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Assessing the effectiveness of remotely piloted aircraft to map exposed soil in urban mangroves

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Abstract
Although mangroves are ecologically important coastal ecosystems and laws are in place to ensure their protection, anthropogenic activities continue to cause the degradation and/or suppression of mangrove vegetation. Traditional methods to measure and monitor this process, including the use of medium spatial resolution orbital images, are unsuitable for fine-scale environmental degradation and recovery analyses, including the measurement of degraded areas in and around mangroves. Thus, this study aims to analyze the effectiveness of using images from remotely piloted aircraft (RPA) in the mapping of exposed soil areas in mangroves. Imaging with RPA was performed in 22 urban mangroves in Paranaguá, Paraná State, Brazil. Orthomosaics were generated from the collected data and submitted to supervised classification. We then calculated global accuracy and Kappa indices and commission and omission errors. Based on data from the RPA images, the identification of areas of exposed soil on the margins and interior of mangroves was effective since the global accuracy index was higher than 96% for all classified orthomosaics and the Kappa index was above 0.95, indicating excellent classification. The mapping shows different concentrations of exposed soil areas in the analyzed mangroves, enabling us to identify three regional patterns of vegetation degradation. The results can inform municipal planning, including revisions to the Integrated Development Master Plan, Basic Sanitation Plan, and Land Regularization Plan. This information may also be used in studies on the recovery and monitoring of mangrove vegetation.

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INTRODUCTION

Mangroves are coastal ecosystems composed of a group of tree species with similar morphological, biochemical, physiological, and reproductive characteristics (SCHAEFFER-NOVELLI et al., 2000; KENNISH, 2016). This type of ecosystem is found in tropical and subtropical coastal areas in transition zones between terrestrial and marine environments, such as estuaries and bays. (OLIVEIRA; TOGNELLA, 2014; KENNISH, 2016).

In Brazil, mangroves follow the coastline for approximately 6,800 km and constitute the largest continuous extent of mangrove in the world. However, most of the country's population (approximately 72%) is also concentrated along the coast. Therefore, rapid development and improper land management planning have resulted in the loss of approximately 88% of the Atlantic Forest Biome, one of the most biodiverse biomes in the world, with consequent effects on mangrove phytophysiognomy (SOSMA, 2021). Currently, vast areas of mangrove vegetation have been eliminated due to urban, port, tourism, and agro-industrial development and expansion (VANNUCCI, 2002).

The mixed landscapes where urban land use intersects with mangrove forests are known as "urban mangroves" and are characterized as environments that are heavily affected by anthropogenic activities, including the release of sewage, industrial, and agricultural waste, pressure from real estate development, and proximity to ports, among others (SCHAEFFER-NOVELLI, 1995; BRANDÃO; GUIMARÃES; TRAVASSOS, 2009).

Urban encroachment on mangroves results in decreases to the ecosystem services provided, including provisioning services (e.g., food production), supporting services (e.g., nutrient cycling, landscape connectivity, biodiversity maintenance, habitat for animal species), regulating services (e.g., erosion control, bulkheads for tidal movements and flood control, contaminant retention, and water purification) and cultural services (recreation, well-being, and scenic beauty) (DUGAN, 1992; SCHAEFFER-NOVELLI et al., 2005; SCHAEFFER-NOVELLI, 2016; PINHEIRO; TALAMONI, 2018). It is important to highlight that given the current climate change scenario, the loss of these ecosystem services can have significant short-term effects on neighboring human populations, due to the lack of regulating services that provide physical protection, which can lead to subsequent decreases and/or the loss of other services.

In Brazil, several laws are in place that ensures the protection of mangroves, including protection of coastal zones in the 1988 Constituição Federal (the Federal Constitution of Brazil), the definition of mangroves as areas of permanent preservation (APP) in Law No. 12.651/12 (BRASIL, 2012), and their classification as Ecological Reserves in resolution No. 004/85 from Conselho Nacional do Meio Ambiente (CONAMA, in Portuguese. A federal council for the Environment of Brazil). However, even with legal protections and despite their ecological importance, several studies point to the degradation of mangroves due to a range of human activities, such as waste disposal (SALEH, 2007), deforestation (DAYALATHA; ALI, 2018), effluent discharge (LEAL et al., 2017; CELERI et al., 2019), shrimp farming (FERNANDES et al., 2018; LIMA; SILVA; CARVALHO, 2019), and urban encroachment (CANEPARO, 1999; MATIAS; SILVA, 2017; MAIA et al., 2019).

Among the tools and methodologies used to analyze and measure the degradation of mangroves, Remote Sensing (RS) and Geographic Information System (GIS) techniques have become increasingly common due to the ability to collect data quickly and frequently and cover wide areas at a reduced cost and less time than traditional field survey methods (AMARAL et al. 2019). The use of Remotely Piloted Aircraft (RPA or drones) offers other benefits, such as portability, accessibility, ease of handling, low to moderate cost, and very high spatial resolution of images (MILLER; ZITER; KOONTZ, 2020). From these images, information on the area, distribution, density, vegetation indices and landscape metrics can be extracted (KUENZER et al., 2011; KANNIAH et al., 2015; WANG et al., 2019).

The first studies to use imaging techniques to map or diagnose mangroves were carried out with medium spatial resolution multispectral orbital images (LANDSAT series) or aerial photographs (GIRI et al., 2011). Data from medium spatial resolution images can be used to assess the general conditions of mangroves but are unsuitable for fine-scale environmental degradation and recovery studies, for example, in areas where mangroves and urban development intersect. The evaluation of mangrove vegetation degradation, through the mapping of exposed soil on a large spatial scale, can support public policies related to environmental and land management planning, particularly in identifying vegetation suppression patterns.

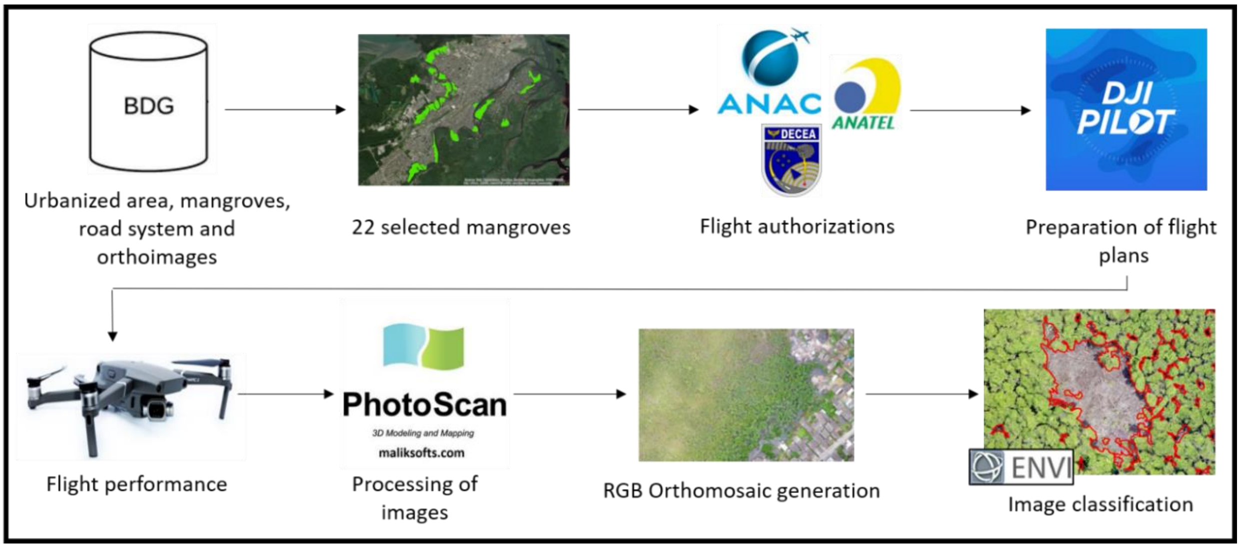
For this purpose, technological solutions such as active orbital sensors with high spatial resolution and orbital sensors with high spectral resolution or active sensors (Light Detection and Ranging – LIDAR, Radio Detection and Ranging – RADAR, among others) can be used (HELD et al., 2003; JIA et al., 2014; KRUMME et al., 2015; CAO et al., 2018; SALUM et al., 2020). However, the high cost associated with these techniques makes such analyses inaccessible or unfeasible. Thus, RPAs offer a comparatively low- to moderate-cost solution for landscape mapping and degradation analyses.

In this context, this study hypothesizes that the very high spatial resolution data captured by RPAs are effective in identifying areas of exposed soil on the margins and interior of mangrove forests. Thus, the objective of this study was to analyze the effectiveness of using RPA imaging to map exposed soil areas in urban mangroves.

MATERIALS AND METHODS

The methodological procedure was divided into steps (Figure 1). We began by developing a geospatial database (GDB) to select the mangroves for analysis, followed by image capture planning, and field surveys. The final steps focused on processing the collected data.

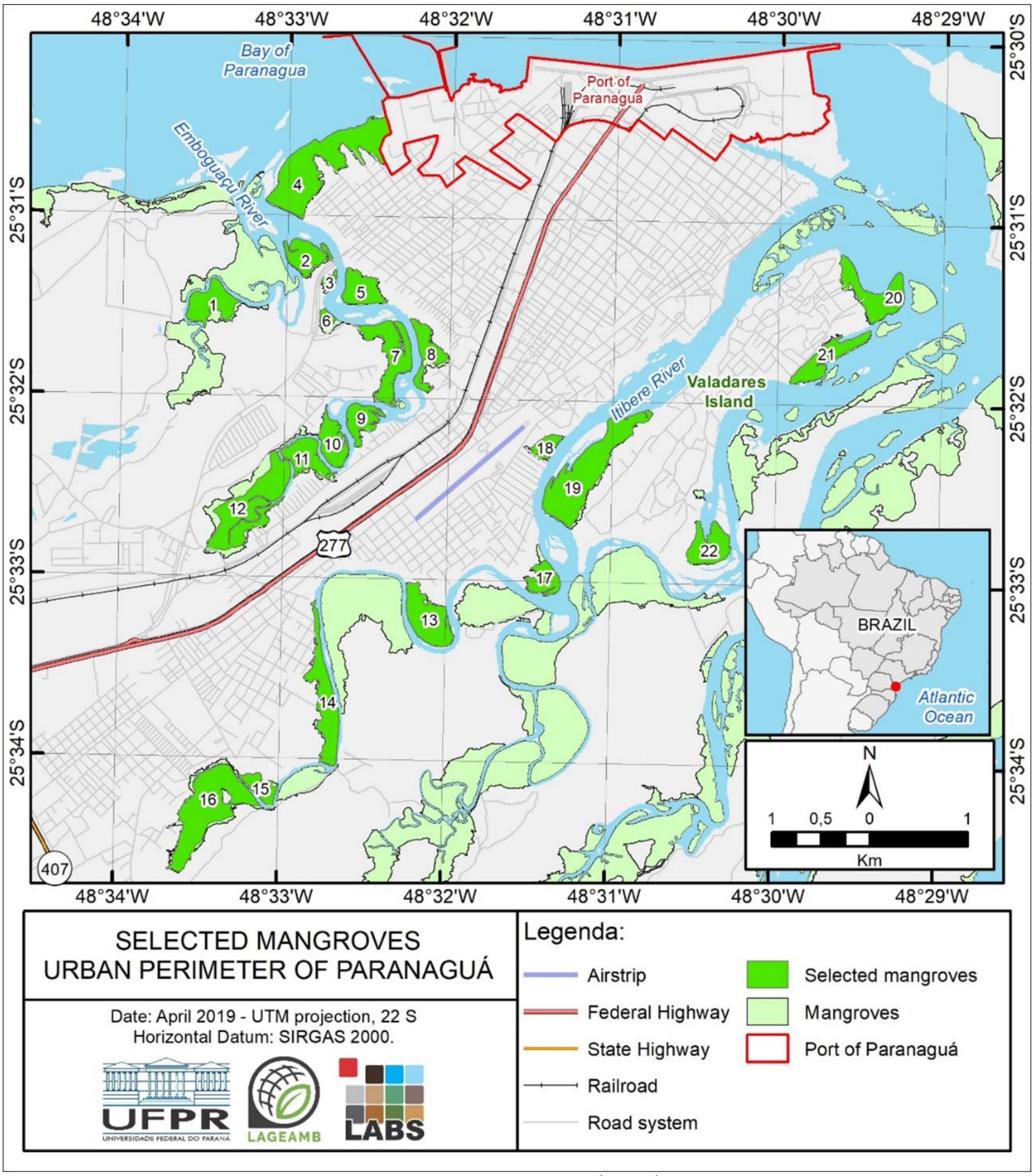
Figure 1 - Steps of the methodological procedure.



Source: The authors (2021).

The study area is located in the municipality of Paranaguá (25°31'12"S - 48°30'32"W), on the central coast of Paraná State, southern Brazil (Figure 2). The 22 selected mangroves (or mangrove forest patches) are in direct contact with the urban area of Paranaguá. The total area analyzed adds up to 361.36 hectares and extends along the banks of the Emboguaçu and Itiberê Rivers and the shore of Valadares Island, all of which are located on Paranaguá Bay.

Figure 2 - Location of selected mangroves in the urban area of Paranaguá, southern Brazil.



Source: The authors (2021).

Database development and selection of areas for mapping

The GDB was developed using secondary geospatial data published by Instituto Água e Terra do Paraná (IAT, in Portuguese), an agency in the state of Paraná responsible for environmental matters, and Secretária Municipal de Urbanismo de Paranaguá (SEMUR, in Portuguese), a municipal secretariat responsible for urban and environmental matters (Table 1) (PAZ; DAL PAI; PAULA, 2020) . The mangrove areas chosen for imaging with RPA were defined using the "select by location" tool in QGIS 3.10, with the parameter "touch" as a geometric predicate in the layers "urban area" and "mangrove". Thus, only the mangrove areas that intersect with the urban area of Paranaguá were selected. Each selected mangrove area received a simple numerical identifier (Figure 2).

Table 1 - List of secondary geospatial data used in this research.

Geospatial data	Data type	Scale/Resolution	Source	Application in this research
Urbanized area	Planialtimetric survey - vector	1:10.000	IAT (2016)	Selection of areas
Mangroves	Planialtimetric survey - vector	1:10.000	IAT (2016)	Selection of areas and planning of surveys
Airstrip	Planialtimetric survey - vector	1:10.000	IAT (2016)	Survey planning
Road system	Planialtimetric survey - vector	1:10.000	IAT (2016)	Survey planning
Orthoimages	Registration survey - raster	0,2 meter	SEMUR (2010)	Georeferencing of generated orthomosaics

Source: The authors (2021).

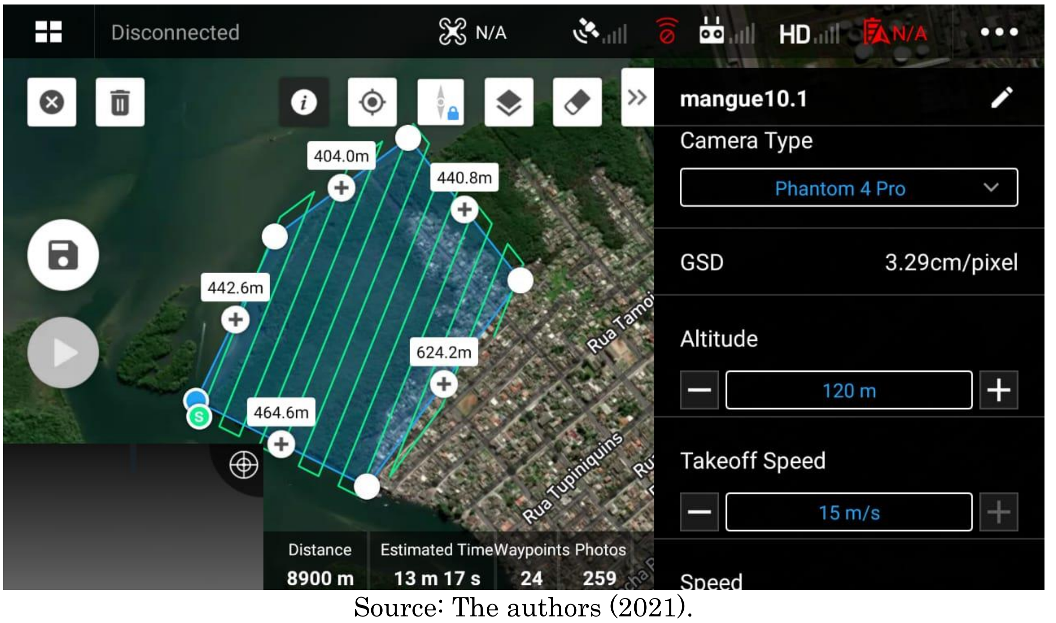
Equipment, planning, and imaging.

A Mavic 2 Pro RPA model was used to obtain the images, equipped with a 20-megapixel Hasselblad camera. Authorization was obtained in compliance with Regulamento Brasileiro da Aviação Civil Especial (RBAC, in Portuguese. A Brazilian regulation for special civil aviation), Agência Nacional de Aviação Cívil (ANAC, in Portuguese. The federal agency responsible for the civil Aviation), Departamento de Controle do Espaço Aéreo (DECEA, in Portuguese. The federal department responsible for the airspace control) and the Agencia Nacional de Telecomunicações (ANATEL, in Portuguese. The federal agency responsible for the telecommunications).

Access to airspace was also requested in the Sistema de Solicitação de Acesso de Aeronaves Remotamente Pilotadas (SARPAS, in Portuguese. The Brazilian system for remotely piloted aircraft access request) from the DECEA. The requisition identified the areas to be imaged, flight dates and times, takeoff points, description of the operation, with RPA altitude set at 393 feet (about 120 meters). Letters of consent signed by authorized personnel at the airport in Paranaguá and a nearby helipad were also obtained. The imaging was carried out from November 18 to 22, 2019, and from January 20 to 31, 2020 The time interval chosen for capturing the images was between 11:00 and 15:00, to avoid shade from the leaves due to the angle of the sun.

Flight plans were prepared in the DJI Pilot application, based on the polygons of the selected mangrove areas, and loaded into the application using the Keyhole Markup Language (KML) format (Figure 3). When the size of the mangrove area exceeded the autonomy range of the RPA (about 30 hectares – 14 minutes), it was divided into two or three flight plans (Figure 3). All flight plans were made with the same technical specifications (Table 2).

Figure 3 - DJI Pilot app screen. Example of flight plan for the first part of the mangrove area 04.



Source: The authors (2021).

Table 2 - Characteristics of flight plans created in the DJI Pilot app.

Specification	Value/Attribute	Meaning
Camera Type	Phantom 4 Pro	Camera type. In the version of the application used, there was no “Mavic 2 Pro” type. We selected “Phantom 4 Pro” compatibility issues.
GSD	3.5 cm/pixels	Ground Sample Distance or distance from the ground sample. The distance the pixel will represent from the terrain. Related to image detail level.
Altitude	120 meters	RPA height during the flight. Defined according to legislation.
Takeoff Speed	15 m/s	Takeoff speed.
Speed	14.3 m/s - 51,48 km/h	Speed in flight.
Elevation Optimization	No	Used when the objective is to generate digital terrain models.
Completion	Return to Home	After imaging, the RPA should return to the takeoff point.
Side Overlap Ratio (%)	70%	Side cover rate.
Frontal Overlap Ratio (%)	70%	Frontal cover rate.
Course angle	Various	Angle that RPA will perform the imaging.
Margin	30 m	Extra area around the loaded polygon. Required to avoid edge effect.

Source: The authors (2021).

Processing of collected data and information extraction

After the flights, the data were processed in the Agisoft PhotoScan 1.3.3 software. We followed the standard software procedure for generating orthomosaics, including image alignment, point cloud creation, digital surface model (DSM) generation, and orthomosaic generation (point cloud + DSM). Processing was performed with the quality set to high.

The generated orthomosaics were exported with a spatial resolution of 0.1 m. Georeferencing was done using images with the highest spatial resolution and best available positional quality. Images were provided by SEMUR and had a 0.2 m spatial resolution, were dated to 2010, and compatible with Padrão de Exatidão Cartográfica Para Produtos Cartográficos Digitais (PEC-PCD, in Portuguese. Brazilian cartographic accuracy standard for digital products, published by Brazilian Army) for scale 1:10,000 (DSG, 2016). Six control points were used in each orthomosaic, with a mean square error of 0.9 m. The low density of control points is due to the difficulty in identifying homologous points and the different spatial resolution between the base image for georeferencing and the generated orthomosaics.

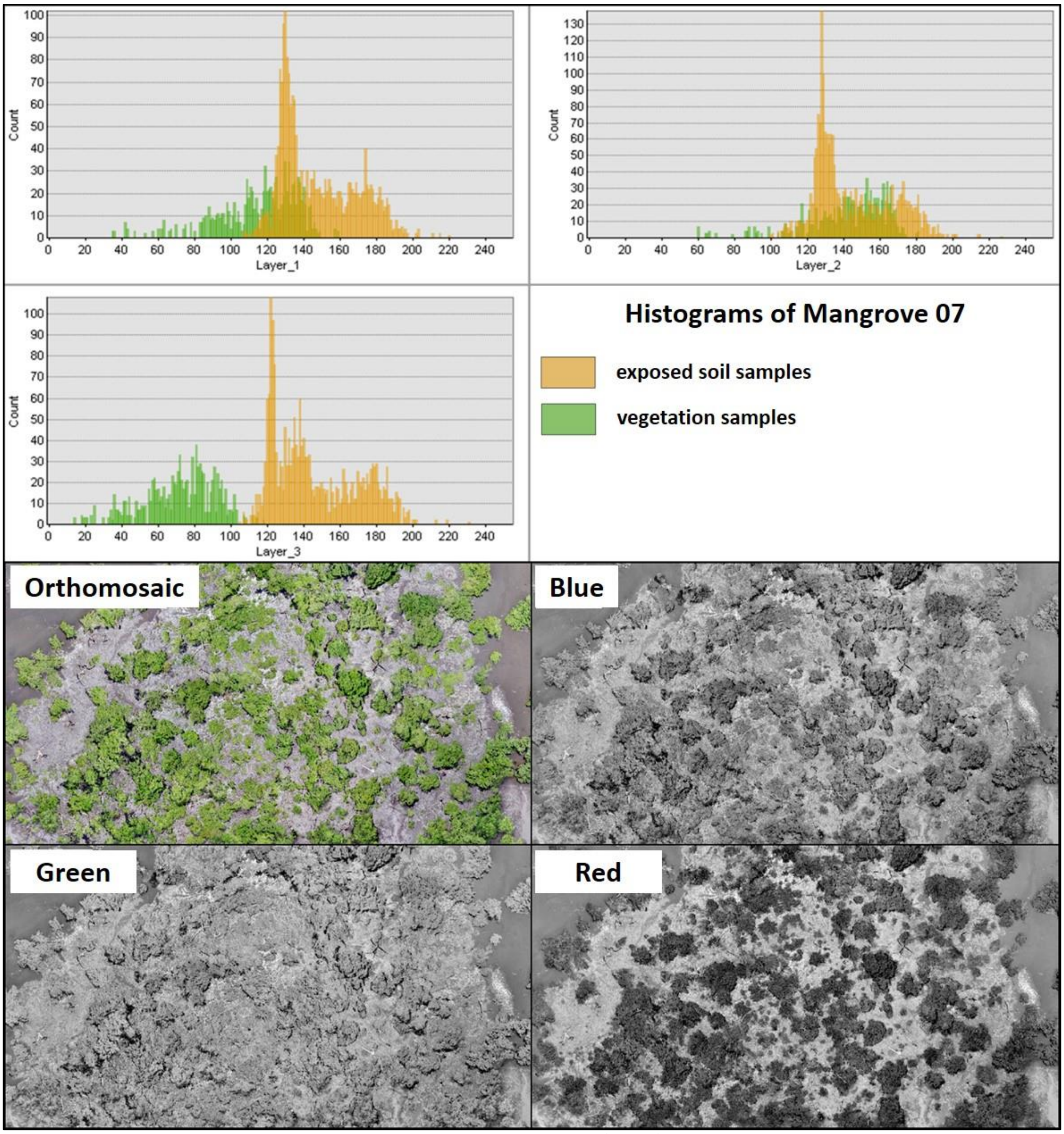
To map the areas of exposed soil in the images, the ENVI 5.3 software was used. A supervised Maximum Likelihood Classification algorithm was used to classify the classes “vegetation” and “exposed soil”. Considering the high spatial resolution of the data, we chose to collect 5000 samples (pixels) for each class based on visual inspection of the orthomosaics. Pixels were selected to represent the variation in gray levels of the generated orthomosaic bands (RGB), and sample selection areas were distributed throughout the orthomosaics to avoid the concentration of data in a single quadrant.

Based on the matrices resulting from the supervised classification, the global and Kappa accuracy indices, along with the commission and omission errors, were calculated in ENVI 5.3. The files in matrix format were converted to vector format (shapefile) in QGIS 3.10. Finally, the total surface area of exposed soil and vegetation classes were calculated.

RESULTS AND DISCUSSION

Due to the large number of analyzed mangrove patches, the results are presented using illustrative examples. Through the analysis of the histograms of the selected samples, we found that the red band (Layer_3) best distinguishes the “vegetation” and “exposed soil” classes (Figure 4), as shown through a visual analysis of each of the orthomosaic bands in mangrove 07 (Figure 4).

Figure 4 - Example of histograms of samples collected for classification of mangrove orthomosaic 07. Below the histograms, individual visualization of each band (Layer_1: blue; Layer_2: green; Layer_3: red).



Source: The authors (2021).

The global accuracy index was greater than 96.29% in all generated orthomosaics, reaching a maximum of 98.98% in mangrove 17 (Table 3). As for the Kappa index, all results were above 0.95, indicating an excellent classification (Table 3) (LANDIS; KOCH, 1977). Lower values found for global accuracy and the Kappa index can be attributed to the presence of clouds in the orthomosaics. Commission and omission errors in all classifications did not exceed 5.07%, indicating efficient classification.

Table 3 - Global accuracy indices, Kappa index and commission and omission errors for the exposed soil class.

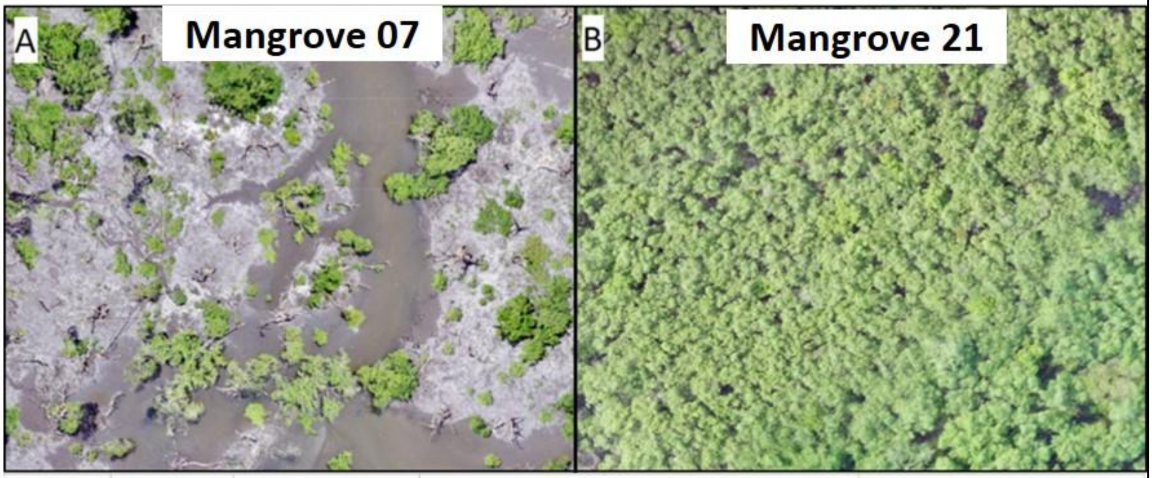
Mangroves	Global Accuracy Index (%)	Kappa Index	Exposed Ground Class Commission Errors (%)	Exposed ground class omission errors (%)
1	97,54	0,97	3,12	3,12
2	96,41	0,95	3,58	3,58
3	97,33	0,97	3,09	3,09
4	97,27	0,96	3,08	3,08
5	98,12	0,97	3,04	3,04
6	96,29	0,95	5,07	5,07
7	97,44	0,97	3,15	3,15
8	97,21	0,96	3,11	3,11
9	97,59	0,96	3,19	3,19
10	97,01	0,96	3,26	3,26
11	97,59	0,96	3,19	3,19
12	98,58	0,97	3,05	3,05
13	98,44	0,97	3,06	3,06
14	96,78	0,95	4,38	4,38
15	98,19	0,97	3,06	3,06
16	98,13	0,97	3,06	3,06
17	98,98	0,98	3,02	3,02
18	97,89	0,96	3,16	3,16
19	97,51	0,97	3,17	3,17
20	98,35	0,97	3,07	3,07
21	98,69	0,98	3,04	3,04
22	96,34	0,98	4,64	4,64

Source: The authors (2021).

On average, the 22 analyzed mangroves have 4.1 ha of exposed soil. In most cases, the identified area of exposed soil is concentrated on the margins of the mangrove patches. Significant differences in the concentration of exposed soil can be seen when comparing the analyzed mangrove patches (Figure 5). Mangrove 07 stands out as having the highest concentration of exposed soil (57.1%), while mangrove 21 shows the lowest levels of exposed soil (5.53%) and, consequently, the highest vegetation density.

An example of the mapping is presented for mangrove 13 (Figure 6). Using as criteria the proportion of exposed soil and geographic position, the studied mangrove areas can be classified into three regional groups: A) mangroves on the banks of the Emboguaçu River; B) mangroves on the banks of the Itiberê River; C) mangroves on Valadares Island (Figure 7).

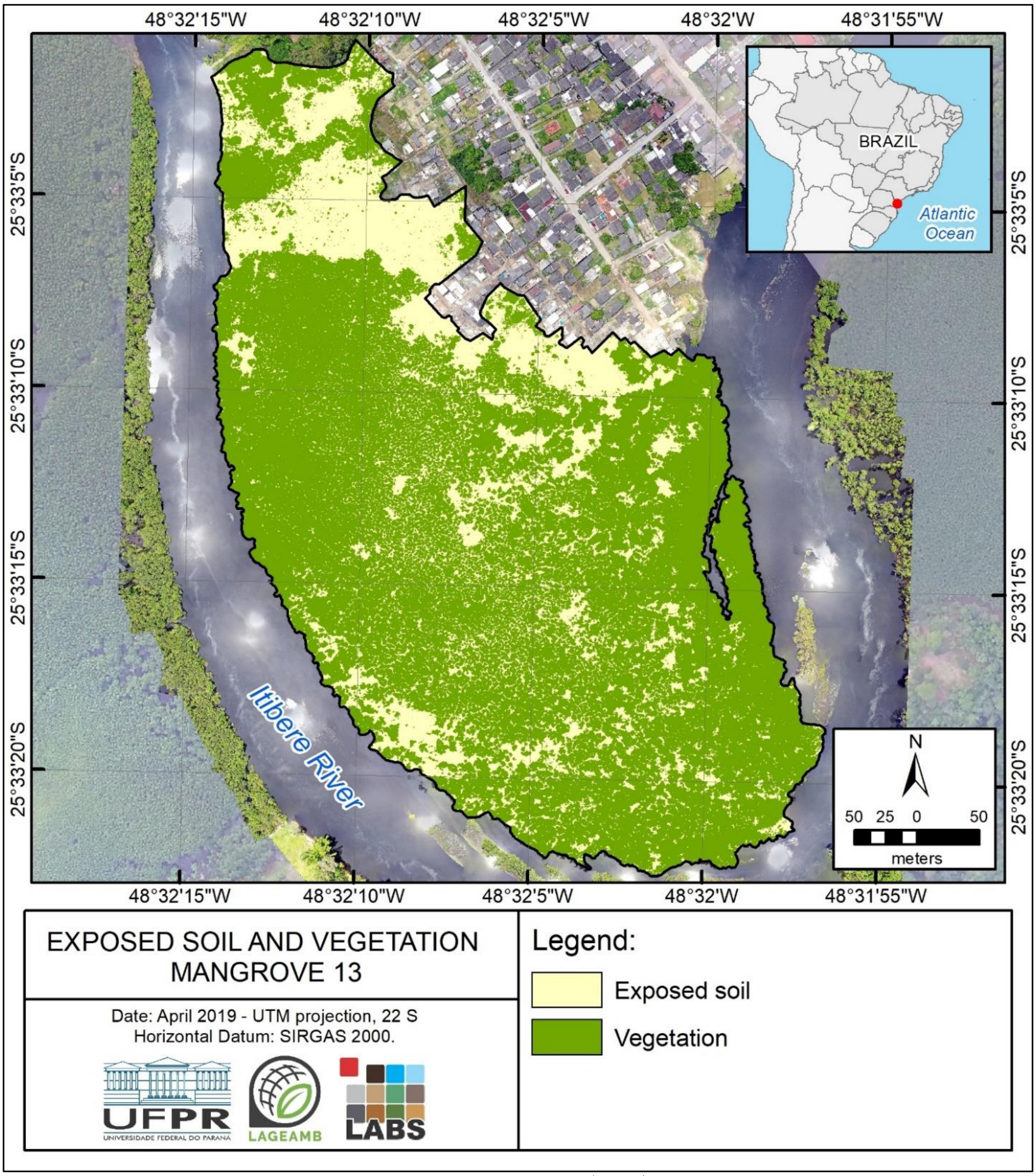
Figure 5 - Comparison of the concentration of exposed soil areas between mangrove 07 (A) and 21 (B) and tabulation of percentages of exposed soil and vegetation in the mangrove forests analyzed.



Mangrove	Area (acre)	% Vegetation	% exposed soil	Area of vegetation (acre)	Area of exposed soil
21	13,32	94,47	5,53	12,58	0,74
4	46,39	90,46	9,54	42,07	4,32
20	17,82	89,19	10,81	15,89	1,93
14	21,45	87,69	12,31	18,81	2,64
16	37,76	87,27	12,73	32,95	4,81
19	38,59	83,77	16,23	32,33	6,26
15	6,05	74,37	25,63	4,5	1,55
13	18,88	74,31	25,69	14,03	4,85
17	8,04	73,3	26,7	5,72	2,32
2	10,95	72,21	27,79	7,91	3,04
18	4,62	69,24	30,76	3,2	1,42
3	1,49	67,92	32,08	1,01	0,48
6	2,01	67,42	32,58	1,35	0,66
22	13,28	66,32	33,68	8,81	4,47
1	14,06	65,44	34,56	9,2	4,86
10	10,84	65,42	34,58	7,09	3,75
5	11,03	64,31	35,69	7,09	3,94
11	11,61	60,8	39,2	7,06	4,55
12	33,64	60,26	39,74	20,27	13,37
9	9,03	55,8	44,2	5,04	3,99
8	10,21	47,26	52,74	4,89	5,32
7	20,3	45,9	54,1	9,32	10,98

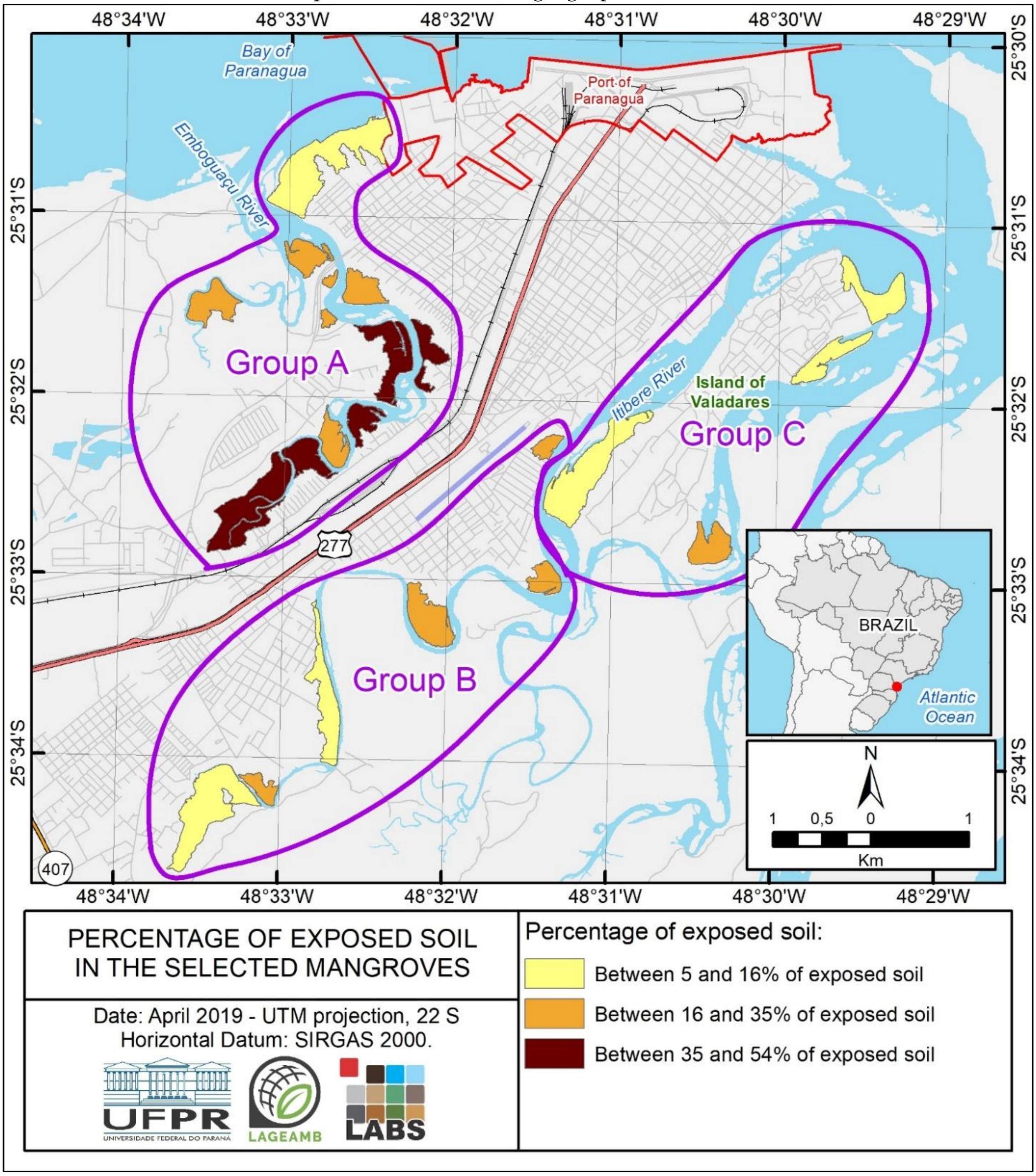
Source: The authors (2021).

Figure 6 - Example of exposed soil mapping in mangrove 13.



Source: The authors (2021).

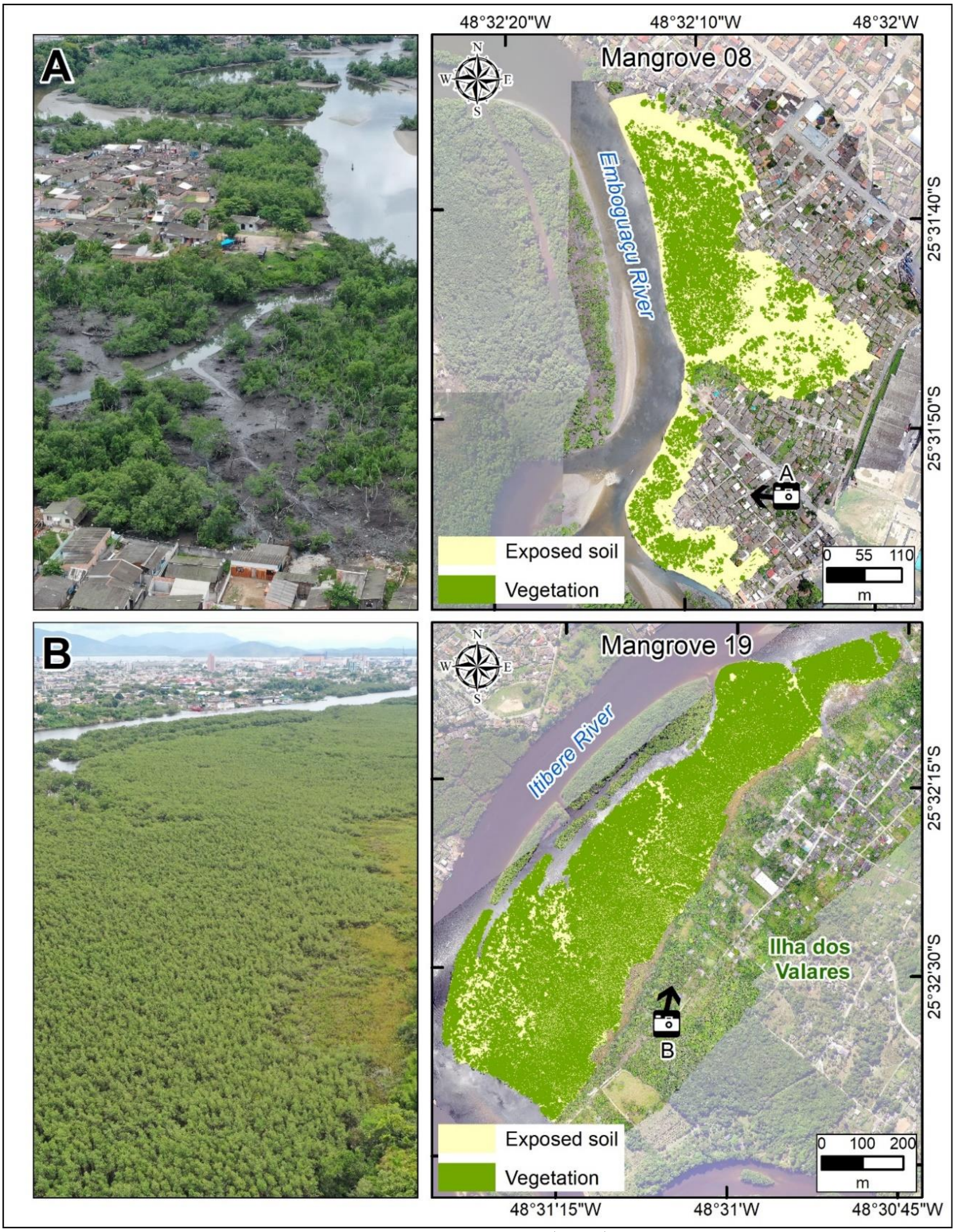
Figure 7 - Regionalization of the mangrove areas analyzed in the study. Criteria: proportion of exposed soil values and geographic location.



Source: The authors (2021).

Proportionally, more mangroves with high levels of exposed soil occur on the banks of the Emboguaçu River (Group A), while those with the greatest proportion of vegetation are found in Group C. Mangroves in Group B showed intermediate values for exposed soil and vegetation. Figure 8 presents a comparison of mangrove 08, Group A, and mangrove 19, Group C.

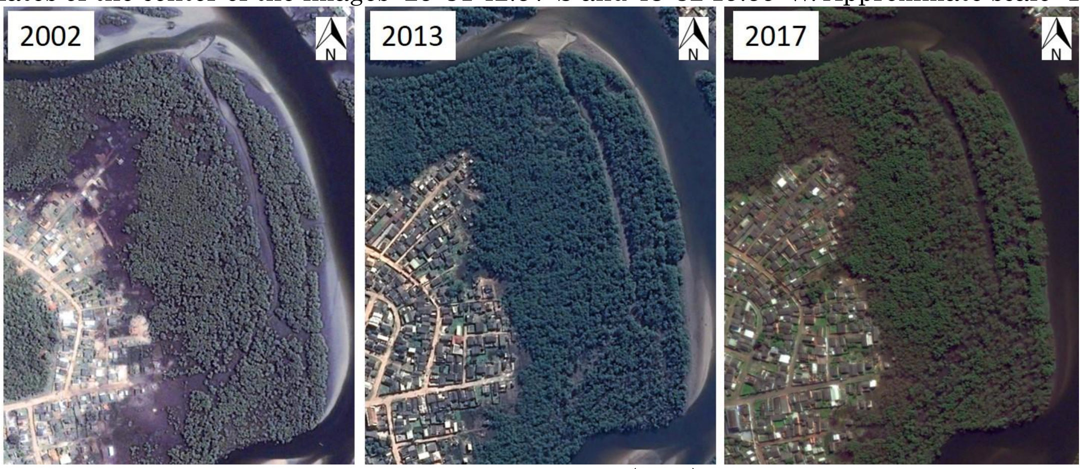
Figure 8 - Oblique images registered with the RPA. Approximate height: 80 meters. Approximate coordinates of the RPA at the time of image recording: A) 25°31'42.26"S and 48°32'33.10"W. B) 25°31'43.57"S and 48°29'48.49"W.



Source: The authors (2021).

In addition to indicating the level of degradation of a mangrove, areas of exposed soil can identify mangrove patches that are suitable for vegetation recovery. In this context, mangrove 07 presented the highest proportion of exposed soil. Based on images from Google Earth, this mangrove patch had significant areas of exposed soil in October 2002, but in April 2013 this trend was reversed, and the area of exposed soil was again covered by mangrove vegetation (Figure 9).

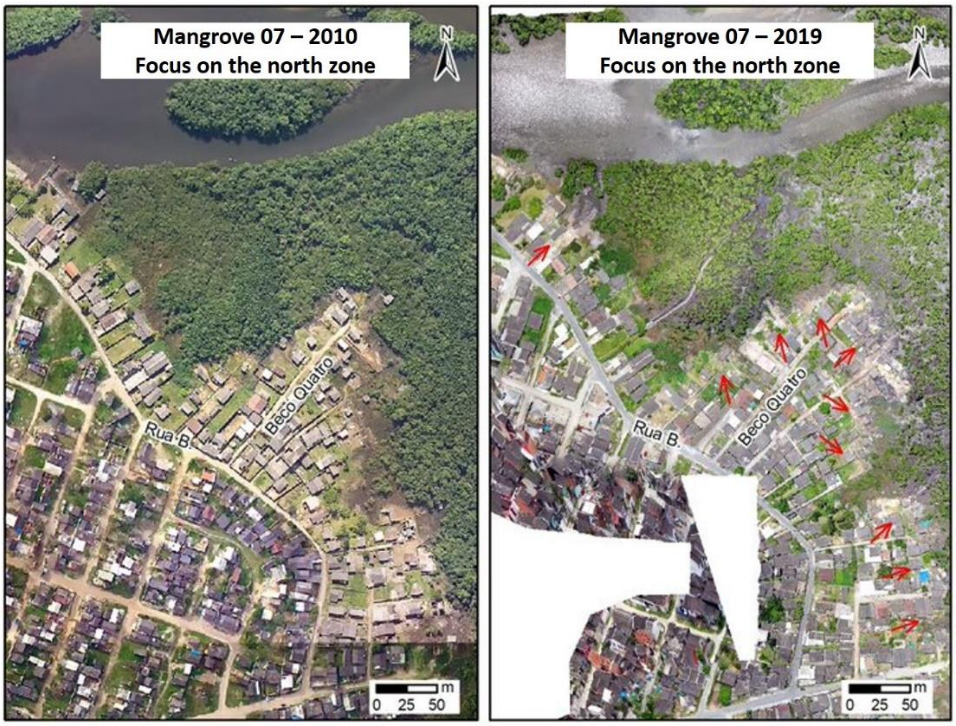
Figure 9 - Spatial and temporal evolution of the mangrove 07 between 2002 and 2017. Approximate coordinates of the center of the images: 25°31'42.57"S and 48°32'19.59"W. Approximate scale: 1:2.500.



Source: Google Earth (2021).

Assessing the variation in vegetation over the last two decades in mangrove 07 (Figures 9 and 10), we can see that after 2002 urban expansion did not cause the mortality of new mangrove individuals. It is likely that in 2002, the area of exposed soil adjacent to the urban land use was caused by activities related to road works and infrastructure, including vegetation suppression, followed by the filling of the mangrove wetland (as indicated by historical analyses of the processes of land occupation in these areas). However, between 2013 and 2017, the same area showed significant vegetation recovery. The natural regeneration of mangroves is related to a range of factors, including the distribution of seedlings, characteristics of the propagules, species colonization patterns, edaphic characteristics (such as salinity and organic matter content), density and composition of other mangrove species, tidal effects, and herbivory, among others (PELOZO, 2012; MADI et al., 2016). Thus, several natural factors can explain the regeneration that occurred in this area, in addition to the possibility of reducing indirect abiotic stressors, such as the dumping of pollutants or solid waste (not related to household waste).

Figure 10 - Focus on the northern sector of the mangrove area 07.

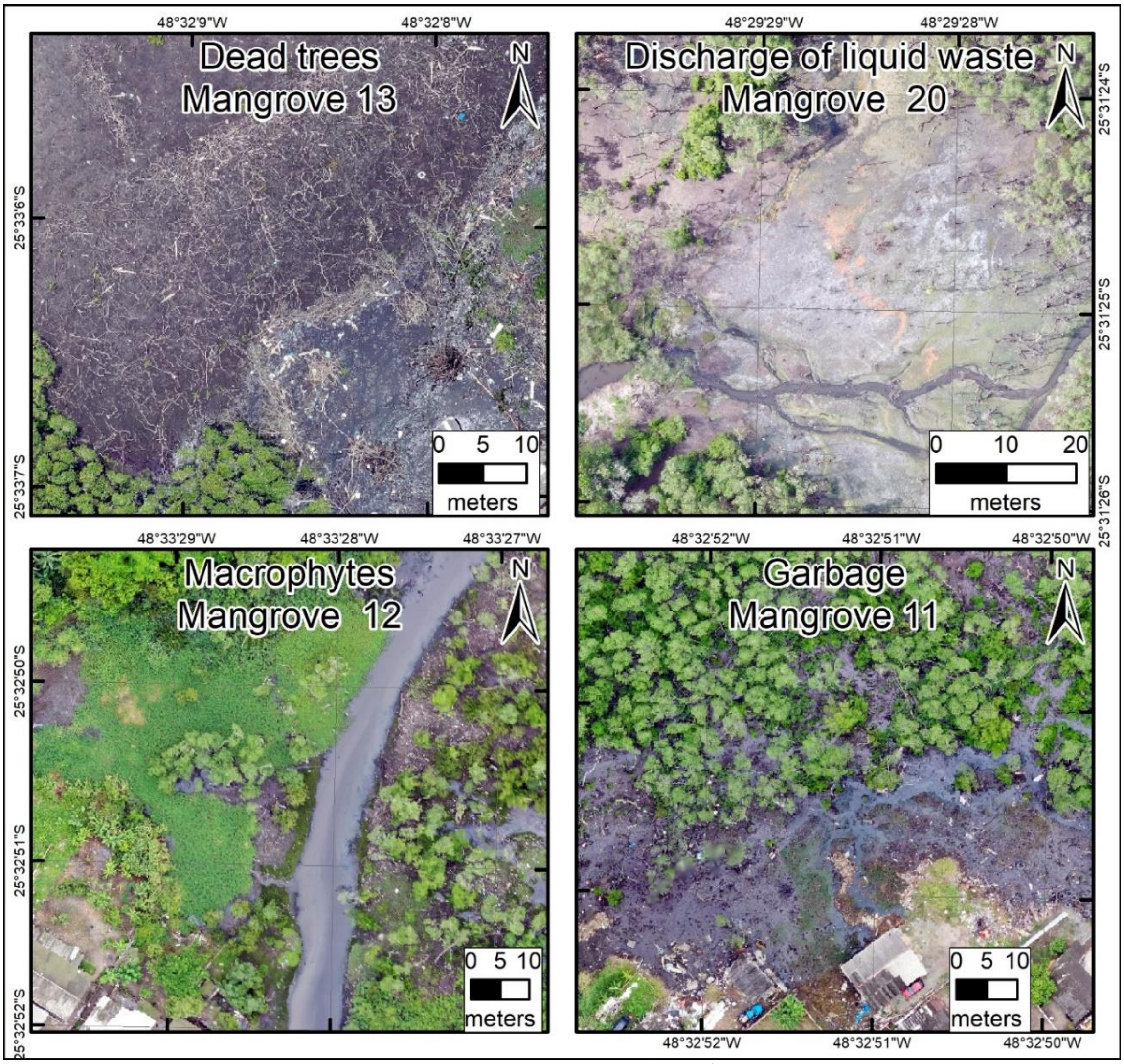


Source: 2010 image – SEMUR (2010). 2019 image - The authors (2021).

However, in 2019 a new process of degradation began that is not associated with urban expansion but may be related to the presence of pollutants in the soil, greater sedimentation along the river due to natural or anthropogenic processes (e.g., construction of dams along the river and the dumping of tires, household garbage, and debris), or even in response to the natural factors mentioned above, such as herbivory. However, to better understand the possible reasons for the degradation of these mangroves, a field analysis is necessary.

With the high spatial resolution provided by the RPA images, it is possible to identify elements such as dead trees, areas with garbage, boat paths, housing subdivisions, and the discharge of solid and liquid waste (Figure 11). Both exposed soil and the presence of these elements can indicate the degree of mangrove degradation, as has been discussed in previous studies (CANEPARO, 1999; CANEPARO, 2000; GIRI et al., 2011; KANNIAH et al., 2015; CELERI et al., 2019).

Figure 11 – Other elements found in orthomosaic generated.



Source: The authors (2021).

It should be noted that the level of detail that can be obtained using data from RPA images is not limited to spatial resolution but includes temporal resolution as well. The same mangrove patch can be re-imaged every few hours or minutes. Additionally, there are multispectral cameras for RPA that enable the development of vegetation indices at a high spatial resolution. These characteristics offer a range of possibilities for mangrove studies, including enabling analyses that were previously unfeasible using data from conventional platforms (orbital images and aerial photographs).

CONCLUSION

Based on the results of the supervised classification, we found that using data from images captured with RPA to identify areas of exposed soil in mangroves at a fine-scale was effective. Additional studies should be carried out to address the spectral response of other elements of interest in this ecosystem, such as dead trees, areas of exposed wet and dry soil, garbage, construction debris, and even the identification of specific mangrove species.

The analyses carried out provide a diagnosis of the occurrence of exposed soil in Paranaguá's urban mangroves, enabling us to locate and classify the level of degradation into three groups. Group A, located on the banks of the Emboguaçu River, has the highest percentage of exposed soil, indicating that this region requires attention in terms of environmental recovery and land management planning.

As a result of the level of detail achieved, this study can also serve as a framework for analyzing the current situation of urban mangroves in Paranaguá. The results obtained herein can be compared with future surveys to provide a detailed temporal and spatial analysis of the landscape. The maps and geospatial data generated in this study were given to the city of Paranaguá and can be used to support activities within the scope of municipal planning, such as updating the Master Plan and preparing the Basic Sanitation and Land Regularization Plans, as well as those related to monitoring and inspection.

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AUTHORS' CONTRIBUTION

Otacílio Lopes de Souza da Paz: conceived the study, determined the proposed methodology, collected and analyzed the data and wrote the text. Participated in the writing of the research project for the acquisition of financing. Sidney Vincent de Paul Vikou: conceived the study, participated in data collection and contributed to the text. Participated in the writing of the research project for the acquisition of financing. Daiane Maria Pilatti: conceived the study, participated in data collection and contributed with the text. Participated in the writing of the research project for the acquisition of financing. He acted in the coordination of the project that this article is linked to. Eduardo Vedor de Paula: conceived the study and contributed to the text. Responsible for acquiring financing. Acts in the coordination of the laboratory where this research was carried out. Marianne de Oliveira: participated in the processing of collected data and interpretation of the results obtained. Contributed with the text.