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Papers

Impact evaluation of the extreme weather event in mangroves of the Brazilian Southeast Coast with remote sensing

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Abstract
Among the various environments present on the planet that deserve due attention, as they have particularities and specificities of chemical, physical and biological orders, mangroves stand out. These ecosystems are mostly located in the intertropical zones where continental and oceanic waters meet, being crucial for a great diversity of animal species that find, in it, conditions that allow them to live and reproduce. In addition, this ecosystem is also for many local residents, such as traditional fishermen and crab farmers, a place for income generation, thus assuming an important socio-economic function. In addition, mangroves, through vegetation, help to protect the coast and act as important carbon sequestrants and stores. Among the less invasive methodologies that make it possible to analyze a series of dynamics of this environment, reducing costs with the field and the risks inherent to its natural characteristics, Remote Sensing stands out. Therefore, the general objective of this research was to evaluate the effectiveness of the NDVI, SAVI and LAI vegetation indices in recording the consequences of an extreme climatic event that occurred on June 1, 2016, in the mangroves of the Reserva de Desenvolvimento Sustentável Municipal Piraquê Açu-Mirim, located in Aracruz (ES), Southeast Coast Brazil. To achieve the objective, time series between February 2016 (before the event) and December 2020 were used. The results, which include maps and statistical graphs, allowed the delimitation of areas according to the intensities of the impacts and their consequences on the vegetation. While the vegetation of Piraquê-Açu underwent regeneration processes in all affected areas, in Piraquê-Mirim the area with the greatest impact remained destroyed. Given the socio-environmental importance of mangroves, it is necessary to implement projects aimed at their recovery. Both the methodology and the indices were efficient to achieve the objectives and can be reproduced in other mangroves.

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INTRODUCTION

Among the various environments on the planet which deserves true attention due to their chemical, physical and biological particularities and specificities, mangrove forests stand out. Present in different places around the planet, these coastal plains ecosystems are mostly located in the intertropical zones, in specific locations where continental and oceanic waters meet.

To avoid misunderstandings, it is necessary to differ mangrove plants from mangrove forests. In summary, it can be said that mangrove refers to the different groups of vegetation located in a mangrove ecosystem which, in turn, is where several biotic and abiotic factors interact. Therefore, the term mangrove will be used, in this work, to refer to the ecosystem.

Present in several places around the planet, mangroves have a crucial role for a great diversity of species that find, in this environment, the conditions for living and reproducing. Furthermore, this ecosystem is for local inhabitants such as traditional fishermen and crab collectors, a place for income generation, undertaking an important socio-economic role. Moreover, mangrove forests, through their vegetation, also act as important carbon sequestrants and stockpilers (SOAVINSKI; MARETTI, 2018). In this respect, when compared to other environments, both in the ability to sequester and store this element, tropical mangrove forests outperform other tropical forests, including the Amazon.

In addition, mangroves serve as a buffer zone between the continent and the ocean, taking the impacts of several events, such as the extremes that arose from processes that might be a result of climate change. In this sense, among many others, researchers like Santos *et al.* (2012); Bernardino *et al.* (2015); Kawamuna *et al.* (2017); e Servino *et al.* (2018), have been dedicating to those geoenvironments part of their energies in researches that, besides the importance and evolution, are still not enough to explain its complexities.

Generally, developing research in mangroves involves risks given the characteristics of these environments which, in some areas, besides presenting fluctuations in the water level due to tidal dynamics, also makes displacement difficult because of the depth of the sediments and (or) the assorted consistency of the soil. Another factor that imposes difficulties or precludes displacement in these places, is due to the characteristics of some species of vegetation that, due to the adaptation process, have intertwined roots forming sort of a natural fence. (SCHAEFFER-NOVELLI *et al.*, 2016; SCHAEFFER-NOVELLI, 2018a, 2018b).

Therefore, among the least invasive methodologies that can provide various analyses, minimizing risks, reducing displacement costs and optimizing time, Remote Sensing (RS) stands out.

The use of RS and vegetation indexes for understating mangrove forest dynamics has become increasingly frequent between researchers. About that, Kawamuna *et al.* (2017) besides classifying images in order to differentiate mangrove forests from other vegetations of the coastal area of Banyuwangi (governance of the province of East Java, Indonesia) they also applied the NDVI to qualify/categorize their vegetative vigor.

With the same methodology, though aiming to distinguish and understand which is the best procedure to obtain information related to mangrove leaf volume. Tian *et al.* (2017) worked in a 68 km² mangrove forest located in the Guangxi province, in China. As a technique, the authors applied indexes LAI and NDVI on images from both the *Remotely Piloted Aircraft* (RPA) and the satellite WorldView-2.

Apart from those, George *et al.* (2018), in their research in the Bay of Bengal (India) made propositions about the bands and ideal spectral indexes to obtain the LAI of the mangrove vegetation. Thus, when working with hyperspectral images from the Earth observation satellite (EO-1), the authors also applied indexes NDVI and SAVI. In their concluding remarks, they detected that short wave infrared (SWIR) and near- infrared (NIR) bands were the ones that presented the greatest potential to form the LAI index.

Regarding the impact analysis of the extreme weather events in mangrove areas, using remote sensors, attention is drawn to the research developed by Servino *et al.* (2018). To quantify the size of the area affected by a hailstorm that occurred in 2016 in two estuaries in the state of Espírito Santo (Brazil), the authors used historical series from the Landsat-8 satellite and the application of NDVI. Among the results, the authors detected more than 500 ha of mangroves fully destroyed by the storm.

Besides the relevance of the authors, due to the size and importance of these mangrove forests, there is still a demand for a better understanding of the repercussion of the event on the environment. For that, the application of both NDVI and other indexes from sensors capable of providing data in a more detailed scale is genuinely important.

Accordingly, the main objective of this research was to evaluate the efficiency of the NDVI, SAVI and LAI from the MSI sensor of the Sentinel-2 to register the consequences of the extreme weather event that took place in June, 1st, 2016 in the mangroves of the Reserva de Desenvolvmento Sustentável Municipal Piraquê Açu-Mirim, in Aracruz (ES). Reserva de Desenvolvimento Sustentável, is a place of environmental protection with exploitation of natural resources, in a sustainable way, by traditional peoples.

MATERIALS AND METHODS

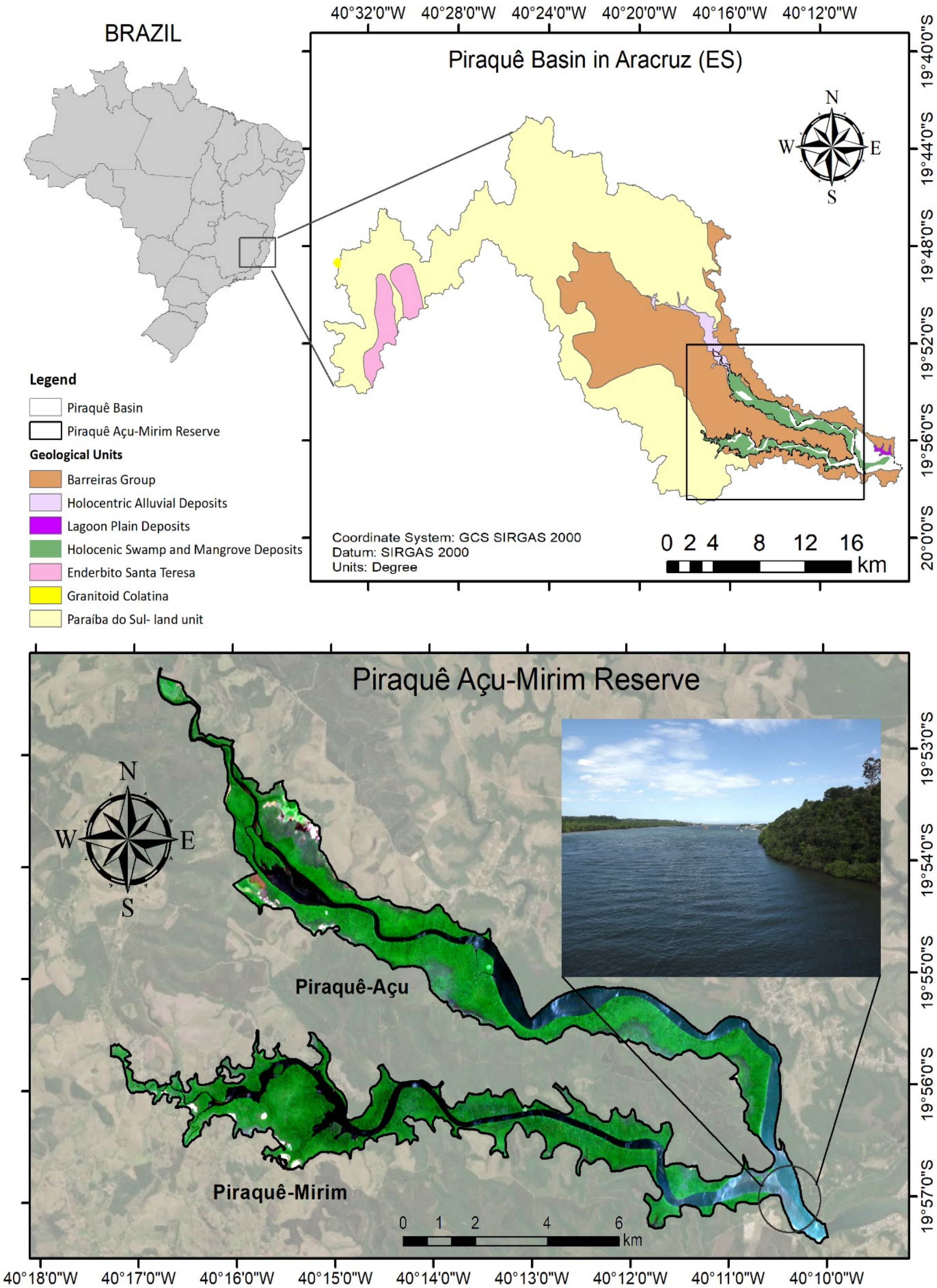
In order to imprint more detailing to the methodological processes of this research, this topic is divided as follows: characterization of the research area; equipment and tools used; source and database; development stages; and methodological procedures.

Characterization of the research area

The researched area is located in the Maritime Ecoregion of Eastern Brazil with two well-defined seasons, so from April to September, it refers to dry winter and from October to March, to wet summer (BERNARDINO *et al.*, 2015).

This specific mangrove forest is, at the same in two estuarine systems that are part of the Reserva de Desenvolvimento Sustentável Municipal Piraquê Açu-Mirim, which comprises a 2079 hectares area in the Municipality of Aracruz (ES), in Southeast Brazil. This Reserve is enclosed in the Piraquê micro basin, having as main rivers the Piraquê Açu and Piraquê Mirim, which when they meet, near the mouth, present a shape analogous to the letter Y (Figure 01). In this location, water depths vary from 4 to 16 meters (LANA; BERNARDINO, 2018).

Figure 01- Study area location.



Source: The authors (2022).

Another characteristic that comprises both estuaries and Reserva de desenvolvimento Sustentável (RDS), is the topographic compartmentation and geological structure. On a scale of 1:250,000 (IBGE, 2019a), the RDS is located in the deposits of Holocene swamps and mangroves, being almost completely surrounded by the Barreiras Group, which was dissected by natural weathering processes.

These processes directly interfere with the drainage of the basin, causing the rivers to get embedded in deep and narrow valleys. Besides, in many areas from the Piraquê-Mirim right river bank, there are rock outcrops and expressive boulder fields due to relief carving.

The use and occupation of the surroundings of the RDSare not much heterogeneous, although there are: destined areas for agriculture with remnants of Atlantic Forest, which are, mostly, part of indigenous reserves; urban constructions, being the major portion composed of plantations of exotic plant species (*Eucalyptus*).

Therefore, it stands out that, from the five mangroves species found in Brazil, three of them can be found on those estuaries, being: *Avicennia schaueriana*; *Laguncularia racemosa*; e *Rhizophora mangle*, where *R. mangle* (red mangrove) has a bigger representativity in the area when compared to the others (SERVINO *et al.*, 2018).

Those species, combined to the rest, are essential for the maintenance of the ecosystem services performed by the mangrove forest, which reverberates locally – as for the native population that depends both from the crab collecting and fishing for supporting their families – and globally and when talking about the marine species that chose this environment as an ideal place to reproduce.

Tools and equipment

Both the acquisition and the data processing were performed using the infrastructure of the Univerdidade Federal de Viçosa (UFV), which is a university located in the city of Viçosa, Minas Gerais - Brazil. All data used on this research were processed and analyzed with the software SNAP and ArcGis™ 10.5.

Source and database

All data used were acquired free of charge from government agencies or institutions linked to them. Thus, all data used were acquired free of charge from government agencies or institutions linked to the *rasters* with the satellite Sentine 2 images, were downloaded from the official website of the Copernicus program, linked to the European Space Agency (ESA). Furthermore, there were used vector files containing the political-administrative limits of the federative units of Brazil and the area related to the RDS studied. The files were acquired, respectively, from the Instituto Brasileiro de Geografia e Estatística (IBGE), which is a public institute of the federal administration, and the Secretaria do Meio Ambiente of Aracruz (ES), which is a department responsible for issues related to the environment.

Phases of Development

In general, the procedures adopted in this study followed a sequence of eight phases developed in the following order:

I. Location of the impacted area from satellite images and time frame definition for data acquisition;
II. Data acquisition for index generation;
III. Application of the Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI) and estimated Leaf Area Index (LAI);
IV. Delimitation of the area of interest and generation of sampling points;
V. Extraction of control point values and graphics generation for impact assessment;
VI. Ground truth;
VII. Preparation and organization of layouts referring to the data generated in the research
VIII. Comparison of processed images from 2016 to 2020

Methodological procedures

With previous knowledge about the weather, events that occurred at the RDS, phase (I) started, using *Google Earth Pro*. From a historical collection of scenes, it was possible to make the time frame of the event, which was based on the visualization of changes in the vegetation cover pattern of the area. Such changes characterized an expressive defoliation and breakage of mangrove vegetation. These procedures were fundamental to perform phase (II), as it enabled the definition of the dates of interest, which were comprised between the years of 2016 and 2020.

Regarding data acquisition (phase II), although there are many images of satellites available for free in the web to the whole Brazilian territory, in coastal regions the availability decreases substantially, due to the constant presence of clouds. This situation makes it more difficult to standardize the dates, because in the open databases it gets difficult to find uncloudy images comprised into the same period in an annual sequence.

Accordingly, after analyzing accurately all the available dates to the place of interest, between the years of 2016 and 2020 and considering both the resolutions and the absence of clouds over the area, the option was to use images from de Sentinel-2 satellite, which, besides having a five-day revisit time, features 12-bit radiometric resolution and 10 m and 20 m spatial resolutions in the bands used.

Therefore, 6 files were selected with the dates: 02/11/2016; 08/09/2016; 01/26/2017; 05/11/2018; 04/21/2019; and 05/10/2020. Among them, the one in February of 2016 represents the area before the occurrence of the weather event that took place in the same year and, thus, serves as a comparative basis for the others.

As for the images acquisition, it is worth to emphasize that they were downloaded in the 1C-Level, that is, they passed through reflectance orthorectification processes on the top of the atmosphere (*Top of Atmosphere*-TOA). In addition, they also went through earth/water and cloud masks. Still about the images, it stands out that the right atmospheric and radiometric corrections were performed using the Sens2Cor package of the SNAP software, in order to improve the products quality, and getting as final product, images in the 2A-Level, where the orthorectifications are in the bottom of the atmosphere (*Bottom of Atmosphere* – BOA).

Once it was done, activities continued to phase (III), which is about generating indexes *Normalized Difference Vegetation Index* (NDVI), *Soil-Adjusted Vegetation Index* (SAVI) and *Leaf Area Index* (LAI). As all indexes are part of the SNAP options package, it was also the choice for generating them. That way, the first to be generated was the NDVI that, among the various radiometric indexes, is one of the most applied in environmental researches. (PEREIRA *et al.* 2018).

Proposed by Rouse *et al.* (1973), NDVI is a graphic indicator which, based on a spectral response, has, besides other functionalities, the capacity to provide information about the vigor of the vegetation. To obtain it, the software divides the result of the difference between the near-infrared (NIR) and the Red bands by the sum of them (Equation 1):

$$NDVI = \frac{NIR-Red}{NIR+Red} \qquad \text{(Equation 1)}$$

In this index, values range from -1 to 1 so that negative values are generally related to surfaces with the presence of water or places with cloud cover, and, positive values but close to 0, indicate that the targets can be either exposed soil or plants with a very low vegetative vigor. Regarding the low vigor indicator, this condition can be the result of both natural processes, related to climatic seasonality (a common situation in deciduous and semi-deciduous plants), as well as others from several causes, such as nutritional deficiencies, pest attacks, anthropic intervention, and climatic abnormalities.

Continuing on the present phase, another graphic indicator related to the vegetation was generated, the SAVI (Equation 2). Proposed by Huete (1988) it differs from the NDVI by incorporating in its mathematical equation, variables with the function to take into consideration places with exposed soil. Thus, when the software processes de equation, it correlates data from the near-infrared (NIR) and red (Red) to a constant (L). The constant serves to adjust the variation of values, which are between 0.25 and 1, depending on the ground cover (BORATO *et al.*, 2013).

$$SAVI = \frac{(1+L)(NIR-Red)}{(L+NIR+Red)} \qquad \text{(Equation 2)}$$

In this matter, 1 indicates low-density forest; 0.5, medium density forest; and 0.25, high-density forest (HUETE, 1988). Therefore, the constant used here had a 0.5 value, as, within the polygonal used to generate the indexes, there are places with both dense vegetation and exposed soil. The acquisition processes of SAVI and NDVI occur through the spectral response of the targets, however, as said, they differ by the variable of exposed soil

Another index used in this research that led to the obtention of spatial information about mangroves reaction to the hailstorm, was the LAI. In general, it is “a biomass indicator for each pixel of the image, therefore constituting a biophysics index which is defined by the ratio of the leaf area of all vegetation per unit of area used by this vegetation” (BORATO *et al.*, 2013, p.7350).

An advantage of this method, from satellite images, is due to the non-destructive factor, so it was not necessary to rip any of the threes’ leaves to estimate the concentrations per unit of measurement. Another advantage when compared to the destructive method is about accessibility as, besides the fact that many threes are tall, which makes it difficult to collect the material (leaves), this procedure involves a set of security measures, bearing in mind that many of those threes are in places with difficult access.

Moreover, the use of satellite images allows covering areas of different sizes in different time periods, thus enabling a broader view of the research object. Accordingly, the use of the LAI in mangrove areas is becoming more frequent, as an example, in the research of Silva (2012); Melo (2017); and Silva *et al.* (2018).

As is the previous indexes, the LAI was obtained from the integrated biophysical process in the *Toolbox of SNAP*. To generate the index, the software uses data both from the angulations (zenith, solar zenith and azimuth) and the eight-band reflectance (B3, B4, B5, B6, B7, B8A, B11 and B12). The whole process arises from neural network algorithms (KGANYAGO *et al.*, 2020; WEISS; BARET, 2016).

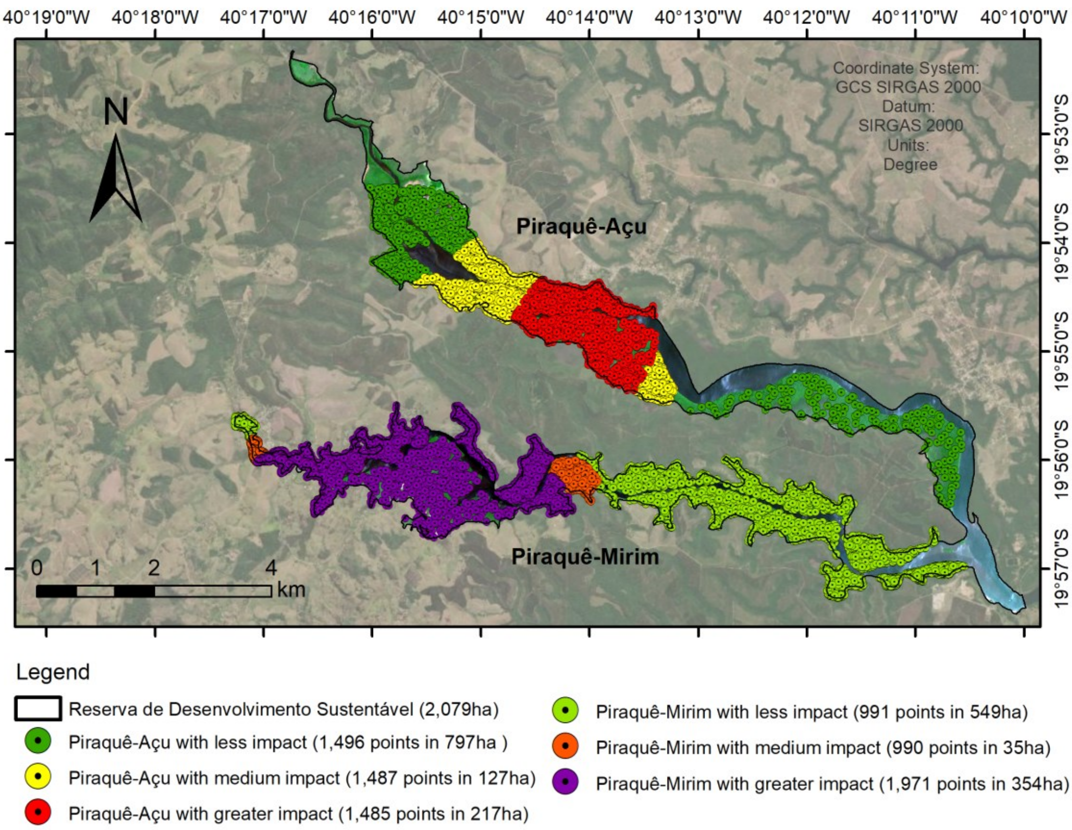
With the generated index, phase IV started. The first procedure, using the ArcGis™ software, was a cutout of the area of interest (RDS). For this purpose, it was used the vector file, made available by the Secretaria Muncipal de Meio Ambiente of Aracruz (ES). Giving sequence, the second procedure performed on this phase, was the delimitation of the areas according to the intensity of the impact. The criterion for that was the comparison between images and the spatial variations of the index values among them. Thus, the best product that better emphasized the variations according to the degree of impact was NDVI of 2017.

As the RDS is composed of two estuaries (Piraquê-Açu e Piraquê-Mirim) and as they had different repercussions about the event, they were analyzed separately and subdivided in major, medium and minor impact. As the subdivisions were made, it began the third procedure of this phase, the generation of sampling points. These, in turn, were randomly generated using the *Create Random Points* tool from the ArcGIS® software.

The criterion for defining the quantity of points for each area was their size as well as the values of spatial variation. Therefore, for each of the impact subdivisions (major, medium and minor) of the Piraquê-Açu, 1,500 points were launched. At the Piraquê-Mirim, the distribution occurred this way: 2,000 points for the area of major impact and 1,000 points for the areas of medium and minor impact. At the end of this procedure, the fourth and last of this phase (IV) started: the elimination of the non-representative points.

For this, the NDVI product from February 2016 was used, which represents the area prior to the occurrence of the event. Basically, sampling points were inserted in this image and their respective pixels values were extracted. With all this data, it was time to eliminate the values correlated to water bodies, that is, negative. Both the number of points, with their distributions according to the areas, and their subdivisions, according to each estuary, can be seen in Figure 02.

Figure 02 - Distribution of sampling points.



Source: The authors (2022).

After phase IV, phase V started, in which, for each generated index, pixel values were extracted, on sampling points, using the *Extract Values to Points* tool from ArcGis™ software. That done, all values were organized in spreadsheets, generating different statistical analysis graphics.

Phase VI to develop this research, aimed mainly to compare data from the remote sensors to ground truth and evaluate both the real state of the mangroves hit by the hailstorm and the capacity of the indexes applied to register the consequences of the impact of the extreme weather event on this environment.

This phase was fundamental to the development of the research, since it enabled a better apprehension and analysis of the consequences of the hailstorm in the mangroves of the two estuaries (Piraquê Açu e Piraquê Mirim). In this regard, with a Garmin 60 Cxs GPS as well as printed maps in different scales, it was established, by planning, an itinerary to recon the RDS and the micro basin that encompasses it.

The path, made by car and with a starting point in the mouth of the rivers, began at Piraquê-Mirim right river bank, circumventing the reserve and returning through the Piraquê-Açu left river bank to the point of departure. During the journey, several stops were made in predefined locations and some others. This field exploration, among other things, allowed to identify the different levels of impacts on the vegetation. These shown to be correlated with the divisions established in phase IV.

Moreover, it was possible to register the state of the mangroves in the impacted areas as well as in the main river mouth (Piraquê Açu). Other registers refer to places with the presence of rock outcrops, boulder fields and representatives of the local microfauna (crab), among others.

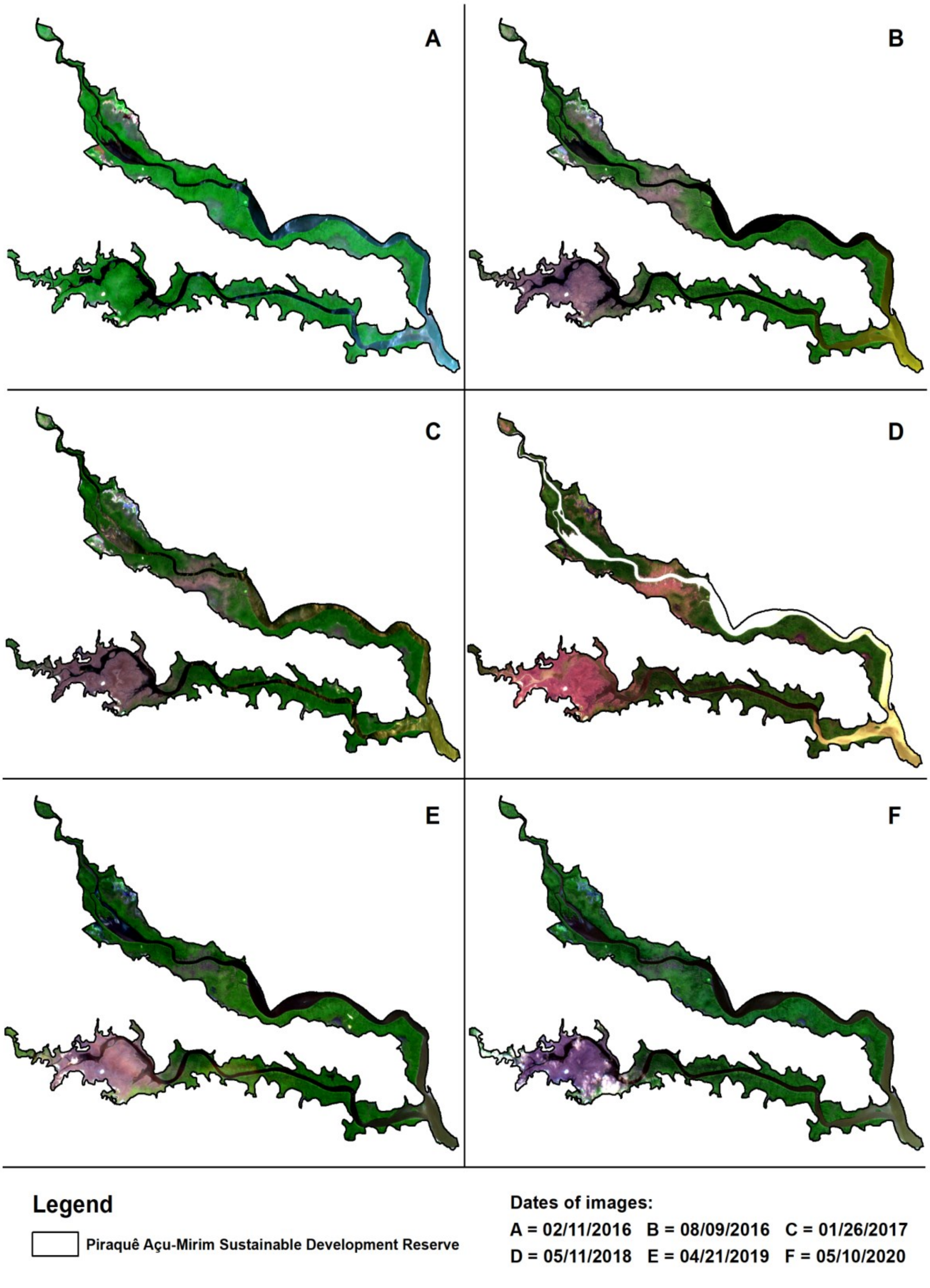
The seventh (VII) research development phase consisted in a compilation of all of the products generated in the previous phases. It was in this phase that the confection and organization of the layouts of the figures, referring to data generated in the research from the index applied in the satellite images and to the different statistical graphics and also to images obtained in the field.

At this phase, the goal was to organize the datakeeping a correlation between the figures presented, that is, for each image data used to generate the indexes and the composition of bands, a letter of the alphabet was assigned. This organization aimed to facilitate the articulation of ideas in the topic referring to the discussion of results. So, for these products, all letters correlate as follows: (A) to the date of February 11th. 2016; (B) on August 2016; (C) on January 26 2017; (D) on May 11, 2018; (E) on April of 2019; and (F) on May 10, 2020.

RESULTS AND DISCUSSION

First, attention is drawn to the images of 02/11/2016 and their respective products, a result from the different indexes applied. As said previously, this image represents the area of the research before the hailstorm, thus, it was used based on the comparison with the others. Additionally, from the three indexes applied for that date, the one which established the biggest correlation with the true color image (Figure 03), about target differentiations, was the NDVI product.

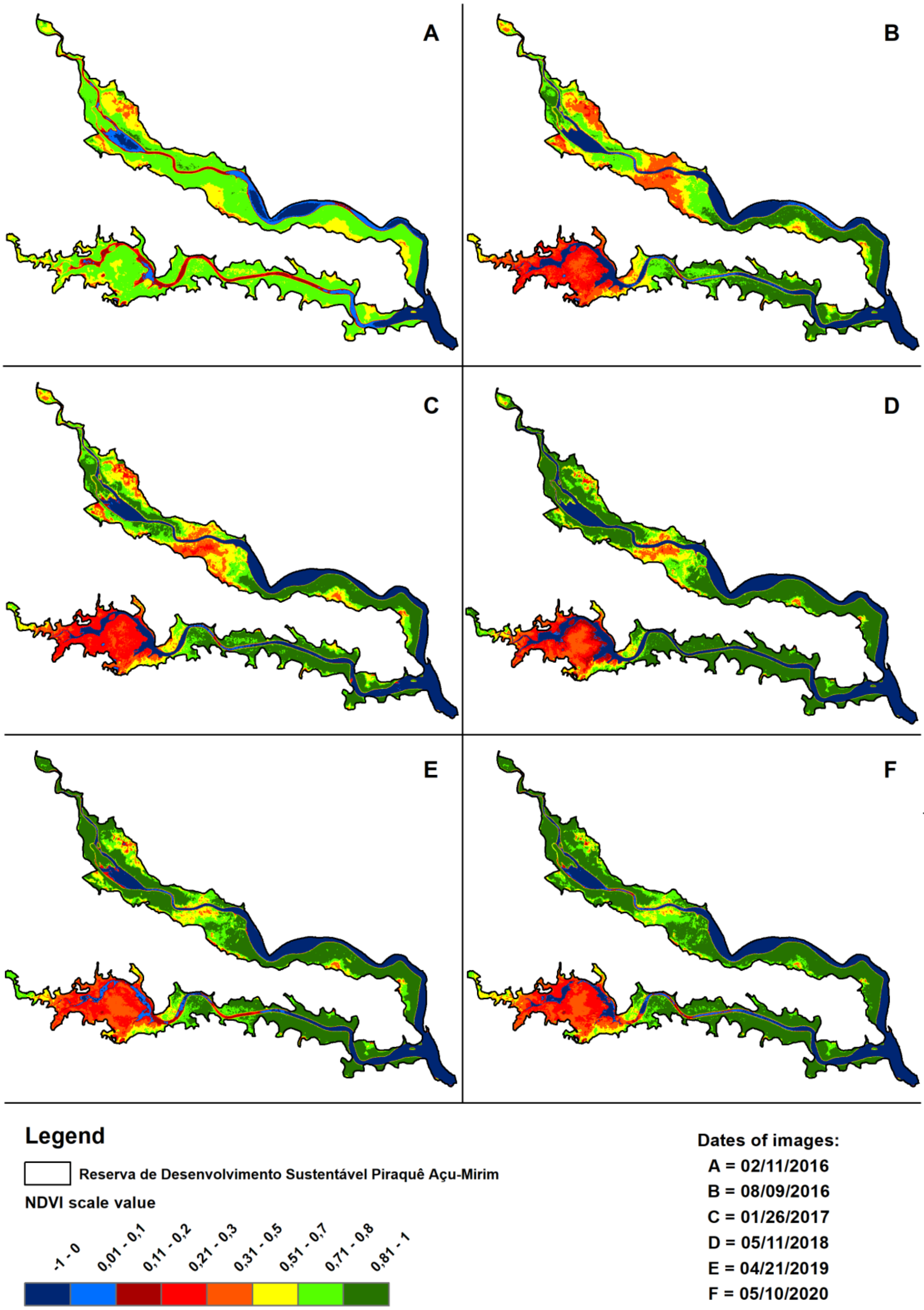
Figure 03 - Composition RGB of the Reserva de Desenvolvimento Sustentável Piraquê Açu-Mirim.



Source: The authors (2022).

Therefore, the targets in blue and red refers to the hydric bodies and sandbanks and the ones in orange, yellow and green are, respectively, exposed soil, pothole vegetation and mangrove forest. Regarding this last component, it is possible to observe in the caption, that its NDVI (Figure 04) values are between 0,71 and 0.8, thus, it can be classified as healthy vegetation.

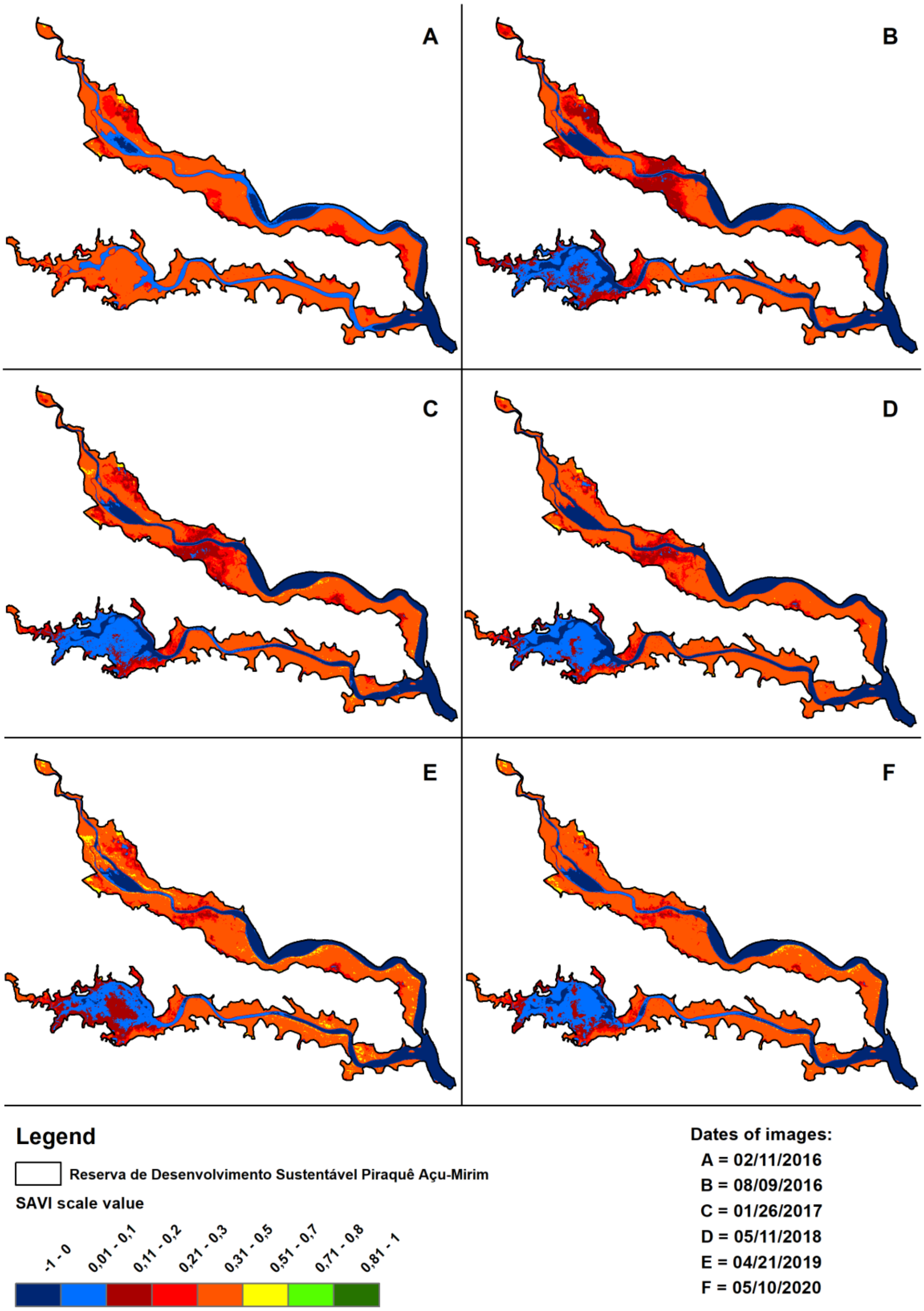
Figure 04 - NDVI of the Reserva de Desenvolvimento Sustentável Piraquê Açu-Mirim for the years 2016 to 2020.



Source: The authors (2022).

Still about the date of 02/11/2016, but analyzing the SAVI (Figure 05-A), it can be seen that, as it includes in its formula a constant value that mitigates the influences of exposed soil, it promoted a generalization of the targets. A generalization that, in some places, masked parts of the pothole vegetation, mainly at Piraquê-Mirim.

Figure 05 – SAVI of the Reserva de Desenvolvimento Sustentável Piraquê Açu-Mirim, for the years 2016 to 2020.

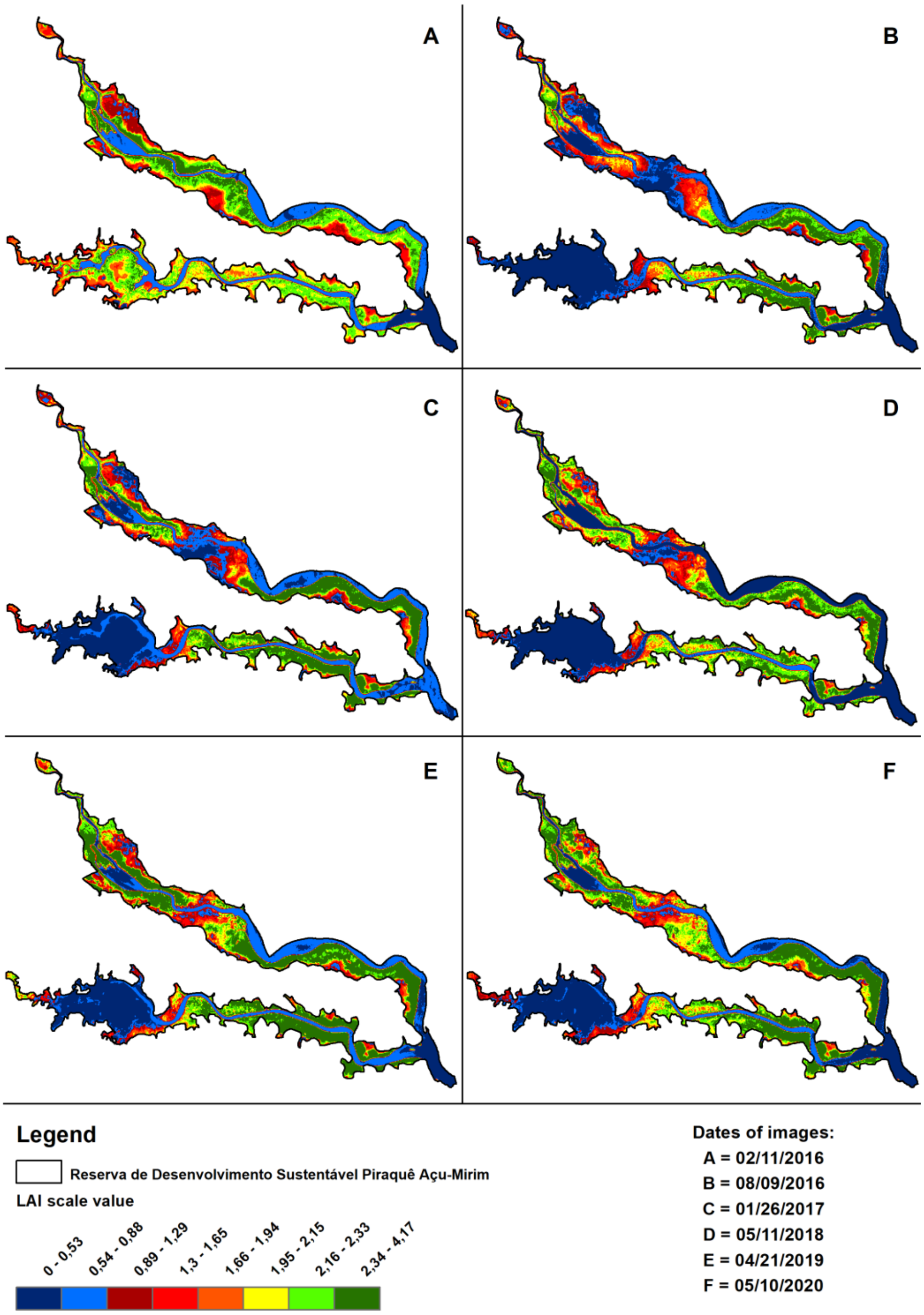


Source: The authors (2022).

This generalization can be avoided by reducing the positive value of the plant health scale, that is, if the -1 to +1 scale is replaced by the -1 to + 0.5 on the map, the classes will not be masked. Nonetheless, this alteration was not made here, since it would preclude a direct comparison among the SAVI index and the NDVI. In this manner, the scale used was the same as the NDVI scale (-1 to +1), as both indexes indicate the vegetative vigor of plants, and their efficiency in mangrove areas was what has been quested.

Regarding the LAI product (Figure 06-A) the correlation between it and the NDVI becomes evident. For that matter, areas that presents little or none foliar biomass presence is precisely the places with pothole vegetations, hydric bodies, sandbanks and exposed soil.

Figure 06 – LAI of the Reserva de Desenvolvimento Sustentável Piraquê Açu-Mirim, for the years2016 to 2020.



Source: The authors (2022).

For the date 08/09/2016, when compared to the true color image (Figure 3-B), all indexes were able to register the changes caused by the hailstorm. These changes can be emphasized by the scale of values for each index and for their statistical data. It is worth mentioning that the SAVI once more promoted generalizations in the image, but it does not impair the use of the index, since the values extracted from the sampling points were capable of register the changes that occurred. Nevertheless, as previously said, in this research the NDVI showed to be much more representative.

When analyzing the products of the generated indexes for the day 01/26/2017, with an exception to SAVI, what can be seen is that the results of LAI and NDVI, but mainly the second one, clearly established a differentiation among the impacted areas in the all of its various degrees. Therefore, using this index, each estuary was divided in minor, medium and major impact areas (Figure 02). The differentiation becomes evident when analyzing the statistical products which, besides showing quantitively the repercussion of the weather event in the RDS, also pointed to the different degrees of resiliency between the mangroves of Piraquê-Mirim and Piraquê-Açu.

Concerning the products of the date 05/11/2018, it is possible to observe a soft change in values. These changes became more evident at Piraquê-Açu and occurred both in areas of medium and major impacts. In general, it can be inferred that the vegetation of the area started a recovery process, which can be better seen in the images of the following years 04/21/2019 and 05/10/2020 where all the indexes were capable of registering the process. About that, is drawn to the differences between the mangroves of Piraquê-Açu (PA) and Piraquê-Mirim (PM).

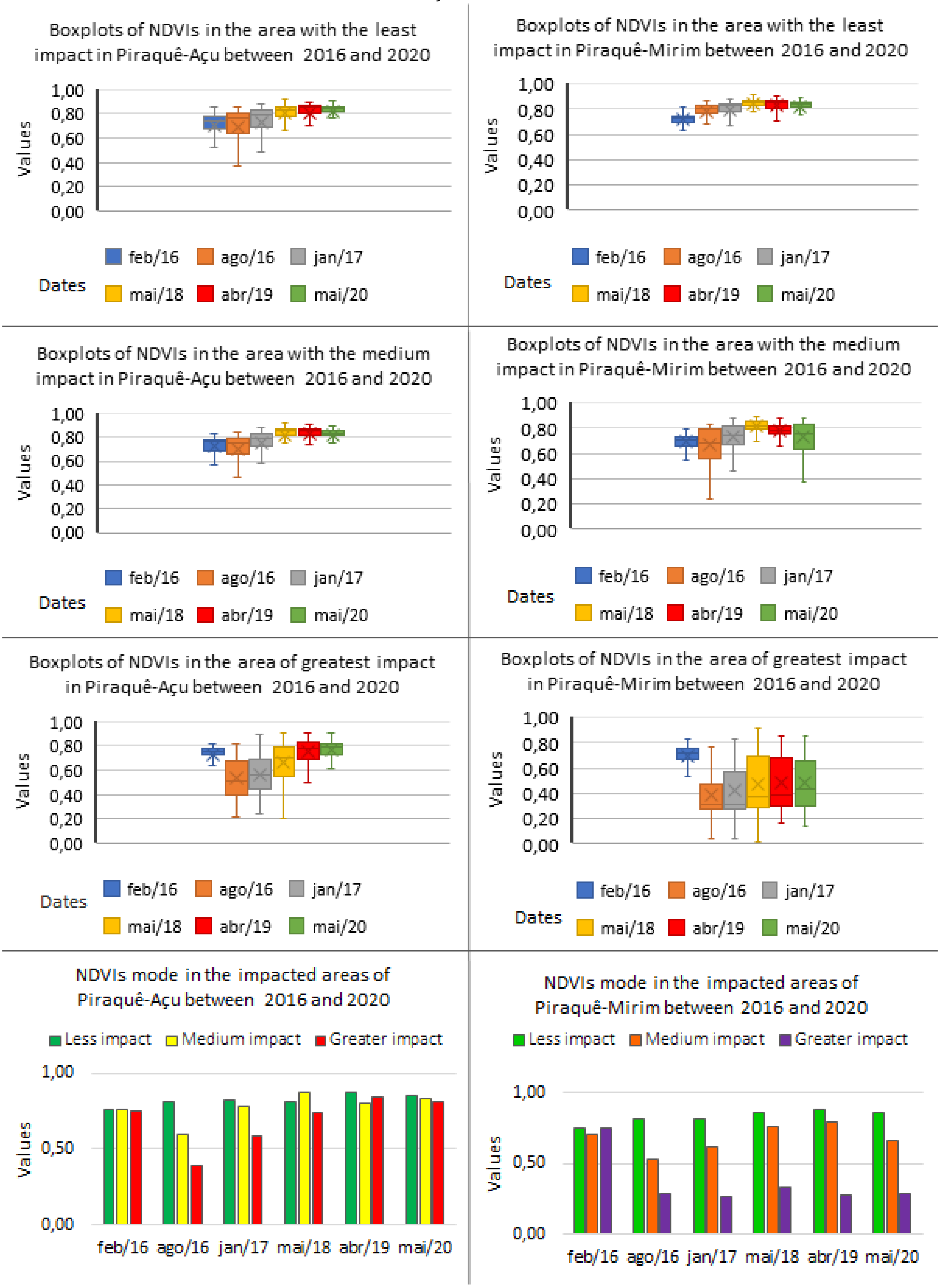
On this matter, taking the NDVI as a base (Figure 04), it can be noted that while in the major impact area of PA, the values from 08/09/2016 onwards went from 0.31 – 0.5 to 0.71 – 0.8 intervals, the same area of PM remained stagnant. The differentiation can also be perceived when observing the images in color (Figure 03) and the graphics for the areas with a different impact rate.

Regarding that, when comparing statistical graphics to the indexes products, it is possible to perceive that in the areas rated as minor impact there were no traces of alterations by the storm. Based on the mode graphics, from each index between 02/11/2016 and 10/05/2020, data showed that, for Piraquê-Açu, the LAI values decreased around 3.5%, the SAVI values decreased 7% and the NDVI values increased 13.5%. Yet, for Piraquê-Açu, the registered values increased, being: 5.5% for LAI; 18.5% for SAVI; 15% for NDVI. Still about the minor impact, when analyzing the NDVI images, there is an impressive increase in the values, indicating an improvement in the mangrove's health within this period.

In the same time frame, but evaluating the classified areas as medium impact, the differences between the estuaries intensify. In the mode graphics for each index, both at the Piraquê-Açu (PA) and in the Piraquê-Mirim (PM) the major decrease in values occurred on 09/08/2016, about two months after the hailstorm. Therefore, the reductions, in the PA, for the LAI, SAVI and NDVI are, respectively, 39%, 26% and 20%, while for the PM, reductions were around 55% in LAI, 40% in SAVI, 25% in NDVI.

Differences on the regeneration capacity of the mangroves, in the medium impact areas and in both estuaries, what the mode graphics show is that, while in Piraquê-Açu, in 2017 the NDVI value had already surpassed what was registered before the event, at Piraquê-Mirim this happened only in 2018. When analyzing the boxplot graphics (Figure 07) in the estuaries for the whole period, it can be noticed a differentiation among the values, showing that, after the hailstorm, at PM the numbers are more spread than at the PA. Despite the differences, when comparing all the products, the recovery of the areas is remarkable.

Figure 07 – Graphs with NDVI statistics for the Reserva de Desenvolvimento Sustentável Piraquê Açu-Mirim

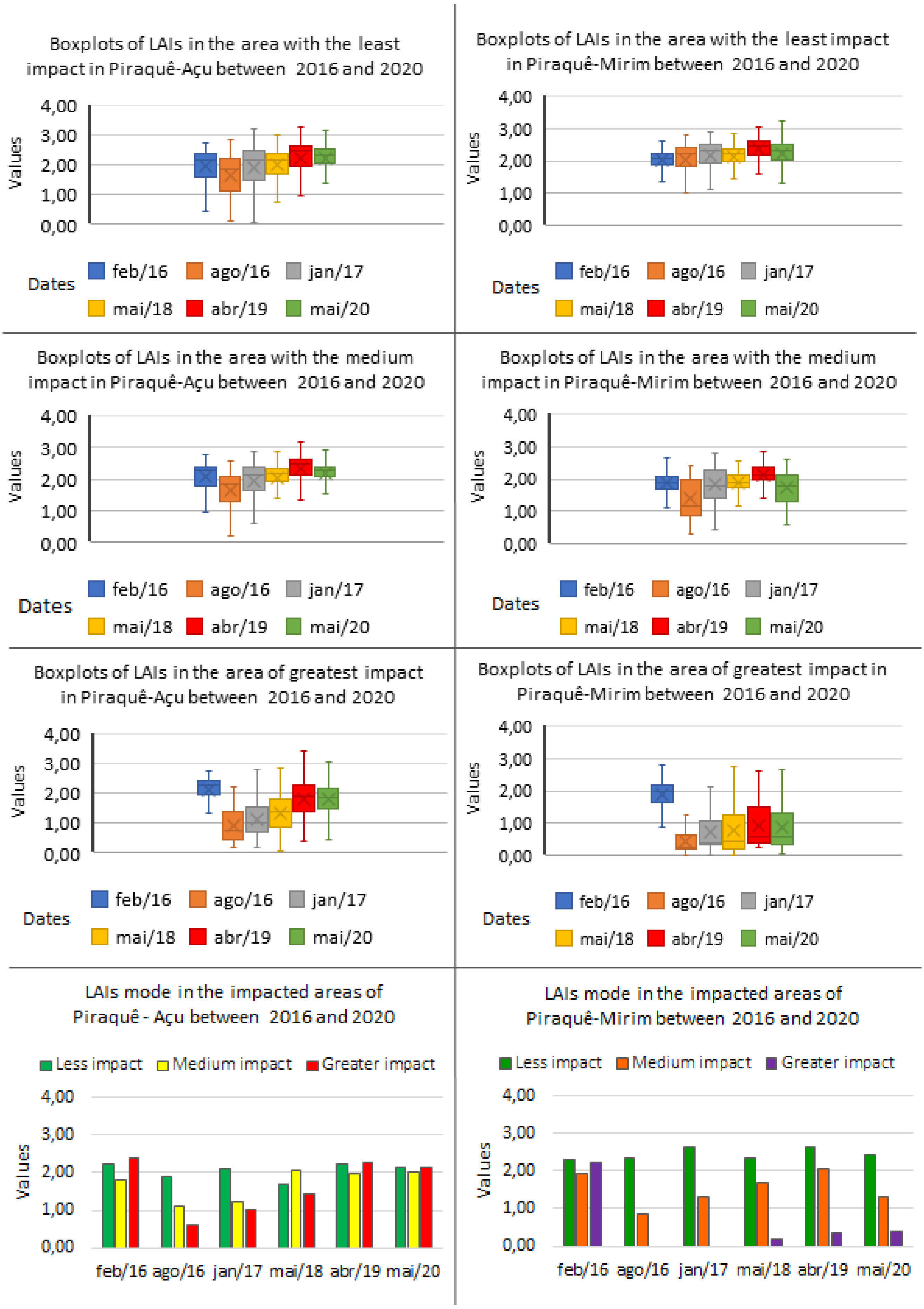


Source: The authors (2022).

The most impacted areas are divided as follows: Piraquê-Açu, of major impact and with over 217 ha; Piraquê-Mirim, of major impact, with 354 ha (Figure 02). As though as in the medium impact areas, the PA also differentiated from the PM in the regeneration process of the mangrove. In the Piraquê-Mirim, despite the fact that the same products have evidenced the impact, the values remained almost unaltered, showing a stagnation as regards to the recovery or regeneration of the mangrove forests.

Concerning the differences, based on the graphics referring to the mode for each index, among 02/11/2016 and 05/10/2020, data showed, for Piraquê-Açu that, while the values of the LAI (Figure 08) decreased by approximately 10.5%, the NDVI recorded an increase of around 8%.

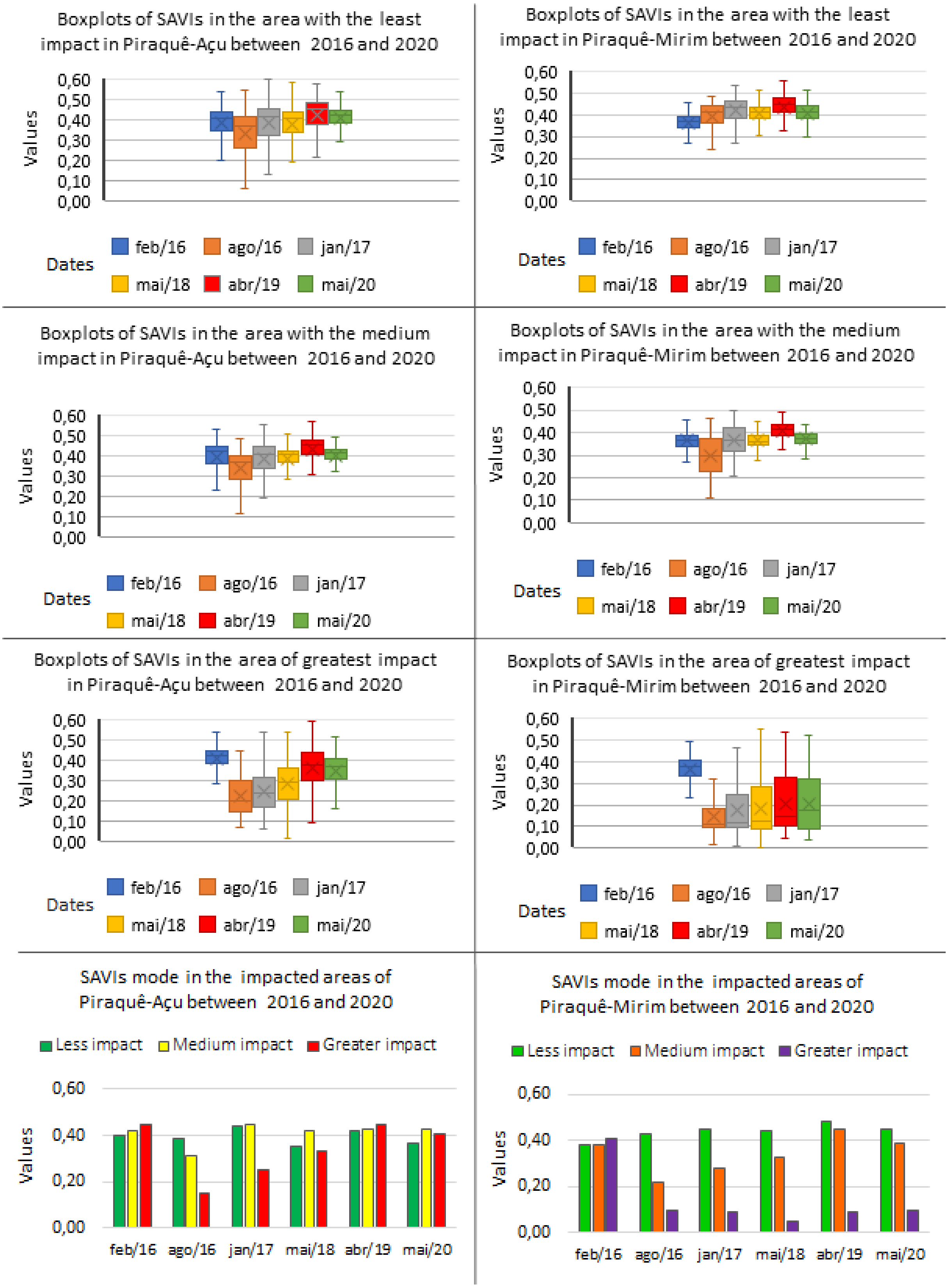
Figure 08 - Graphs with LAI statistics for the Reserva de Desenvolvimento Sustentável Piraquê Açu-Mirim



Source: The authors (2022).

In this same estuary, the SAVI graphs (Figure 09) registered a reduction of values of approximately 8%. In contrast, at Piraquê-Mirim, all indexes registered falls in the mode values with reductions of 83% in the LAI; 75% in the SAVI; 61% in the NDVI.

Figure 09 – Graphs with SAVI statistics for the Reserva de Desenvolvimento Sustentável Piraquê Açu-Mirim.



Source: The authors (2022).

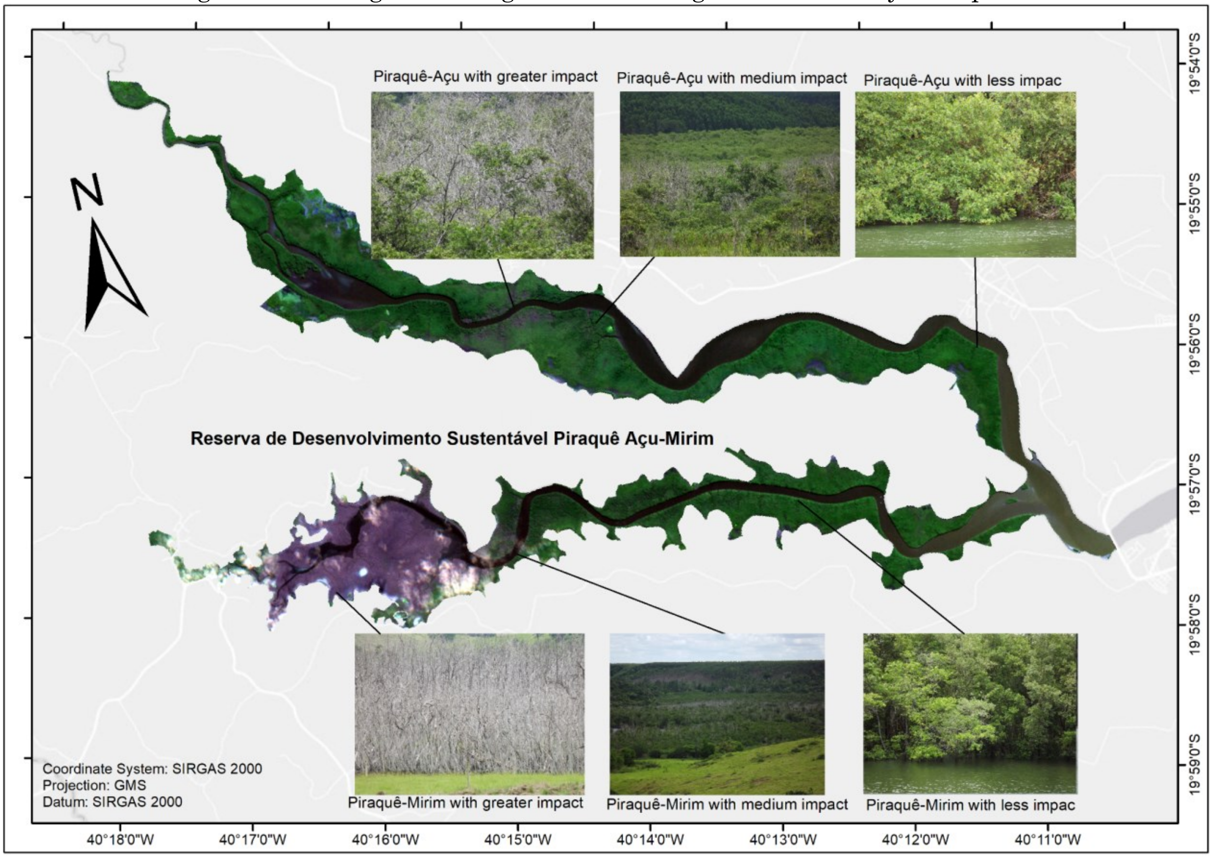
In Piraquê-Açu, since 08/09/2016 (a period of a strong reduction in the medium and average values and a rise in the dispersion due to the hailstorm), there is a gradual increase of the two first statistical parameters and a reduction in the spread.

At the Piraquê-Mirim, as well as the Piraquê-Açu, since 08/09/2020 it also occurs a small raise in the values of the mediums and averages. With respect to spreads, it happens an alternance among reductions and raises but, in general, they still maintain as relatively high. One explanation for the raises is the border effect, where values can be correlated to the points located in the borders of the areas rated as medium impact and which, little by little, are regenerating.

The information generated by the indexes shows a mismatch in the resilience between the Piraquê-Açu and Piraquê-Mirim mangroves, a situation that certainly interferes in the countless ecosystem interactions in this environment. When carefully evaluating this information, it can be noticed some stagnation on the recovery of the Piraquê-Mirim mangrove. Due to this situation and bearing in mind the amount of ecosystem services performed by mangrove forests, a need for an intervention to reverse such a stage arises.

In the field records (Figure 10), it was possible to establish correlations between the results of the indexes and the actual situation of the vegetation at different levels of impact.

Figure 10 – Images of mangroves according to the intensity of impacts.



Source: The authors (2022).

In relation to the records made in the field, it is possible to verify (Figure 11), in addition to the cartographic bases used for the planning of the routes, a little of the local diversity, such as the rock outcrop, the width of the river mouth and one of the places of intense soil bioturbation activity promoted by crabs, one of its agents.

Figure 11 – Ground truth and different landscapes in the study areas.

Source: The authors (2022).

As can be seen, the expedition made it possible to correlate the laboratory results with the field reality, consolidating the effectiveness of the indexes in recording changes in the landscape of this environment.

FINAL CONSIDERATIONS

All indexes were able to register the impact of the hailstorm as well as the reaction capacity of the mangrove to face it. In the mangroves analyzed, SAVI images (Figure 05), despite identifying the impacted places, due to the minimum and maximum values stipulated (-1 to +1), could not register the recovery stages of some areas. Nonetheless, the statistical products (Figure 07) referring to the pixel's values, proved to be effective to perform the registration. Regarding the NDVI and LAI products, besides being efficient to register the weather event, they also demonstrated a complementarity in the evaluation process.

It is claimed that the triggering vegetation mortality happened after the hailstorm, but analyses for medium and long term in an integrated way to the environment are still necessary. This is important not only to understand the dynamics of the studied area, but also to propose processes enabling its planning and managing.

However, both the results and the methodology used in this research proved to be efficient in the analysis of the impact of the hailstorm on the mangroves. The data presented can be useful for projects aimed at recovering the reserve, which is of real socio-cultural, socio-environmental and socio-economic importance.

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AUTHORS' CONTRIBUTION

Marco Antonio Saraiva da Silva conceived the study, processed, organized and analyzed the data, and wrote the text. André Luiz Lopes de Faria, the first author's supervisor, analyzed the data and made corrections and adjustments to the text.