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Temporal dynamics of land use and cover in Paurá Lagoon region, Middle Coast of Rio Grande do Sul (RS), Brazil

Dinâmica temporal de uso e cobertura do solo na região da Lagoa do Paurá, Litoral Médio do Rio Grande do Sul (RS), Brasil

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ABSTRACT: Land use and land cover studies can help in the monitoring and management of important landscapes and priority areas for conservation, especially those threatened by anthropogenic processes. The Middle Coastal region of Rio Grande do Sul (RS) – the southernmost State of Brazil, comprises a variety of ecosystems recognized as highly important for conservation. Threats to their integrity include *Pinus* sp forestry and its rapid invasiveness over natural areas, like the surroundings of Paurá Lagoon (-31°34', -51°17' and -31°35', -51°18'). Through remote sensing and field observations, the present study sought to identify, quantify and map the main thematic classes of land use and coverage in the vicinities of the Paurá Lagoon. Changes and influencing factors over 26 years were studied using four Landsat TM 5 satellite images, dated from 06/02/1985, 30/07/1996, 23/05/2006 and 28/10/2011. Besides lagoon water, eight other thematic classes were identified and quantified: Dune, Vegetated Dune, Restinga Forest, Wet Grassland/Marsh, Sandy Field/Exposed Soil, Pasture Field, Forestry and Forested Dune. Various relevant changes in the landscape were observed, measured and compared over time, including the occupation of the legally-bound permanent preservation areas (PPA) by *Pinus* sp and its subsequent partial

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disposal in compliance with environmental licensing. Creation of a local conservation unit is recommended. Measures are suggested for an integrated management of this coastal environment, enabling preservation of the landscape and its mosaic of ecosystems in conjunction with sustainable land use. Information raised in this paper may assist planning and decision-making for licensing, management and monitoring of the Paurá Lagoon region and other similar important coastal regions.

Keywords: coastal ecosystems, invasive and exotic trees, *Pinus,* priority areas for conservation, remote sensing.

RESUMO: Estudos sobre o uso e a cobertura do solo podem auxiliar o monitoramento e a gestão de paisagens e áreas prioritárias para conservação, especialmente aquelas ameaçadas por processos antropogênicos. A região do Litoral Médio do Rio Grande do Sul (RS) - o Estado mais meridional do Brasil, dispõe de uma variedade de ecossistemas reconhecidos como de alta importância para a conservação. Ameaças à sua integridade incluem a silvicultura de Pinus *sp e a sua rápida capacidade de invasão de áreas naturais, como ocorre próximo à Lagoa do Paurá (-31° 34', -51° 17' e -31° 35', -51°18'). Através de sensoriamento remoto e observações em campo, o presente estudo procurou identificar, quantificar e mapear as principais classes temáticas de uso e cobertura do solo nas imediações da Lagoa do Paurá. Alterações e seus fatores influenciadores foram estudados em um período de mais de 26 anos, por meio de quatro imagens do satélite Landsat TM 5, datadas de 06/02/1985, 30/07/1996, 23/05/2006 e 28/10/2011. Além da água da lagoa, outras oito classes temáticas foram identificadas e quantificadas: Duna, Duna Vegetada, Mata de Restinga, Campo Úmido/Banhado, Campo/Solo Exposto, Campo de Pastagem, Silvicultura e Duna Reflorestada. Várias mudanças relevantes na paisagem foram observadas, medidas e comparadas ao longo do tempo, incluindo a ocupação das áreas de preservação permanente (APP) por* Pinus *sp e seu posterior corte parcial, em conformidade com o licenciamento ambiental. A criação de uma unidade de conservação local é recomendada. São sugeridas medidas para a gestão integrada deste ambiente costeiro, que permitam a preservação da paisagem e do mosaico de ecossistemas, conjuntamente com o uso sustentável do solo. A informação levantada neste trabalho pode assistir o planejamento e a tomada de decisões para licenciamento, gestão e monitoramento da região da Lagoa do Paurá e de outras regiões costeiras semelhantes.*

Palavras-chave: ecossistemas costeiros, árvores exóticas e invasoras, Pinus*, áreas prioritárias para conservação, sensoriamento remoto.*

1. INTRODUCTION

The accelerated rate of natural landscape and environment change is largely due to anthropogenic processes, such as agriculture, forestry and urbanization. According to Chapin *et al.* (2000), land cover change is likely to be the most significant variable impacting on biodiversity for at least the next 100 years. This is an issue of great concern, especially for priority and environmentally fragile areas that should be protected. As reviewed by Zhou *et al.* (2011), several researchers have addressed this issue by studying land cover and land use. Geoprocessing tools are useful to diagnose, quantify and spatially represent changes in landscapes and conflicts of land use and occupation. These tools provide powerful support to coastal environmental planning and management. Moreover, as emphasized and reviewed by Mayer and Lopez (2011), the analysis of changes in land cover and land use using remote sensing can be an important tool to implement, control, monitor and evaluate actions and policies by environmental agencies. Information derived should be especially useful to coastal priority areas for conservation.

The Eastern Middle Coast of Rio Grande do Sul State is one of the regions listed among the priority areas for conservation in Brazil (Ministério do Meio Ambiente, 2007). This geographical area is 270 km long and corresponds to approximately 45% of the Coastal Plain of Rio Grande do Sul (CPRS) total coastal length (FEPAM, 2015; Mäder *et al.,* 2011). According to Schäfer *et al.* (2009a), the CPRS presents a set of unique, highly complex, aquatic and terrestrial ecosystems. It was originated from the accumulation of juxtaposed sedimentary deposits in four parallel 'barrier-lagoon' systems formed during the Quaternary period. From these deposits and in parallel to the seashore, a line of freshwater lakes, lagoons, wetlands surrounded by wet and dry Pampean fields, fields of dunes and *restinga*-type forested dunes has developed with a rich biodiversity. For instance, the diversity of intercontinental migratory bird species is notable, and the *Lagoa do Peixe* National Park (PNLP) was created for their conservation in 1986 (Presidência da República do Brasil, 1986). The PNLP integrates the International Network of Hemispheric Reserves for Wetlands Birds Conservation and, since 1993, it is one of the 13 Brazilian sites currently designated for preservation by the Ramsar International Convention (Ministério do Meio Ambiente, w/d; Ramsar, w/d).

Nevertheless, this ecologically important region faces anthropogenic impacts, such as exotic tree forestation, agriculture and husbandry, and still lacks the envisaged environmental zoning management tool for proper territorial planning and protection.

Forestation with *Pinus* sp, focused on the furniture and resin industries, is one of the most impactful factors threatening the Eastern Middle Coast ecosystems. According to Gianuca and Tagliani (2012), this activity began in the region's municipality of São José do Norte in the 1970s, with federal incentives from the former Brazilian Institute of Forestry Development – IBDF. With the advent of the medium density fiberboard (MDF) and Medium Density Particleboard (MDP) wood industry and its multiple furnishing and marine applications, the regional pine forestry has increased to become a major source of local income. *Pinus* sp plantations occupy an area of approximately 13,000 hectares, contributing with 73% of the GDP and employing more than half of the municipality's labor.

However, *Pinus* trees have a great invasive potential (Richardson and Rejmánek, 2004). Once introduced and adapted to the environment, they rapidly reproduce to occupy the space of other species, producing significant changes in the natural ecological processes. *Pinus* can become dominant; alter the landscape and, especially, the habitat of native fauna and flora species (Ziller and Galvão, 2002). These negative effects of *Pinus* plantations in both natural and semi-natural ecosystems have been intensively studied in the Southern hemisphere, where the planted species are non-native (Lavi *et al.,* 2005).

Investigations on *Pinus* spread in the presently studied coastal region were conducted previously by others using remote sensing and geoprocessing techniques. Portz *et al.* (2011) identified the spatial distribution of pine plantation inside and in the surroundings of the PNLP for more than two decades (1986-2009). Burgueño *et al.* (2013), working in the vicinities of the PNLP, assessed the interrelationship of cords of transgressive dunes with *Pinus* plantations. Comparing images of 1964 and 2007, Gianuca and Tagliani (2012) analysed landscape changes around *Pinus* plantations in the region of Barra do Estreito (São José do Norte). Focusing on these and other potential impact factors, further investigations are still needed on the components of land cover and land use, and on the historical dynamics of landscapes in conservation priority areas of the Eastern Middle Coast.

In this context, the objectives of this study were to identify, quantify and map the main thematic classes of land cover and land use in the surroundings of *Paurá* Lagoon (São José do Norte). To that end, comparative temporal analyses of Landsat TM 5 satellite images were sought to check variations in area and distribution over a period of time, and to point out the possible contributing factors of landscape changes.

2. MATERIAL AND METHODS

2.1. Study Area

The *Paurá* Lagoon is located south of PNLP, in the rural area of the municipality of São José do Norte, Eastern Middle Coast of Rio Grande do Sul, between the coordinates -31°34', -51°17' and -31°35', -51º18' (Figure 1). The municipality is part of the stretch comprised of a large sandbank (*restinga*) which separates the *Patos* Lagoon and the Atlantic Ocean, where there is predominance of dune fields, marine and lagoon plains (Viero and Silva, 2010). The oblong shaped *Paurá* Lagoon is positioned in the southwest-northeast direction, in parallel and distant ca. 1.8 km to the marine coastline. It is one of the shallowest freshwater lagoons of the coastal plain, with an average depth of 0.77 m, 1.81 km of length and 0.7 km² of area, according to measurements of Schäfer *et al.* (2009b) in the summer of 2008. Seasonal differences regarding *Paurá* lagoon surface area and its surrounding permanent preservation area were previously presented by Miranda and Lipp-Nissinen (2017).

The fauna is rich in invertebrates, vertebrates of open land areas, bird life and aquatic species (Cordeiro and Hasenack, 2012; Scherer, 2009; Schäfer *et al.,* 2009a).

There are livestock in the fields and pine forestry activities in commercial orchards. Next to the *Paurá* Lagoon, *Pinus* forestry has been developed continuously as a commercial activity since 1976. The enterprise was regulated by the State Environmental Agency for the first time in 2010, through the Operating License No. 06793/2010 (FEPAM, 2010).

Previous surveys (Paranapanema, 1999; Schäfer *et al.,* 2009a and 2009b) indicated that the soils are predominantly planosols, secondarily associated with quartz sands and humic gleysols in portions more poorly drained. Those studies also described the regional climate as subtropical, Cfa type according to the Köppen system, moderate temperate, rainy, mostly with northeast winds and with an average annual temperature above 18°C.

The *Paurá* Lagoon region and the whole Middle Coast were included in the "RS Biodiversity Project - Biodiversity as a Contributing Factor to the Development of Rio Grande do Sul" a public priority policy for nature conservation through sustainable and traditional land uses (Rio Grande do Sul, 2008).

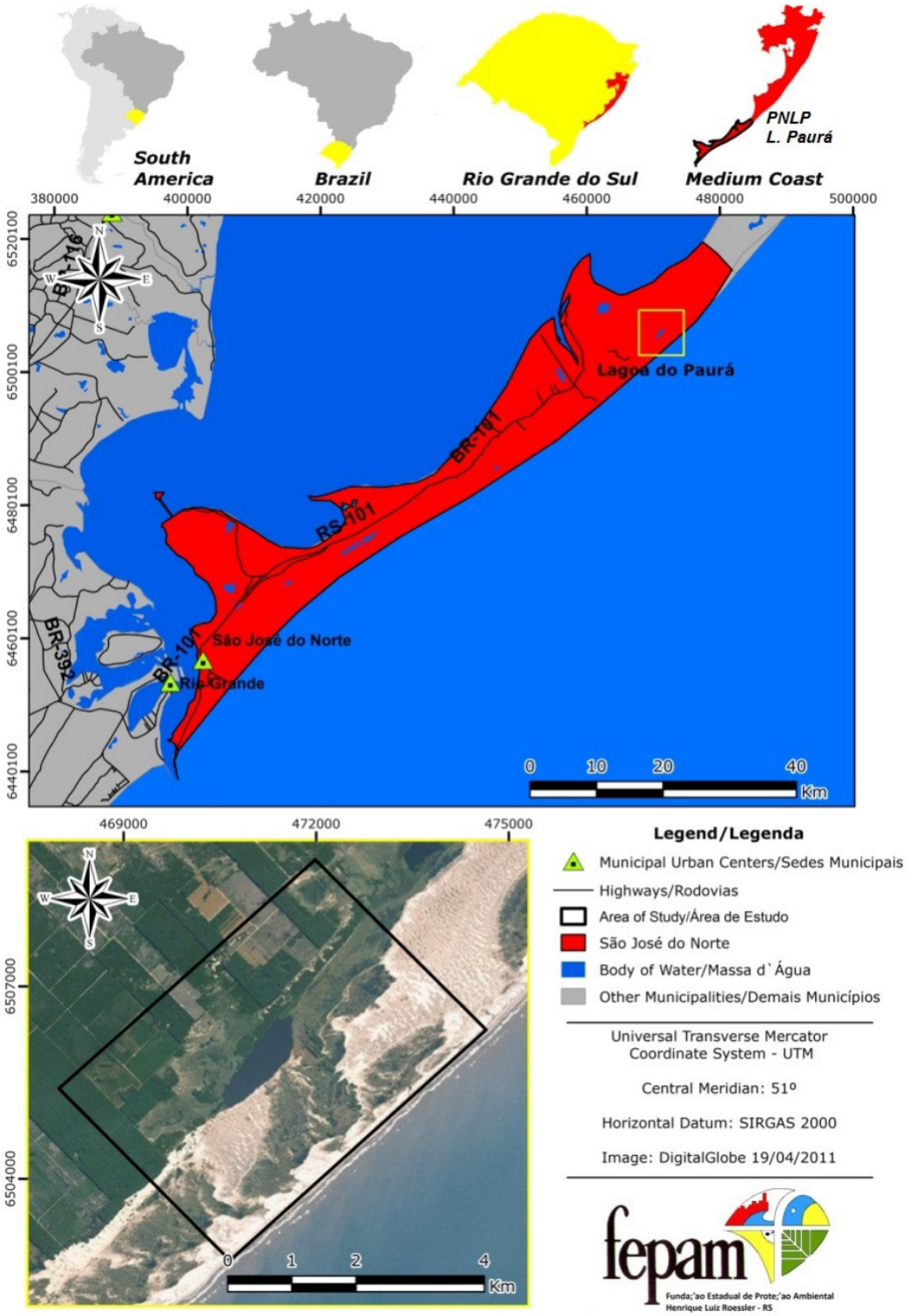

Figure 1 - Location of the study area in the municipality of São José do Norte, Eastern Middle Coast of RS State. In detail, polygon of the study area surrounding the *Paurá* Lagoon, Landsat TM 5 (1985) image, RGB321 band composition, scale 1: 40,000.

Figura 1 - Mapa do município de São José do Norte, Litoral Médio Leste do estado do RS. Em detalhe, polígono da área de estudo no entorno da Lagoa do Paurá, imagem Landsat TM 5 (1985), composição de bandas RGB321, escala 1:40.000.

2.2. Selection of Satellite Images

Landsat TM 5 satellite images have been downloaded from the Brazilian National Institute for Space Research (INPE) database (http://www.dgi.inpe.br/CDSR/). The Landsat 5 sensor TM (Thematic Maper) provides images from 1984 to 2013, which were captured through its seven bands in the electromagnetic spectrum, in the 0.45 to 2.35 µm interval (INPE, 2014). The geometrical resolution of the images in bands 1, 2, 3, 4, 5 and 7 is 30 m, meaning that each image pixel represents a ground area of 0.9 ha. For band 6, the thermal band, geometric resolution is 120m, that is, each pixel is 1.4 ha (INPE, 2014). The images captured by Landsat TM 5 cover a ground area of 185 km x 185 km, with a temporal resolution of 16 days, that is, the same area is revisited by the satellite over the period of 16 days (INPE, 2014).

Four satellite scenes were chosen for the study, dated 02/06/1985, 30/07/1996, 23/05/2006 and 28/10/2011. These were selected among the best accessible images at orbit 221 and point 082 having the lowest cloud cover possible (maximum 50% coverage) and time intervals sufficient to depict changes in land cover during the 1985-2011 period.

The Landsat TM 5 images were registered using the free software SPRING 4.3.3, considering a mean square error of less than one pixel. Image georeferencing was performed using 25 ground control points from a GeoCover image obtained from the Global Land Cover Facility, University of Maryland, USA (2014). The following parameters were used: TM sensor, orbit 221, point 082, WRS - 2, GeoCover, and image dated November 12, 2002.

The images georeferenced in the UTM coordinate system and Datum SAD69 were inserted in a SPRING 4.3.3 database. The combination of spectral bands RGB543 was chosen as the best setting for the identification of thematic classes of land use and coverage.

2.3. Classification and mapping of land use and coverage

The four georeferenced images, composed in RGB543 bands, were inserted into the ArcGIS® Desktop 10.0 application for identification procedures, interpretation, mapping and measurement of classes. Contrast and lighting were adjusted to enhance the visualization of the components of each image.

Placing the *Paurá* Lagoon in the center, a rectangle of 1,894 ha was defined as the study area of influence (Figure 1). Manual identification of thematic classes in each image was done by comparing textural, spatial, spectral, and contextual features of the targets, through visual interpretation on the scale of 1:40,000. These data were analysed together with observations made during field visits. *In situ* identification and localization of different types of land coverage were conducted: sand dunes, vegetated dunes, pastures, pine forestry, native forests, wet fields, water bodies and exposed soil. In addition, historical aerial photographs, literature descriptions, and cartographic documents were assessed to provide additional information on the study area. These analyses were useful to clarify dubious points in transitional areas between classes, for example: between scarcely vegetated dunes and plain sand dunes, and between pastures and wet fields. Interactive vectorization was performed to more accurately delimitate the small portions of the thematic polygons using a 1:6,000 scale.

Field visits to the study area were conducted on 19 July 2013 (winter) and 28 January 2014 (summer) for site recognition and visual confirmation of findings from satellite image analyses.

3. RESULTS AND DISCUSSION

The following eight classes of land use and land cover were defined and identified from the four images and field observations, resulting in four temporal thematic maps (Figure 2): Dune, Vegetated Dune, *Restinga* Forest, Wet Field/Marshland, Sandy Field/Exposed Soil, Pasture Field, Forestry and Forestry on Dune. Additionally, lagoon's water area was also estimated in each image. As from the 1996 image, the Forestry on Dune class appears over a portion of Vegetated Dune located to the northeast and perpendicularly of the lagoon (Figure 2).

Nominated classes are defined below. Some definitions were based on previous descriptions of similar regions within the RS Middle Eastern Coast done by other authors.

Dune: Includes sandy fields next to the beach and mobile or sessile dunes of small height, with or without thin and sparse vegetation, which generate high reflection of solar rays from its mineral composition (adapted from Schäfer *et al.,* 2009b).

Vegetated Dune: Sand dune area colonized by vegetation with sufficient density to present different radiance value compared to that from the Dune class. It is generally located behind or next to the Dune class (adapted from Schäfer *et al.,* 2009b).

Restinga Forest: Area on the elevation of a sandbank (an interior, secondary dune) colonized by relatively midrange and low height native, tree species, with notable abundance of Myrtaceae family members, ex.: *Eugenia* spp, presence of large *figueira* trees (*Ficus cestrifolia* Schott), *jerivá* palms (*Syagrus romanzofiana*

(Cham.) Glassman), cockspur-coral trees (*corticeira* or *seibo* - *Erythrina cristagalli* L.), several types of lianas and other common components of sandbank woods at this latitude (adapted from Scherer, 2009).

Forestry: Commercial *Pinus* sp planting areas.

Pasture Field: Cattle grazing area covered by grass, herbaceous and shrub plants, native or introduced.

Forestry in Dune: Short dunes covered with older planting and newer natural dispersion of pine trees.

Wet Field/Marshland: Wetlands permanently or seasonally flooded, covered with macrophytes, such as water hyacinth, lilies and grasses (Schäfer *et al.,* 2009b). These sparse, transition areas are usually bordering the lower north and south shores of the lagoon.

Sandy Field/Exposed Soil: Exposed sandy soil areas, in some cases covered with very sparse herbaceous vegetation, resultant from the removal of *Pinus* trees, inside or around forestry plots (adapted from Schäfer *et al.,* 2009b).

After vectorization, the areas occupied by each thematic class were quantified, Table 1. In Figure 3, the percentages of each thematic class, on the total study area and in each of the years studied, are presented.

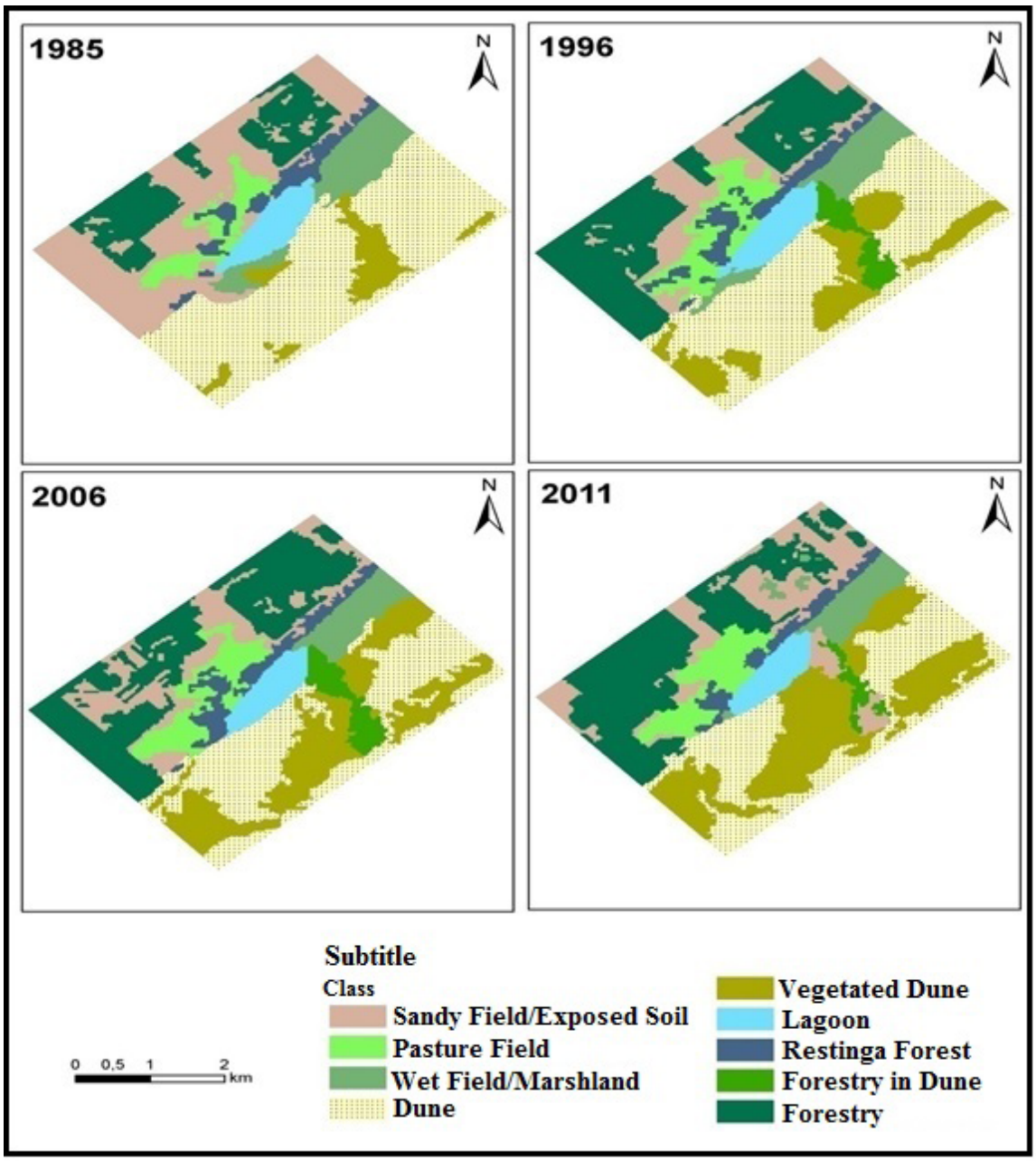

Figure 2. Maps of land use and coverage in *Paurá* Lagoon surroundings, in 1985, 1996, 2006 and 2011.

Figura 2. Mapas de uso e cobertura do solo no entorno da Lagoa do Paurá, em 1985, 1996, 2006 e 2011.

Table 1 - Area occupied by the thematic classes in the study area around *Paurá* Lagoon, in 1985, 1996, 2006 and 2011.

Tabela 1 - Área ocupada pelas classes temáticas na área de estudo em redor da Lagoa do Paurá, em 1985, 1996, 2006 e 2011.

Thematic Class	Area (ha)			
	1985	1996	2006	2011
Sandy Field/ Exposed Soil	467	197	226	255
Pasture Field	83	120	115	117
Wet field/ Marshland	141	108	90	99
Dune	702	584	447	409
Vegetated Dune	109	215	345	428
Lagoon Water	82	84	71	69
***Restinga* Forest**	77	93	86	61
Forestry in Dunes	-	61	66	29
Forestry	230	430	444	423
Total	1891	1891	1891	1891

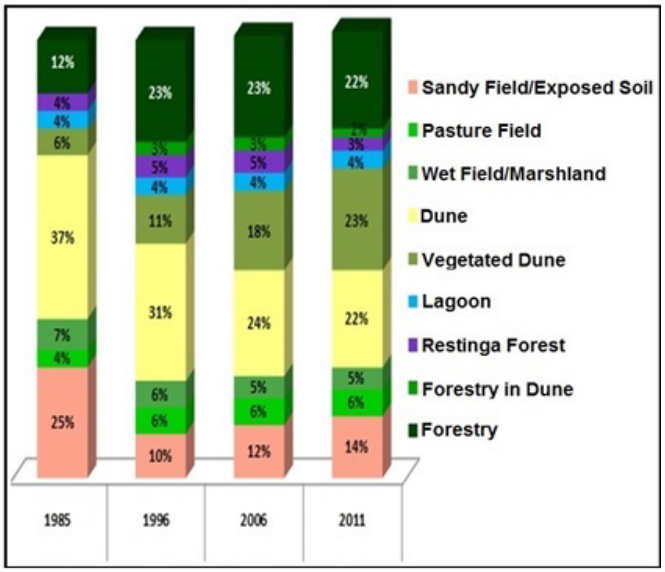

Figure 3 – Percentage area occupied by each thematic class in the total area mapped in 1985, 1996, 2006 and 2011.

Figura 3 – Percentagem de área ocupada por cada classe temática no total de área mapeada nos anos de 1985, 1996, 2006 e 2011.

Among the changes observed in the period 1985-2011, the increase in area of Vegetated Dune, from 109 ha to 428 ha, was the most remarkable. During the 26 years, that class almost quadrupled in area, from 6% coverage (1985) to 23% (2011) of the total study area. This increase in vegetation over the Dune class took place, largely, with the introduction of favorable conditions to plant colonization. This was facilitated by *Pinus* trees planted on the dunes located northeast and perpendicularly to the lagoon. The stands of pines worked as a physical barrier against the strong northeastern winds, a common stress factor in this region. In addition, pine trees, planted and naturally dispersed over dunes, allowed the accumulation of ground moisture, which enabled plant growth and the spread of vegetation on the sand.

These conditions also favored colonization of herbaceous and shrub species more adapted to the coastal zone, contributing to the establishment of Vegetated Dunes. This fact is confirmed by Cordazzo *et al.* (2006) thoroughly studying the plants of southern Brazilian coastal dunes. For these authors, natural plant establishment in this region is dependent on the reduction of stress factors common to the coast, such as wind and salinity, and the increase in soil moisture, similarly to what has probably occurred in the present study area. The adaptability of herbaceous and shrub species to stressors may be decisive for fixing vegetation on dunes and their cover increase, as related by those authors. The decrease of dune area, estimated at 702 ha, 586 ha, 449 ha and 409 ha in 1985, 1996, 2006 and 2011, respectively, is mainly related to the increase of the Vegetated Dune class on the east and northeast lagoon's shore (Figure 2).

The Dune class represented the largest percentage area in 1985: 37% of the total, decreasing to 22% in 2011. In accordance to Souza and Grüber (2005), free dunes are a class in constant movement, with strong dynamics causing permanent changes to the local landscape. In the area of this study, as well as along the RS coast, the northeast wind is generally responsible for the movement of the dune sands, mainly to the southwest. Regarding to this dynamic, Tomazelli (1993 *apud* Souza and Grüber, 2005) estimated the average annual rate of migration of coastal mobile dunes in RS as 26 m/year. Consequently, sand from dunes tends to enter and deposit itself on the bottom of the water bodies, such as the *Paurá* Lagoon. In addition, plants occupying the frontal dunes, especially the grass *Panicum racemosum* and the daisy-of-dunes, *Senecio crassifolius*, having high plasticity, ability to withstand climate-soil rapid variations and to spread rhizomatous extensions, are able to perform a pioneer role, fixing the dunes. Such pioneer vegetation contributes to the succession of other invasive, more selective plants in secondary dunes. Calliari *et al.* (2005), studying the variability of dunes along RS coast, concluded that the orientation of the coastline against the prevailing NE wind is the most important factor in determining the height of the frontal dunes and the width of the beach. According to these authors, the Middle Coast layout being, in some sections, obliquely negative in relation to the NE wind determines the formation of quite low dunes (< 0.5 m), as the ones found in this study area. As a result, a sandy plain with deflation basins, low vegetation (20 to 45%) and the incidence of large blowouts are characteristics of those beaches.

Towards north and northeast of *Paurá* Lagoon, there is a narrow spillway draining to the sea. Corroborating other regional studies (Calliari *et al.*, 2005 and Cordazzo *et al.*, 2006), that water course may be responsible for features observed during visits to the study area and on satellite images: diversification, increased plant growth and consequent accumulation of sand and fixing dunes of greater height.

The gradual reduction of Wet Field/Marshland areas from 141 ha to 108 ha and then to 90 ha, respectively, in 1985, 1996 and 2006, occurred both at the south end, and in the northern end of the lagoon. The temporal analysis of the images indicates the sands mobilized by the wind as the reduction factors of Wet Field/Marshland and the expansion of Dune class in the southern end of the lagoon. While in its northern part, the planting and dispersal of *Pinus*, equivalent to the Forestry in Dune class, came to occupy part of the wet grassland on that margin (Figures 2 and 4). The high consumption of water characteristic of the woody, fast-growing pine trees could drain those wet and flooded lowlands.

A small and gradual reduction in the lagoon flooded area occurred in the second half of the reporting period: 82 ha in 1985, 84 ha in 1996, 71 ha in 2006, and 69 ha in 2011. Previous results from a 20 years-historical series study evidenced that among the factors which can influence the *Paurá* lagoon dimensions are rainfall and evapotranspiration (Miranda and Lipp-Nissinen, 2017). According to Schäfer *et al.* (2009b), the location and shallowness of the *Paurá* Lagoon contribute to its asymmetry, which favors further conformational changes caused by wind and migratory dunes. As in other similar lakes, these tend to slowly and gradually decrease the body of water by colmatation. In this process, sedimentation by fine sand and coarse uptake of silt occurs inside the small ponds and lagoons, especially those located next to dunes and sandy fields. Concomitantly, the solidification caused by the presence of the mixture with sea water tends to accelerate the clogging of these water bodies, reducing its depth and current movements (Chomenko and Schäfer, 1984).

The *Restinga* Forest area variation overtime – 77 ha in 1985, 93 ha in 1996, 86 ha in 2006 and 61 ha in 2011 – was possibly due to the negative pressure of human activities, as indicated by field observations. The proximity of pine stands to this important natural component of the regional landscape entails the spontaneous spread of the exotic trees and its establishment at the edges of the forest fragment (Figures SI-I.1 and SI-I.2), facilitating their competition over native plant species. Maintenance of those *Pinus* stands at the northwest of the lagoon, without a strict control through proper management, will further compromise the vulnerable biodiversity in this forest remnant, altering the local landscape. Burgueño *et al.* (2013) reported that several studies, conducted in other *restinga* forest remnants in lacustrine environments nearby *Paurá* Lagoon, demonstrated the negative effects of *Pinus* sp invasions. Burgueño *et al.* (2013) and Foti *et al.* (2012) have shown that the differences in hydroperiod (*i.e.,* percentage of time that a site is inundated) induce lower abundance of native species in natural wetland environments. According to those authors, hydroperiod influences abiotic and biotic factors affecting native fauna and flora composition, such as dissolved oxygen, pH, nutrients, and primary production, predation and competition. In addition, rapid growth, high competitiveness, compared to grasses and woody shrubs, and the large reservoir of pine seeds in the soil from plantations since the decades of 1970 and 1980, also explain the extent of the *Pinus* invasion. Further, ecophysiological features of *Pinus* (Manzanera *et al.,* 2016) provide competence for tree colonization in dry, poor soils and marginal habitats, such as the low interdune areas, the dunes and the edges

Figure 4 – View of *Paurá* Lagoon's north bank margin (summer, January 2014). C/B: Wet Field/Swamp; P: Forestry in Dune (old pine plantation); D: natural dispersion of pine; L: Lagoon; MR: *Restinga* Forest.

Figura 4 – Vista da margem norte da Lagoa do Paurá (Verão, janeiro 2014). C/B: Campo Úmido/Banhado; P: Silvicultura em Duna (antigo talhão plantado); D: dispersão natural de Pinus; L: Lagoa; MR: Mata de Restinga.

of floristic fragments, resulting in its invasive success and the consequential temporal changes in diversity and extension, and the fragmentation of native *restinga* forest remnants surrounding *Paurá* Lagoon.

Similar results from Anjos and Buffon (2013), while mapping land use and cover in the Tainhas State Park, northern RS, showed an increase of more than 60 times the pine area. That thematic class, defined as '*Pinus* sp. Forestry' by those authors, was appointed as the main reduction factor of the 'Natural Forest' class in Tainhas Park, between 1984 and 2009.

Another factor observed in the present study is the presence of cattle, commuting from the adjacent pasture field (SI-I.4) to the *restinga* forest in search of shelter and food. This way, the animals can degrade, or hinder the development of *restinga* forest. Although the number of animals currently seen in the field does not characterize the activity as intensive farming, cattle trampling and grazing could still harm herbaceous, shrub and tree components of the *restinga* fragment. As a result, open spaces and less native plant regeneration and growth would occur, mainly in the fragment borders. Similar situation was found by Scherer (2009) studying other stretches of *restinga* forest in the Middle Coast, and in other regions of RS Southern Coastal Plain.

Over the studied period, the area of *Pinus* Forestry class changed as follows: 230 ha (12%) in 1985, 430 ha (23%) in 1996, 444 ha (23%) in 2006 and 423 ha (22%) in 2011.

In the 1996 image, new pine cropping is seen towards the southwest and northwest directions of the study area, occupying portions of Sandy Field/Exposed Soil (Figure 2). In 2006, there was a slight increase in the Forestry category, while a significant reduction is seen in the 2011 image, resulting from the cutting of a portion of older trees in the northwest of the lagoon (Figure 2).

The large amount of pine trees dispersed from the plantations and the speed of its establishment in fragile and important ecosystems in the study area, tend to lead to major changes in the local landscape. Preventive measures are necessary through frequent monitoring and control actions, such as removal of pine tree plots very close to native vegetation, identification and clear cutting of invasive trees, as well as the removal of pine branches and other related waste on the ground.

With respect to the northwest portion of the study area, the elimination of pine trees therein is recommended, to increase the distance between the pine plantation and the *restinga* forest fragment. Control measures such as continuous cutting were also proposed by Portz *et al.* (2011) in a study that showed expansion of plantations and ca. four times natural dispersion of *Pinus* between 1986 and 2009 in the surroundings of *Peixe* and *Pai João* lagoons, both located to the north of the present study area.

Variations in the quantified dimensions of Sandy Field/Soil Exposed areas are mainly related to alternating pine tree planting with cutting in the areas of forest nursery. The placement of this thematic class was 467 ha (25%) in 1985, 197 ha (10%) in 1996, 226 ha (12%) in 2006 and 255 ha (14%) in 2011.

Field observations in January 2014, along with results from geoprocessing and image analysis, indicated that the methodology used was suitable to identify the most notable changes in the area. These procedures enabled understanding of land use and cover dynamics in the period from 1985 to 2011 and 2014.

The smallest and more tenuous landscape changes, such as the colonization of a large number of young *Pinus* saplings over the legally protected lagoon dunes and marginal permanent preservation areas (PPA) (Figure 4 and SI-I.3), however, were not efficiently revealed by the scale and resolution of the Landsat TM 5 images available. During the field visits, many young pine trees were seen naturally setting up as PPA invaders in the same places where older planted trees had already been cut, as demonstrated by the 2011 map (Figure 2). Similarly, naturally dispersed pines were observed in other PPA areas, such as the edges of the *Restinga* Forest remnant and on dunes to the east and south of the lagoon.

The removals of the old planted trees in dunes and marginal PPA occurred, most likely, in compliance to legal conditions after the regularization of the activity through its licensing by the State Environmental Agency (FEPAM, 2010).

Hence, remote sensing monitoring of locations that have a continuous presence of invasive plant species should be further supported by field *in situ* observations. Moreover, a refinement in the methodology, for instance using satellite images from sensors with different radiometric and spatial resolutions, could result in a more accurate classification. Although, it should be considered that the acquisition of satellite images, not freely available as those from the Landsat series, can increase administrative costs. This study had no intention to test or develop an image classification method. The method employed here, of feature extraction through interactive vectorization, was based on the *in situ* visual knowledge of the targets, their textural, spectral and shape aspects, and also on the spatial relation among the identifiable targets in the satellite images.

Findings from this study emphasize the importance of a structured and operational geographical information system (GIS) in public environmental agencies to assist remote sensing work related to research, planning,

control and management of ecologically important and vulnerable regions, as the Southern Brazilian coast.

4. CONCLUSIONS

In this study, Landsat TM 5 satellite freely available images combined with field observations were suitable to identify, quantify and map the area of interest, enabling the recognition of landscape changes in the *Paurá* Lagoon and surroundings over 29 years, since 1985. The use of higher spatial and radiometric resolution satellite images may further improve the accuracy and effectiveness of the methodology.

Among the changes highlighted in the study area, the anthropogenic influence was clearly visible. Permanent preservation areas were occupied either by earlier deliberate *Pinus* planting, or by its natural, fast dispersion. The establishment of pine trees on dunes worked as a physical barrier against the wind, facilitating the increase of humidity and expansion of herbaceous vegetation over dunes. Following licensing of the commercial enterprise, cutting of pine trees in the PPA around the lagoon and in the Forestry in Dune class was not efficient to eradicate *Pinus* dispersion on dunes and margins, nor its invasion towards the native *restinga* forest and neighboring fields.

Management measures for natural landscape protection should be adopted in the area, in line with conservation priorities. These include a systematic management of the commercial pine forestry, fencing of livestock grazing areas, constant cutting, cleaning and control to eradicate pine trees in dunes, wetlands, borders of the *restinga* forest and within the legally bound of 100 m PPA along the lagoon margin. The creation of a protected conservation area, including the *Paurá* Lagoon region is recommended.

Findings and recommendations from this study can be considered during the renewal of existing, or new, environmental licenses for pine forestry enterprises in the coastal area. Location of pine dispersions in legally protected areas, for instance, would indicate the removal and control of those trees as requirements for licensing.

The information generated herein could also assist planning and decision-making towards integrated management and conservation in the study area and other economic-ecologically important coastal regions.

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