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Multi-temporal analysis of land cover changes due to hurricanes Iota and Eta on the islands of San Andres, Providencia and Santa Catalina

Alejandro Álvarez-Echeverry [a], Luis Jairo Toro-Restrepo [a], July Andrea Suárez-Gómez [a] & Juan David Osorio-Cano [b]

[a] Universidad Nacional de Colombia, Sede Medellín, Facultad de Ciencias Agrarias, Departamento de Ciencias Forestales. Grupo de Teledetección y Manejo Forestal, Medellín, Colombia. alalvarezec@unal.edu.co, ljtoro@unal.edu.co, jasuarezgom@unal.edu.co
[b] Universidad Nacional de Colombia, Sede Caribe, Grupo Estudios Ambientales del Caribe, Archipiélago de San Andrés, Providencia y Santa Catalina, San Andrés Isla, Colombia. jdosori0@unal.edu.co

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Abstract
This study analyzes the how the land cover on the islands of San Andres, Providencia and Santa Catalina, Colombia, was impacted by hurricanes Iota and Eta in 2020. A multitemporal analysis using Sentinel-2 satellite images of the years 2020 and 2021 was conducted to identify changes in land cover and the spectral responses of the NDVI, NDWI, BSI and NBR indices. The results indicate that on Providencia and Santa Catalina the most affected types of land cover were forests, mangroves, secondary vegetation and beaches, particularly in the north and northeast of Providencia and throughout the entire area of Santa Catalina. On San Andres, mangrove forests and grasslands on the eastern and southern coastal edge of the island were the most affected types of cover. This kind of analysis is important to decision makers in coastal land planning because it represents the behavior of land cover in coastal areas in response to disturbances induced by hurricanes, and thus helps us to understand how such extreme natural phenomena influence islands.

Keywords: multi-temporal analysis; hurricane; remote sensing; spectral indices; land cover.

Análisis multitemporal de los cambios en la cobertura terrestre por los huracanes Iota y Eta en las islas de San Andrés, Providencia y Santa Catalina

Resumen
Este estudio analiza el impacto generado en las coberturas terrestres de las islas de San Andrés, Providencia y Santa Catalina, Colombia debido a la influencia de los huracanes Iota y Eta del año 2020. Se emplea un análisis multitemporal a partir de imágenes satelitales Sentinel-2 de los años 2020 y 2021 para identificar cambios en las coberturas terrestres y en las respuestas espectrales de los índices NDVI, NDWI, BSI y NBR. Los resultados indican que en Providencia y Santa Catalina las coberturas más afectadas fueron los bosques, manglares, vegetación secundaria y playas, especialmente en el norte y noreste de Providencia, así como en toda el área de Santa Catalina. En la isla de San Andrés se afectaron principalmente los bosques de manglar y pastos sobre el borde costero del este y sur de la isla. Este tipo de análisis son de gran importancia para los responsables de la planificación territorial costera, ya que permite representar el comportamiento de las coberturas en zonas costeras ante perturbaciones causadas por huracanes, de esta manera, facilita la comprensión del impacto que estos fenómenos naturales extremos tienen en las islas.

Palabras clave: análisis multitemporal; huracanes; sensores remotos; índices espectrales; coberturas terrestres.

1 Introduction

Hurricanes are extreme and dangerous meteorological phenomena that primarily occur in the Caribbean Sea (Fig. 1) between June and November, causing severe damage to both humans and the environment. Hurricanes typically have a significant impact on the distribution and structure of trees [1], altering biodiversity and vegetation in places where

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natural events occur [1]. Between the years 1900 and 2010, 60 hurricanes have been recorded in the Colombian Caribbean, 17 of which impacted the island of San Andres. The most severe hurricanes that caused the greatest damage include Hattie (1961), Alma (1970), Irene (1971), Joan (1988), Katrina (1999) and Beta (2005) [2,3]. Extreme events are more intense and frequent as a result of climate change, as category IV and V hurricanes have doubled since the 60's at distances less than 600 km from the island of San Andres. [4].

Hurricanes Iota and Eta struck Colombia's Caribbean Island territories between November 2 and November 17, 2020, wreaking devastation on the islands of San Andres, Providencia, and Santa Catalina with their strong rainfall, thunderstorms, and mudflows [5]. According to NOAA [6], Hurricane Eta began on October 31, 2020, and dissipated on November 13, reaching category 4 between November 2 and 3 around Puerto Cabezas, Nicaragua, approximately 200 km from Providencia and Santa Catalina and at a distance of 210 km from San Andres. Meanwhile, Hurricane Iota developed on November 13, 2020 and dissipated on November 18, becoming a category 5 hurricane on November 16 about 10 km north of Providencia and Santa Catalina. In Providencia and Santa Catalina, 98% of the infrastructure was destroyed.as a result of the hurricane's torrential rainfall, winds of up to 250 km/h, and flooding [7].

The archipelago suffered severe environmental consequences as a result of hurricanes Iota and Eta. These include a lack of clean drinking water, unhygienic conditions, and a marked decline in both terrestrial and marine ecosystems. 90% of the tropical dry forest was severely damaged, leading to the degradation of the islands' ecological structures. Moreover, there was significant damage to 70% of the mangroves on the islands' northeastern and northern borders [5].

In Colombia, several multi-temporal analyses have been carried out to identify changes in land cover generated by restoration plans and programs [8, 9], mining projects [10-12], and anthropogenic interventions in the Colombian Caribbean [13-18].

In [8], Landsat satellite images from 2003 and 2016 were used in a supervised classification procedure to quantify changes in forested areas after a reforestation program. In the municipality of Madrid, Cundinamarca, an analysis was conducted to identify changes in land cover and use in the "Casablanca" protective forest reserve area [9].

Likewise, multi-temporal analyses have been carried out in areas affected by mining projects to evaluate the impact of mining on vegetation, as demonstrated by [10] in their study of gold mines in the municipality of Manizales. [11] detected changes in the land cover of the Cerromatoso mine between 2011 and 2015. In [12], the extent to which the Ituango hydroelectric project affected vegetation cover and the Cauca River channel between 2009 and 2019 was examined using Sentinel-2 images

Studies have been conducted in the Colombian Caribbean to better understand how land cover has changed and to assess the impacts of various disturbances and improvement initiatives. For instance, in the department of Sucre, human activity has been found to lead to an increase in savannah cover [13]. In the municipality of Manaure, Guajira, land cover analysis was used to identify the expansion of desert areas and the relationship between desert expansion and population growth. [14]. Furthermore, in Uraba Antioquia, the change in land cover caused by flooding and coastal erosion was evaluated using satellite images from 1998 and 2017 [15].

In general, research in the Colombian Caribbean has been conducted to identify changes in mangroves caused by agricultural and animal operations, particularly the shrimp business [16]. Likewise, changes in land cover and soil distribution in areas of high ecological value have been investigated [17]. Finally, in Providencia, a study was conducted to assess deforestation on the island from 2005 to 2009 [18].

It is important to emphasize that while research has examined changes in coverage in the Caribbean region of Colombia, there are few multi-temporal analyses available that help us comprehend how hurricanes and tropical storms affect the islands and territory in this region.

In countries and territories located in the Caribbean Sea, such as the islands of the Dominican Republic and Puerto Rico, multi-temporal analyses have been carried out to identify the impact and assess damage from Hurricane Maria in 2017. These analyses used Landsat-8 and Sentinel-2 satellite images corresponding to the years 2015, 2016 and 2017 [19]. Additionally, [20] examined the connection between the impact of Hurricane Stan in 2005 and the land usage of coffee farms in Chiapas, Mexico by examining Spot images taken 2, 14, and 40 months after the hurricane as well as eight months prior to it.

The islands of San Andres, Providencia, and Santa Catalina suffered detrimental environmental and social repercussions as a result of hurricanes Iota and Eta. There is therefore a need to identify and analyze the changes and possible consequences that these natural phenomena have had on the islands' land cover. New strategies need to be presented to decision makers in order to prevent and mitigate for the environmental impacts caused by hurricanes. Therefore, a multi-temporal analysis was carried out using Sentinel-2 multispectral images to identify the effects that hurricanes have on land cover and determine changes in their spectral responses. The present study aims to: (1) examine the impact of hurricanes Iota and Eta on the land coverage of the islands of Santa Catalina, Providencia, and San Andres; (2) identify the regions most impacted by changes in coverage between 2020 and 2021; and (3) interpret and evaluate the variations in NDVI, NDWI, BSI and NBR spectral indices in the pre- and post-hurricane scenarios.

2 Methodology

2.1 Study area

The Islands of San Andres (SAI), Providencia and Santa Catalina (PSC) are located in the Caribbean Sea and are part of the Colombian insular territory. San Andres has an area of 26.76 km^2, Providencia covers 20.64 km^2, while Santa Catalina, which is next to Providencia, has an area of 1.17 km^2. San Andres is located 637 km northwest of mainland

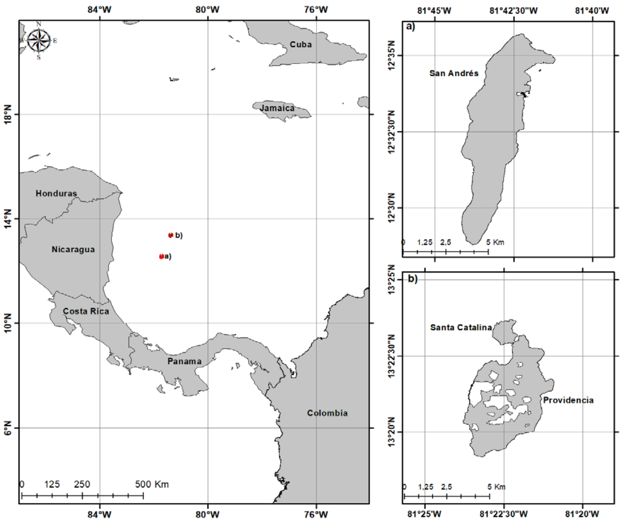

Figure 1. Study area. a) San Andres and b) Providencia and Santa Catalina islands
Source: Authors.

Colombia and 200 km away from Nicaragua, while Providencia and Santa Catalina are located 80 km northwest of San Andrés (see Fig. 1). According to data from the population census of Colombia, in the year 2018 the island of San Andres had a population of 48,299 inhabitants, while Providencia and Santa Catalina had 4,545 inhabitants [21].

2.2 Selection and processing of satellite images

The Sentinel-2 satellite mission belongs to the ESA (European Space Agency) and is well-regarded due to its varied applications, high spatial, temporal, spectral, radiometric resolution, and its easy accessibility. Sentinel-2 satellite images have a spatial resolution between 10 and 20 m, which is considered ideal for the classification of land coverage [22].

The data sets used in this study consist of satellite images obtained and processed on the Google Earth Engine platform. A filter was applied to select image sets with a percentage of clouds less than 10% in order to acquire the lowest possible proportion of cloudiness. A filter by date was also applied to obtain a set of images taken between April and May 2020 and April and May 2021, and thus represent scenarios before and after the hurricanes. These dates were selected based on the availability of images with little cloud cover and were taken at the same times of the year to minimize climate variability.

The high percentage of clouds in the satellite images of Providencia makes it difficult to classify coverage and calculate spectral indices. Therefore, a clipping mask was assigned to remove areas with high cloud cover, which includes a 50-meter buffer around the islands' coastline and the cloud extraction area. A buffer of 50 m above the coastline was applied for the San Andres study area.

2.3 Calculation of spectral indices

The normalized vegetation index (NDVI) was used to determine the amount of surface vegetation and to evaluate the health status of the plants [19], while the Normalized Difference Water Index (NDWI) was used to highlight bodies of water by measuring moisture content. The Bare Soil Index (BSI) was used to determine areas with little vegetation cover or without any vegetation cover, which helped identify degraded areas, beaches and bare soil. The Normalized Burn Ratio (NBR) was used to determine and rule out areas with high degradation or vegetation affected by forest fires [23].

The percentage difference between the values obtained in 2020 and 2021 was calculated (see eq. 1) to determine the locations that exhibited the greatest differences in spectral indices (NDVI, NDWI, BSI and NBR).

$$\left[\frac{Value\ 2021 - Value\ 2020}{Value\ 2020}\right] * 100 \qquad (1)$$

2.4 Classification and comparison of land cover

Land cover was classified and compared by analyzing satellite images from the same area taken at different times [17]. Hence, a multi-temporal analysis was carried out based on supervised classifications and photointerpretation of Sentinel-2 images in settings before and after the passage of hurricanes Iota and Eta. This type of study identifies, analyzes and compares land cover changes induced by anthropogenic and natural events [24].

The Google Earth Engine platform, which geospatially analyzes satellite images stored in the cloud without the need to download them, was utilized to classify land cover. This leveraged the computing power of Google, procedural agility and the variety of analyses [25].

The supervised classification of coverage was carried out using the Support Vector Machine (SVM) classification method, which is a Machine-Learning algorithm that has performed well in different training areas. This allows training areas and classes with similar spectral characteristics to be developed [24]. Analysis is done based on coverage classes, which takes into account the shape, texture, color and roughness of the pixels of the satellite images. The types of coverage used are identified in Table 1.

Table 1.
Types of coverage

Land cover	Description
Forests	Areas with high density of trees and little anthropogenic intervention
Mangrove forests	Mangrove forest area bordering the sea
Secondary vegetation	Areas with high and medium density of vegetation with a succession process
Pastures	Land with grass, weeds and low density of trees with high anthropic intervention
Bare ground	Land surface devoid of vegetation
Urban areas	Continuous and discontinuous urban areas with the presence of homes, buildings, roads, docks
Water bodies	The sea, rivers, dams and other bodies of waters
Beaches	Areas of beaches on coastlines
Degraded areas	Areas with tree vegetation affected and burned by hurricanes and anthropogenic interventions

Source: Authors.

The areas that presented cloudiness were not considered in the classification and were excluded from the analysis and comparison areas. Finally, to reduce error and guarantee greater similarity to what is displayed in the satellite images, manual adjustments to the coverage were made in areas with less coherence.

The accuracy of the coverage results was evaluated using a confusion matrix and the Kappa index to determine agreement and correctness of the coverage validation points [22]. 20 random samples per type of coverage were considered for validation. These points were obtained from the collection of Sentinel-2 satellite images in the same temporalities evaluated.

Changes in land cover were quantified in the pre- and post-hurricane scenarios. The areas corresponding to each type of cover were calculated and changes, whether loss or gain, were analyzed. This comparison of coverage made it possible to identify the areas that experienced significant change and those that remained stable, as well as determine the positive and negative changes in coverage.

3 Results

3.1 Normalized Difference Index (NDVI)

The NDVI for the scenarios between April and May in 2020 and April and May 2021 show the presence of healthy and dense vegetation when the values are close to 1, while areas with less vegetation present lighter tones and lower values. In contrast, the absence of vegetation, indicating a predominance of soils, beaches and grasses, corresponds to values close to 0. Bodies of water, due to their level of absorbance and reflectance, exhibit values lower than 0 and have light gray tones.

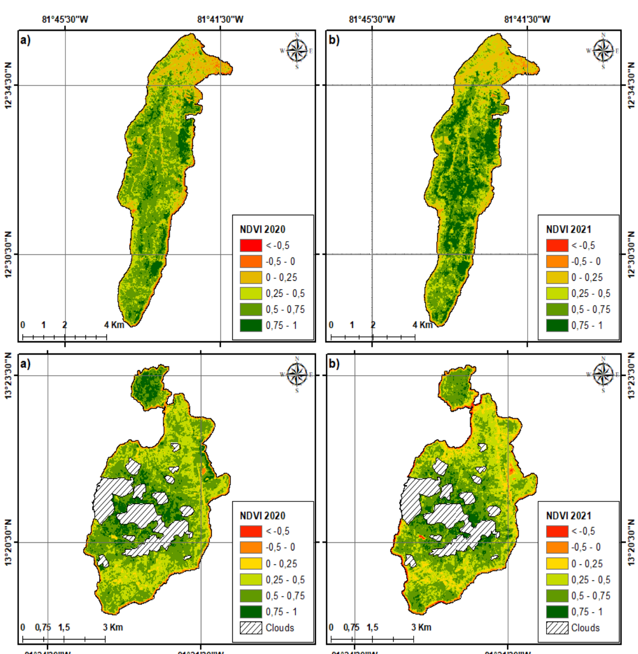

Figure 2. NDVI for the islands of San Andres (lower panel) and Providencia and Santa Catalina (upper panel) for the year a) 2020 and b) 2021.
Source: Authors.

Fig. 2 and Table 2 illustrate the 2020 and 2021 NDVI results in SAI and PSC. For 2020 (Fig. 2a), there are high NDVI values in Santa Catalina and in the northeast, central and southern areas of Providencia. For 2021 (Fig. 2b), the values decrease, especially in strips close to the coastline, and in the northeast of Providencia and Santa Catalina. On the island of San Andres, the NDVI index does not show major variations. Slight decreases are observed in some sectors adjacent to the coastline, particularly in the southwest and northeast of the island.

Fig. 3 presents the NDVI percentage difference (Diff (%)) between the years 2020 and 2021. In the northeast and on the coastal edge of Providencia, negative differences greater than 50% are observed along the coastline and on the border with Santa Catalina. There are negative differences greater than 100% in some strips in the north, northeast and east of Providencia as well as in the entire south of Santa Catalina. In the mangrove forests and the bordering areas between the two islands the index values decrease by up to 100%. The central region of SAI (Fig. 3b) shows a minor increase in the NDVI index (less than 50%), while there is a decrease in the northeast, north, and western coastal edge.

3.2 Normalized Difference Water Index (NDWI)

Fig. 4 and Table 3 show the NDWI values on SAI and PSC for 2020 and 2021. The NDWI index presents values close to 1 for bodies of water and areas with humidity

Table 2.
Results of the NDVI index for San Andres (SAI), Providencia and Santa Catalina (PSC) considering average, standard deviation (STD), minimum (Min) and maximum (Max) values and the mean of the difference (Mean diff).

NDVI	Mean	STD	Min	Max	Mean diff (%)
PSC2020	0.510	0.233	-0.525	0.868	0.000
PSC2021	0.445	0.306	-0.997	0.900	-14.79
SAI 2020	0.471	0.243	-0.268	0.921	0.000
SAI 2021	0.489	0.273	-0.431	0.928	-0.315

Source: Authors.

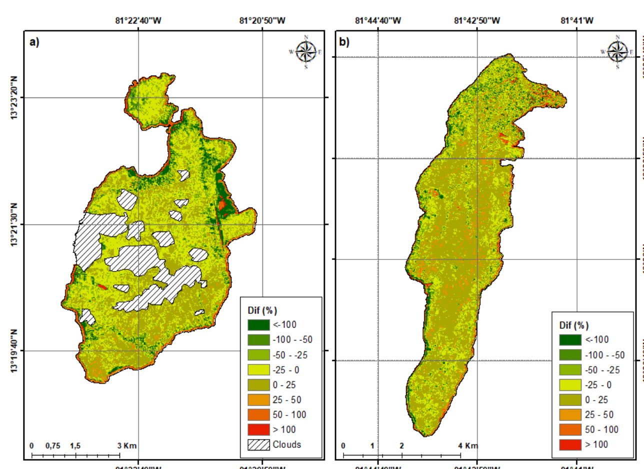

Figure 3. NDVI percentage differences for a) Providencia and Santa Catalina and b) San Andres between the years 2020 and 2021.
Source: Authors.

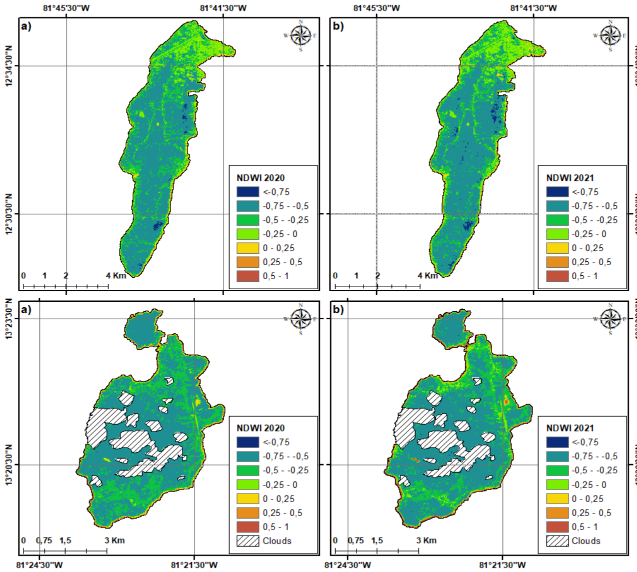

Figure 4. NDWI for the island of San Andres (lower panel) and Providencia and Santa Catalina (upper panel) for the year a) 2020 and b) 2021.
Source: Authors.

Table 3.
Results of the NDWI index for San Andrés (SAI), Providencia and Santa Catalina (PSC) considering average, standard deviation (STD), minimum (Min) and maximum (Max) values and the mean of the difference (Mean diff).

NDWI	Mean	STD	Min	Max	Mean diff (%)
PSC 2020	-0.475	0.240	-0.762	0.729	0.000
PSC 2021	-0.453	0.318	-0.787	0.999	0.695
SAI 2020	-0.445	0.225	-0.821	0.622	0.000
SAI 2021	-0.452	0.254	-0.838	0.604	-8.733

Source: Authors.

saturation, and negative values for dry or waterless areas. The 2020 scenario on PSC (Fig. 4a, upper panel) clearly identifies sea along the entire edge of the islands, as well as in the northeast of Providencia where there is a predominance of mangrove areas. For 2021 (Fig. 4b, upper panel), the index values increase mainly in the northeast and in some strips along the coast of Providencia, but on average there are higher index values in 2020 (see Table 3).

On San Andres, the NDWI does not indicate significant variations in the water masses. There is a slight increase in the index in the northeast and southwest of the island, as these are mangrove areas and have more humid surfaces, as well as in sectors bordering the edge of the island, mainly on the southwestern side. However, on average the index decreased in 2021 (see Table 3).

Fig. 5 shows the NDWI percentage difference between the 2020 and 2021 scenarios. On the island of Providencia, there are negative differences that range between 50% and 100% along the coastal edge and in the northeastern sector, as well as in the southern area and on the coastal edge of Santa Catalina. On the other hand, on San Andres the most significant negative differences are located on the eastern and southern coastal edges and generally in the north of the island, where anthropogenic influence can be seen.

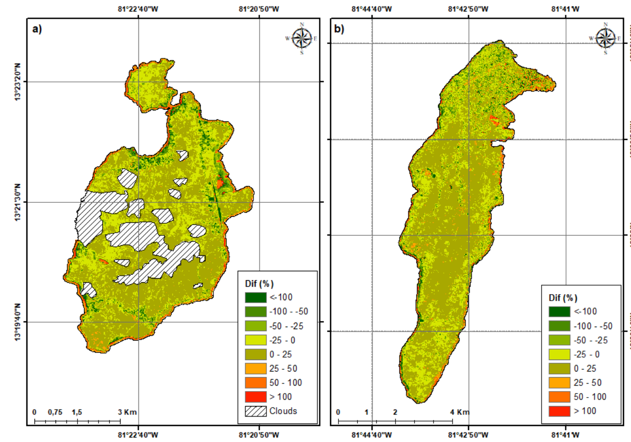

Figure 5. NDWI percentage difference for a) Providencia and Santa Catalina and b) San Andres between the years 2020 and 2021.
Source: Authors.

3.3 *Bare Soil Index (BSI)*

The results of the BSI index are shown in Fig. 6 and Table 4, where values near to 1 represent areas with bare soil or little vegetation. On the island of Providencia, in 2020 the maximum values (Fig. 6a, upper panel) are distributed in urban areas where there has been anthropic intervention. In 2021, (Fig. 6b, upper panel), the BSI increased, especially on Santa Catalina, in the northeast of Providencia and in the strip that connects the two islands.

The BSI values in 2020 on the island of San Andres are higher around the eastern side and lower around the center and southwestern side of the island. On average (see Table 4), the BSI index decreased slightly in 2021, which indicates a decrease in the presence of bare soil or areas of little vegetation.

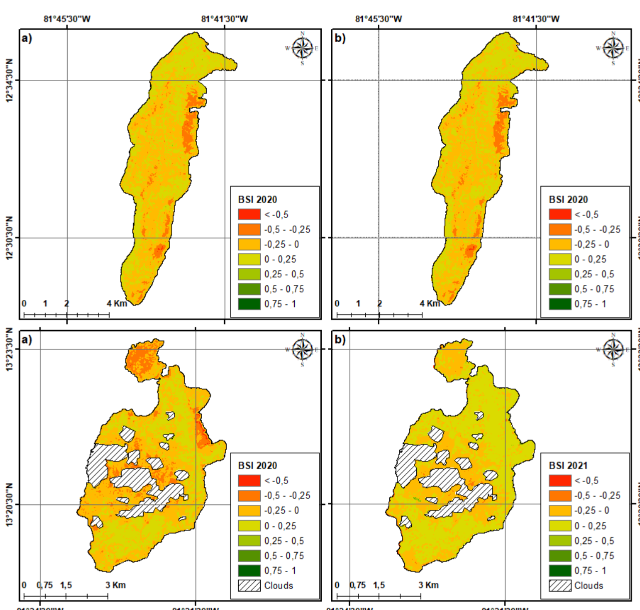

Figure 6. BSI for the islands of San Andres (lower panel) and Providencia and Santa Catalina (upper panel) for the year a) 2020 and b) 2021.
Source: Authors.

Table 4.
Results of the BSI index for San Andres (SAI), Providencia and Santa Catalina (PSC) considering average, standard deviation (STD), minimum (Min) and maximum (Max) values and the mean of the difference (Mean diff).

BSI	Mean	STD	Min	Max	Mean diff (%)
PSC 2020	-0.070	0.135	-0.540	0.219	0.000
PSC 2021	0.014	0.112	-0.825	0.569	42.62
SAI 2020	-0.040	0.126	-0.549	0.301	0.000
SAI 2021	-0.069	0.139	-0.516	0.270	22.79

Source: Authors.

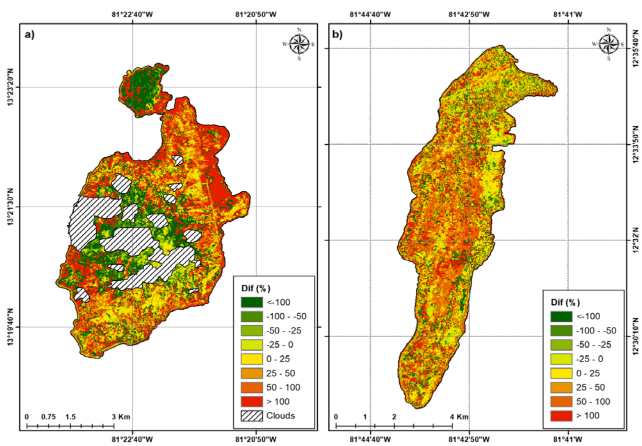

Figure 7. BSI percentage difference for a) Providencia and Santa Catalina and b) San Andres between the years 2020 and 2021.
Source: Authors.

Fig. 7 presents the BSI percentage difference between 2020 and 2021. On Providencia, the greatest variations occur along the coastal edge and in the northeast of the island. On Santa Catalina there are negative variations > 50% over almost the entire area. On San Andres, the greatest negative variations occur on the western edge and center of the island, and to a lesser extent on the eastern side.

3.4 *Normalized Burn Ratio (NBR)*

The results of the NBR index are shown in Fig. 8 and Table 5, where negative values represent areas degraded by fires and positive values represent healthy vegetation. On the island of Providencia, in 2020 the negative values (Fig. 8a, upper panel) are distributed in some small areas on the island. In 2021, (Fig. 8b, upper panel), the NBR decreased, on average over the entire island but maintaining positive values.

The NBR values in 2020 on the island of San Andres are negative especially in urban areas and some small areas of vegetation. On average (see Table 5), the BSI index decreased slightly in 2021 but maintaining mostly positive values. Fig. 9 presents the NBR percentage difference between 2020 and 2021. On Providencia and Santa Catalina, the greatest variations occur along the coastal edge and in the northeast, north and southwest of the island. On San Andres, the greatest variations occur along the coastal edge. On none of the islands there are representative areas that indicate influence by forest fires.

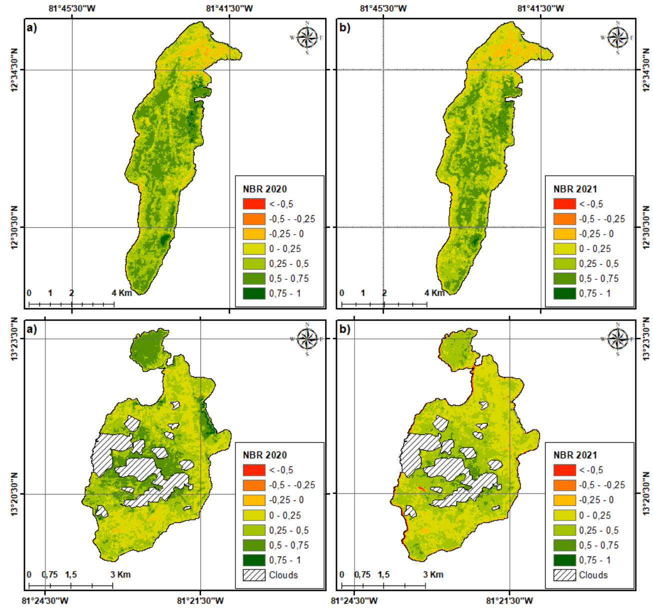

Figure 8. NBR for the islands of San Andres (lower panel) and Providencia and Santa Catalina (upper panel) for the year a) 2020 and b) 2021.
Source: Authors.

Table 5.
Results of the NBR index for San Andres (SAI), Providencia and Santa Catalina (PSC) considering average, standard deviation (STD), minimum (Min) and maximum (Max) values and the mean of the difference (Mean diff).

NBR	Mean	STD	Min	Max	Mean diff (%)
PSC 2020	0.337	0.180	-0.259	0.830	0.000
PSC 2021	0.240	0.211	-0.991	0.763	-33.018
SAI 2020	0.370	0.212	-0.482	0.823	0.000
SAI 2021	0.321	0.214	-0.347	0.805	-18.787

Source: Authors.

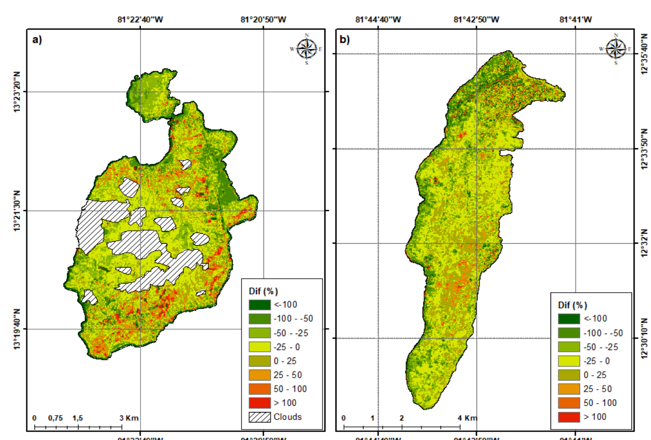

Figure 9. NBR percentage difference for a) Providencia and Santa Catalina and b) San Andres between the years 2020 and 2021. Source: Authors.

3.5 *Coverage classification*

Fig. 10 illustrates the coverage classification for Providencia and Santa Catalina for the 2020 scenario (Fig. 10a). It can be observed that on Santa Catalina there is a

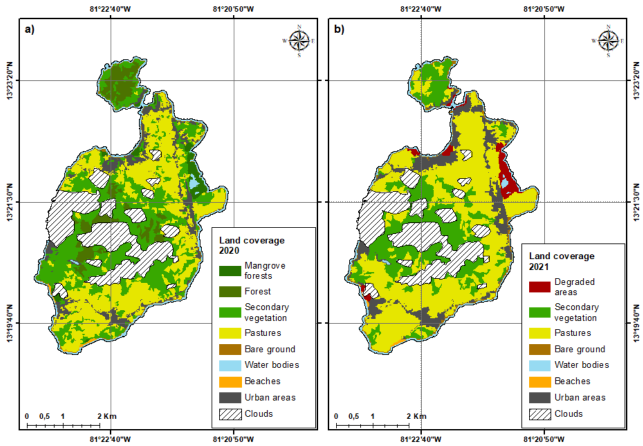

Figure 10. Land coverage classification of Providencia and Santa Catalina for a) before the hurricanes (year 2020) and b) after the hurricanes (year 2021).
Source: Authors.

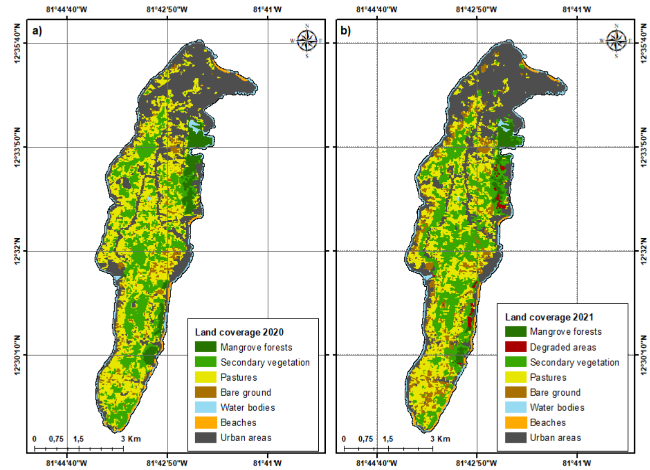

Figure 11. Land coverage on San Andres a) before the hurricanes (year 2020) and b) after the hurricanes (year 2021).
Source: Authors.

greater proportion of forests and pastures. On Providencia, there are mangrove forests in the northeast of the island and along the coastline. There are also patches of forests in the central area of both islands. Pastures and secondary vegetation are also present throughout the islands, mainly close to urban areas. There are small patches of bare soil along the littoral edge of the islands. In the southern of Providencia, pastures are more representative.

In 2021 (Fig. 10b), there is a decrease in forest coverage on the island of Santa Catalina. On Providencia, pastures and urban areas increase while mangrove forests and secondary vegetation decrease. In the southern part of Providencia, beach coverage decreases. Urban areas are seen to increase throughout the island. New coverage is mainly associated with mangrove forests that have been degraded by hurricanes.

Table 6 presents a map of land coverage and changes in coverage from 2020 to 2021. It can be observed that in 2021 the forests and mangroves from 2020 are no longer there. Moreover, secondary vegetation decreased by 31.22%, bodies of water by 8.03% and beaches by 9.65%. In contrast, pastures, bare land and urban areas increased by 41.10%, 24.22% and 36.48%, respectively. In 2021, the degraded areas had an estimated area of 56.82 ha.

Table 6.
Area according to type of coverage for Providencia and Santa Catalina (PSC) for 2020 and 2021.

Coverage	PSC 2020 (ha)	PSC 2021 (ha)	Difference (%)
Forest	144.15	0.00	-100.00
Mangrove forests	46.59	0.00	-100.00
Secondary vegetation	671.96	462.19	-31.22
Pastures	694.17	979.47	41.10
Bare ground	34.19	42.48	24.22
Urban areas	166.91	227.79	36.48
Water bodies	130.17	119.72	-8.03
Beaches	3.31	2.99	-9.65
Degraded areas	0.00	56.82	100.00
Total	1891.46	1891.46	0.00

Source: Authors.

Fig 11. classifies the coverage on the island of San Andres. In the 2020 image (Fig. 11a), mangrove forests predominate in the eastern fringe and along some coastal edges of the island. Urban areas are concentrated mainly in the north and along the main road and coastal border. Secondary vegetation, grasses and bare soils are distributed throughout the center, while the beaches are distributed along the coastal edge. Also, water bodies can be observed in the northeastern area in the mangroves and at a small point in the middle of the island called "Big Pond".

Fig. 11b classifies the land coverage in 2021, where a significant decrease in mangrove forest can be observed throughout the entire island. Secondary vegetation and bare land visibly increase on the island, while there are small variations in pastures, urban areas, water bodies and beaches. Likewise, new coverage associated with areas degraded by the passage of hurricane Eta and Iota can be identified.

Land coverage areas and changes in 2020 and 2021 are presented in Table 7. There is a significant increase in bare land of about 48.1%, followed by secondary vegetation (8.75%), beaches (8.35%), and water bodies (7.37%). On the other hand, mangrove forests decrease by 56.68% and pastures decrease by 19.81%. The degraded areas cover an area of 21.27 ha.

Table 7.
Area by type of coverage on San Andres for 2020 and 2021.

Coverage	SAI 2020 (ha)	SAI 2021 (ha)	Difference (%)
Mangrove forests	140.33	89.57	-56.68
Secondary vegetation	634.23	695.02	8.75
Pastures	944.41	788.25	-19.81
Bare ground	119.29	229.99	48.13
Urban fabric	862.26	862.59	0.04
Water bodies	155.65	168.04	7.37
Beaches	15.76	17.19	8.35
Degraded areas	0.00	21.27	100.00
Total	2871.93	2871.93	0.00

Source: Authors.

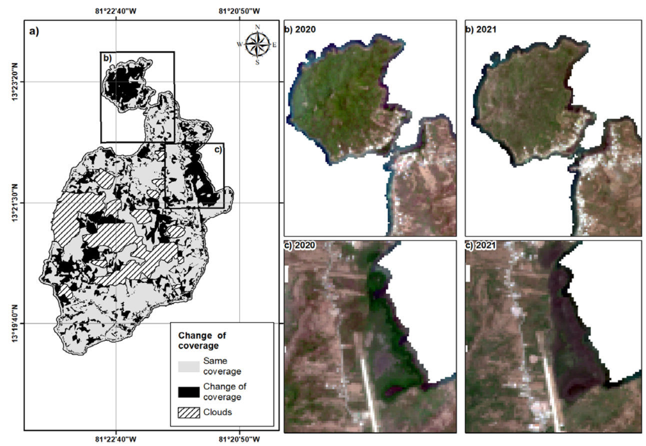

Figure 12. a) Coverage changes between 2020 and 2021 in Providencia and Santa Catalina and b) Santa Catalina and north of Providencia c) airport and mangrove areas.
Source: Authors.

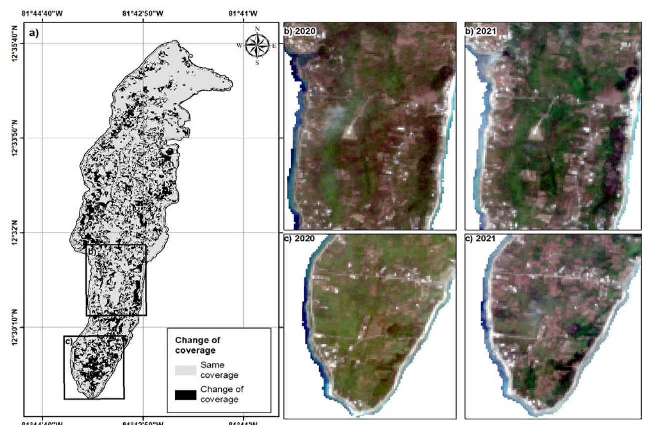

Figure 13. Coverage changes between 2020 and 2021 a) on San Andres as a whole, b) in the south of San Andres, and c) in the zone of The Cove in San Andres.
Source: Authors.

3.6 Change in coverage

On Providencia and Santa Catalina there was a significant change in land cover between 2020 and 2021 (see Fig. 12). The areas of Providencia that saw the biggest changes were in the island's northeast, mangrove region, and east. Changes can be seen throughout the entire island of Santa Catalina. Fig. 12 shows Sentinel-2 satellite images from 2020 and 2021 for a better illustration of the results.

Fig. 13 shows the coverage changes on San Andres between 2020 and 2021. The most significant changes occur along the coast, particularly in the south, southeast, and southwest of the island.

3.7 *Accuracy of coverage classification*

In order to evaluate the accuracy of the coverage classification, a confusion matrix was generated to calculate the Kappa index (K). Coverages with K values > 0.8 are considered to have a high level of success, while K values between 0.8 and 0.4 are at an intermediate level and K values < 0.4 correspond to a low level of success [20, 26]. The coverage of San Andres shows higher K values than Providencia and Santa Catalina. For San Andres, the Kappa indices in 2020 and 2021 were 0.89 and 0.93 respectively, while for Providencia and Santa Catalina they were 0.84 and 0.93 respectively.

4 Discussion

Spectral indices based on the analysis of multispectral satellite images play a fundamental role in the evaluation and monitoring of vegetation, since they allow the vigor of vegetation to be quantified and changes in the study area to be estimated [27]. Since each index has a different spectral response, the NDVI, NDWI, BSI and NBR indices were used to identify the state and type of land cover before and after the passing of hurricanes Iota and Eta. The NDVI helps identify the state and biomass of the vegetation, the NDWI illustrates water bodies and areas with high water saturation, especially in forests near the sea, the BSI shows areas with bare soil or low vegetation density, and the NBR is used to identify and rule out areas influences by forest fires.

The similar behavior in the spectral responses of the three indices showed that the northeast of San Andres and the island's western shoreline experienced the most significant changes. In Providencia, significant changes are observed in the east, near the airport and in the mangrove forests, as well as along the coastal edge. In Santa Catalina, most changes were observed along the coastline and in the western strip of the island. The variations shown by the indices occurred mainly in areas characteristic of mangrove forests and in areas with greater susceptibility to flooding by hurricanes, as reported by [28, 29]. Likewise, the increase in salinity in forested areas and estuarine wetlands may mean they are more sensitive to disturbances caused by hurricanes [30].

Spectral responses for Providencia and Santa Catalina presented more significant changes and variations than San Andres. This was expected and is strongly linked to the proximity that these islands had to the passage of Hurricane Iota. On the island of Puerto Rico, an inverse correlation was found between the distance to the track of Hurricane Maria and the negative variations of the NDVI [19]. This means that the smaller the distance between the island and the passage of the hurricane, the greater the impact on the land coverage.

The NDVI for Providencia decreased by more than 50% around the mangrove forests and on the coastal edge. On Santa Catalina, the NDVI differences occurred on the coastline and in the west of the island. The greatest decreases on San Andres occurred along the western coastline and in strips of mangrove areas located in the northeast of the island. Similarly, other studies have reported a decrease in NDVI for mangrove forests and wetlands after the passage of hurricanes [19, 20]. In Alabama, after Hurricane Katrina (2005), there was a NDVI decrease of about 50% between May and September 2005 [30]. A factor that can cause low NDVI index values in post-hurricane settings is the presence of large amounts of marine litter. Deposits of wreckage from homes and dead vegetation from defoliation and uprooting.

generate a large accumulation of debris and waste, as occurred in Providencia and Santa Catalina [31].

The NBR index helps identify vegetation affected by forest fires after hurricanes [23]. However, the index values after Eta and Iota do not indicate areas affected by forest fires on the islands. instead, the significant decreases in index values are more closely related to the loss of plant heald.

The areas of natural coverage on the islands of Providencia and Santa Catalina decreased more than on San Andres due to the passage of hurricanes Eta and Iota. Most changes involve a transition from forested areas with a high vegetation density to pastures, bare soil and degraded areas. Similar changes (reduction of individual trees, stems, area and basal height) occurred in Providencia after the passage of hurricane Beta in 2005 [32] as well as in the Dominican Republic and Puerto Rico after the passage of Hurricane Maria [19].

It is crucial to emphasize that despite its spectral properties, crop cover can be mistaken for secondary vegetation and woods. Due to crop exposure and potential changes in cover, these agricultural areas are also extremely vulnerable [20].

On San Andres, there was less variation in the coverage of water bodies, secondary vegetation, beaches and urban areas from 2020 to 2021. Likewise, water bodies and urban areas did not present notable changes on Providencia and Santa Catalina either. However, beaches were more significantly affected on Providencia, especially one located in the south (Manzanillo beach), losing 9.65% of its area between 2020 and 2021. Similarly, some beaches on Providencia were also eroded and decreased in area with the passage of Hurricane Beta in 2005 [33].

In some small areas of the islands of San Andres and Providencia, darker tones were presented close to urban areas. This mainly indicates an increase in density of grasses, bare soil and secondary vegetation, or a greater density of vegetation and individual trees. Such changes may be due to anthropic agricultural activities which have been developed on the islands in a traditional way to counteract economic difficulties caused by hurricanes and as a management alternative to mitigate the effects of climate change [34].

Accurately classifying cover is a significant challenge as the type of cover and the spectral differences present in satellite images may be confused, especially when considering meteorological conditions such as the presence of clouds. Furthermore, the use of satellite images with a spatial resolution of 20 meters can generate errors when training the algorithm to generate the correct classification of coverage. For these reasons, it is crucial to evaluate the quality of the output and its agreement with reality using methods that measure accuracy, such as the confusion matrix and the Kappa index.

5 Conclusions

In this work, a methodology of multitemporal analysis of land cover and spectral indices was developed. The natural covers in Providencia y Santa Catalina were significantly affected by hurricanes Iota and Eta, compared to San Andres between April and May of 2020 and 2021.

For future studies, we recommend exploring the evolution of the vegetation covers affected on the islands after the hurricanes, and using of multitemporal analyzes at different spectral and temporal scales.

Finally, it is worth emphasizing that this form of geospatial analysis is critical. Based on the findings of these studies and the identification of hurricane-prone areas, decision makers can focus their territorial planning efforts in ways that most effectively reduce the impact of such hazards,

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A. Álvarez-Echeverry, received his BSc. Eng in Environmental Engineering in 2021, and Sp. in Geographic Information Systems in 2023, both from the Universidad Nacional de Colombia, Medellin campus. He has worked in the application of remote sensors and GIS in development and research projects.
ORCID: 0009-0003-4889-2327

J.A. Suárez-Gómez, obtained her BSc. Eng in Forest Engineering in 2010, and MSc in Environment and Development in 2014, both from the Universidad Nacional de Colombia, Medellin campus. Her expertise is in the application of remote sensing and GIS to territorial and urban planning, landscape ecology and restoration. She has been a part-time professor at the School of Agricultural Sciences at the Universidad Nacional de Colombia, Medellín since 2016. She is a member of the Remote Sensing and Forest Management Research Group
ORCID: 0000-0002-6848-043X

L.J. Toro-Restrepo, obtained his BSc. Eng. in Forest Engineering in 1992, and MSc. degree in Geomorphology and Soils in 2000, both from the Universidad Nacional de Colombia, Medellín campus. He received his PhD degree in Forestry Sciences and Natural Resource Engineering from the Universidad de Córdoba in 2011. As an associate professor at the School of Agricultural Sciences at Universidad Nacional de Colombia, Medellín, he leads the Remote Sensing and Forest Management Research Group.
ORCID: 0000-0002-3049-692X

J.D. Osorio-Cano, obtained his Bsc. Eng in Civil Engineering in 2005, Msc. in Engineering - Hydraulic Resources in 2010, and his PhD in Marine Science in 2017, all from Universidad Nacional de Colombia, Medellín campus. His area of interest is coastal engineering, oceanography, coastal ecosystems and hydrodynamics. He is a professor at the Universidad Nacional de Colombia, Caribe, and he belongs to the Caribbean Environmental Studies Research Group.
ORCID: 0000-0002-5324-7790