UNIVERSIDADE FEDERAL DO PARANÁ

FELIPE SAAD

IDENTIFICAÇÃO AUTOMATIZADA DE *A. angustifolia* EM IMAGENS DO SATÉLITE DE ALTA RESOLUÇÃO WORLDVIEW-2

CURITIBA

2020

FELIPE SAAD

IDENTIFICAÇÃO AUTOMATIZADA DE *A. angustifolia* EM IMAGENS DO SATÉLITE DE ALTA RESOLUÇÃO WORLDVIEW-2.

Dissertação apresentada ao Curso de Pós-Graduação em Ecologia e Conservação, Setor de Ciências Biológicas, da Universidade Federal do Paraná, como requisito parcial à obtenção do título de Mestre em Ecologia e Conservação.

Orientador: Dr. Marcos Bergmann Carlucci – Universidade Federal do Paraná

Co-orientador: Dr. Peter Leimgruber – Smithsonian Conservation Biology

CURITIBA

2020

Universidade Federal do Paraná
Sistema de Bibliotecas
(Giana Mara Seniski Silva – CRB/9 1406)

Saad, Felipe
Identificação automatizada de *A. angustifolia* em imagens do satélite de alta resolução Worldview-2. / Felipe Saad. – Curitiba, 2020.
43 p.: il.

Orientador: Marcos Bergmann Carlucci
Coorientador: Peter Leimgruber

Dissertação (mestrado) - Universidade Federal do Paraná, Setor de Ciências Biológicas. Programa de Pós-Graduação em Ecologia e Conservação.

1. Sensoriamento remoto. 2. Desmatamento. 3. Mata Atlântica. I. Título. II. Carlucci, Marcos Bergmann, 1985-. III. Leimgruber, Peter. IV. Universidade Federal do Paraná. Setor de Ciências Biológicas. Programa de Pós-Graduação em Ecologia e Conservação.

CDD (22. ed.) 577.34

TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação em ECOLOGIA E CONSERVAÇÃO da Universidade Federal do Paraná foram convocados para realizar a arguição da Dissertação de Mestrado de **FELIPE SAAD**, intitulada: **IDENTIFICAÇÃO AUTOMATIZADA DE A. ANGUSTIFOLIA EM IMAGENS DO SATÉLITE DE ALTA RESOLUÇÃO WORLDVIEW-2**, sob orientação do Prof. Dr. MARCOS BERGMANN CARLUCCI, após terem inquirido o aluno e realizado a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

A outorga do título de Mestre está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

Curitiba, 13 de Março de 2020.

MARCOS BERGMANN CARLUCCI
Presidente da Banca Examinadora

GABRIEL SELBACH HOFMANN
Avaliador Externo (INSTITUTO FEDERAL DO RIO GRANDE DO SUL)

MARCIA CRISTINA MENDES MARQUES
Avaliador Interno (UNIVERSIDADE FEDERAL DO PARANÁ)

AGRADECIMENTOS

Agradeço à CAPES pela bolsa de mestrado, ao Programa de Pós-Graduação em Ecologia e Conservação da UFPR e aos orientadores Marcos Bergmann Carlucci e Peter Leimgruber pela amizade e pelo apoio necessário para planejar, desenvolver e concluir o projeto. Agradeço aos meus pais, Sonia e Jorge, por estarem do meu lado mais uma vez em um novo caminho, sem eles esse mestrado não seria possível. Agradeço minha namorada, Gabi, que esteve presente e me ajudando em todas as fases que passei, não só no mestrado. Ao meu irmão e cunhada, Fernando e Bia, que mesmo longe sempre me apoioram a continuar.

Agradeço muito aos meus avós, Maria, Valmor, Angélica e Antônio, por me apoiarem cada um de seu jeito, sempre visando o melhor pra mim, e também ao restante da família. Agora chegou a vez da rapaziada, fico feliz em continuar uma amizade de anos e receber apoio da “patota”: Fernando, Gabi, Bia, Ryka, Gilerme, Thayollo, Caio, Amandão, Zé, Jé e Liz. Muito obrigado também aos piás da Darko, Jean e Marcelo, que fizeram parte das madrugadas desse mestrado, me ajudando a desestressar nos momentos mais tensos e sendo bons amigos.

Fico feliz em ter participado do Laboratório de Ecologia Funcional de Comunidades (LABEF) e agradeço aos meus amigos Marcos, Fernanda, Giulia, Bruna, Andressa, Luan e Ana. Agradeço aos amigos que fiz no PPGECO pelas ajudas e parcerias em disciplinas. Agradeço também ao pessoal do Smithsonian Conservation Biology Institute, Peter, Sumalika, Rosana, Jared, Ramiro e Storm, pela amizade e pela oportunidade de realizar treinamentos para meu projeto nos Estados Unidos.

RESUMO

Duas grandes causas para o declínio da biodiversidade global são a perda e a fragmentação de habitats. A mudança do uso do solo vem sendo acelerada globalmente, e, consequentemente são necessárias estratégias e novas tecnologias para a conservação de remanescentes de ecossistemas nativos e a restauração de áreas degradadas. Algumas das técnicas que podem ser utilizadas como novas tecnologias são aliadas ao sensoriamento remoto, que vêm se tornando amplamente úteis por terem resultados eficientes, rápidos e atingirem diversas escalas espaciais. No Brasil, um grande bioma que vem sendo estudado por técnicas de sensoriamento remoto de maneira sistemática há décadas é a Mata Atlântica, que é reconhecida por ser um "*hotspot*" de biodiversidade global. Historicamente, um dos tipos florestais da Mata Atlântica mais explorados foi a Floresta com Araucária, caracterizada pela presença da conífera *Araucaria angustifolia*. Ao longo do último século, sua área de distribuição sofreu uma redução drástica devido ao desmatamento, levando *A. angustifolia* ao risco de extinção. Portanto, são urgentes avaliações precisas e rápidas da distribuição e abundância dessa espécie a fim de auxiliar seu manejo e sua conservação. O objetivo deste estudo foi usar o sensoriamento remoto para desenvolver uma abordagem em múltiplas escalas para detectar, mapear e delinear estandes de *A. angustifolia* e, se possível, indivíduos isolados. Para isso, utilizamos imagens de satélite Worldview-2 em três áreas de estudo inseridas no núcleo da distribuição da Floresta com Araucária, no Estado do Paraná, Brasil. Utilizando o algoritmo Random Forest, conseguimos delinear estandes de *A. angustifolia* com precisão superior a 90% em todos os locais de estudo. Os resultados mostram que *A. angustifolia* não possui uma assinatura espectral constante entre os três locais, mas apresenta uma diferença em relação ao restante das espécies que ocupavam as áreas de estudo, permitindo assim, sua diferenciação. Sabendo exatamente onde estão os indivíduos dessa espécie, poderemos orientar estudos futuros sobre priorização espacial para a conservação da Floresta com Araucária.

Palavras chave: Assinatura espectral, Desmatamento, Random Forest, Sensoriamento Remoto.

ABSTRACT

Two important causes for the decline in global biodiversity are habitat loss and fragmentation. Land use change is accelerating globally, and consequently, we urgently need strategies for the conservation of native ecosystems remnants and the restoration of degraded areas. Remote sensing technologies have become widely used for fast and efficient assessments and detection across multiple spatial scales. Brazil's Atlantic Forest is a recognized global biodiversity hotspot. The *Araucaria* mixed forest, characterized by the coniferous *Araucaria angustifolia*, was previously one of the dominant forest types in the Atlantic forests but its area has declined severely due to deforestation. Consequently, *A. angustifolia* is now a species at risk of extinction. Therefore, accurate assessments of this species' distribution and abundance across its former range are urgently needed to inform conservation management. The aim of this study was to use remote sensing to develop a multi-scale approach to detect, map and delineate *A. angustifolia* stands and, if possible, individual trees. For this, we used Worldview-2 satellite images for three study sites in the core of the *Araucaria* mixed forest distribution, in Paraná State, Brazil. Using a Random Forest algorithm, we were able to delineate *A. angustifolia* stands with an accuracy greater than 90% in all of our study sites. We were able to observe that *A. angustifolia* does not have a constant spectral signature among sites, but a constant difference from the rest of the species that occupied the study areas. By knowing exactly where the individuals of this species are, we will be able to guide future studies on spatial prioritization for the conservation of *Araucaria* mixed forest.

Keywords: Deforestation, Remote sensing, Random Forest, Spectral Signature

APRESENTAÇÃO

A presente dissertação foi redigida em formato de artigo a ser submetido à revista Remote Sensing of Environment, que tem como foco publicações sobre o uso do sensoriamento remoto aplicado ao meio ambiente, incluindo temas como identificação de espécies e conservação.

O uso do sensoriamento remoto e do geoprocessamento tem fornecido novas oportunidades para o monitoramento de espécies (Fagan et al. 2015). Podemos ver exemplos de estudos de como o sensoriamento remoto utilizando sensores óticos, pontos de GPS e radares podem obter dados fundamentais para ecologia e conservação ao redor do mundo, como dados sobre padrões de movimentação animal (Tucker et al. 2018) e avaliação de cobertura florestal (Hislop et al. 2019; Rose et al. 2015; Turner et al., 2015; Vadrevu et al. 2019). No Brasil, existem diversos projetos que buscam fazer uso do sensoriamento remoto, como de órgãos governamentais como o Instituto Nacional de Pesquisas Espaciais (INPE), que disponibiliza dados de diversos satélites em diversos períodos de tempo.

Um bioma brasileiro que vem sendo bem estudado com o uso de sensoriamento remoto é a Mata Atlântica (veja por exemplo, Ribeiro et al. 2009; Rezende et al. 2018; SOS Mata Atlântica & INPE 2019), que é um *hotspot* de biodiversidade mundial, com elevados níveis de endemismo e fragmentação. Estima-se que reste apenas de 11 a 28% de sua cobertura original (Ribeiro et al. 2009; Rezende et al. 2018). Uma das fitofisionomias mais exploradas da Mata Atlântica é a Floresta com Araucária, que é caracterizada pela presença da *Araucaria angustifolia*, uma espécie atualmente ameaçada de extinção (Carlucci et al. 2013; IUCN, 2013). Estudos recentes apontam que sua fragmentação está em níveis alarmantes, com coberturas que podem chegar a apenas cerca de 6% de sua área original (Zorek in prep., 2020). Sendo assim, são necessárias ações urgentes para a conservação das espécies da Floresta com Araucária. Em nosso projeto, desenvolvemos e investigamos a acurácia de identificação automatizada de *Araucaria angustifolia* em imagens do satélite de alta resolução Worldview 2 usando o algoritmo Random Forest no Google Earth Engine e no software R.

REFERÊNCIAS

Carlucci, M. B.; Prieto, P. V.; Liz, R.; et al. Araucariaceae. In: G. Martinelli; M. A. Moraes (Orgs.); Livro Vermelho da Flora do Brasil. p.185–186, 2013. Rio de Janeiro: Jardim Botânico do Rio de Janeiro.

Fagan, M. E., R. S. DeFries, S. E. Sesnie, J. P. Arroyo-Mora, C. Soto, A. Singh, P. A. Townsend, and R. L. Chazdon. 2015. Mapping species composition of forests and tree plantations in northeastern Costa Rica with an integration of hyperspectral and multitemporal landsat imagery. Remote Sensing 7:5660–5696.

Hislop, S., S. Jones, M. Soto-Berelov, A. Skidmore, A. Haywood, and T. H. Nguyen. 2019. High fire disturbance in forests leads to longer recovery, but varies by forest type. Remote Sensing in Ecology and Conservation:1–13.

IUCN, 2013. IUCN Red List of Threatened Species. Version 2018. Available at

Rezende, C. L., F. R. Scarano, E. D. Assad, C. A. Joly, J. P. Metzger, B. B. N. Strassburg, M. Tabarelli, G. A. Fonseca, and R. A. Mittermeier. 2018. From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. Perspectives in Ecology and Conservation 16:208–214.

Ribeiro, M.C.; Metzger, J.P.; Martensen, A.C.; Ponzoni, F.J.; Hirota, M.M., 2009. The Brazilian Atlantic Forest: how much is left, and how is the remaining forest distributed? Implications for 25 conservation. Biological Conservation, 142, 1141–1153.

Rose, R. A., D. Byler, J. R. Eastman, R. Fleishman, G. Geller, S. Goetz, L. Guild, H. Hamilton, M. Hansen, R. Headley, J. Hewson, N. Horning, B. Kaplin, N. Laporte, A. Leidner, P. Leimgruber, J. Morisette, J. Musinsky, L. Pintea, A. Prados, V. C. Radeloff, M. Rowen, S. Saatchi, S. Schill, K.Tabor, W. Turner, A. Vodacek, J. Vogelmann, M. Wegmann, D. Wilkie, and C. Wilson. 2015. Ten ways remote sensing can contribute to conservation. Conservation Biology 29: 350–359. doi: 10.1111/cobi.12397.

SOS Mata Atlântica, INPE, 2019. Atlas dos Remanescentes Florestais da Mata Atlântica - Relatório Técnico Período 2017–2018 Fundação SOS Mata Atlântica and Instituto Nacional de Pesquisas Espaciais - INPE, São Paulo

Turner, W., C. Rondinini, N. Pettorelli, B. Mora, A. K. Leidner, Z. Szantoi, G. Buchanan, S. Dech, J. Dwyer, M. Herold, L. P. Koh, P. Leimgruber, H. Taubenboeck, M. Wegmann, M. Wikelski, and C. Woodcock. (2015). Free and open-access satellite data are key to biodiversity conservation. Biological Conservation 182:173-176.

Vadrevu, K. P., K. Lasko, L. Giglio, W. Schroeder, S. Biswas, and C. Justice. 2019. Trends in Vegetation fires in South and Southeast Asian Countries. Scientific Reports 9:1–13.

Zorek, B., Biswas, S., Brum, F. T., Leimgruber, P., Carlucci., M. B., In prep. Mapping of Araucaria Mixed Forest fragments in South America with remote sensing approaches

LISTA DE FIGURAS

Sumário

IDENTIFICATION OF *A. angustifolia* USING VERY HIGH RESOLUTION IMAGES FROM WORLDVIEW-2 SATELLITE.

Authors: Felipe Saad, Sumalika Biswas, Huang Qiongyu, Ana Paula Dalla Corte, Márcio Coraiolla, Sarah Macey, Peter Leimgruber & Marcos Bergmann Carlucci.
Journal: Remote Sensing of Environment.

ABSTRACT

Two important causes for the decline in global biodiversity are habitat loss and fragmentation. Land use change is accelerating globally, and consequently, we urgently need strategies for the conservation of native ecosystem remnants and the restoration of degraded areas. Remote sensing technologies have become widely used for fast and efficient assessments and detection across multiple spatial scales. Brazil's Atlantic Forest is a recognized global biodiversity hotspot. The *Araucaria* mixed forest, characterized by the coniferous *Araucaria angustifolia*, was previously one of the dominant forest types in the Atlantic forests but its area has declined severely due to deforestation. Consequently, *A. angustifolia* is now a species at risk of extinction. Therefore, accurate assessments of this species' distribution and abundance across its former range are urgently needed to inform conservation management. The aim of this study was to use remote sensing to develop a multi-scale approach to detect, map and delineate *A. angustifolia* stands and, if possible, individual trees. For this, we used Worldview-2 satellite images for three study sites in the core of the *Araucaria* mixed forest distribution, in Paraná State, Brazil. Using a Random Forest algorithm, we were able to delineate *A. angustifolia* stands with an accuracy greater than 90% in all of our study sites. We were able to observe that *A. angustifolia* does not have a constant spectral signature among sites, but a constant difference from the rest of the species that occupied the study areas. By knowing exactly where the individuals of this species are, we will be able to guide future studies on spatial prioritization for the conservation of the *Araucaria* mixed forest.

Keywords: Deforestation, Spectral Signature, Remote sensing, Random Forest

1 INTRODUCTION

Global changes resulting from human activities, such as urban development and land use conversion to agriculture, are widespread and have been resulting in dramatic declines in global biodiversity (Komatsu et al. 2019; Marco et al. 2019). Rapid land conversion in global biodiversity hotpots are likely to have some of the most dramatic impacts. One such example is the Brazilian Atlantic Forest (Mata Atlântica), which is characterized by very high species diversity and endemism (Myers et al 2000; Zwiener et al. 2017). Estimates made by Ribeiro et al. (2009) show that the actual land cover of the Brazilian Atlantic Forest ranged from 11.4% to 16% (using satellite imagery from 2005), out of which 32% to 40% correspond to small fragments (<100ha).

Araucaria mixed forest is one of the main Atlantic Forest phytophysiognomies. It is predominantly found on the Southern Brazilian Plateau (Planalto Sul-Brasileiro), stretching from southern São Paulo State in Brazil and part of the Misiones province in Argentina. The *Araucaria* mixed forest is named after the tree species *Araucaria angustifolia*, which is a conifer species with a candelabrum-shaped crown that is threatened to extinction. *Araucaria angustifolia* is classified as endangered (EN) by the Brazilian Red List (Carlucci et al. 2013) and critically endangered (CR) by the IUCN Red List (IUCN 2013). *Araucaria* mixed forest is very rich in biodiversity, especially phylogenetic diversity, because it is composed of lineages from very different moments of the evolutionary history of vascular plants and it forms mosaics with native montane grasslands (Behling & Pillar 2007; Duarte et al. 2014).

Araucaria mixed forests are very threatened due to a long history of severe habitat fragmentation, caused mostly by logging and conversion to other land uses (Koch

& Correa 2010; Ribeiro et al. 2009). Based on current literature, just 12.6% of the original coverage of the *Araucaria* mixed forest remains (Ribeiro et al., 2009). However, these assessments are already outdated, as they based on satellite imagery from 2005, and are limited to broad-scale mapping of general plant communities (Ribeiro et al., 2009). Little information exists about the actual extent of *Araucaria* mixed forest cover, let alone an approximate size of the remaining population of *A. angustifolia*. More detailed assessments and maps of *A. angustifolia* forest cover and distribution are urgently needed to inform conservation and management decisions. Moreover, accurate maps of *Araucaria* distribution could be used for future restoration of degraded areas (Brancalion et al. 2016).

Zorek et al. (In Prep) provide an updated estimate of *Araucaria* mixed forest status and distribution using existing mid-resolution optical (combination of Sentinel 1 and Landsat) satellite data. However, Zorek et al (In Prep) were not able to delineate individual trees or estimate how many trees exist in the remnant patches that were detected, the accuracies were variable and more detailed mapping at finer scales would be desirable to reduce the confusion of *A. angustifolia* with other similar trees and forest types. Therefore, it was not possible to ask questions at the individual or population scale. Answering such questions is important for a better understanding of the conservation status of *Araucaria* mixed forest remnants. Particularly, *A. angustifolia* as a species may be used as a proxy of the conservation status of the *Araucaria* mixed forest fragments, because it is typically the dominant species in old-growth *Araucaria* forests (Koch & Correa 2010).

Trying to reach better analysis and assessment, the remote sensing technology and geoprocessing analyses (e.g. tools, data, and algorithms) appear as ways towards providing new and exciting opportunities to more accurately delineate, measure, and monitor species and habitat type status and distribution (Fagan et al. 2015). Around the world, we have some good examples of how remote sensing using optical sensors, GPS points and radar can obtain extremely important data for ecology and conservation, for instance in studies that evaluate animal movement (Tucker et al. 2018), in monitoring projects and in studies that evaluate the state of forest cover (Hislop et al. 2019; Rose et al. 2015; Turner et al., 2015; Vadrevu et al. 2019). These advances benefit from increased availability of remote sensing data collected at different altitudes by different platforms (e.g., satellite, airplane, unmanned aerial vehicles), as well as the development of new sensors (e.g., LiDAR, hyperspectral), improvements in radiometric and spatial resolution of the data collected, and vastly enhanced algorithms. Such improvements may provide technologies for accurately detecting and mapping critical biodiversity elements such as *Araucaria angustifolia*, and thus allow us to develop data that is critically needed for the conservation of these species and their associated natural communities.

In this study, we developed a remote sensing approach to detect, map and delineate individual *A. angustifolia* trees. Our approach integrates on-the-ground field surveys, and object-based identification of *Araucaria* trees from WorldView-2 satellite imagery. Our goal was to develop the methods and tools to estimate not only the accurate distribution of *A. angustifolia* across three sites in the south of Brazil but also estimate the population size; i.e. how many trees are left in each site.

2 METHODS

2.1 Study sites

We mapped *Araucaria angustifolia* across three study sites located in Paraná State, Brazil (Fig. 1). The smallest site, Capão do Tigre, located in Curitiba municipality, covers an area of 4.45 ha, followed by Canguiri Farm in Quatro Barras municipality, which covers 103.79 ha. The largest site, Gralha-Azul Farm was in Fazenda Rio Grande municipality and covers 571.00 ha.

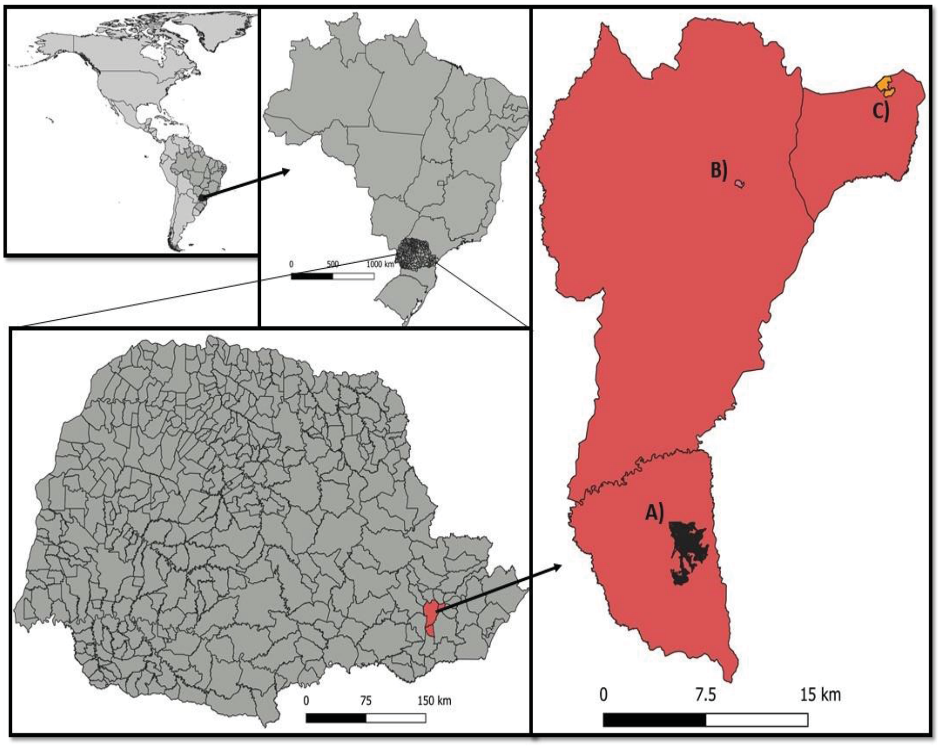

Figure 1: Study sites in the state of Paraná, Brazil. A) Gralha-azul Farm (FEGA) – Fazenda Rio Grande/PR (25°39'29.21"S, 49°17'17.20"W); B) Capão do Tigre – Curitiba/PR (25°26'53.01"S, 49°14'21.74"W); C) Canguiri Farm – Quatro Barras/PR (25°23'23.06"S, 49° 7'53.4

2.2 Remote Sensing Approach

We used Worldview-2 satellite images (from year 2018) to consistently map and delineate *A. angustifolia* stands and trees in all study sites (Fig. 2). The Worldview – 2 image have a panchromatic spatial resolution of 0.46 meter GSD at Nadir, 0.52 meter GSD at 20 degrees off-Nadir, multispectral spatial resolution of 1.84 meters GSD at Nadir, 2.08 meters GSD at 20 degrees off-Nadir. Its dynamic range is 11-bits per pixel. All of our images have a cloud coverage less than 15%. We use all the spectral bands to our analysis (Coastal – Blue – Green – Yellow – Red – Red Edge – Near-infrared 1 – Near-infrared 2).

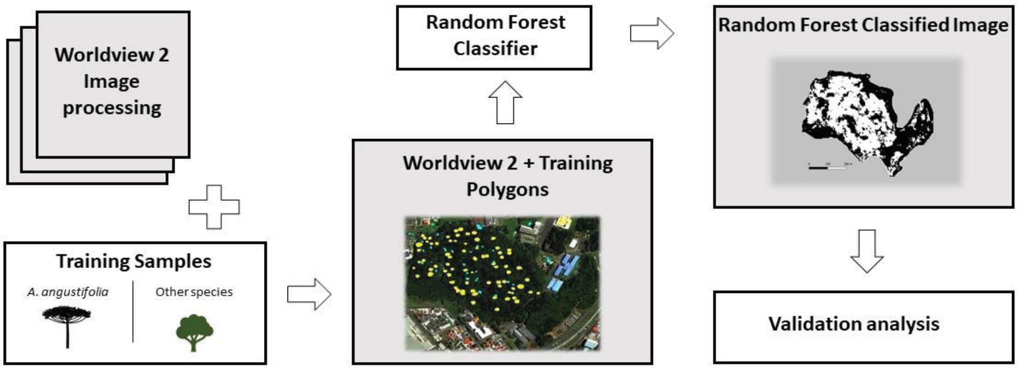

Figure 2: Flow chart of the steps of the remote sensing analysis.1- Worldview 2 Image processing: Combination of multispectral and panchromatic data; 2 and 3- Delineation of training polygons; 4 and 5- Classification with Random Forest in Google Earth Engine; 6 - Validation analysis: Accuracy assessment (Out of bag and Ground points control).

2.3 Image Processing and Classification

After clipping the imagery to regions of interest surrounding our study area (Fig. 3) we performed radiometric correction, applied an atmospheric correction using the Fast Line-of-sight Atmospheric Analysis of Hypercubes algorithm- FLAASH (ESRI, 2011) (Fig. 3b). To visually enhance the multispectral data, we applied pan sharpening (Fig. 3c). After the image processing, we made a clip of each image, selecting just the study area (excluding cities, roads, and buildings) using the software ArcGIS.

Figure 3: a) Clip of the region of Capão do Tigre study site. b) Atmospheric correction (FLAASH). c) Pan sharpening.

To classify images and differentiate *A. angustifolia* from other species, we used a pixel-based approach with supervised classification, which delineates individuals of *A. angustifolia* and other forest species (only forest pixels were used for classification) (Fig. 4), trying to establish an accurate model to identify the species.

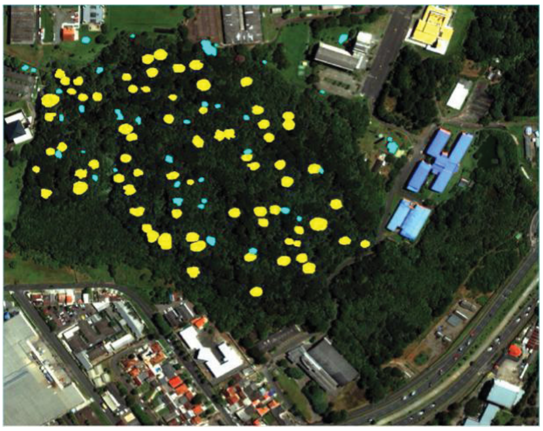

Figure 4: Outline of training polygons in Capão do Tigre. Araucaria angustifolia crowns are outlined in yellow. Other species are outlined in blue.

For our supervised classification, Random Forest machine learning (RF) algorithm was implemented in Google Earth Engine (GEE). The RF algorithm constructs multiple and random decision trees that are bootstrapped to classify a dataset, and allows the analyst to control data noise and avoid overfitting (Breiman, 2001).

We delineated 60 training polygons for each category (*A. angustifolia* and other species) in the Capão do Tigre study site, 150 training polygons for each category in Canguiri Farm and 350 training polygons for each category in Gralha-azul Farm. Based on these training data, we ran RF in GEE with 500 random trees in each study site.

2.4 Estimation of how many *Araucaria* individuals exist in the areas

We proposed a formula to estimate how many *Araucaria* trees are inside the study sites:

$$\frac{TCA}{APS} = NAI$$

In which

TCA = Total area marked as *A. angustifolia* in the classification,

APS = Average area of the crown polygons inside each study site, and

NAI = Number of *Araucaria* trees.

As the average diameter of the *A. angustifolia* crown polygons, we used 10.8m (average diameter) as proposed by Kein (2017).

2.5 Validation and accuracy assessments

We evaluated the accuracy of our *A. angustifolia* maps across all three study sites using the out-of-bag (OOB) data provided by the RF algorithm in GEE. The OOB uses 30% of the training data as a validation dataset to measure the accuracy of the classification.

Additionally, for a more independent assessment, we were able to utilize data from a ground survey conducted by Centro de Excelência em Pesquisas sobre Fixação Carbono na Biomassa - BIOFIX Lab, Federal University of Paraná, for one of the study sites. These data consist of GPS coordinates for 335 individuals of *A. angustifolia* at the Capão do Tigre site (Vasconcellos et al., In prep). We overlaid these GPS data with our *A. angustifolia* map and determined how many points were missing.

2.6 Statistical analysis

We used the R Studio software (R, 2019) to evaluate the differences in the spectral signature of *A. angustifolia* and other tree species. After our classification using

RF in GEE, we generate two classes (*A. angustifolia* and other species). We select 100 random pixels inside each class boundary and extract the wavelength values of each pixel using raster package. Using the ggplot2 package we generate boxplots and density plots to compare the profile of each satellite band with each classification class.

3 RESULTS

3.1. Mapping *Araucaria angustifolia* from high-resolution satellite imagery

Individual trees of *A. angustifolia* found in native forest patches can be identified and mapped from pan-sharpened Worldview-2 imagery, using their unique multispectral characteristics (Fig. 5). Based on our random forest classifications, we found considerable variation in the prevalence of *A. angustifolia* in the canopies of the study sites (Table 1). *Araucaria angustifolia* was the dominant tree in terms of cover in Capão Tigre (51.24%; Table 1), less dominant in the Canguiri Farm (32.55%; Table 1), and relatively sparse at Gralha-Azul Farm (15.35%; Table 1).

Table 1: Canopy area and percent of *Araucaria angustifolia* compared to other canopy trees across three study sites in Paraná State, Brazil.

Study area	Total forest [ha]	*A. angustifolia* [ha]	Other forest [ha]
Gralha-Azul Farm	571.00	87.65 (15.35%)	483.35 (84.65%)
Canguiri Farm	103.79	33.78 (32.55%)	70.01(67.45%)
Capão Tigre	4.45	2.52 (56.49%)	1.93 (43.51%)

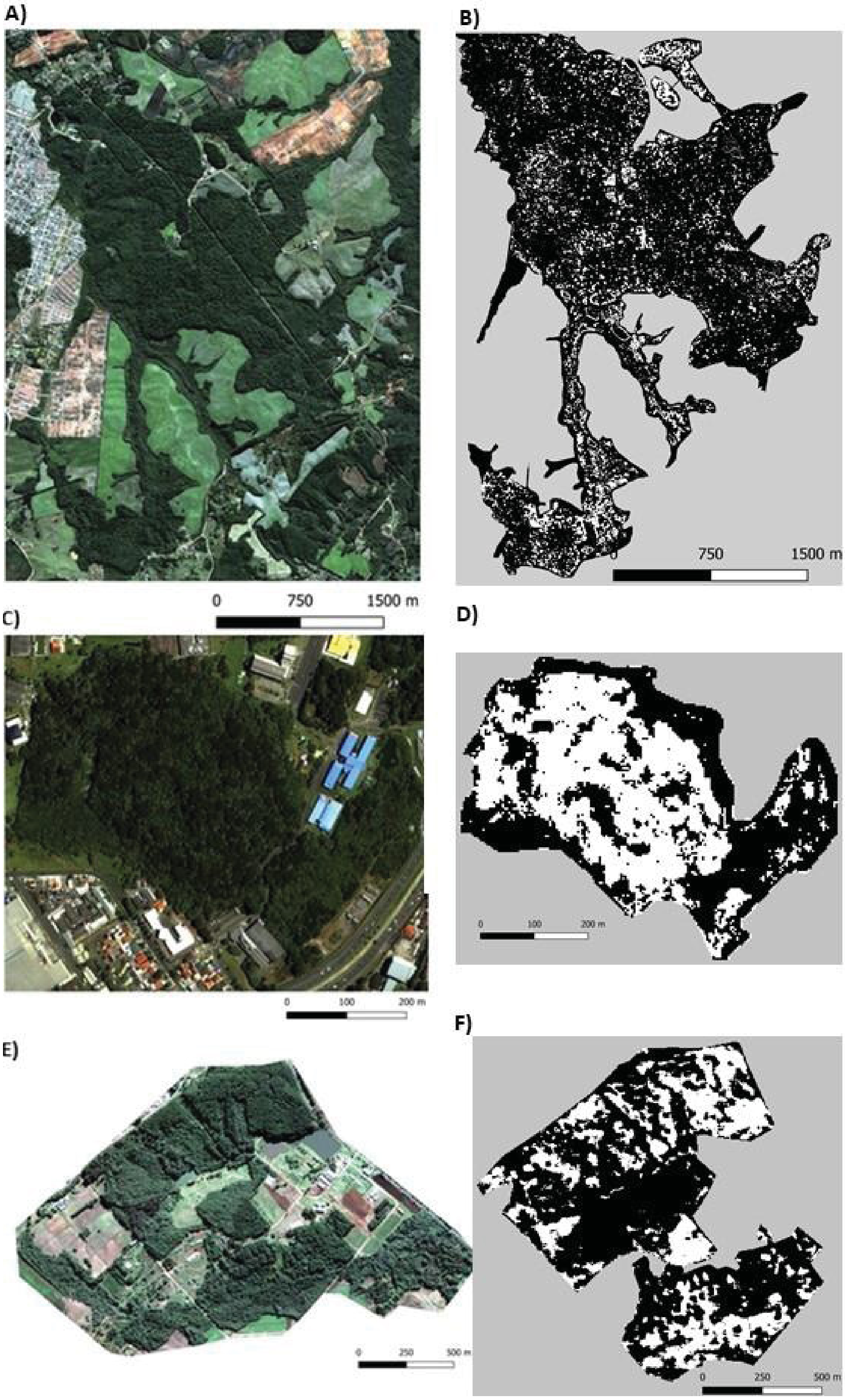

Figure 5: Worldview-2 RGB image (A, C, E) and resulting forest canopy maps delineating Araucaria angustifolia stands and trees using a Random Forest classified (B, D, F) across three study areas in Parana State, Brazil. Araucaria angustifolia trees in white; forest

species in black. A and B) Gralha-Azul Farm; C and D) Capão do Tigre; E and F) Canguiri Farm.

3.2. Spectral response of *A. angustifolia* trees

A. angustifolia trees exhibited a distinct spectral response across Worldview-2 bands (Fig. 6). Although there was a general pattern, we observed differences in spectral response across the three study sites. In our biggest site (Gralha-azul Farm), *A. angustifolia* showed lower reflectance range than other tree species for bands 2 (Blue), 3 (Green), 5 (Red), 6 (Red Edge) and 7 (NIR 1) (Fig.6A). In our smaller study site (Capão do Tigre) the differences in reflectance's appeared mainly for bands 3 (Green), 4 (Yellow), 5 (Red), 6 (Red Edge), 7 (NIR 1) and 8 (NIR 2) (Fig.6B). At Canguiri Farm, reflectance was higher for *A. angustifolia* for bands 3 (Green), 4 (Yellow), 5 (Red), 6 (Red Edge), 7 (NIR 1) and 8 (NIR 2) (Fig.6C). These differences were also apparent in density plots (Fig. 7).

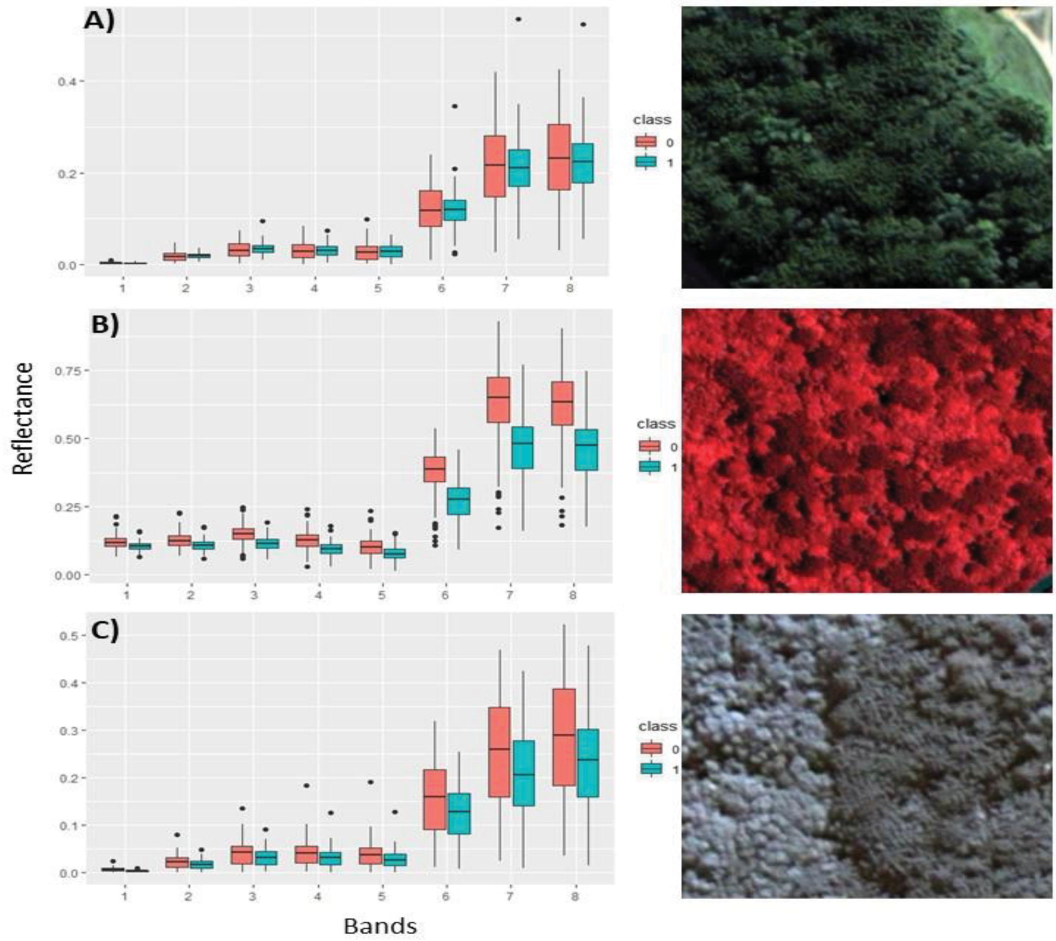

Figure 6: Paired boxplot of spectral responses of Araucaria angustifolia and other forest trees in Brazilian Atlantic forest across three study sites in Paraná State, Brazil. Class 1: A. angustifolia, Class 0: Other species. Reflectance values were derived from Worldview-2imagery (Bands: 1 – Coastal; 2 – Blue; 3 – Green; 4 – Yellow; 5 – Red; 6 – Red Edge; 7- Near-Infrared 1; 8 – Near-Infrared 2). A) Gralha-Azul Farm boxplot; B) Capão do Tigre boxplot; C) Canguiri Farm boxplot. The right side of the plot shows the Worldview-2with the best band composition for visually separating the A. angustifolia, according A. angustifolia can be recognized in the images as: A) Darker forms in green; B) Darker forms in red; C) Darker forms in gray/green.

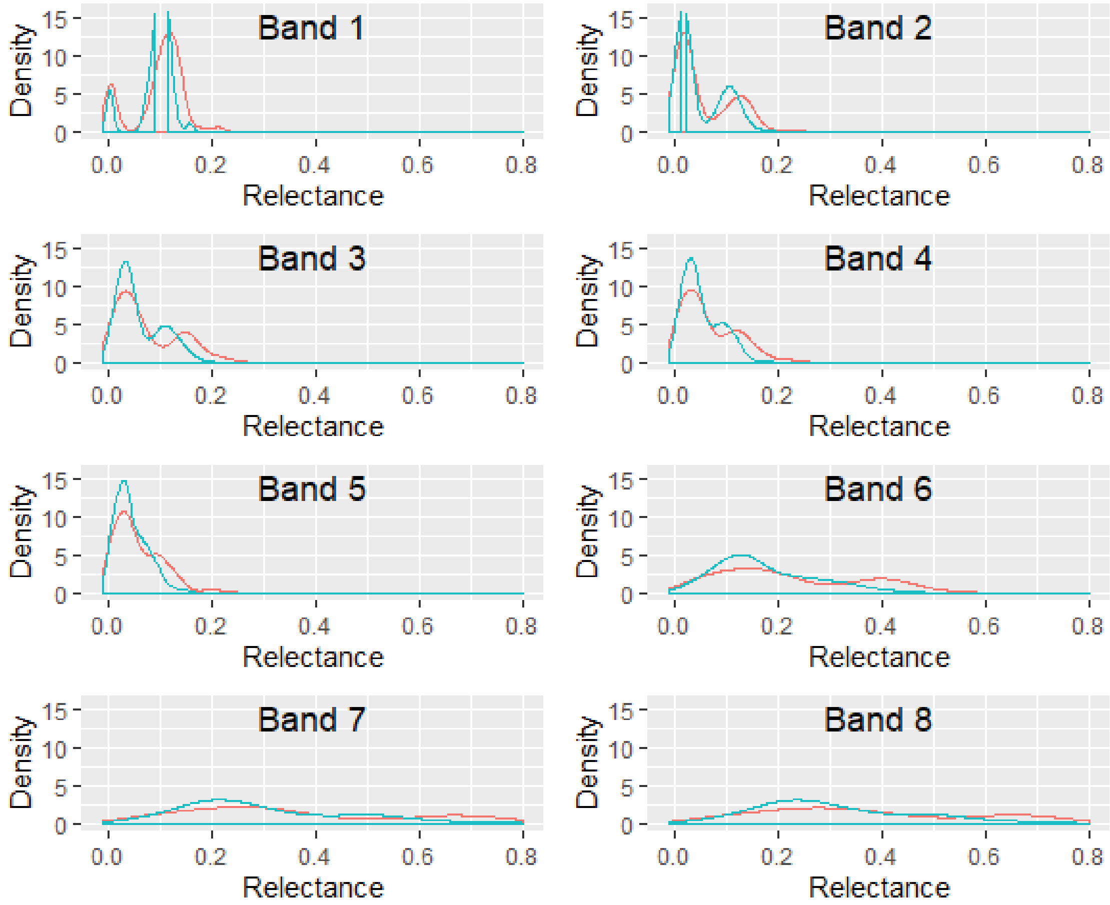

Figure 7: Density plots of spectral responses of Araucaria angustifolia and other forest trees in Brazilian Atlantic forest across from Worldview-2imagery at an ensemble of all the sites, Parana State, Brazil. Bands: 1 – Coastal; 2 – Blue; 3 – Green; 4 – Yellow; 5 – Red; 6 – Red Edge; 7- Near-Infrared 1; 8 – Near-Infrared 2. A. angustifolia are represented by red curves and other species by blue.

3.3. Validation – Random Forest

There was high accuracy for separating *A. angustifolia* from other forest at all study sites, with an overall "Out-of Bag" accuracy of 0.9369 (93.69%) for Gralha Azul Farm (Table 2), 0.9763 (97.63%), for Capão de Tigre (Table 3), and 0.9714 (97.14%) for Canguiri Farm (Table 4).

Table 2: Commission and Omission error of Gralha-azul Farm.

Gralha-Azul Farm	*A. angustifolia*	Other trees species	Total	Commission error
A. angustifolia	1901	196	2097	9%
Other trees species	129	2926	3055	4%
Total	2030	3122	5152	
Omission error	6%	6%		

Table 3: Commission and Omission error of Canguiri Farm.

Canguiri Farm	*A. angustifolia*	Other trees species	Total	Commission error
A. angustifolia	407	11	418	2%
Other trees species	12	340	352	3%
Total	419	351	764	
Omission error	2%	3%		

Table 4: Commission and Omission error of Capão do Tigre

Capão do Tigre	*A. angustifolia*	Other trees species	Total	Commission error
A. angustifolia	979	17	996	1%
Other trees species	12	132	144	8%
Total	991	149	1140	
Omission error	1%	11%		

3.4. Estimating the number of *Araucaria angustifolia* trees from canopy maps.

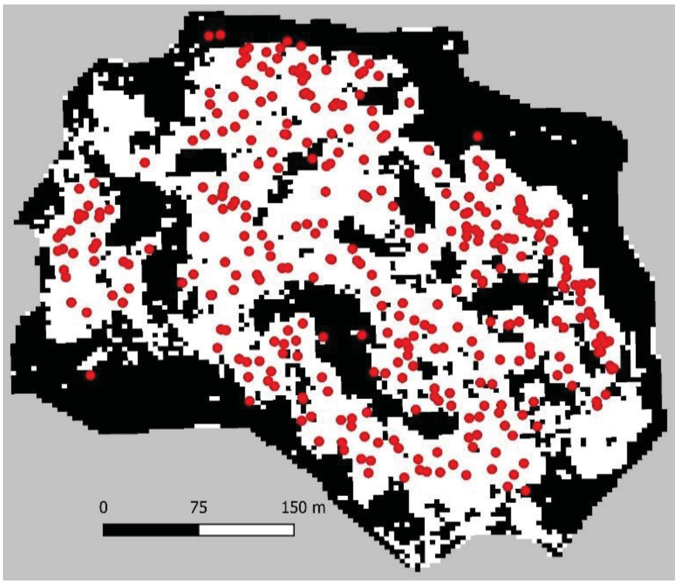

Figure 8: Validation for Araucaria angustifolia map at Capão de Tigre study sites in Paraná State, Brazil. Red dots are the GPS points of 335 A. angustifolia individuals identified on the ground. White = A. angustifolia trees from classification, black = other forests.

Using the simple calculations that related average crown size reported for *A. angustifolia* to the area covered by this species in our maps, we estimated that there are at least 13,518 trees distributed across our study areas. Abundance and density of trees was very different across our sites, with very higher densities in the smaller sites (Table 5).

3.5 Validation using ground-survey data

Based on a ground survey at Capão de Tigre, we found that our map was nearly 90% accurate in detecting Araucaria trees (Fig. 8). While the ground survey detected 355 individual *A. angustifolia*, we estimated 280 based on satellite analysis of the canopy and average crown size. The omissions are likely due to the inability of mapping understory *A. angustifolia* individuals using optical remote sensing data from Worldview-2 (In our ground-survey data, there are 43 individuals with DBH < 20 cm, which probably do not reach the canopy).

Table 4: Number of *A. angustifolia* individuals in each study site and per hectare

Study site	Nº of *A. angustifolia*	*A. angustifolia Density [trees / ha]*
Gralha-Azul Farm	9570	16.76
Capão do Tigre	280	62.92
Canguiri Farm	3668	35.34

4 DISCUSSION

Using a random forest algorithm, we found that *Araucaria angustifolia* trees showed different spectral signatures compared to a joint signature or all other canopy trees. This finding shows that pan-sharpened Worldview-2 imagery is highly suited for a multispectral classification of trees in the canopies of the *Araucaria* mixed forest. We show that in smaller sites, we have different patterns of bands importance to differentiate the trees species when compared to biggest sites. This difference can be associated to the density of *A. angustifolia* individuals (Table 4), where low densities can be associated to an approximation in the spectral profile of the *A. angustifolia* with other species, but even so it is still possible to make the classification with high accuracy.

The success of the algorithm based on all spectral bands is mainly due to the difference in the shape of the canopy and leaves of *A. angustifolia* individuals compared to other species. Conifer trees should have less absorption and more reflectance in the red band (because broadleaf has more chlorophyll, which absorbs red). Less absorption and more reflectance in the near infra-red bands because conifer leaves usually have a lower water content (Hall et al. 1992; Roberts et al. 2004).

Other studies on tree recognition using satellite imagery have studied different environments and other trees (Dalponte et al. 2012; Immitzer et al. 2012). Immitzer et al. (2012) used Worldview-2 images to detect 10 trees species in a temperate forest in Austria, and they got good results. In our case, however, we aimed to identify a specific tree within a more diverse forest with respect to the shapes of the crowns and number of species.

Consequently, this is a pioneering study in terms of using high resolution images from the Worlview-2 satellite to identify *A. angustifolia* crowns of a specific tree species. Pesck et al. (2018), using fuzzy logic and K Nearest Neighbor (KNN) applied to Quickbird II images, were also able to identify *A. angustifolia* crowns. Nevertheless, they studied just one site. We showed that there might be major differences between study sites in terms of reflectance, which can be explained based on the density of *A. angustifolia* in each area. Therefore, studying only one site is not enough to pursue a more general algorithm that in the future may be able to identify *Araucaria* crowns over broad spatial scales.

We have some advantages and disadvantages in our methods. Our main advantages are the high accuracies (>90%) across all our study sites and that we have ground data to confirm the exact positions of *A. angustifolia* trees provided by our satellite classification. Our main disadvantage is that we are not able to recognize young trees under the canopies of adult trees, which would be important to understand whether there are new individuals recruiting. This issue could be solved with field work in specific interest study areas after a more general classification.

Araucaria angustifolia is highly endangered by the unsustainable exploitation. Developing new and efficient approaches to mapping all remaining trees of this species is critical for its conservation. Our approach could be extended to try and assess the number of *Araucaria* trees in a forest stand or the entire extension of the *Araucaria* mixed forest. Evaluating the number of individuals can help in management actions by enabling, for instance, to verify expansion or contraction of the species. Our framework can be used to evaluate where *A. angustifolia* individuals are and how many individuals of the species exist in specific sites without need of field work, which can be money and time demanding.

5. CONCLUSIONS

The central aim of this study was testing the integrated use of Worldview-2 imagery and random forest classifiers to identify and delineate *A. angustifolia* individuals from satellite. Using Random Forest on Google Earth Engine we were able to identify with high accuracy individuals of the species. We found that the spectral signature of the *A. angustifolia* tree indeed differs from other cooccurring species, but that it varies between sites, which seems related to the density of *A. angustifolia* stands in the mixed forest.

6 AUTHOR CONTRIBUTION STATEMENT

FS: Conceptualization, Methodology, Software, Formal analysis, Writing, Project administration. MBC: Conceptualization, Methodology, Writing - Review and Editing, Project administration. PLr: Writing – Review and Editing , Conceptualization, Methodology, Project administration, Software. SB: Conceptualization, Software, Writing - Review, Formal analysis, Methodology. QH: Conceptualization, Satellite Images. APDC: Ground survey and analysis. MC: Conceptualization. SM: Conceptualization

7 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.

8 ACKNOWLEDGEMENTS

We appreciate the extensive efforts from the developers of the satellite datasets to make their products available. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001, via PROEX and PRINT grants. FS received support by the Smithsonian Conservation and

Biology Institute via a student grant. We thank G. S. Hofmann and M. C. M. Marques for useful comments on the manuscript.

9. REFERENCES

Behling, H. & Pillar, V.D. (2007) Late Quaternary vegetation, biodiversity and fire dynamics on the southern Brazilian highland and their implication for conservation and management of modern Araucaria forest and grassland ecosystems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 362, 243.

Brancalion, P.H.S., Garcia, L.C., Loyola, R., Rodrigues, R.R., Pillar, V.D. & Lewinsohn, T.M. (2016) A critical analysis of the Native Vegetation Protection Law of Brazil (2012): updates and ongoing initiatives. *Natureza & Conservação*, 14, 1–15.

Breiman, L., 2001. Random forests. Mach. Learn. 45, 5–32. Carroll, M.L., Townshend, J.R., DiMiceli, C.M., Noojipady, P., Sohlberg, R.A., 2009. A new global raster water mask at 250 m resolution. Int. J. Digital Earth 2 (4), 291–308.

Carlucci, M. B.; Prieto, P. V.; Liz, R.; et al. Araucariaceae. In: G. Martinelli; M. A. Moraes (Orgs.); Livro Vermelho da Flora do Brasil. p.185–186, 2013. Rio de Janeiro: Jardim Botânico do Rio de Janeiro.

Dalponte, M., L. Bruzzone, and D. Gianelle. 2012. Tree species classification in the Southern Alps based on the fusion of very high geometrical resolution multispectral/hyperspectral images and LiDAR data. Remote Sensing of Environment 123:258–270.

Di Marco, M., T. D. Harwood, A. J. Hoskins, C. Ware, S. L. L. Hill, and S. Ferrier. 2019. Projecting impacts of global climate and land-use scenarios on plant biodiversity using compositional-turnover modelling. Global Change Biology 25:2763–2778.

Duarte, L.D.S., Bergamin, R.S., Marcilio-Silva, V., Seger, G.D.D.S. & Marques, M.C.M. (2014) Phylobetadiversity among Forest Types in the Brazilian Atlantic Forest Complex ed K. Ma. *PLoS ONE*, 9, e105043.

ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.

Fagan, M. E., R. S. DeFries, S. E. Sesnie, J. P. Arroyo-Mora, C. Soto, A. Singh, P. A. Townsend, and R. L. Chazdon. 2015. Mapping species composition of forests and tree plantations in northeastern Costa Rica with an integration of hyperspectral and multitemporal landsat imagery. Remote Sensing 7:5660–5696.

Fahrig, L., (2003). Effects of habitat fragmentation on biodiversity. Annual Review of Ecology, Evolution, and Systematics, v. 34, n. 2003, p. 487–515.

Hall, F.G.; Huemmrich, K.F.; Strebel, D.E.; Goetz, S.J.; Nickeson, J.E.; Woods, K.E. Biophysical, Morphological, Canopy Optical Property, and Productivity Data from the Superior National Forest; NASA Technical Memorandum 104568; NASA Goddard Space Flight Center: Greenbelt, MD, USA, 1992; p. 150.

Hislop, S., S. Jones, M. Soto-Berelov, A. Skidmore, A. Haywood, and T. H. Nguyen. 2019. High fire disturbance in forests leads to longer recovery, but varies by forest type. Remote Sensing in Ecology and Conservation:1–13.

Immitzer, M., C. Atzberger, and T. Koukal. 2012. Tree species classification with Random forest using very high spatial resolution 8-band worldView-2 satellite data. Remote Sensing 4:2661–2693.

IUCN, 2013. IUCN Red List of Threatened Species. Version 2018. Available at

Klein, D. R. 2017. MORFOMETRIA E CRESCIMENTO DIAMÉTRICO DE *Araucaria angustifolia* (Bertol.) Kuntze NO PLANALTO SUL CATARINENSE:122.

Koch, Z. & Correa, M.C. (2010) *Araucária: a Floresta do Brasil Meridional*. Olhar Brasileiro.

Komatsu, K. J., M. L. Avolio, N. P. Lemoine, F. Isbell, E. Grman, G. R. Houseman, S. E. Koerner, D. S. Johnson, K. R. Wilcox, J. M. Alatalo, J. P. Anderson, R. Aerts, S. G. Baer,

A. H. Baldwin, J. Bates, C. Beierkuhnlein, R. T. Belote, J. Blair, J. M. G. Bloor, P. J. Bohlen, E. W. Bork, E. H. Boughton, W. D. Bowman, A. J. Britton, J. F. Cahill, E. Chaneton, N. R. Chiariello, J. Cheng, S. L. Collins, J. H. C. Cornelissen, G. Du, A. Eskelinen, J. Firn, B. Foster, L. Gough, K. Gross, L. M. Hallet, X. Han, H. Harmens, M. J. Hovenden, A. Jagerbrand, A. Jentsch, C. Kern, K. Klanderud, A. K. Knapp, J. Kreyling, W. Li, Y. Luo, R. L. McCulley, J. R. McLaren, J. P. Megonigal, J. W. Morgan, V. Onipchenko, S. C. Pennings, J. S. Prevéy, J. N. Price, P. B. Reich, C. H. Robinson, F. L. Russell, O. E. Sala, E. W. Seabloom, M. D. Smith, N. A. Soudzilovskaia, L. Souza, K. Suding, K. B. Suttle, T. Svejcar, D. Tilmand, P. Tognetti, R. Turkington, S. White, Z. Xu, L. Yahdjian, Q. Yu, P. Zhang, and Y. Zhang. 2019. Global change effects on plant communities are magnified by time and the number of global change factors imposed. Proceedings of the National Academy of Sciences of the United States of America 116:17867–17873.

Myers, N., Mittermeier A., 2000. Biodiversity Hotspots for Conservation Priorities. *Nature* 403, nº 6772: 853–58.

Pesck, V. A., T. F. Stepka, G. dos S. Lisboa, L. C. de J. França, and C. L. Cerqueira. 2018. Delineamento de copas de *Araucaria angustifolia* utilizando lógica Fuzzy em imagens Quickbird II. Advances in Forestry Science 5:385–390.

Rezende, C. L., F. R. Scarano, E. D. Assad, C. A. Joly, J. P. Metzger, B. B. N. Strassburg, M. Tabarelli, G. A. Fonseca, and R. A. Mittermeier. 2018. From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. Perspectives in Ecology and Conservation 16:208–214.

Ribeiro, M.C.; Metzger, J.P.; Martensen, A.C.; Ponzoni, F.J.; Hirota, M.M., 2009. The Brazilian Atlantic Forest: how much is left, and how is the remaining forest distributed? Implications for 25 conservation. Biological Conservation, 142, 1141–1153.

Roberts, D.A.; Ustin, S.L.; Ogunjemiyo, S.; Greenberg, J.; Dobrowski, S.Z.; Chen, J.; Hinckley, T.M. (2004). Spectral and Structural Measures of Northwest Forest Vegetation at Leaf to Landscape Scales. *Ecosystems*, *7*, 545–562.

Rose, R. A., D. Byler, J. R. Eastman, R. Fleishman, G. Geller, S. Goetz, L. Guild, H. Hamilton, M. Hansen, R. Headley, J. Hewson, N. Horning, B. Kaplin, N. Laporte, A. Leidner, P. Leimgruber, J. Morisette, J. Musinsky, L. Pintea, A. Prados, V. C. Radeloff, M. Rowen, S. Saatchi, S. Schill, K.Tabor, W. Turner, A. Vodacek, J. Vogelmann, M. Wegmann, D. Wilkie, and C. Wilson. (2015). Ten ways remote sensing can contribute to conservation. Conservation Biology 29: 350–359. doi: 10.1111/cobi.12397.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

SOS Mata Atlântica & INPE, 2019. Atlas dos Remanescentes Florestais da Mata Atlântica - Relatório Técnico Período 2017–2018 Fundação SOS Mata Atlântica and Instituto Nacional de Pesquisas Espaciais - INPE, São Paulo

Tucker, M. A., K. Böhning-gaese, W. F. Fagan, J. M. Fryxell, B. Van Moorter, S. C. Alberts, A. H. Ali, A. M. Allen, N. Attias, T. Avgar, H. Bartlam-brooks, B. Bayarbaatar, J. L. Belant, A. Bertassoni, D. Beyer, L. Bidner, F. M. Van Beest, S. Blake, N. Blaum, C. Bracis, D. Brown, P. J. N. De Bruyn, F. Cagnacci, D. Diefenbach, I. Douglas-hamilton, J. Fennessy, C. Fichtel, W. Fiedler, C. Fischer, I. Fischhoff, C. H. Fleming, A. T. Ford, S. A. Fritz, B. Gehr, J. R. Goheen, E. Gurarie, M. Hebblewhite, M. Heurich, A. J. M. Hewison, C. Hof, E. Hurme, L. A. Isbell, R. Janssen, F. Jeltsch, P. Kaczensky, A. Kane, P. M. Kappeler, M. Kauffman, R. Kays, D. Kimuyu, F. Koch, B. Kranstauber, S. Lapoint, J. Mattisson, E. P. Medici, U. Mellone, E. Merrill, T. A. Morrison, S. L. Díaz-muñoz, A. Mysterud, D. Nandintsetseg, R. Nathan, A. Niamir, J. Odden, R. B. O. Hara, L. G. R. Oliveira-santos, K. A. Olson, B. D. Patterson, R. C. De Paula, L. Pedrotti, B. Reineking, and M. Rimmler. 2018. R ES E A RC H mammalian movement 469:466–469.

Turner, W., C. Rondinini, N. Pettorelli, B. Mora, A. K. Leidner, Z. Szantoi, G. Buchanan, S. Dech, J. Dwyer, M. Herold, L. P. Koh, P. Leimgruber, H. Taubenboeck, M. Wegmann, M. Wikelski, and C. Woodcock. (2015). Free and open-access satellite data are key to biodiversity conservation. Biological Conservation 182:173-176.

Vadrevu, K. P., K. Lasko, L. Giglio, W. Schroeder, S. Biswas, and C. Justice. 2019. Trends in Vegetation fires in South and Southeast Asian Countries. Scientific Reports 9:1–13.

Vasconcellos, B. N., Corte, A. P. D., In prep**.** Estimativa de variáveis dendrométricas individuais de *Araucaria angustifolia* por meio de dados Laser Scanner aéreo e terrestre.

Wendling, Ivar; Zanette, Flávio. 2017. Araucária: particularidades, propagação e manejo de plantios. Embrapa - Brasília, 1-163.

Zorek, B., Biswas, S., Brum, F. T., Leimgruber, P., Carlucci., M. B., In prep. Mapping of Araucaria Mixed Forest fragments in South America with remote sensing approaches

Zwiener, V, P., Padial, A., Marques, C., M., Faleiro, F., Loyola, R., e Peterson, A. T., 2017. Planning for conservation and restoration under climate and land use change in the Brazilian Atlantic Forest. Diversity and Distributions 23, 955–66.

CONSIDERAÇÕES FINAIS

O objetivo central deste estudo foi testar o uso integrado de imagens de alta resolução do satélite Worldview-2 com o algoritmo de classificação supervisionada Random Forest para identificar e delinear indivíduos de *A. angustifolia* nas imagens do satélite. Usando o algoritmo tivemos acurácias maiores do que 90% em todas nossas áreas de estudo. Nós encontramos diferenças nas assinaturas espectrais dos indivíduos de *A. angustifolia* frente outras espécies, o que parece ser relacionado com a densidade de indivíduos presentes em cada sítio de estudo.

REFERÊNCIAS

Behling, H. & Pillar, V.D. (2007) Late Quaternary vegetation, biodiversity and fire dynamics on the southern Brazilian highland and their implication for conservation and management of modern Araucaria forest and grassland ecosystems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 362, 243.

Brancalion, P.H.S., Garcia, L.C., Loyola, R., Rodrigues, R.R., Pillar, V.D. & Lewinsohn, T.M. (2016) A critical analysis of the Native Vegetation Protection Law of Brazil (2012): updates and ongoing initiatives. *Natureza & Conservação*, 14, 1–15.

Breiman, L., 2001. Random forests. Mach. Learn. 45, 5–32. Carroll, M.L., Townshend, J.R., DiMiceli, C.M., Noojipady, P., Sohlberg, R.A., 2009. A new global raster water mask at 250 m resolution. Int. J. Digital Earth 2 (4), 291–308.

Carlucci, M. B.; Prieto, P. V.; Liz, R.; et al. Araucariaceae. In: G. Martinelli; M. A. Moraes (Orgs.); Livro Vermelho da Flora do Brasil. p.185–186, 2013. Rio de Janeiro: Jardim Botânico do Rio de Janeiro.

Dalponte, M., L. Bruzzone, and D. Gianelle. 2012. Tree species classification in the Southern Alps based on the fusion of very high geometrical resolution multispectral/hyperspectral images and LiDAR data. Remote Sensing of Environment 123:258–270.

Di Marco, M., T. D. Harwood, A. J. Hoskins, C. Ware, S. L. L. Hill, and S. Ferrier. 2019. Projecting impacts of global climate and land-use scenarios on plant biodiversity using compositional-turnover modelling. Global Change Biology 25:2763–2778.

Duarte, L.D.S., Bergamin, R.S., Marcilio-Silva, V., Seger, G.D.D.S. & Marques, M.C.M. (2014) Phylobetadiversity among Forest Types in the Brazilian Atlantic Forest Complex ed K. Ma. *PLoS ONE*, 9, e105043.

ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.

Fagan, M. E., R. S. DeFries, S. E. Sesnie, J. P. Arroyo-Mora, C. Soto, A. Singh, P. A. Townsend, and R. L. Chazdon. 2015. Mapping species composition of forests and tree plantations in northeastern Costa Rica with an integration of hyperspectral and multitemporal landsat imagery. Remote Sensing 7:5660–5696.

Fahrig, L., (2003). Effects of habitat fragmentation on biodiversity. Annual Review of Ecology, Evolution, and Systematics, v. 34, n. 2003, p. 487–515.

Hall, F.G.; Huemmrich, K.F.; Strebel, D.E.; Goetz, S.J.; Nickeson, J.E.; Woods, K.E. Biophysical, Morphological, Canopy Optical Property, and Productivity Data from the Superior National Forest; NASA Technical Memorandum 104568; NASA Goddard Space Flight Center: Greenbelt, MD, USA, 1992; p. 150.

Hislop, S., S. Jones, M. Soto-Berelov, A. Skidmore, A. Haywood, and T. H. Nguyen. 2019. High fire disturbance in forests leads to longer recovery, but varies by forest type. Remote Sensing in Ecology and Conservation:1–13.

Immitzer, M., C. Atzberger, and T. Koukal. 2012. Tree species classification with Random forest using very high spatial resolution 8-band worldView-2 satellite data. Remote Sensing 4:2661–2693.

IUCN, 2013. IUCN Red List of Threatened Species. Version 2018. Available at

Klein, D. R. 2017. MORFOMETRIA E CRESCIMENTO DIAMÉTRICO DE *Araucaria angustifolia* (Bertol.) Kuntze NO PLANALTO SUL CATARINENSE:122.

Koch, Z. & Correa, M.C. (2010) *Araucária: a Floresta do Brasil Meridional*. Olhar Brasileiro.

Komatsu, K. J., M. L. Avolio, N. P. Lemoine, F. Isbell, E. Grman, G. R. Houseman, S. E. Koerner, D. S. Johnson, K. R. Wilcox, J. M. Alatalo, J. P. Anderson, R. Aerts, S. G. Baer, A. H. Baldwin, J. Bates, C. Beierkuhnlein, R. T. Belote, J. Blair, J. M. G. Bloor, P. J. Bohlen, E. W. Bork, E. H. Boughton, W. D. Bowman, A. J. Britton, J. F. Cahill, E. Chaneton, N. R. Chiariello, J. Cheng, S. L. Collins, J. H. C. Cornelissen, G. Du, A. Eskelinen, J. Firn, B. Foster, L. Gough, K. Gross, L. M. Hallet, X. Han, H. Harmens, M. J. Hovenden, A. Jagerbrand, A. Jentsch, C. Kern, K. Klanderud, A. K. Knapp, J. Kreyling, W. Li, Y. Luo, R. L. McCulley, J. R. McLaren, J. P. Megonigal, J. W. Morgan, V. Onipchenko, S. C. Pennings, J. S. Prevéy, J. N. Price, P. B. Reich, C. H. Robinson, F. L. Russell, O. E. Sala, E. W. Seabloom, M. D. Smith, N. A. Soudzilovskaia, L. Souza, K. Suding, K. B. Suttle, T. Svejcar, D. Tilmand, P. Tognetti, R. Turkington, S. White, Z. Xu, L. Yahdjian, Q. Yu, P. Zhang, and Y. Zhang. 2019. Global change effects on plant communities are magnified by time and the number of global change factors imposed. Proceedings of the National Academy of Sciences of the United States of America 116:17867–17873.

Myers, N., Mittermeier A., 2000. Biodiversity Hotspots for Conservation Priorities. *Nature* 403, nº 6772: 853–58.

Pesck, V. A., T. F. Stepka, G. dos S. Lisboa, L. C. de J. França, and C. L. Cerqueira. 2018. Delineamento de copas de *Araucaria angustifolia* utilizando lógica Fuzzy em imagens Quickbird II. Advances in Forestry Science 5:385–390.

Rezende, C. L., F. R. Scarano, E. D. Assad, C. A. Joly, J. P. Metzger, B. B. N. Strassburg, M. Tabarelli, G. A. Fonseca, and R. A. Mittermeier. 2018. From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. Perspectives in Ecology and Conservation 16:208–214.

Ribeiro, M.C.; Metzger, J.P.; Martensen, A.C.; Ponzoni, F.J.; Hirota, M.M., 2009. The Brazilian Atlantic Forest: how much is left, and how is the remaining forest distributed? Implications for 25 conservation. Biological Conservation, 142, 1141–1153.

Roberts, D.A.; Ustin, S.L.; Ogunjemiyo, S.; Greenberg, J.; Dobrowski, S.Z.; Chen, J.; Hinckley, T.M. (2004). Spectral and Structural Measures of Northwest Forest Vegetation at Leaf to Landscape Scales. *Ecosystems*, *7*, 545–562.

Rose, R. A., D. Byler, J. R. Eastman, R. Fleishman, G. Geller, S. Goetz, L. Guild, H. Hamilton, M. Hansen, R. Headley, J. Hewson, N. Horning, B. Kaplin, N. Laporte, A. Leidner, P.

Leimgruber, J. Morisette, J. Musinsky, L. Pintea, A. Prados, V. C. Radeloff, M. Rowen, S. Saatchi, S. Schill, K.Tabor, W. Turner, A. Vodacek, J. Vogelmann, M. Wegmann, D. Wilkie, and C. Wilson. (2015). Ten ways remote sensing can contribute to conservation. Conservation Biology 29: 350–359. doi: 10.1111/cobi.12397.

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

SOS Mata Atlântica & INPE, 2019. Atlas dos Remanescentes Florestais da Mata Atlântica - Relatório Técnico Período 2017–2018 Fundação SOS Mata Atlântica and Instituto Nacional de Pesquisas Espaciais - INPE, São Paulo

Tucker, M. A., K. Böhning-gaese, W. F. Fagan, J. M. Fryxell, B. Van Moorter, S. C. Alberts, A. H. Ali, A. M. Allen, N. Attias, T. Avgar, H. Bartlam-brooks, B. Bayarbaatar, J. L. Belant, A. Bertassoni, D. Beyer, L. Bidner, F. M. Van Beest, S. Blake, N. Blaum, C. Bracis, D. Brown, P. J. N. De Bruyn, F. Cagnacci, D. Diefenbach, I. Douglas-hamilton, J. Fennessy, C. Fichtel, W. Fiedler, C. Fischer, I. Fischhoff, C. H. Fleming, A. T. Ford, S. A. Fritz, B. Gehr, J. R. Goheen, E. Gurarie, M. Hebblewhite, M. Heurich, A. J. M. Hewison, C. Hof, E. Hurme, L. A. Isbell, R. Janssen, F. Jeltsch, P. Kaczensky, A. Kane, P. M. Kappeler, M. Kauffman, R. Kays, D. Kimuyu, F. Koch, B. Kranstauber, S. Lapoint, J. Mattisson, E. P. Medici, U. Mellone, E. Merrill, T. A. Morrison, S. L. Díaz-muñoz, A. Mysterud, D. Nandintsetseg, R. Nathan, A. Niamir, J. Odden, R. B. O. Hara, L. G. R. Oliveira-santos, K. A. Olson, B. D. Patterson, R. C. De Paula, L. Pedrotti, B. Reineking, and M. Rimmler. 2018. R ES E A RC H mammalian movement 469:466–469.

Turner, W., C. Rondinini, N. Pettorelli, B. Mora, A. K. Leidner, Z. Szantoi, G. Buchanan, S. Dech, J. Dwyer, M. Herold, L. P. Koh, P. Leimgruber, H. Taubenboeck, M. Wegmann, M. Wikelski, and C. Woodcock. (2015). Free and open-access satellite data are key to biodiversity conservation. Biological Conservation 182:173-176.

Vadrevu, K. P., K. Lasko, L. Giglio, W. Schroeder, S. Biswas, and C. Justice. 2019. Trends in Vegetation fires in South and Southeast Asian Countries. Scientific Reports 9:1–13.

Vasconcellos, B. N., Corte, A. P. D., In prep. Estimativa de variáveis dendrométricas individuais de *Araucaria angustifolia* por meio de dados Laser Scanner aéreo e terrestre.

Wendling, Ivar; Zanette, Flávio. 2017. Araucária: particularidades, propagação e manejo de plantios. Embrapa - Brasília, 1-163.

Zorek, B., Biswas, S., Brum, F. T., Leimgruber, P., Carlucci., M. B., In prep. Mapping of Araucaria Mixed Forest fragments in South America with remote sensing approaches

Zwiener, V, P., Padial, A., Marques, C., M., Faleiro, F., Loyola, R., e Peterson, A. T., 2017. Planning for conservation and restoration under climate and land use change in the Brazilian Atlantic Forest. Diversity and Distributions 23, 955–66.