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Delimitation of permanent preservation areas of Paurá Lagoon (Middle Coast of Rio Grande do Sul, Brazil) using multitemporal satellite image analysis

Delimitação da área de preservação permanente da Lagoa do Paurá (Litoral Médio do Rio Grande do Sul, Brasil), usando análises multitemporais de imagens de satélite

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ABSTRACT: Permanent Preservation Areas (PPA) are determined by the Brazilian Forest Code (Federal Law nº 12.651/2012) to protect biodiversity, soil, water, and climatic integrity. Around lakes and lagoons in rural areas, the law establishes marginal strips of PPA with a minimum width of 100 m (or 50 m for lakes with less than 20 ha). Some of these water bodies may have their surface dimensions markedly changed due to seasonal variations. PPA demarcated during periods of maximum water level would present ecological advantages. However, such variations were not included as criteria for PPA around lakes and lagoons in the new 2012 Forest Code. Moreover, seasonal variations effects are not yet sufficiently known in water bodies of most regions. In this work, a methodology previously developed was used to delimitate and measure water surface area and PPA of Paurá Lagoon during maximum water overflow - due to rain water excess (WE), and water deficit - due to rain water scarcity (WS). This lagoon is situated in a coastal area ranked as conservation priority in Brazil (31°34' S, 51°18' W; 31°34' S, 51°17' W; 31°35' S, 51°18' W and 31°35' S, 51°19' W). Analyses of rainfall records covering the 1992-2012 time series, water balance and remote sensing with freely available GIS application (SPRING) were employed to select satellite images from WS and WE dates. Two Landsat-5 TM images, dated 29/04/2009 (WS) and 06/09/1998 (WE) were selected and geoprocessed to detect differences in areas under WS and WE, respectively. For lagoon surface area and PPA, 66.29

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ha and 42.36 ha were calculated during WS, and 92.27 ha and 53.25 ha during WE, respectively. At maximum WE (local winter and spring), lagoon surface area was 25.98 ha larger, while PPA had an addition of 10.89 ha. Although Landsat images have spatial resolution limitations, the methodology allowed the identification of the most suitable annual period to delimitate a larger area around the water body. Following *in situ* demarcation, the resulting larger PPA may provide superior ecological benefits to priority conservation regions. The methodology tested may be a useful tool to integrated management of lakes and wetlands in coastal zones.

Keywords: coastal lakes; Forest Code; priority conservation areas; rainfall; remote sensing; seasonality

RESUMO: As Áreas de Preservação Permanente (APP) são determinadas pelo Código Florestal Brasileiro (Lei Federal nº 12.651 / 2012) para proteger a biodiversidade, solo, água e integridade climática. Em torno de lagos e lagoas em áreas rurais, a lei estabelece faixas marginais de APP com uma largura mínima de 100 m (ou 50 m para lagos com menos de 20 ha). Alguns desses corpos de água podem ter suas dimensões de superfície marcadamente alteradas devido às variações sazonais. APP demarcadas durante os períodos de cotas máximas do nível de água apresentariam vantagens ecológicas. No entanto, tais variações não foram incluídas como critérios para a definição das APP em torno de lagos e lagoas no novo Código Florestal 2012. Além disso, os efeitos das variações sazonais ainda não são suficientemente conhecidos nos corpos de água da maioria das regiões. Neste trabalho, a área do espelho d'água e a APP da Lagoa do Paurá foram delimitadas e medidas durante as datas de máxima inundação - devido ao excesso de chuva (WE) e máximo deficit hídrico – devido à escassez de chuva (WS). Esta lagoa está situada em uma área da planície costeira sul classificada como prioridade para a conservação no Brasil (31°34'S, 51°18'W; 31°34'S, 51°17'W; 31°35'S, 51°18'W and 31°35'S, 51°19'W). Foram analisados registros pluviométricos cobrindo a série histórica 1992-2012, balanço hídrico e imagens de satélite disponíveis gratuitamente. Duas imagens do Landsat-5 TM, datadas de 29/04/2009 (WS) e 06/09/1998 (WE), foram selecionadas e processadas para detectar diferenças nas áreas sob WS e WE, respectivamente. Para área superficial da lagoa e para a sua APP, 66,29 ha e 42,36 ha foram calculados durante WS, e 92,27 ha e 53,25 ha durante WE, respectivamente. Em WE (inverno e primavera), a área da lagoa obtida é maior cerca de 25,98 ha, enquanto a APP apresentou um aumento de 10,89 ha. Apesar das limitações de resolução espacial das imagens Landsat, a metodologia permitiu a identificação do período anual mais apropriado para delimitar uma área maior em torno do corpo de água. Assim, a demarcação in situ de uma maior APP de lagoa poderá reverter em benefícios ecológicos superiores para regiões prioritárias à conservação. A metodologia testada presentemente poderá ser uma ferramenta útil à gestão integrada de lagoas e áreas úmidas de zonas costeiras.

Palavras-chave: áreas prioritárias para conservação; Código Florestal; lagoas costeiras; pluviosidade; sensoriamento remoto; sazonalidade

1. INTRODUCTION

Permanent Preservation Areas (PPA) were determined by the Brazilian Forest Code in 1965, recently changed by Federal Law nº 12651/2012, aiming at protection of native vegetation, biodiversity, soil, water, and climate integrity (Presidência da República Federativa do Brasil, 2012).

With relevant ecosystemic functions, such as protection against flood, erosion and soil deterioration, maintenance of regional temperature, humidity, natural landscapes and geological stability, reduction of heat island effect and local pollution, the implementation of PPA is essential to maintain the quality of life.

Several geographical types of PPA are defined by the new Forest Code edition of 2012. For ponds, lakes and lagoons in rural areas, PPA are considered the surrounding areas with a minimum width of 100 m, or 50 m for water bodies with an area of up to 20 ha. Failure to comply with the Forest Code, for instance to develop agricultural activities or building infrastructure, can compromise a large range of environmental services, being costly from the socioeconomic and ecological points of view, as registered by Tundisi & Matsumura-Tundisi (2010).

The correct application of the legislation should bring significant results to a continental size country like Brazil, with an extensive hydrographic network and high biological diversity. Thus, the verification of compliance with the PPA legislation through identification, monitoring and enforcement is an important task to environmental agencies.

Remote Sensing and Geographic Information Systems (GIS) have made it possible to reveal important aspects of the properties of ecosystems (Sausen *et al.,* 2006). These geotechnologies can be applied to the delimitation of PPA and monitoring of environmental dynamics, among other uses for environmental management. In the literature, there is an increasing number of studies using remote sensing to the delimitation of watercourses and their PPA. Although in a much smaller number, some similar studies in lagoons, lakes and ponds can also be found. Reis *et al.* (2009), using a cartographic base vector complemented with satellite imagery, generated a map of land use and cover delimitating Lake *Jaturnaíba* (Rio de Janeiro) area in a polygon and from there delimited a 100 m area of influence (buffer) using ArcGIS application tools. Similar strategy was used by Cecílio & Coutinho (2011), analyzing the different land uses in the vicinity of *Guanandi* Lake (Espírito Santo) using Fuzzy Logic adapted to the Analytic Hierarchy Process (AHP) application in a GIS environment for the demarcation of PPA. Mesquita *et al.* (2012) mapped the types of use and occupation of the PPA in *Uruaú* Lake (Ceará), contemplating the analysis of landscape changes and GIS techniques for the preparation of maps of this touristic coastal spot. In all the reported cases, the delimitation of the PPA was conducted by measuring the width from the lake edge at the time of satellite image, independently of the time of the year, season, or dynamics of the water body. More recently, Santos (2013) analyzing Landsat TM 5 images from 2000 and 2010, observed several lakes and lagoons in the northeastern Brazilian coast (state of Rio Grande do Norte) directly influenced by the rainfall regime, with considerable surface water changes along the year, especially those located near the coastal region (inter-dune lakes), where there is significant human occupation.

On the other hand, GIS applications and products can be expensive, for example to small and medium-size rural entrepreneurs, while trying to comply with the federal PPA legislation. This can be made worse by the frequent unavailability of previous studies, such as about water levels and topography, therefore hampering the development of analyses. An alternative solution would be the use of freely available GIS applications, even though their resulting products might not have the highest spatial resolution (Sillero & Tarroso, 2010).

With that concern, a pilot project to develop a methodology for lake and lagoon PPA delimitation (Domingues *et al.* 2015) was previously conducted. In that study, seasonal variations, time of the year of maximum lake water level and its influence on lake and its PPA dimensions were verified. The water body chosen, *Gateados* Lagoon, is situated in the rural area of Mostardas, Southern Brazilian Coastal Plain, more precisely in the Middle Coast region of Rio Grande do Sul State - RS. The Southern Coastal Plain is an area of high ecological importance, normalized as priority for conservation by the Brazilian Ministry of Environment (Ministério do Meio Ambiente, 2007). Despite that, this coastal region is subjected to severe impacts, such as irrigated rice cropping, *Pinus* forestry, urban expansion and cattle grazing. As a result, a methodology using remote sensing was proposed for demarcation of PPA around coastal lakes and lagoons. As described by Domingues *et al.* (2015), this approach considers historical lake surface variations, according to the water availability conditions contributing to lake dynamics.

Within this context, the present study aims to define the PPA of *Paurá* Lagoon. As an important focus of conservation interest, the *Paurá* Lagoon is situated further south in the Middle Coast of RS (Figure 1 and Supporting information I). To that end, we intend to apply the methodology previously described for *Gateados* Lagoon (Domingues *et al.*, 2015) and verify its repeatability in a different environment of the Southern Coastal Plain. The conditions of higher and lower water surface, *i.e.* maximum and minimum lagoon levels, are considered in a remote sensing analysis of freely-available satellite images.

2. METHODOLOGY

2.1 Study Area

The *Paurá* Lagoon is located within the coordinates 31°34’ S, 51°18’ W; 31°34’ S, 51°17’ W; 31°35’ S, 51°18’ W and 31°35’ S, 51°19’ W. It is located south of the *Lagoa do Peixe* National Park (LPNP) and in the northern limit of the municipality of São José do Norte, RS, which is bordered by the Atlantic Ocean to the east, by the large *Patos* Lagoon to the west, and to the south by the *Canal da Barra* – an important channel linking the latter lagoon to the sea (Figure 1 and Supporting information I). The *Patos* Lagoon is the largest coastal barrier-lagoon system in Brazil, with an area of 10,000 km^2, and the second largest lagoon in Latin America (Dillenburg & Hesp, 2009; Hales & Petry, 2013). The main economic activities in the region are agriculture and forestry of the exotic *Pinus elliottis*. Previous regional surveys (Paranapanema, 1999; Schäfer *et al.,* 2009a and 2009b) indicated that the regional climate is subtropical, CFA by the Köppen classification, rainy, moderate temperate, with northeastern winds to the southwest. The average annual rainfall in the region is 1500 mm and 125 mm monthly (INPE, 2014), with relatively heavy rainfall in the winter, more specifically in the quarter July-August-September (Cavalcanti *et al.*, 2009). Planosols are predominantly associated with quartz sands. The *Paurá* Lagoon is characterized by its elongate shape in parallel to the shore, 1.8 km of length and shallow depth (0.77 m), according to 2008 summer data (Schäfer *et al.,* 2009b).

The lagoon's influence region has a straight stretch of beach, sandy fields with rolling low stature dunes devoid of vegetation, or partially covered with herbaceous plants, predominantly *Panicum racemosum* (Poaceae) and *Androtrichum trigynum* (Cyperaceae). There are marshlands associated with wet grasslands next to the lagoon and a *Mata de Restinga* – a continuous strip of sandbank forest established over an ancient dune, with several tree species, predominantly of the *Myrtaceae* family, besides lianas, epiphytes and shrubs. In the surroundings, there are exotic pine forestry and fields with cattle. The fauna is rich in terrestrial vertebrates of open areas, as well as aquatic fauna and bird life (Schäfer *et al*., 2009a).

2.2 Rainfall

The rainfall historical series chosen comprises daily, monthly and annual data from a period of 20 years – from 1992 to 2012 - registered at the Tavares Weather Station. Total rainfall of each month within this period was calculated. From these data, the number of days without rainfall in each month was determined. These were important to assist the identification of periods of water deficiency (rain water scarcity -WS) and water overflow (rain water excess WE) - relating to the minimum and maximum dimensions of the lagoon, respectively. Thereby, WS and WE were used as criteria assisting the selection of satellite images.

To confirm the selection of the most representative WS and WE images, the accumulated rainfall in the 31 days preceding the acquisition of each image was quantified. That was done to search for periods of greater constancy of rainfall records. The 31 days presenting the longest period with little or no rainfall indicated the best choice of a WS representative image, while the wettest 31 day-period confirmed the choice of the WE image.

2.3 Water Balance

Water balance conditions of the *Paurá* Lagoon region were extracted from a State agroclimatic zoning reference

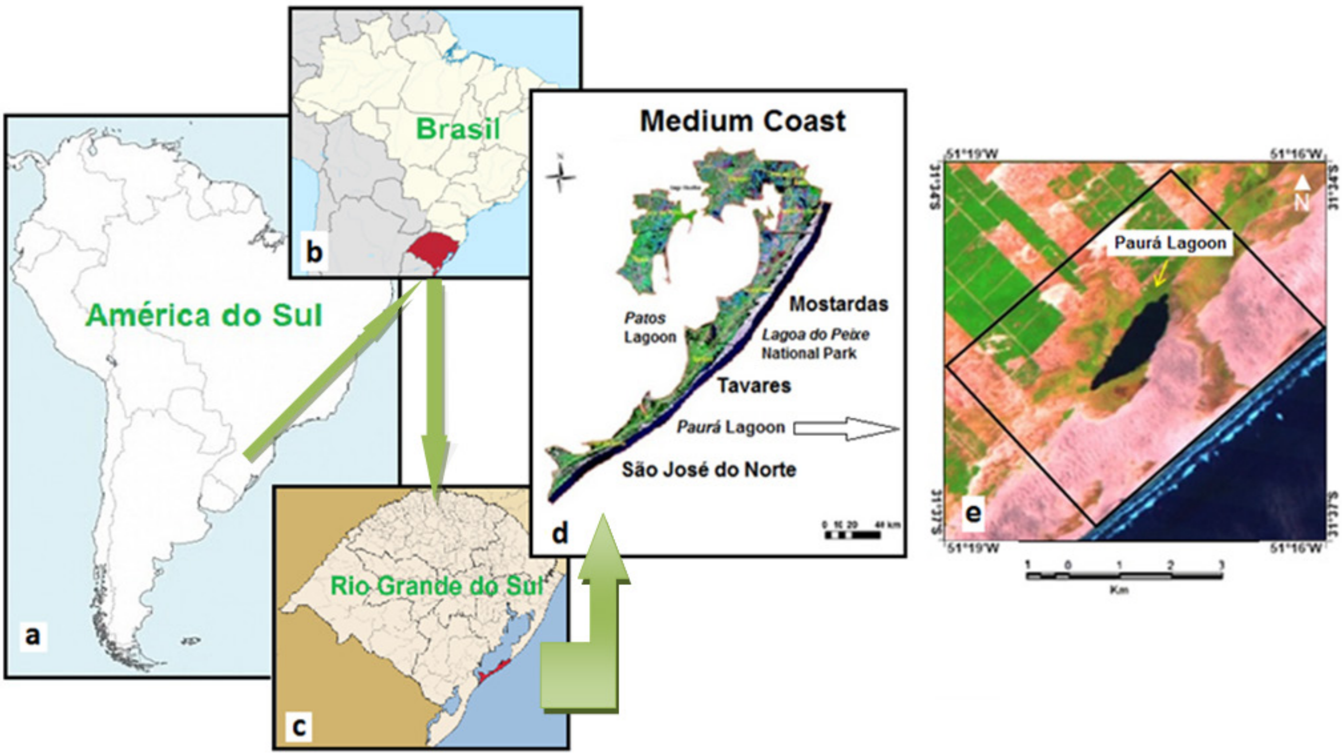

Figure 1 - Location of the study area (e) in the municipality of São José do Norte (red in c), within the Middle Coast region (d) of Rio Grande do Sul (c) - the southernmost state in Brazil (b), South America (a). The *Paurá* Lagoon is indicated in a Landsat 5 image (1993) 543 RGB band composition (e).

Figura 1 - *Mapas de localização da área de estudo (e) no município de São José do Norte (c), Litoral Médio (d) do estado do Rio Grande do Sul (c), o estado mais a sul do Brasil (b), América do Sul (a). A Lagoa do Paurá está indicada em imagem Landsat 5 (1993), composição de bandas 543 RGB (e).*

(Secretaria do Planejamento e Coordenação, 1978). The water balance was calculated with data available from the neighbor municipality of Mostardas. The same hydrological reference study was used additionally in order to identify WS and WE periods, and to assist satellite image selection.

2.4 Selection of Satellite Images

Through the digital image catalog of the Brazilian National Institute for Space Research (INPE), Landsat 5 - TM satellite scenes were obtained free of charge to explore a historical series from 1985 until 2011.

Landsat 5 scenes have a spatial resolution of 30 m, that is, each pixel of the image is 30 m wide and 30 m long, with a total land area of 900 m² (0,09 ha). Each scene covers a land area of 34,225 km² (185 km x 185 km). This satellite captures images in seven different bands of the electromagnetic spectrum with a temporal resolution of 16 days (NASA, 2012). For this work, 89 digital Landsat 5 images were preselected from INPE's online catalog. To avoid exceptional weather patterns, images from periods recorded as 'Strong' for both *El Niño* and *La Niña* climatic oscillations (CPTEC, 2014) were not considered. Two images from this total were chosen in order to represent WE and WS periods in *Paurá* Lagoon. For the selection of the two images the following criteria were established:

- Images with little cloud cover, especially above the lagoon;
- WS images chosen during negative water balance period, with the lowest accumulated rainfall values in the 31 days prior to the image date;
- WE images chosen during the positive water balance period, with the highest accumulated rainfall values in the 31 days prior to the image date.

2.5 Download and Geoprocessing of Images

The Landsat 5 satellite images database was accessed after registration at INPE's Satellite Image Catalog in http://www.dgi.inpe.br/CDSR/. Two scenes were downloaded, using the following basic parameters: TM sensor, orbit 221, point 082. The scenes, each one with the dimensions of 185 km x 185 km, were recorded in the SPRING 4.3.3 application, considering a mean square error of less than one pixel. The SPRING processing resources and image classification application is a free of charge geographical information software, developed and available online from INPE.

A GeoCover Landsat 7 image, dated 12 November 2002 (University of Maryland, USA, Global Land Cover Facility, http://glcf.umd.edu/research/portal/geocover/) was downloaded for registration of the selected Landsat 5 images, with the following parameters: ETM + sensor, orbit 221, point 082, WRS-2. The registration process in the SPRING 4.3.3 was carried out using 23 points of support from the GeoCover image, the projection system Universal Transverse of Mercator (UTM) and the South American Datum SAD69, polynomial of degree 2, nearest neighbour interpolation and mean square error of less than one pixel.

2.6 Delimitation and Calculation of Flooded Area

The delineation of the lagoon's water surface (also termed 'lamina' or 'flooded area') was firstly done by insertion of the two geoprocessed images in a database created in the SPRING 4.3.3 application. The lagoon's shoreline was then identified by its texture, form and spatial configuration. Vectorization followed by manual delimitation and quantification of the flooded area on each image, using a 1:6,000 scale. Best results were achieved with a 543 band combination in the RGB channels, matching the mid-infrared band (band 5), near infrared (band 4) and red (band 3). Using the SPRING buffer tool, a polygon line was drawn along the lagoon margin. The quantification of the delimited flooded area was carried out with the SPRING 4.3.3 metric operations tool, by summing up the number of internal pixels of the polygon generated within the lagoon's marginal line.

2.7 Demarcation and PPA Calculation

The demarcation of the 100 m wide legal marginal PPA strip from the lagoon's dry border was carried out using the SPRING 4.3.3 distance map tool. PPA dimension was calculated by summing up the number of pixels within the polygon formed by the range of 100 m, demarcated from the dry edge of the flooded area.

The methodology employed is summarized in the diagram of Figure 2.

2.8 Field visits

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

3. RESULTS

Total rainfall volume calculated from each month and the number of days without rainfall in each month, during the studied historical series of 1992 to 2012 (Tables I to X, Figure I and Figure II in Supporting Information II - SI-

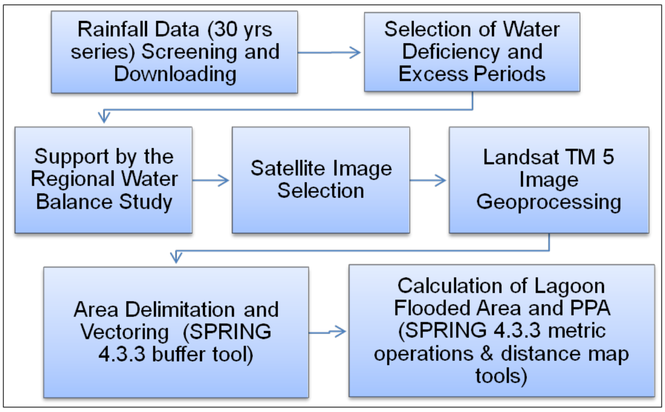

Figure 2 – Summary of the methodological steps done for lagoon PPA delimitation.

Figura 2 – Diagrama dos passos metodológicos realizados para a delimitação da APP de lagoa.

II), assisted the selection of the two best representative Landsat 5 images of water overflow (or excess - WE) and water deficiency (or stress - WS) in the *Paurá* Lagoon. These images, shown in Figure 3, were dated 06 September 1998 (WE) and 29 April 2009 (WS).

An accumulated rainfall volume of 255.0 mm during the 31 days preceding 06/09/1998 (maximum lagoon level period, 23 days without rain) was obtained. While only 3.7 mm (29 days without rain) were found for the 31 days period up to 29/04/2009 (minimum lagoon level period), meaning a difference of 251.3 mm of rain (Figure II in SI-III).

In addition, the regional water balance reference study (Secretaria da Coordenação e Planejamento, 1978) assisted the selection of periods with greater and lower water availability in the lagoon. It also allowed the identification of periods with greater losses by evapotranspiration and higher recharges by precipitation. The water balance indicated a period marked by WS from late spring until early autumn (November to April, Figure I in SI-III). The greatest water loss appears due to the high potential evapotranspiration, especially during the summer months (December, January, February and March), when wind and temperature values are higher. The water balance study shows that water use is higher in the drought period, further exacerbating the retreat of the lagoon flooded area during the drier season. This is clearly shown in Figure 3A, where a smaller wetland area is seen in the WS date image.

The positive water balance period is characterized by an initial period of water replacement in the months of April, May and June (autumn and early winter) with rainfall precipitation values exceeding potential evapotranspiration values. And for another period of WE in the months between July and October (mid-winter

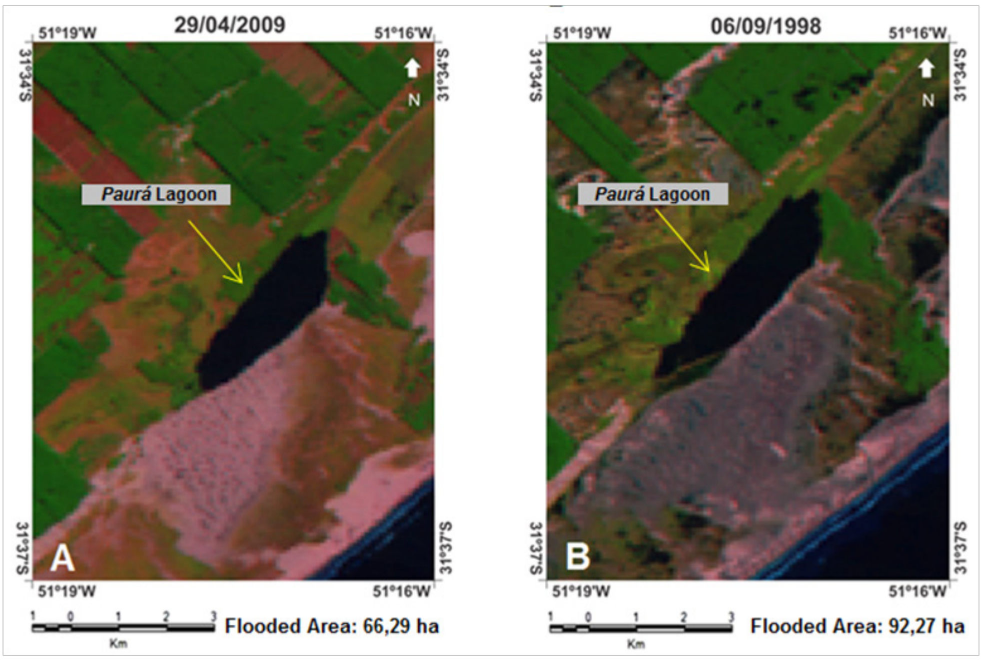

Figure 3 – Landsat 5 images and water surface area variations in Paurá Lagoon, São José do Norte-RS: (A) during maximum water deficit (29/04/2009) and (B) maximum water excess (06/09/1998), according to the 1992-2012 historical series.

Figure 3 - *Imagens Landsat 5 e a variação das áreas de superfície de água na Lagoa do Paurá, São José do Norte-RS: (A) durante período de máximo déficit hídrico (29/04/2009) e (B) de máximo excesso hídrico (1998/06/09), de acordo com dados pluviométricos da série histórica 1992- 2012.*

and early spring), due to the water replacement in the previous period and the greater accumulation of water precipitated during these latter months. The lagoon flooded area tends to be larger during the WE period, as seen in Figure 3B, corresponding to autumn and winter scenes.

Regarding the PPA estimated and delineated in Figure 4, the difference between the two images was 10.89 ha, which equals to a PPA area 1.26 times larger in WE than in WS conditions. The addition of the flooded area to the PPA in WE results in a total of 145.52 ha to be legally preserved. That is, in the WE period (06/09/1998), the largest lagoon area reached 92.27 ha with 53.25 ha of PPA, while during WS (24/04/2009), the smallest lagoon flooded area measured 66.29 ha with a PPA of 42.36 ha. Such increase represents 25.98 ha in addition to the flooded area during the period of greater water availability (i.e. maximum level), which is equivalent to 1.40 times the lagoon flooded area during the dry season (Figure I in SI-IV).

Large amounts of macrophytes' remnants were seen withering on the north bank of the lagoon, indicating the rise of water in a WE period and its subsequent retraction (Figure 5A). Other in site observations included a shallow marsh along the northern portion of the lagoon (Figure 5B), fields and sand dunes covered with an old pine tree plantation around the northeast margin. Part of this plantation had been cut, as verified by stumps from cut logs still apparent along the PPA (Figure 5C). Additionally, there was a high number of new pine trees naturally dispersed along the north-northeastern marginal PPA and on the surrounding dunes (Figure 5D). Parallel to the west margin of the lagoon, a forest sandbank over an inner dune (*restinga* forest) follows northwards flanking the wet grassland. Such vegetated dune was probably formed during the last Cenozoic barrier, as indicated by its location (Figure 5E). Exotic pine trees individuals were spotted colonizing the borders of that native *restinga* forest (Figure 5F).

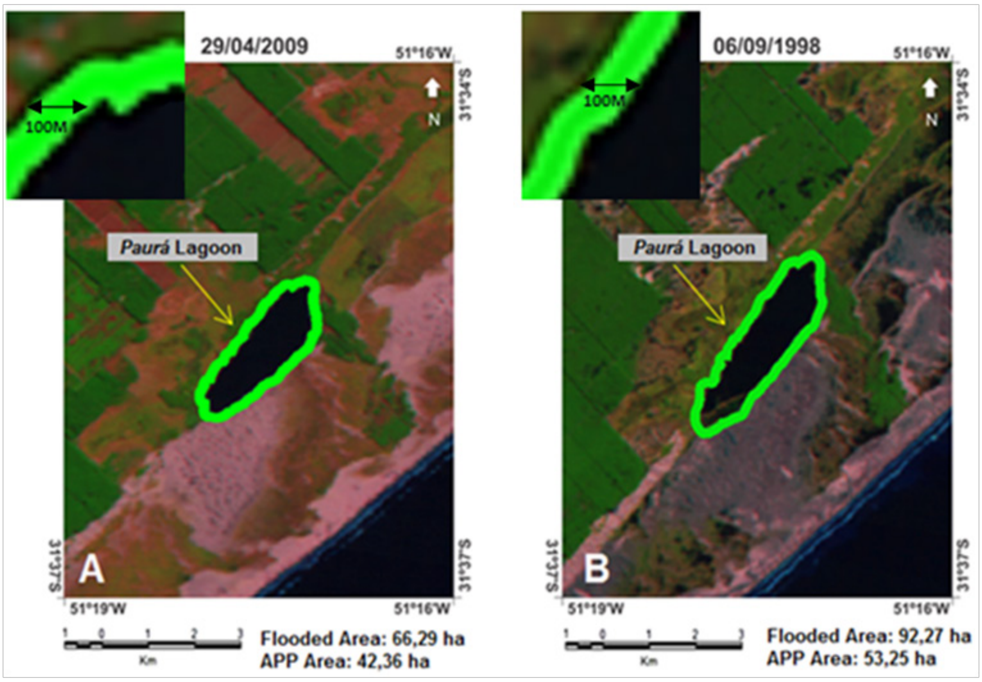

Figure 4 - Delimitation of the permanent preservation area (PPA) during periods of (A) water deficit (29/04/2009) and (B) water overflow (06/09/1998), from satellite images of the Landsat time series 5 (1985-2011) and rainfall data (1992-2012), with their calculated values for water surface and PPA of Lagoon Paurá, São José do Norte-RS.

Figura 4 - *Delimitação da área de preservação permanente (APP) nos períodos de (A) déficit (29/04/2009) e (B) excesso hídrico (06/09/1998), a partir de séries históricas de imagens do satélite Landsat 5 (1985-2011) e de dados de precipitação pluviométrica (1992-2012), com respectivos valores calculados para área alagada e APP da Lagoa do Paurá, São José do Norte-RS.*

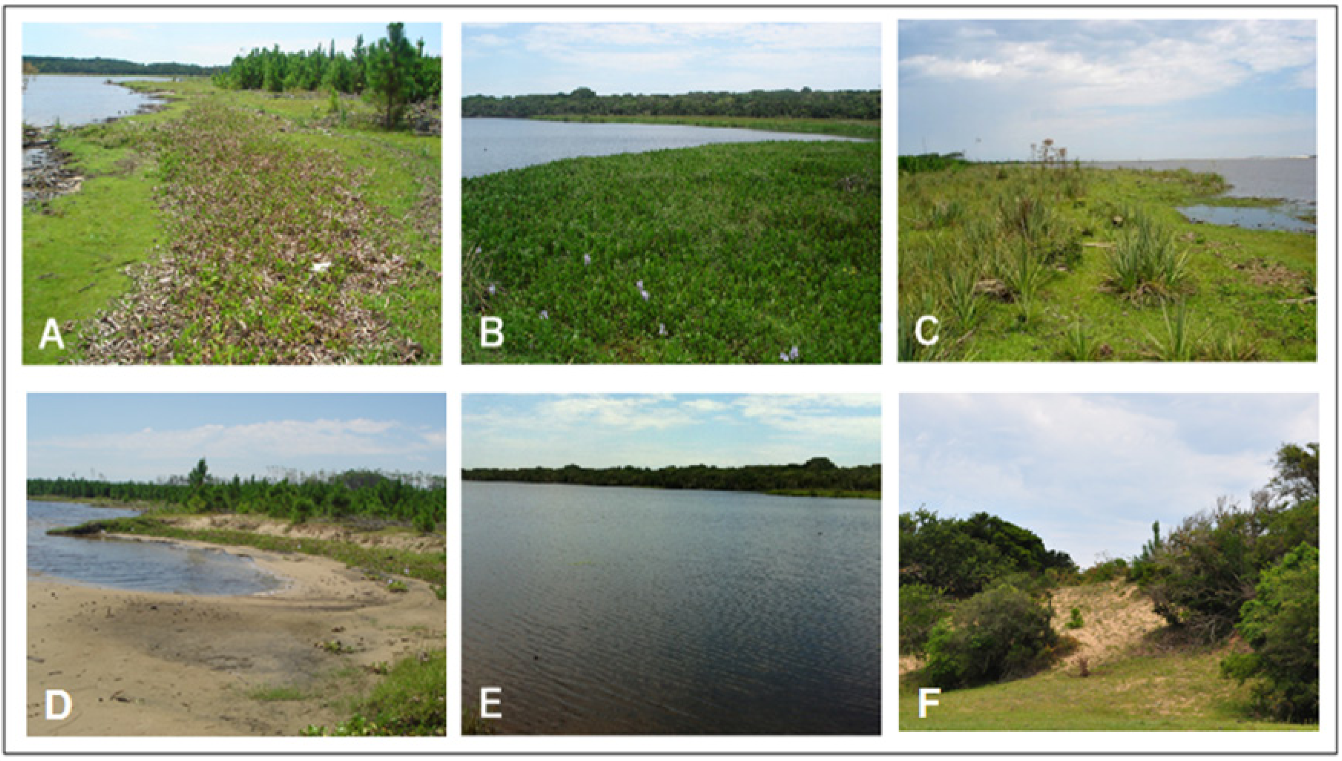

Figure 5 - Photographic records obtained in the field trip to Paurá Lagoon on 28 January 2014: A - Remnants of aquatic macrophytes plants on the north margin; B - Wetland with macrophytes in the northern portion; C - Exotic *Pinus* trunks cut close to the ground in the PPA; D - PPA with scatter *Pinus* and old plot, right on the background dune; E - View of the native forest sandbank on the west margin; F - Exotic *Pinus* invasion in the forest sandbank.

Figura 5 - Registros fotográficos obtidos na saída de campo à Lagoa do Paurá, em 28 de janeiro de 2014. A - Resquícios de plantas macrófitas aquáticas sobre a margem norte; B - Banhado na porção norte; C - Corte raso de Pinus exóticos na APP; D - APP com dispersão de Pinus e talhão antigo, à direita, sobre duna; E - Vista da mata nativa de restinga na margem oeste; F - Invasão de Pinus exóticos na mata de restinga.

4. DISCUSSION

Results obtained from *Paurá* Lagoon PPA area dynamics could be compared to those obtained previously for *Gateados* Lagoon, using the same methodology (Domingues *et al.,* 2015). *Paurá's* PPA and flooded area increased 1.26 times and 1.40 times, respectively, during water overflow conditions. While in *Gateados* Lagoon, both PPA and flooded area increased twice during water overflow conditions. Larger increases seen in *Gateados* could be partially explained by an extra WE overflow from the nearby significantly larger *Patos* and *Casamento* lagoons through a system of wetlands and groundwater links (Domingues *et al*., 2015). While the *Paurá* Lagoon, situated further away from another large fresh water body and on a sandier, more permeable soil, would displays a better WE drainage and a less pronounced surface area increase.

According to the legal provisions of the Forest Code, considerable land gains for ecosystem preservation were indicated by satellite image analyses of the two bodies of water, provided the PPA delineation was made during the maximum water surface level.

As remarked by Domingues *et al.* (2015), similarly to the area calculated here under WS, other significant unobserved PPA losses around lakes and lagoons may occur routinely elsewhere in the country, as a result from the lack of legal definitions. That is, the current Brazilian Forest Code, while defining the limits of PPA, does not consider water balance nor rainfall seasonality as criteria for lake PPA demarcation. The new 2012 Code also disregards local environmental peculiarities, such as geomorphology, soil and climate, which are known to influence the morphology of lacustrine bodies of water, such as those found in abundance along the Brazilian Coastal Plain.

Marchett *et al.* (2012) also observed seasonal surface variation in another lagoon from the RS Coastal Plain. By delimiting the *Cidreira-Rondinha* Lagoon on four Landsat 5 TM satellite images from different dates over one year, they obtained four different boundary margins attributed mainly to climatic conditions and water use for irrigation. As reported by those authors, the delimitation of the water body on more than one season enabled a better understanding of its dynamics, in comparison to using only one image or topographic map. Similarly, Santos (2013), based on the analysis of Landsat TM images dated 26/09/2000 and 06/09/2010 of several lakes and lagoons in the extreme northeastern coast of Brazil (Nísia Floresta, Rio Grande do Norte state), mapped different water features for the respective years. That author detected a 59% decrease in total lake water surface lamina from 2000 (2,022.5 ha) to 2010 (1,476.6 ha), which was credited to a considerable rainfall difference: 2034.0 mm recorded in 2000 against 910.6 mm in 2010. The conclusions from Santos (2013) and Marchett *et al.* (2012) corroborate findings in the present study.

In relation to the flooded surface of *Paurá* Lagoon, measurements made by others (Schäfer *et al.*, 2009b) reported 70 ha during the summer of 2008, which were quite similar to the 69.29 ha obtained during WS period (early autumn, 2009) in the present study.

Factors distinct of the hydrological regime may also influence the variation in the level of lakes in this coastal region. Gianuca & Tagliani (2012), analyzing aerial photos of 1964 and Landsat 5 TM images of 2007 from the neighboring locality of *Estreito*, in the south of *Paurá* Lagoon, suggested that the horizontal increase in the lagoon flooded area was due to the obstruction of natural drainages by the exotic pine plantations nearby. However, drainage changes would lead to increases in the water level especially during periods of high rainfall. Studies by Schäfer *et al.* (2009a) indicated that most asymmetrical and shallow lagoons of the RS Middle Coast region have suffered a gradual decrease in area by clogging due to accumulation of sand from dunes moved by the predominant northeast winds. It is possible that the same occurs in *Paurá* Lagoon. In the present study, a comparison between 1998 and 2009 images shows greater accumulation of sand around the south side of the lagoon during the latter year.

In addition to the seasonal hydrological regime, the dynamics of *Paurá* Lagoon is probably suffering influences from the presence of planted or naturally dispersed exotic pine trees in the surrounding area. Evidences from others have demonstrated that large pine plantations near small bodies of water could influence their area, by reducing the level or slowing the advance of surface water. Studying the spatial dispersion of pine plantations in the National Park of *Lagoa do Peixe* and its surroundings, Portz *et al.* (2011) cite a document from the Brazilian National Institute of Environment - IBAMA (Letter nº001/06 - PNLP - IBAMA, dated 09/01/2006), describing impacts of *Pinus* tree monoculture, which include relegation/reduction of the water table, the decrease in humidity and consequent change in rainfall. These changes in the water regime affect directly and indirectly the hydrological system of the water body, causing the drying of wetlands, and affecting flora and fauna. The water balance of the lagoon is also affected, as these wetlands act as sponges retaining water for periods of drought. Therefore, it would be important to eliminate existing exotic *Pinus* from *Paurá* lagoon PPA and control new invasions through an appropriate tree management in neighboring forestry enterprises.

Landsat satellite images were chosen here, because they are available free of charge in the internet and provide comparable registers spanning over more than three decades. Several authors cited here have also used Landsat images for similar reasons (Gianuca & Tagliani, 2012; Marchett *et al.*, 2012; Santos, 2013; Schäffer *et al.*, 2009a). Methodologies such as the presently applied, providing satisfactory results while employing less expensive GIS tools, are particularly advantageous to small and medium size landowners, as well as to local environmental agencies, usually devoid of sufficient resources. Nevertheless, PPA and lagoon flooded area measurements determined using Landsat 5 images have an inherent error due to the image pixel size (30 m x 30 m). This fact does not invalidate the results found here, although it highlights the need for a cautionary interpretation of the values which solely should not be considered as absolute. As done here, site recognition to confirm measurements should still be carried out in the field. Whenever greater accuracy in results is needed, higher spatial resolution images from other satellites could be employed, usually upon purchase of a license fee.

Findings of this study reinforce the importance of understanding the dynamics of the water body, to thereby allow a greater range of ecological functions of the PPA, especially in coastal zones and other areas of notable importance to conservation.

5. CONCLUSIONS

We have verified and confirmed the applicability of a method previously developed to demarcate PPA of lakes and lagoons of the Southern Brazilian Coastal Plain (Domingues *et. al.*, 2015). Combining analyses of multitemporal satellite images, pluviometrical data and water balance, the PPA and water surface area of *Paurá* lagoon were delineated, measured and compared at maximum periods of water deficit and water overflow.

Lagoon PPA with larger dimensions were found during maximum water level conditions. Therefore, *in situ* area demarcation between mid winter and early spring (July to October) would be highly advantageous to the preservation of *Paurá* Lagoon and associated ecosystems.

In compliance to the new 2012 Brazilian Forest Code, *in situ* PPA demarcation considering annual water body dynamics, together with an effective integrated exotic tree management for *Pinus* control, would be crucial to maintain landscape, water regime and biodiversity in the Southern Brazilian Coastal Plain.

In addition to control and monitoring, environmental agencies and other governing bodies should consider these findings when planning and implementing policies, such as those for ecological-economic integrated management. Directives derived would assist landowners and entrepreneurs to comply with law in a more ecological way.

The methodology applied here may be also adapted to protect wetland and lake-associated ecosystems from other coastal or non-coastal regions.

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REFERENCES

Cavalcanti, I.F.A.; Ferreira, N.J; Silva, M.G.A. J.; Dias, M.A.F.S. (2009) - Tempo e clima no Brasil. 463 p., Oficina de Textos, São Paulo, Brasil.

Cecílio, R.A.; Coutinho, L.M. (2011) - Delimitação e estudo de vulnerabilidade da Área de Preservação Permanente no entorno da Lagoa Guanandi, Itapemirim-ES. In: Simpósio Brasileiro de Sensoriamento Remoto. 5, p.58-68, INPE. Curitiba, PR, Brasil. Available on-line at: http://www.dsr.inpe.br/sbsr2011/files/p0236.pdf. (Accessed September 2015).

Centro de Previsão de Tempo e Estudos Climáticos (CPTEC) (2014) – El Niño, La Nina – Últimas Ocorrências. Available on-line at: http://enos.cptec.inpe.br. (Accessed June 2014).

Corrêa, F.; Claudino, M. C.; Bastos, R. F.; Huckembeck, S.; Garcia, A. M (2012) - Feeding ecology and prey preferences of a piscivorous fish in the Lagoa do Peixe National Park, a Biosphere Reserve in Southern Brazil. Environ. Biol. Fish v. 93, n.1. p.1–12. DOI 10.1007/s10641-011-9881-4

Dillenburg, S.R.; Hesp, P.A. (2009). Editors. Geology and Geomorphology of Holocene Coastal Barriers of Brazil. 1st ed. Berlin, Germany: Springer-Verlag.

Domingues A.L.; Lipp-Nissinen, K.H., Miranda, L.S.; Buriol, G.A.; (2015) - Delimitação da área de preservação permanente da Lagoa dos Gateados, na Planície Costeira do Rio Grande do Sul (RS), utilizando séries de imagens de satélite e dados hidrológicos históricos. *Revista Brasileira de Geografia Física*. Recife. 8 (3): 776-792. ISSN 1984-2295. DOI: 10.5935/1984-2295.20150031.

Hales, J.; Petry, P. (2013) - Laguna dos Patos. In: Fresh Waters Ecoregions of the World. Available on-line at: http://www.feow.org/ecoregions/details/laguna_dos_patos (Accessed September 2015).

Gianuca, K.S.; Tagliani, C.R.A. (2012) - Análise em um Sistema de Informação Geográfica (SIG) das alterações na paisagem em ambientes adjacentes a plantios de pinus no Distrito do Estreito, município de São José do Norte, Brasil. *Revista da Gestão Costeira Integrada*, v. 12, n.1, p. 43-55. DOI: 10.5894/rgci285.

Instituto Nacional de Pesquisas Espaciais (INPE) (s/d) - Departamento de Sensoriamento Remoto. Series View. Available on-line at: https://www.dsr.inpe.br/laf/series/index.php (Accessed September 2014).

Marchett, C.A.; Schuh, S.M.; Ahlert, S.; Schäfer, A. E. (2012) - Uso de imagens de Landsat-5-TM em diferentes datas para a definição dos limites de lagoas costeiras do RS. In: Seminário de Estudos Limnológicos em Clima Tropical. 3. UFSM. Santa Maria, RS, Brasil. Available on-line at http://www.ufsm.br/selcs2012. (Accessed July 2014).

Mesquita, E.A.; Brito, M.L. da C.; Romana, L. do Ó P. (2012) - Geoprocessamento aplicado ao mapeamento das formas de uso da terra na Área de Preservação Permanente da Lagoa do Uruaú. *Revista Geonorte*, Edição Especial (Special Edition), v.2, n.4, p.1509-1518. Beberibe, CE, Brasil. Available on-line at http://www.revistageonorte.ufam.edu.br/attachments/009_GEOPROCESSAMENTO%20APLICADO%20AO%20MAPEAMENTO%20DAS%20FORMAS%20DE%20USO%20DA%20TERRA.pdf (Accessed January 2015).

Ministério do Meio Ambiente - MMA. (2007) - Portaria MMA nº 9, de 23 de janeiro de 2007. Available on-line at http://www.mma.gov.br/estruturas/chm/_arquivos/biodiversidade31.pdf (Accessed June 2014).

NASA (2012) - Introductory Landsat tutorial. Available on-line at http://zulu.ssc.nasa.gov/mrsid/tutorial/Landsat%20Tutorial-V1.html (Accessed April 2014).

Sillero, N.; Tarroso, P. (2010) - Free GIS for herpetologists: free data sources on Internet and comparison analysis of proprietary and free/open source software. Acta Herpetologica, [S.l.], v. 5, n. 1, p. 63-85. ISSN 1827-9643. Available at: <http://www.fupress.net/index.php/ah/article/view/8535/7996>. (Accessed November 2016). DOI:10.13128/Acta_Herpetol-8535.

Paranapanema (1999) - Projeto Bujuru: Complexo Mineiro - lavra, beneficiamento e transporte de minerais pesados. *Relatório de Impacto Ambiental - RIMA*. Magna Engenharia. 1v. Porto Alegre, RS, Brasil.

Pereira, M. S.; Poerschke, F. (2010) New bird records from Lagoa do Peixe National Park, southern Brazil. *Biotemas*, Florianopolis (ISSN 2175-7925), v. 23, n. 1, p. 241-246. Available on-line at https://periodicos.ufsc.br/index.php/biotemas/article/view/2175-7925.2010v23n1p241 (Accessed October 2015). DOI: 10.5007/2175-7925.2010v23n1p241

Presidência da República Federativa do Brasil (2012) - Lei nº 12.651, de 25 de maio de 2012. Diário Oficial da União. Brasília, DF, 19 jul. 2012. Available on-line at http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Lei/L12651.htm (Accessed May 2014).

Portz, L.; Manzolli, R.P.; Saldanha, D.L.; Correa, I.C.S. (2011) - Dispersão de espécie exótica no Parque Nacional da Lagoa do Peixe e seu entorno. *Revista Brasileira de Geografia Física* (ISSN 1984-2295), v.4, n.1, p.35-38. Porto Alegre, RS, Brasil. Available on-line at http://www.revista.ufpe.br/rbgfe/index.php/revista/article/viewFile/171/152

Reis, R.B.; Cardoso, P.V.; Cruz, C.B.M.; Vicens, R.S. (2009) - Mapeamento e caracterização das Áreas de Preservação Permanente na Área de Proteção Ambiental do Rio São João/ Mico Leão Dourado. In: Anais XIV Simpósio Brasileiro de Sensoriamento Remoto. 14, p. 5397-5404, INPE. Natal, RN, Brasil. Available on-line at http://marte.sid.inpe.br/col/dpi.inpe.br/sbsr@80/2008/11.17.13.37/doc/5397-5404.pdf

Santos, W.A.A. (2013) - Uso do Sensoriamento Remoto multiespectral para determinação da variação de lâminas d'água das lagoas no município de Nísia Floresta, Rio Grande do Norte, Brasil. *Revista Brasileira de Geografia Física*, (ISSN 1984 – 2295), 06(06): 1635-1647. Available on-line at http://www.revista.ufpe.br/rbgfe/index.php/revista/article/view/480/497

Sausen, T.M. (2006) - SELPER populariza imagens de satélite. *Info GEO Revista de Análise Geográfica*. 41: 30-32. Curitiba, PR, Brasil.

Schäfer, A.E.; Lanzer, R. M.; Pereira, R. (2009a) - *Atlas Socioambiental dos Municípios de Mostardas, Tavares, São José do Norte e Santa Vitória do Palmar.* 372p. Il., EDUCS. Caxias do Sul, RS, Brasil. ISBN 857-0615175. Available on-line at https://docs.google.com/file/d/0Byw_g7Puk0zzeDBrMEs1Z04tRWM/edit.

Schäfer, A.E.; Marchett, C.; Bianchi, A. (org). (2009b) - *Recursos hídricos dos municípios de Mostardas, Tavares, São José do Norte, Santa Vitória do Palmar.* Manual de gestão sustentada: EDUCS. Caxias do Sul, RS, Brasil. ISBN 978-85-7061-519-0.

Secretaria Estadual do Meio Ambiente - SEMA (2012) - Projeto RS Biodiversidade. Available on-line at http://www.sema.rs.gov.br/ (Accessed September 2015).

Secretaria do Planejamento e Coordenação. (1978) - *Plano integrado para o desenvolvimento do Litoral Norte do Rio Grande do Sul, adequação e uso do solo, zoneamento agroclimático.* Editora Meridional. 296p., EMMA. Porto Alegre, RS, Brasil.

Tundisi, J. G.; Matsumura-Tundisi, T. (2010) - Impactos potenciais das alterações do Código Florestal nos recursos hídricos. *Biota Neotropica*, v.10, n.4, p.67-75. Available on-line at http://www.redalyc.org/pdf/1991/199118978010.pdf. ISSN: 1676-0611