapid colonization and great dispersion ability, not being adapted to low light conditions and to competition (Tilman, 1985). Besides, the needles of *Pinus* sp. release substances that inhibit the germination of most native species. Water bodies as lakes and lagoons are next to plantations in several places, and thereby they receive the inhibiting substances (Knak, 1999). In addition, pines

plantation difficult recharging coastal aquifers, which are used to increase cultivated areas (Rodrigues Capítulo et al., 2018). The degradation of dunefields related to the presence of exotic vegetation is also observed in the central area of Chile in both short and long term, with changes in wind dynamics and, consequently, a probable modification of the existing aeolian morphologies (Manríquez-Tirado, 2021).

Besides adverse impacts on flora and fauna of many sites (Doody, 2013), the development of exotic invasive vegetation in coastal dunes reduces wind velocity, saline spray, and aeolian sediment input (Kim et al., 2014b). Studies indicate that the barrier influence on the wind flow resulting from pine plantations (or other tree species) generally extends five times from its height to the windward direction (Vigiak et al., 2003; Wang and Takle, 1996 apud Choi et al., 2013).

With the aim of preserving environments with great ecological relevance and scenic beauty in Brazil, the creation of Conservation Units, such as the "National Parks" category, was proposed by the Government. The Lagoa do Peixe National Park (LPNP) was created in 1986 and later designated as a Ramsar site (Wetlands of International Importance) and a Biosphere Reserve due to its importance for ecological conservation. The park includes a complex set of coastal ecosystems (dunes, sandbank, lagoons, and beaches) of extreme importance for migratory birds from the Northern Hemisphere and the southern part of the American continent (Hazin, 2008). The park is including in the Western Hemisphere Shorebird Reserve Network (https://whsrn.org). One of the actions for the conservation and recovery of the LPNP ecosystems, initiated in this century, is the eradication and control of invasive exotic vegetation, especially pine plantations (Portz et al., 2011b). In LPNP, a program of dune vegetation recovery was developed since 2006, with pine trees deforestation actions. The activities were interrupted a few times and stopped in 2008, due to access difficulties and problems related to monitoring activities. During this 2-years period 40 ha were cut and activities returned in November 2011 (Burgueño et al., 2013).

Specifically, in the LPNP case study there is a controversy in these actions, due to the removal of this exotic species may promote the advance of the dunes and may lead to the filling of the Peixe lagoon in the future, by the aeolian sediment inputs. The other possibility is that dune field can gradually return to a more natural stage, where the cyclicality of sedimentary dynamics would prevent the lagoon from filling.

This research aims to analyze the main geomorphological changes in the dunefield on the eastern shore of Peixe lagoon associated with the introduction of *Pinus* sp. forests in past decades and the controlled removal of these plantations since the beginning of this century, in order to assess efficiency and impact of these actions, as well as to propose alternatives for the management of invasive exotic vegetation in coastal dune ecosystems.

1.1. Regional setting

The Rio Grande do Sul (RS, Southern Brazil) coastal plain extends over 620 km alongshore. The northern region of RS state is formed by the Serra Geral Formation (Paraná Basin) scraps; in the southern coastal region of RS, the scraps end into a large alluvial coastal plain. The Coastal Plain of the Rio Grande do Sul (CPRS) is characterized by coastal sandy barriers and lagoons (Fernandez et al., 2019), formed during the Quaternary by the overlap of sedimentary deposits of four barrier-lagoon depositional systems designated from I (325 ka BP) to IV (6 ka BP to Present) by Villwock et al. (1986). Each barrier-lagoon system corresponds to a high-frequency depositional sequence (Rosa et al., 2017; 2011). Dillenburg et al. (2020) presented a smaller scale intermediary system (Barrier IIIa), correlated with the interstadial Marine Isotope Stage 3. The Holocene Barrier-lagoon System IV present contemporaneous sectors showing opposing stacking patterns, with progradational segments separated by retrogradational segments (Barboza et al., 2011, 2018, 2018; Bitencourt et al., 2020; Dillenburg et al.,

2000; Dillenburg and Barboza, 2014). According to Angulo et al. (2006) during the Middle Holocene the sea-level reached a maximum height of +1 to +3 m at approximately 5.6 ka BP, followed by an overall fall until the present. Records of Middle-Late Holocene sea-level oscillations obtained in the study region by Barboza and Tomazelli (2003) and Dillenburg et al. (2006, 2009) fit the envelope curve of Angulo et al. (2006).

The four barrier-lagoon systems - with ages of 325, 230, 125 and 8 ka to recent, respectively (Rosa et al., 2017) - were formed during sea level highstands as identified by Villwock et al. (1986) and represent a high-frequency depositional sequence (Rosa et al., 2017). The Holocene barrier-lagoon is characterized by the formation and migration of a transgressive dunefield barrier, initiated in the final stages of the post-glacial marine transgression about 7–8 ka B.P. (Dillenburg et al., 2006). Simultaneous progradational and retrogradational patterns have been identified in the Holocene barrier of the RS coastal plain (Dillenburg et al. 2000, 2009, Rosa et al. 2017; Barboza et al. 2011, 2018; Barboza et al., 2011). Many different geomorphological features have been developed in the region during the Holocene, such as coastal lakes, lagoons, dunefields, beach ridge and foredune plains.

Coastal dunefield evolution in RS is described by Tomazelli (1994), where transverse dunes evolve to barchanoid chains, and later to isolated barchans dunes. Studies demonstrate that the changes in dune morphology on the RS coast are due to a downwind decrease in sediment supply (Tomazelli, 1994), and climate changes (Martinho et al., 2010; Barboza et al., 2013).

Transgressive dunefields are other abundant morphologies present in the CPRS. The low roughness topography (coastal plain), appropriate wind regimes, and a large supply of quartz fine sand from the beaches of RS contributed to the formation and evolution of one of the most extensive coastal dune systems of Brazil (Tomazelli and Villwock, 1992). Transgressive dunefields are broad aeolian sand deposits formed by the downwind movement of sand sheets and free dunes over vegetated to semi-vegetated terrain (Hesp et al., 2005). These are typically bordered by precipitation ridges, often fronted by deflation basins and plains (Hesp and Thom, 1990). Barchan dunes and barchanoid ridges are common features along the CPRS (Bigarella et al., 2006; Giannini, 1993; Martinho et al., 2010; Tomazelli, 1990). In the marginal portions of the dunefields, there are predominant parabolic sand dunes because of the shortage of sand and more abundant vegetation (Tomazelli et al., 2008). The dunes are present along the entire coast of the CPRS, being drastically reduced in sectors where urbanization is more developed (Esteves, 2004); in urbanized areas only foredunes are formed (Portz et al 2010, 2015, 2016, 2016; Tomazelli et al., 2008).

The regional winds that influence the region are connected to the atmospheric flow over the RS, defined by the dynamics between the Atlantic Subtropical Anticyclone, the intermittent movements of polar masses, and the barometric depression of northeastern Argentina (Camargo and Silva, 2002). The variation of this dynamic results in seasonal wind variations. During spring and summer, the weather in the coastal plain is usually warm and windy, with predominant winds from NE and E; during fall and winter, the area is dominated by cold fronts regularly reaching the CPRS from SW to NE (Nimer, 1989). In response to the prevailing winds, in general, the free dunes migrate toward SW (Camargo and Silva, 2002; Guimarães, 2005; Martinho et al., 2008; Portz et al., 2015; Tomazelli, 1993). In addition, southern Brazil has strong and consistent precipitation anomalies associated with ENSO. It shows an increase in rainfall during El Niño events and a decrease for La Niña events (Grimm et al., 1998; Grimm and Tedeschi, 2009).

1.2. Study area

The Lagoa do Peixe National Park is a wide protected area located in the municipalities of Mostardas and Tavares, in the middle region of the CPRS, over the coastal sand barrier between the biggest Patos lagoon and the Atlantic Ocean. The national park was created in 1986, covering an area of about 34,400 ha. It includes forest, wetlands, marshes, dunes,

beaches, and several lagoons, with the Peixe lagoon being the main water body of the park. The study area corresponds to a sector of about 650 ha of the dunefield in the coastal barrier of the LPNP close to the inlet of the lagoon (Fig. 1).

The Peixe lagoon is about 35 km long, 2 km wide, and approximately 30 cm deep, despite a maximum depth of 2 m can be found in the lagoon channel by the sea (Arejano, 2006). The Holocene transgression and retrogradational evolution of the sand barrier, with lagoon sediments developed over ancient eolian deposits, explain the origin of this lagoon (Dillenburg et al., 2000; Dillenburg and Barboza, 2014; Rosa et al., 2017). The seasonal variation of the lagoon water between fresh and salty depends on the rain inputs and the seawater intrusion. The lagoon is generally connected with the sea by an inlet; however, in some years, littoral drift and intense aeolian sand transport in dry season closes it. Later, the inlet usually opens in the winter by heavy rain; other times, it is artificially opened (MMA, 2013). The peculiar characteristics of this lagoon allow the development of large biomass used as food by migratory birds. However, it is an extremely fragile environment due to the precipitation variability in the region, the low depths of the lagoon associated with the lack of important tributaries, and the aeolian input of sediments because of the transgressive dunes (Portz et al., 2011a). Alongshore, transgressive dunefields cover approximately 45% of the LPNP (Moraes, 2009), with width ranging between 0.8 km close to the Peixe lagoon inlet and 5 km in the northern limit of the LPNP. The dunes are very prominent and better represented in the northern area with 15 m high barchan dunes perpendicularly orientated to the NE wind direction (Knak, 1999).

Several human activities had been developed in the LPNP during the last decades, and are presently causing high ecological impacts, such as the artificial opening of the Peixe lagoon inlet, drainage channels to the lagoon, buildings, intensive fishing, and plantation of exotic vegetation (*Pinus elliottii)* (Crippa et al., 2013; Portz et al., 2011b).

2. Materials and methods

2.1. Remote sensing: spatial distribution of aeolian forms and exotic vegetation

Remote sensing products, such as vertical aerial photographs (for the years 1948 and 2001) and high-resolution satellite images from Google Earth® (for the years 2003, 2005, 2011, 2014, and 2018), were used in this study. Aerial photographs were digitized and georeferenced in the ArcMap® software using control points (notable points) collected in fieldwork using DGPS. All the remote sensing products were reprojected to the UTM projection (zone 22S) and WGS84 datum. A minimum of 10 control points for image was used in the georeferencing process, and the mean squared error was less than 1.0 m. Satellite images were also georeferenced using the same control points. The use of images from Google Earth is a technique already established in several publications (Hu et al., 2013; Liang et al., 2018; Lipp-Nissinen et al., 2018; Lorenz et al., 2013; Ludwig et al., 2016; Portz et al., 2014; Qi et al., 2016; Revollo Sarmiento et al., 2016). Photointerpretation techniques were used to analyze the products, in order to obtain a spatio-temporal analysis for the period 1948–2018 of (i) the evolution of aeolian forms over time and (ii) the influence of pine plantations in the dunefield area, their later removal, and natural dispersion.

The dune slipfaces and crests were used to mapping dunes by photointerpretation. These morphologies correspond to light or dark linear ridges in the images, depending on the relationship between the lighting configuration (subsolar azimuth) and the trends and types of dunes (Vaz et al., 2015). Each dune was analyzed and vectorized considering these characteristics. These features were mapped using a line segment (vector data).

Areas with exotic vegetation forestry were manually delimited in digital vector georeferenced files (polygons) by aerial and satellite images visual interpretation. The verification/validation of the polygons
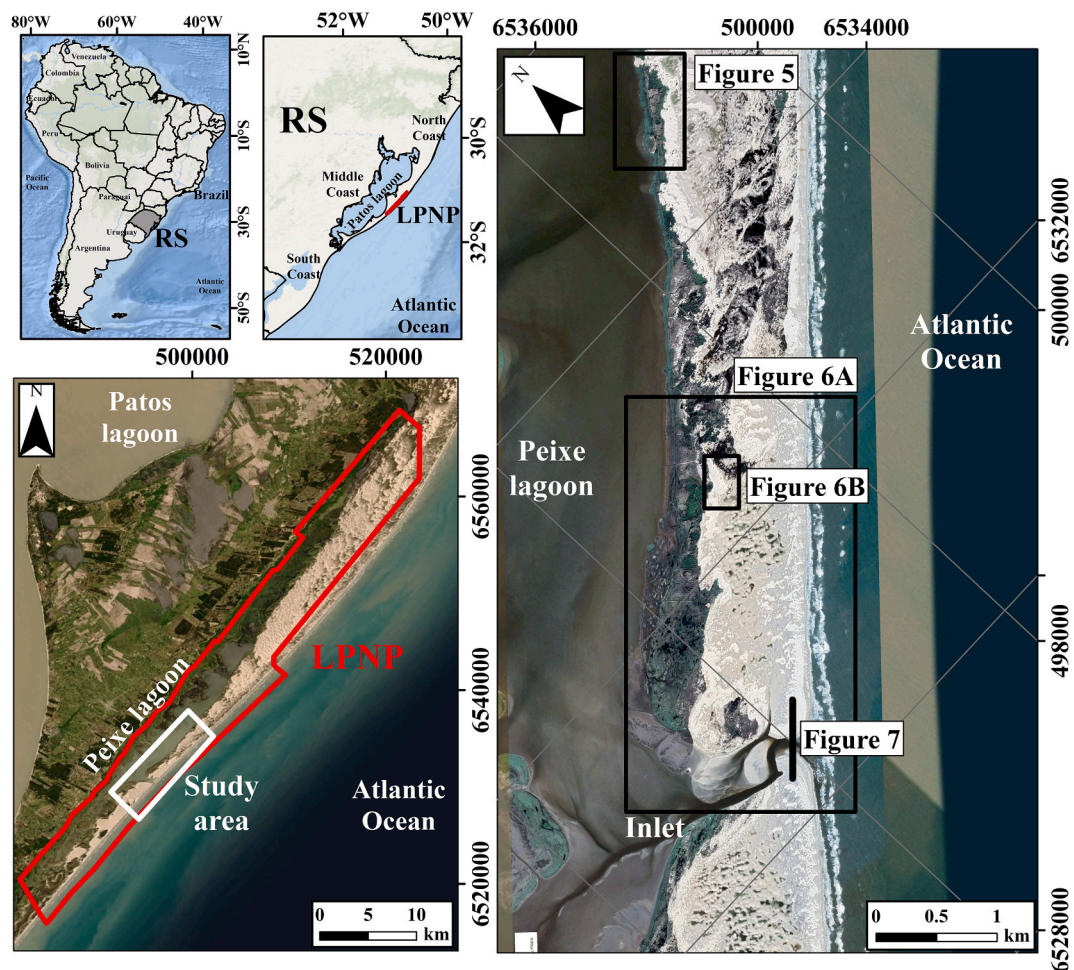
Fig. 1. - Location of the study area on the Middle coast of Rio Grande do Sul - South of Brazil. (Basemap Arcgis 10.6 - UTM-WGS84-Zone22S). LPNP: Lagoa do Peixe National Park.

was performed in field work with the use of DGPS and drone. This method requires a greater capacity for interpretation by the operator and is time intensive as each polygon should be analyzed individually. Nevertheless, it may be considered as the best way to work because automatic and semi-automatic image classifications often generate errors (Portz et al., 2011b). All the analysis, interpretation, and quantification procedures were performed using Geographic Information System software (ArcMap® 10.6).

2.2. Mapping with Global Navigation Satellite System

In a small sector of the central zone of the study area, topographic surveys of the dune crest were carried out before (2010) and after (2014, 2015, 2016, and 2018) the removal of pines in the sector. The survey was performed using the DGPS-RTK in stop-and-go mode with the metric planar and an altimetric precision of less than 1 cm in all collections. The ArcMap® 10.6 calculated the dune crest displacement.

2.3. Ground Penetrating Radar (GPR) survey

The GPR profile was acquired when the inlet was closed using a RAMAC model of the MALA GeoScience data acquisition system with a central frequency of 200 MHz and a two-way travel time range of 125 ns reaching a penetration depth of 6 m. High pass, stacking, and gain filters were applied during the data acquisition. The profile orientation (Fig. 1) was surveyed using the common offset method above the backshore deposition with the closed inlet. For positioning the profile, the GPR had

a Global Navigation Satellite System (GNSS) Trimble® ProXRT unit, datum WGS84. For the present study, the profile was post-processed with Reflex-Win®, Radan™, and Prism2® software packages, followed by trace analysis to validate the depositional environments according to Leandro et al. (2019), background removal, band-pass frequency filter, gain equalization, and time to depth conversion. A dielectric constant of 10 was used for wet sand to convert travel-time to depth representing a velocity of 0.09 m/ns (Daniels et al., 1995). The interpretation of the data was conducted by the method of seismostratigraphy (Payton, 1977) adapted to GPR (Neal, 2004) based on terminations (onlap, downlap, toplap, and truncations), the geometry of reflection, and stacking patterns (Abreu et al., 2010; Neal et al., 2016).

3. Results

3.1. Dune system evolution

Drastic changes occurred in the study area during the last 70 years, where the type, number, size, and location of the dunes changed significantly, and the extension of the dunefield showed high variations due to the development of pine plantations and degraded areas. The total extension of the study area slightly ranges between 614 and 637 ha, mainly because of the spread of the aeolian deposits from the sand barrier toward the Peixe lagoon and particularly toward the inlet, while the shoreline in the seaside of the sand barrier remained stable (Figs. 2 and 3).

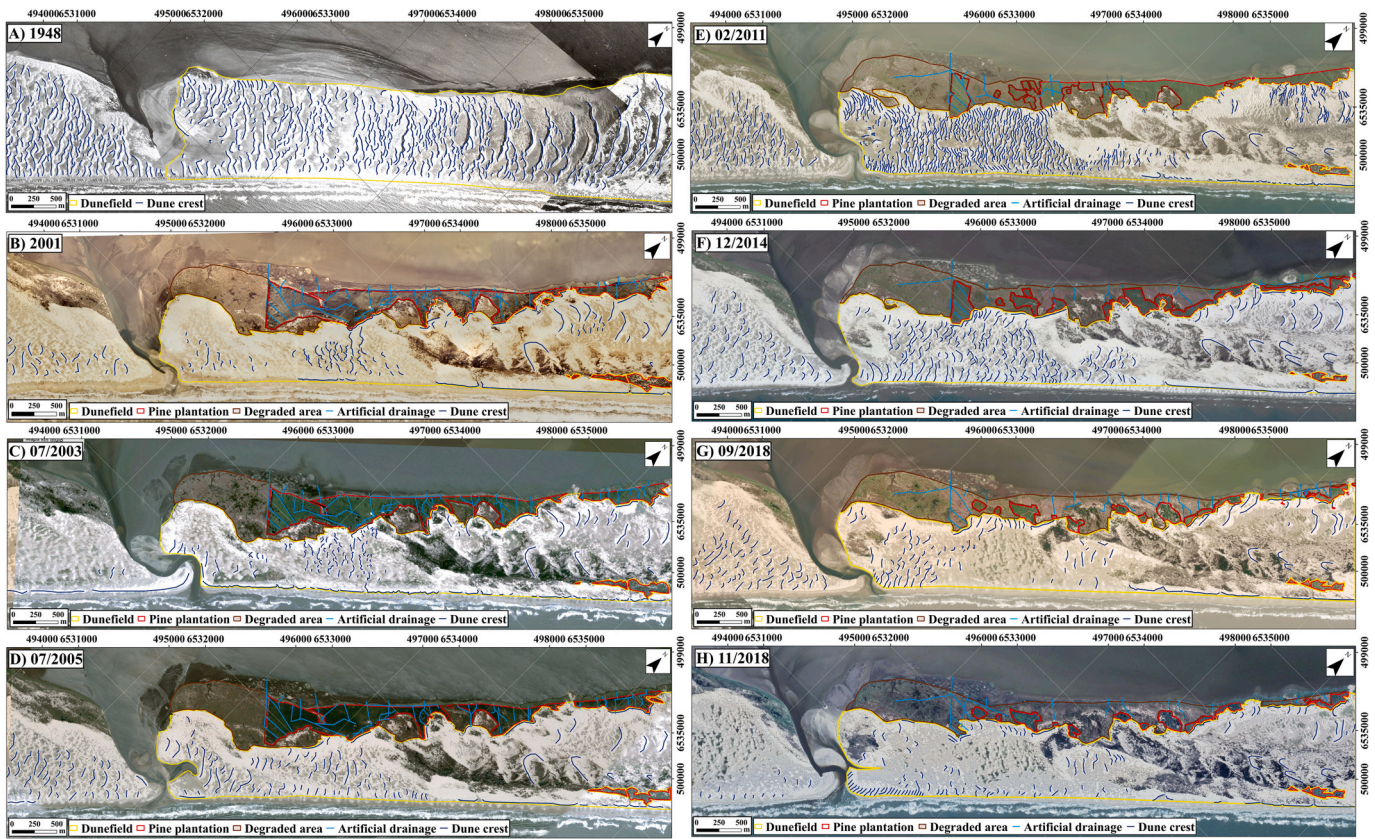In the initial natural stage (1948), a high volume of aeolian

Fig. 2. Evolution (1948–2018) of dunefield, pines plantation, and degraded area (Base images: aerial photographs from 1948 to 2001, satellite images from 2003 to 2018).
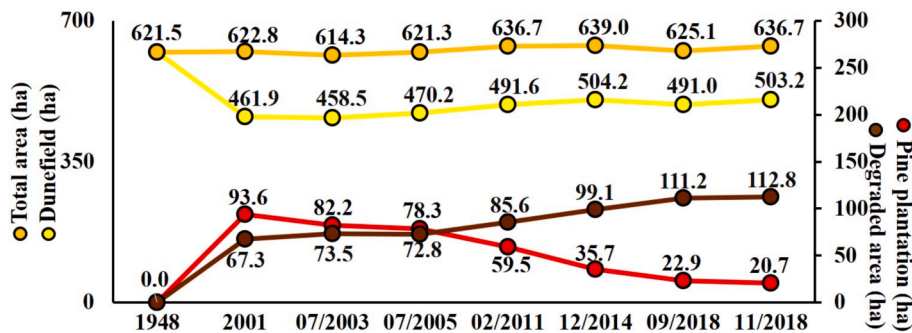

Fig. 3. Evolution (1948–2018) of the total area, dunefield, pines plantation, and degraded areas extension (ha). The pines plantation was carried out in the 70 and 80 decades, from 2001 to 2005, the pines plantation were reduced by wood exploitations, and since 2006, the controlled deforestation for dunefield recuperation began; however, only a small portion of the deforested area became transgressive dunefield again.

sediments was present in the dunefield, with a predominance of high transverse dunes in the northern sector and low barchan ridges in the southern section, isolated by interdune areas, without vegetation, and covering all the sandy barrier (621.5 ha) between the Peixe lagoon and the Atlantic Ocean. Dune crests were mainly orientated cross-shore (Fig. 2A).

In the year 2001, because of the intensive pine plantations during the 70–80 decades, the dunefield area reduced to 462 ha, i.e., it had reduced to 74.17% of the initial area (Fig. 3). A total of 15.03% of the study area was occupied by pine plantations, mainly located in the landward side of the sandy barrier and some minor areas in the backshore or foredune of the northern sector. Downwind of the pine plantations, another 10.81% of the dunefield was degraded containing dispersed pines, bushy vegetation, some pathways, and several country houses. The transgressive dunes were stabilized in the contact between the dunefield and the pine

plantations (Fig. 4). Developed foredunes were present in the sea limit with the crest parallel to the shoreline. An extensive interdune area was developed in the central and the northern sectors because of the interruption of aeolian sediment input due to pine plantation in the foredune. It was overlaid by sand sheets due to the cannibalization of the ancient big transverse and barchan ridges. In these interdunes areas, the formation of parabolic dunes is observed, influenced by the increase in humidity and vegetation in this sector (Fig. 2B).

In 2003, the dunefield presented the lower extension (≈458 ha) over the studied period (Fig. 3). Most of the barchan ridges dimensions were reduced. The foredunes were continuous alongshore, and a new large interdune area had developed close to the Peixe lagoon inlet. The big interdune area in the central sector showed a similar extension to the one that occurred in 2001, and the cannibalization of the ancient big transverse dunes continued. In addition, a subaquatic lobe was formed

Fig. 4. Transgressive dune stabilized by *Pinus* sp. plantation.

in the Peixe lagoon inlet by aeolian sand transport from the dunefield; however, the meandering evolution of the inlet eroded the seaward limit of the dunefield (Fig. 2C).

The sedimentary pattern in 2005 was similar to the previous years. Nevertheless, some changes were identified. For example, the dunefield area increased to 470.2 ha (Fig. 3) and the foredune reduced to 50% of the previous extension. The interdune area in the back of the foredune also reduced and was replaced by cross-shore transverse dunes. The size of some barchan ridges increased. The Peixe lagoon inlet presented a rectification, which is unknown if was due to natural or artificial causes, and the previous channel was partially filled (Fig. 2D).

The extension of the dunefield significantly increased from 2005 to 2011, reaching up to 491.6 ha (77.21% of the total area), and there was also a big increase in the number of barchan dunes, mainly in the southern sector of the study area. In the central sector, the aeolian input of sediments reduced the extension of the big interdune area, where the cannibalization of the ancient big transverse dunes continued (Fig. 2E). The area occupied by pine plantations was reduced to 59.5 ha (9.34%); however, a higher increase in the extension of the degraded areas was identified, which covered 85.6 ha (13.44%) in 2011, which means that many of the areas with pines plantation were then replaced by degraded areas (Fig. 3).

The dunefield reached a maximum of 504 ha (Fig. 3) in the year 2014. In the landward limit of the dunefield, the dunes reduced their dimensions and migrated over both degraded areas and deforested areas. Inside the dunefield, the number and size of barchan ridges increased, and the dimension of the big interdune area in the northern sector reduced. The foredunes area also decreased, with an increase in the cross-shore transverse dunes. Submarine fans were developed in the Peixe lagoon inlet by aeolian sediment input, and it again acquired a more curved form (Fig. 2E).

In 2018, a small reduction in the dunefield extension was observed (491 and 503 ha in September and November, respectively), mainly due to the northward migration of the Peixe lagoon inlet. However, the landward migration of the dunes and the reduction of the big interdune area in the central sector continued, because of the aeolian input of sediments. The number of dune crests decreased, and sand sheets covered most of the interdune area in the southern sector. In the back-shore, a continued reduction of the foredunes area and the formation of cross-shore transverse dunes close to the inlet were observed (Fig. 2F). The deforestation resulted in a minimum (residual) area of pine plantations (22.9 and 20.7 ha in September and November, respectively). However, most of these areas with pine plantations were again mainly replaced by degraded areas, which continued their expansion, reaching up to 112.8 ha at the end of the studied period (Fig. 3).

3.2. Controlled deforestation of exotic Pinus sp. plantations

The maximum expansion of pine plantations occurred in the year 2001, reaching up to 93.6 ha. In the next few years, the area of pine plantation slightly reduced due to small-wood exploitations. However, since 2006, the controlled deforestation in the LPNP and the migration of the reactivated transgressive dunes drastically reduced the pine plantation areas. Controlled deforestation was progressively carried out in the landward limit of the dunefield from the northern to the southern sector; it was not carried out in the foredune. During the deforestation process, most of the pine trees were cut, and the remaining few lines of pine plantation that were in contact with the dunefield were preserved (Fig. 5D). As a result, the extension of pine plantations in 2018 was distributed only in isolated areas and covered 22.11% of the initial area in 2001 (Fig. 3). The residual pine plantations prevented the aeolian input of sediments from transgressive dunes to the lagoon; however, the input of sediments occurred where the natural or artificial drainage channels intersected the pine plantations developing washout deltas and swamp areas into the lagoon (Fig. 5).

After pine trees deforestation, the landward limit of the dunefield migrated toward SW with a maximum displacement of 320 m between 2001 and 2018 in the central sector (an average of 18.82 m per year; Fig. 6A). The topographic monitoring of a transgressive dune, previously retained by the pine plantation, confirmed its migration toward SW after deforestation with maximum and minimum displacements of 83.1 m and 19.7 m, respectively, and an average migration rate of 4.61 m per year between 2010 and 2018 for the dune crest (Fig. 6B).

3.3. Sediment filling and evolution of the peixe lagoon inlet

The southern part of the Peixe lagoon inlet has a deeper channel with semi-fixed characteristics and presented almost no modifications in location over the decades. However, in the northern portion, the inlet varied over the decades with periods of complete closure, i.e. in 1948 (Fig. 2A). The geophysical profile indicated the presence of a filled paleochannel. The sedimentary record of the sand barrier showed the formation of three depositional units. The reflection of the signal, onlap, and downlap structures occurred on three surfaces with excavation characteristics (Fig. 7). The older Unit I was composed of beach sediments related to the lateral progradation of the sand barrier. Over it, the Unit II corresponded to the sediment filling of the inlet channel. Finally, the Unit III corresponded to the closure of the channel due to the overlapping of aeolian sediments and the spread of the sand barrier.

4. Discussions

4.1. Wood exploitations and the degradation of coastal dunefields

The costal sector of the LPNP is considered a transition between the southern sector of the CPRS, with transgressive shoreline migration and retrogradation of the coastal sediment environments, and the northern sector of the CPRS, with a regressive shoreline migration and progradation of the coastal deposits (Barboza et al., 2018; Bitencourt, Dillenburg, et al., 2020; Rosa et al., 2017; Dillenburg and Barboza, 2014). It
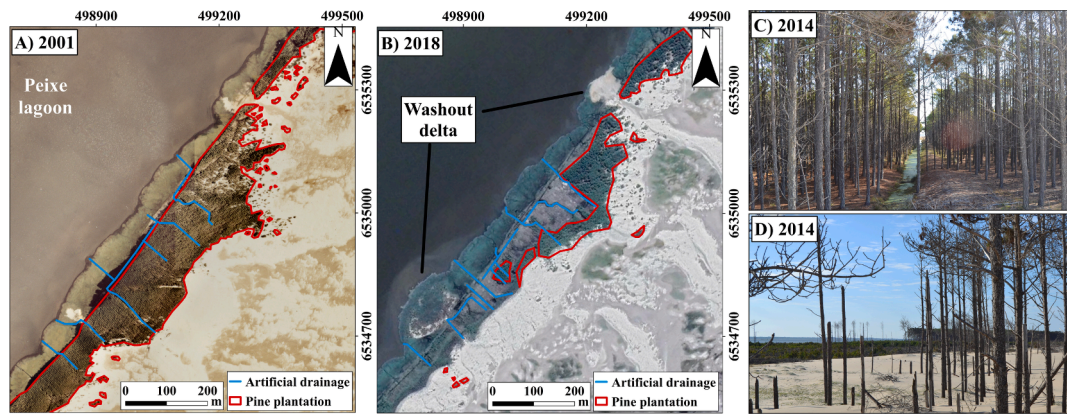
Fig. 5. Details of pine deforestation (refer Fig. 1 for location). A) before deforestation (aerial photograph), B) after deforestation (satellite image), C) Artificial drainage channel, and D) stripe of pines kept in place in the landward limit of the dunefield. Note the development of washout deltas at the end of both the northern natural drainage and the southern artificial channel.
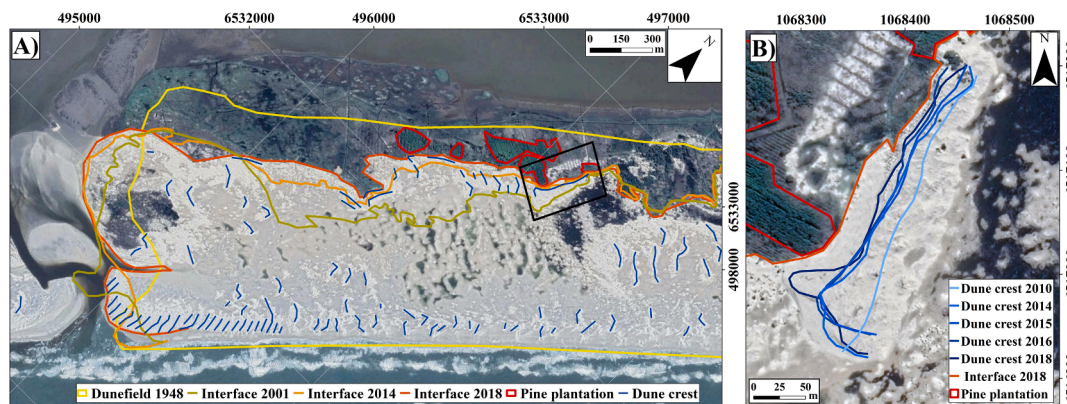
Fig. 6. Evolution of the limits of the transgressive dunefield due to pine plantations and subsequent deforestation A) migration of the interface, B) westward migration of a dune crest before (2010), and after (2014–2018) deforestation (base: satellite image November 2018). "Interface": interface between dunefield and degraded area.

explains the stability of the shoreline in the study area (Fig. 2). Consequently, the availability of aeolian sediments from the beaches must be similar for the whole studied period. Nevertheless, the development of foredunes with maximum extension in 2003 denoted a reduction in the input of sediments to the dunefield and the consequent formation of interdune areas with sand sheets and parabolic dunes on the back of the foredune.

The evolution of the study area that remains occupied by the dunefield is in accordance with the geomorphologic model for the central sector of Rio Grande do Sul, in which transverse dunes and barchanoid chains change to isolated barchan dunes, low parabolic dunes, and flat sand sheets (Martinho, 2008; Martinho et al., 2010). Parabolic dunes are restricted to the humid sector close to the coastline, where pine plantations are also present. In fact, in the 70' decade, a high increase of vegetation cover was identified for the transgressive dunefields in Southern Brazil, which was related to the variations in the wind regime, increase in rain precipitation, and reduction in aeolian sediment transport. These processes were related to the effects of both ENSO and polar fronts (Mendes and Giannini, 2015; Miot da Silva et al., 2013). An increase in the precipitation in the last 60 years was also identified in northern Buenos Aires province (Argentina) with a consequent increase of vegetation cover and a decrease of dune migration rates (Marcomini and Naidana, 2006). In addition to these changes in wind regime and rain precipitation, pine plantations in this sector (close to the beach) have a direct influence on the formation of these parabolic dunes.

Beyond the natural increase of vegetation cover and the decrease of dune migration rates, in 2001 the LPNP pine plantations covered 15.03% of the total dunefield area (Fig. 3). Therefore, the windbreak due to the plantation produces the stabilization of sand dunes (Metwally et al., 2016; Scottá et al., 2015). Moreover, wind velocity is reduced to half in the leeward side of the forest, compared with the significantly less reduction behind brush for example (Choi et al., 2013). This bulkhead to wind flow due to pine plantations (and other trees) extends over five times their height (Vigiak et al., 2003; Wang e Takle, 1996; apud Choi et al., 2013). In the windward side of pine plantations in the LPNP, transgressive dunes were stabilized (Fig. 4); while in the leeward side of the pine plantations, extensive degraded areas with minor pine areas growing by natural dispersion and other exotic vegetation were developed (Figs. 2 and 3).

An additional impact of the pine plantations in the coastal areas has been identified in the LPNP, where construction of artificial drainage channels from pine plantations areas to the lagoon generated sediment inputs to the Peixe lagoon, developing washout deltas and swamp areas (Fig. 5). The number of drainage channels varies according to the area occupied by the plantations. In 2001 there were 26 drainage channels in the study area, being reduced in November 2018 to 12. In Fig. 5, the washout delta areas increased from 16,50 to 24,19 m^2 between 2001 and 2018, due to drainage of the dunefield area. The Peixe lagoon is very shallow and, therefore, the migration of transgressive inputs implicates a risk for their conservation (Portz et al., 2011a). The pine plantation contributed to stabilizing the transgressive dunes; however, their artificial drainage channels generated a partial filling of the lagoon (Fig. 5).

The main reduction of the dunefield extension occurred close to the lagoon, where pine plantations were mainly developed. However, a
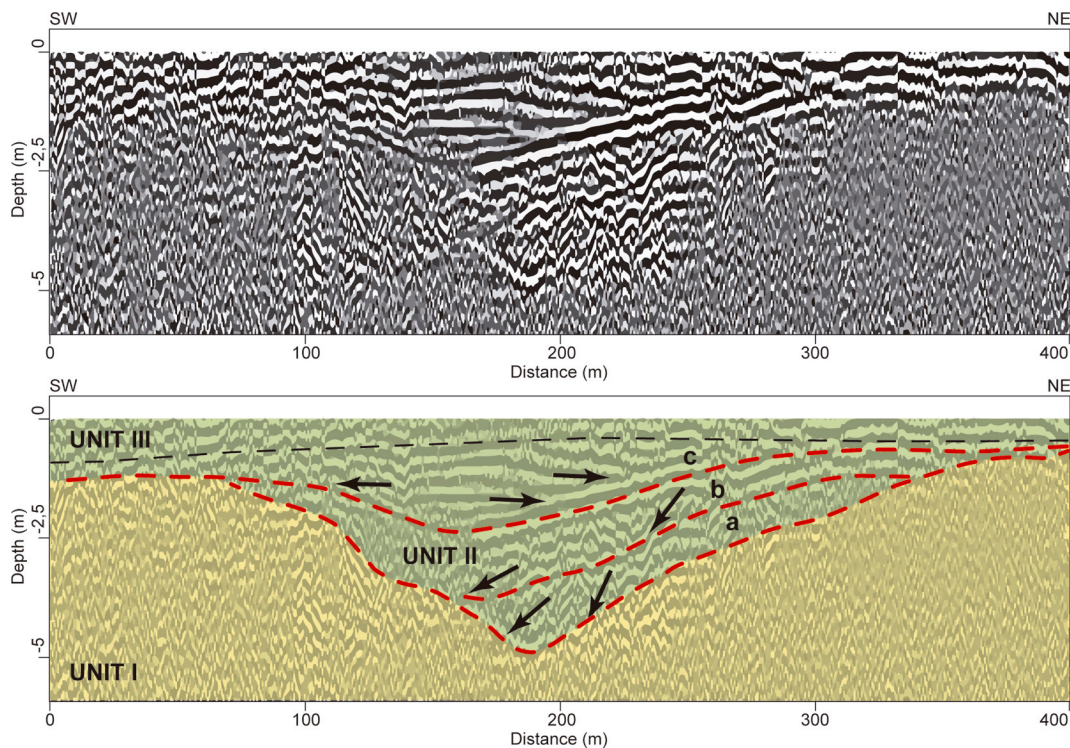
Fig. 7. Ground Penetrating Radar (GPR) profile acquired above backshore deposition (refer Fig. 1 for location), where three stratigraphic units/processes are defined: progradation of the ancient sand barrier (Unit I); sediment filling of the inlet channel by sedimentary aeolian transport (from NE to SW) (Unit II a, b) and littoral drift (Unit II c); overlapping of aeolian sediments after closure of the channel (Unit III).

great interdune area was also developed in the leeward side of the foredune with pine plantations in the central sector of the study area. Cannibalization is a natural process in transgressive dunefields (Finkl and Makowski, 2019), but in the LPNP, the cannibalization of high transverse dunes was induced by the pine plantations in the foredunes, which prevented the input of sediments into the back transverse and barchan dunes, which finally were degraded to sand sheets and parabolic dunes (Fig. 2).

Therefore, the development of pine plantations and associated degraded areas, combined with the regional climatic oscillations are the causes that explain the drastic reduction of the LPNP dunefield extension from 1948 to 2001, along with the changes in the morphology, size, and the number of active dunes (Figs. 2 and 3).

The intense aeolian transport in the study area modified the total extension of the dunefield (Fig. 3), mainly because of the output of sediments filling the Peixe lagoon close to the northern margin of the inlet (Figs. 2 and 6) and even generating some temporary closures of the inlet (Figs. 2A and 7).

The acquired subsurface data demonstrate that the Holocene barrier in this sector has an evolution affected by the erosion of the Peixe lagoon inlet. Because the direction of the dominant littoral drift in the CPRS is towards the north (Absalonsen & ToldoJR, 2007; da Motta et al., 2015), when inlet dynamics export these sediments, they return to the beaches that supply sediments to the dunefield. This dynamic is evident through the analysis of the Ground Penetrating Radar (GPR) profiles (Fig. 7), where it was possible to differentiate three stratigraphic units and the mentioned two processes. The formation of the barrier for progradation of ancient sediments previously (Unit I) to the formation of the inlet. Where the filling of the inlet occurs initially by the predominant sedimentary transport in the dunefield from NE towards SW, as recorded by the reflectors in downlap of Unit II (a, b). Subsequently, the coastal drift builds a bar that closes the inlet (Unit II c). Finally, with the inlet closed, the dune field transgresses and interrupts the natural cycle of sediments, marked by Unit III reflectors. This feedback of aeolian sediments was

previously observed in other inlets in Brazil (Barboza et al., 2014; Biancini et al., 2014; Leal et al., 2016). After the pine plantations and development of degraded areas, this output of sediments from the dunefield to the inlet occurred over a narrower area (Figs. 2 and 6A).

4.2. Deforestation and partial dunefield recuperation

Dunefield deforestation has been carried out in several countries during recent decades in order to achieve remobilization of vegetated dunes and remove of invasive plant species (Arens et al., 2012; Pye et al., 2014; van Boxel et al., 1997), despite some controversies (Doody, 2013). Pine plantations in the LPNP coastal dunefields were considered exotic and invasive species. Therefore, under the jurisdiction of the Brazilian Federal Government, the environmental authorities of the LPNP began deforestation in 2006. This controlled deforestation was interrupted in 2008 and restarted in 2011 (Burgueño et al., 2013). The reduction of the pine plantations was mainly carried out close to the Peixe lagoon (Fig. 2).

The controversy in the case of the LPNP deforestation is higher because the resultant drift direction of the aeolian sediment transport is toward WSW-W (Martinho, 2008) and, therefore, deforestation of pine plantations might generate high sediment inputs to the Peixe lagoon (Portz et al., 2011a). In order to avoid this risk of sediment filling of the lagoon, a progressive replacement of the pines by native bushy vegetation was performed. The techniques indicated for the deforestation were:

- Maintenance of three parallel lines of pine in the interface with the dunefield with a low density (about 120 trees per ha) to permit insolation and re-colonization by the native shrubs. These remaining trees were ring bound to produce their gradual death, while they acted as a partial bulkhead to the wind, nesting areas for the avifauna, and a barrier to the input of vegetal rests to the lagoon (Bechara et al., 2013).

- The deposition of seedless dry branches over the dunes close to the remaining trees in order to reduce the aeolian sediment transport, based in successful projects for foredune regeneration in the region (Portz et al. 2015, 2016).
- Continuous monitoring of the deforested areas due to the high potential of pine for natural dispersion and the manual retreat of incipient pines growing in. In other regions, the control of natural pine dispersion after deforestation is carried out by controlled burning (Tu et al., 2001).

Dune deforestation in the inner margin of the dunefield of the LPNP produced a drastic reduction of the bulkhead to wind flow and, consequently, changes in the sedimentary dynamics, geomorphology and vegetation. The transgressive fixed dunes close to the deforested areas were reactivated, reducing their height, and migrating towards the lagoon (Fig. 6). As a result, areas with transgressive dunes increased (Fig. 2). Along with deforestation, a second factor that boosted the recuperation of dune bedforms was dry weather in 2007/2008, as observed by Schossler (2016), increasing the availability of aeolian sediments to the dunefield. Nevertheless, after dune deforestation, the higher increase was not in areas with transgressive dunefields but in degraded areas (Fig. 2). Therefore, unfortunately, the success of the dunefield recuperation after deforestation was only partial.

In addition to these stages of restoring the dunefield mobility close to the Peixe lagoon, new stages towards beach and foredune dynamics must be incorporated. This stage must also incorporate the pines removal in this coastal sector. Foredune experiments show that the large-scale processes of dune mobility can be restored when they are connected to the coastline (Arens, at al 2012).

5. Conclusions

In the international controversy between removing or not the invasive allotone forest from the dune system, this study demonstrates that removing this exotic vegetation through dune vegetation recovery programs, is often unsuccessful and can generate more degraded areas that recuperation of dunefield areas. However, it is possible to consider this issue not only through the biological perception of the native vegetation recovery, but also through the changes in sedimentary morphodynamics resulting from the presence of allochthonous forests. In this case study, it was essential to carry out this forest removal, to ensure the dunefield geodynamics, and, therefore, a base (biotope) of the natural system, i.e. the maintenance of the lagoon and dunefield.

The transgressive dunefield of the Lagoa de Peixe Natural Park was drastically modified in the 70′-80′ decades by intensive pine plantation and the leeward development of associated degraded areas with pines growing by natural dispersion and allochthonous shrubs. Combined with these local anthropic impacts, regional climatic oscillations produced increase in rain precipitation and reduced wind velocity.

As a result of the anthropic impact and the climatic oscillations, the extension of dunefield reduced 74.17% from 1948 to 2001, while the pine plantations occupied 15.03% and degraded areas a 10.81% of the total dunefield area, respectively. Pine plantations generated a bulkhead to wind flow and stabilized the transgressive dunes in the inner side of the dunefield. The number and size of the barchan dunes decreased.

Pine plantations in the backshore and foredune generated a drastic reduction in the input of aeolian sediments from the beaches. Consequently, a great interdune area with sand sheets in the central sector developed and was associated with the cannibalization of the highest transgressive dunes of the LPNP and development of parabolic dunes.

Pine plantations in the inner margin of the coastal barrier were created for wood exploitation; however, they also helped to avoid sediment filling of the lagoon, which is very important because of the high ecological value of the lagoon. Nevertheless, some minor inputs of sediments to the lagoon occurred by the artificial drainage channels.

Since 2006, the controlled pine deforestation allowed a little increase of natural aeolian areas due to the reactivation and landward migration of transgressive dunes. Therefore, in 2018, the extension of the dunefield corresponded to 79.03% of the total area, while the pine plantations reduced to 3.25%. In summary, the well-developed dunefield of 1948 was replaced by a minor dunefield, with lower barchan dunes, while the high transverse dunes disappeared; a foredune is present in the backshore of the northern sector of the LPNP, and large interdune areas with some parabolic dunes were also developed.

The deforestation and recuperation project of the dunefield is based on several techniques that avoided the sediment filling of the lagoon. These techniques included: the maintenance of three parallel lines with a low density of pines in the interface with the dunefield, the ring binding of these pines to promote a slow death and substitution by autochthonous vegetation, the deposition of seedless dry branches over the dunes close to the remaining trees to reduce the aeolian sediment transport, and the continuous monitoring of the deforested areas and manual retreat of incipient pines growing in.

After deforestation, the extension of degraded areas increased, reaching up to 17.71% of the total area. It means that the success of pine deforestation and dunefield recuperation was only partial as most of the pine plantations were replaced with degraded areas. Therefore, complementary techniques should be applied to recuperated ancient dunefield areas currently occupied by these degraded areas. Nevertheless, it is important to emphasize that the deforestation plan helped to avoid the aeolian input of sediments to the lagoon, which is very important to the maintenance of the lagoon, which is the most important ecological unit of the LPNP.

Many dune systems in Southern South America (with similar ecosystems) had Pinus plantation programs in the 70–80s, probably resulting in similar changes of those found in this area. This study gives a scientific basis for the development of dune system recovery projects.

CRediT author statement

Luana Carla Portz: Conceptualization; Data curation; Formal analysis; Methodology; Resources; Roles/Writing - original draft; Writing - review & editing. Rogério Portantiolo Manzolli. Conceptualization; Data curation; Formal analysis; Methodology; Resources; Roles/Writing - original draft; Writing - review & editing. Javier Alcántara-Carrió: Formal analysis; Methodology; Roles/Writing - original draft; Writing - review & editing. Gabriela Camboim Rockett: Formal analysis; Methodology; Roles/Writing - original draft; Writing - review & editing. Eduardo Guimarães Barboza: Formal analysis; Writing - review & editing.

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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