Ocean and Coastal Research

BRIEF COMMUNICATION

http://doi.org/10.1590/2675-2824072.23171
ISSN 2675-2824

Spatiotemporal analysis of mangrove vegetation in a protected area using spectral indices

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Abstract

Mangrove is an important transitional ecosystem between terrestrial and marine environments, with a typical vegetation (mangrove) that tolerates the intense variation of salinity coming from the tides. The application of remote sensing techniques based on spectral indices enables the development of spatiotemporal monitoring of this vegetation, thus subsidizing ecosystem management. This study aimed to evaluate the spatiotemporal analysis of mangrove vegetation in RESEX Acaú-Goiana based on spectral indices. The study area was the mangrove in RESEX Acaú-Goiana, a protected area of sustainable use in northeastern Brazil between the states of Pernambuco and Paraíba. Images from the TM/ Landsat 5 and OLI/Landsat 8 sensors from 1992, 2006, 2010, and 2019 were used and the normalized difference vegetation (NDVI), normalized difference water (NDWI), and modular mangrove recognition indices were applied. NDVI varied from 0.5 to > 0.75; NDWI, from 0.25 to 0.75; and MMRI, from −0.6 and −0.3. 2019 showed the lowest average of these indices. The evolution of the establishment of carciniculture (shrimp farming) nurseries in the inner portion of the reserve becomes evident, which may result in environmental damage to the ecosystem. Results will serve as input for developing monitoring strategies and managing the reserve.

Keywords: Coastal ecosystem, Remote sensing, Management

Mangroves are vital coastal ecosystems situated in tropical and subtropical regions, serving as an interface between terrestrial and marine environments and having the ability to thrive amidst intense salinity variation due to tidal influences (Kathiresan and Bingham, 2001). The vegetation in mangroves has evolved to adapt to tidal amplitudes, salinity fluctuations, and the challenging conditions of muddy, low-oxygen environments (Spalding et al., 1997). These ecosystems play a crucial role as nurseries for marine and estuarine biodiversity — particularly during the reproduction phases of various species — and provide a multitude of ecosystem services (Vo et al., 2012; Thompson and Rog, 2019; Getzner and Islam, 2020). Socioeconomic dynamics are intricately linked to mangrove ecosystems, notably by the utilization of local faunal resources

Submitted: 07-Nov-2023
Approved: 17-May-2024

Editor: Rubens Lopes

from artisanal fishing, which involves exploiting diverse fish species, crustaceans, and mollusks, contributing to livelihoods, and generating income (Silva-Cavalcanti and Costa, 2011; Pinto et al., 2015; Nascimento et al., 2017).

Mangrove forests face threats from deforestation, the establishment of monocultures, and climate change-induced scenarios such as coastal ecosystem acidification and rising sea levels, all of which disrupt the functioning of this ecosystem (Adame et al., 2021). Although deforestation rates in mangrove forests have decreased in the last decade, significant scientific gaps remain, necessitating further investigation into aspects such as mangrove area dimensions and the spatial-temporal percentage of lost areas (Friess et al., 2019).

Globally, the total mangrove area in 2000 totaled approximately 137,760 km², distributed across 118 countries (Giri et al., 2010). However, from 2000 to 2016, a 2.1% reduction in mangrove area occurred worldwide, representing a loss of approximately 3,363 km² (Goldberg et al., 2020). In Brazil, mangrove forest covered approximately 9900 km² in 2018, with Maranhão, Pará, Amapá, and Bahia showing the highest concentration, accounting for 85% of the total mangrove cover (Diniz et al., 2019). Notably, the state of Rio Grande do Sul, in southern Brazil, lacks mangrove areas within its territory. Thus, the mangrove ecosystem spans from Amapá in northern Brazil to Santa Catarina in southern Brazil (Schaeffer-Novelli, 2018).

Given these ongoing changes, it is imperative to develop monitoring studies for mangrove forests — particularly from a spatiotemporal perspective — to facilitate the formulation of effective coastal management strategies (Cunha-Lignon et al., 2009). Monitoring mangrove forest fragmentation should be integrated into ecosystem conservation strategies (Bryan-Brown et al., 2020). This study aims to assess the spatiotemporal dynamics of mangrove vegetation in the Acaú-Goiana Extractive Reserve (RESEX Acaú-Goiana), in northeastern Brazil, using spectral indices. It aims to furnish pertinent information regarding the spatiotemporal variations of mangroves in the region, thereby aiding the management of this protected area.

This research was conducted within the RESEX Acaú-Goiana, established in 2007 and encompassing an area of 6,678 hectares in Northeastern Brazil, situated between the states of Paraíba and Pernambuco (07º 33’ 59” S; 34º 50’ 14” W). This reserve was established to safeguard artisanal fishing and local fish resources and is inhabited by six beneficiary fishing communities responsible for territory use and management (Fadigas and Garcia, 2010).

The mangrove area within the RESEX Acaú-Goiana is subjected to pressure from adjacent sugar-alcohol industries and carciniculture (shrimp farming), particularly those operating within the boundaries of the reserve (Guimarães et al., 2010; Freire-Silva et al., 2020). This expansion exacerbates coastal areas degradation, thereby impacting the mangrove ecosystem distribution within the region (Costa et al., 2009; Barletta and Lima, 2019; Costa-Silva, 2020).

For data acquisition, satellite images from the Thematic Mapper (TM/Landsat-5) and Operational Land Imager (OLI/Landsat-8) sensors, collection 2 (Landsat Collection 2) and processing level 2, were obtained from the United States Geological Survey repository. The selection of collection 2 and processing level 2 images was because of their improved geometric accuracy, calibration, and surface reflectance calibration, referred to as “scientific products”.

The historical image series spans from 1992 to 2019. It was sampled for analysis given the coastal location of the study area as it is often affected by clouds, which hinders target observation and index generation. Consequently, image selection prioritized cloud-free conditions within the RESEX Acaú-Goiana domain, limiting the number of available images. Additionally, consideration was given to pre- and post- creation dates of the RESEX during image acquisition.

Selected images correspond to the following dates: (i) May 15, 1992; (ii) August 28, 2006; (iii) October 8, 2010; and (iv) October 17, 2019. Preprocessing steps involved radiometric conversion and band clipping, executed on QGIS, version 3.16.7 (Hannover).

The radiometric conversion of Landsat science products (level 2) from digital number to surface reflectance can be given by equation 1.

$$P\_\lambda = M\_\rho * Q\_cal + A\_\rho \text{ ;(Equation 1)}$$

Whereby:

P_λ: surface reflectance (calculated by the LEDAPS algorithm);

M_ρ: band-specific multiplicative scaling factor in the image metadata file (M_ρ= 0.0000275);

A_ρ: band-specific additive scaling factor in the image metadata file (A_ρ= −0.2);

Q_cal: quantified and calibrated pixel values of the standard products (digital number);

After the radiometric conversion of the bands, the images were cropped to the study area, to restrict the calculation of the indices to the region of the Acaú-Goiana Extractive Reserve (RESEX). The indices calculated in this research were the normalized difference vegetation index (NDVI), the normalized difference water index (NDWI), and the modular mangrove recognition index (MMRI).

NDVI can be calculated from equation 2 (Rouse et al., 1974), and [−1, 1] is the interval range:

$$NDVI=(\rho\_NIR-\rho\_RED)/(\rho\_NIR+\rho\_RED) \text{ (Equation 2)}$$

Whereby:

ρ_NIR: reflectance in the near-infrared spectral region;

ρ_RED: reflectance in the red spectral region.

As for the NDWI, proposed by Gao (1996), also known as NDMI (normalized difference moisture index), it can follow changes in biomass and vegetation moisture stress and can be calculated from the expression below (equation 3), and [−1, 1] is the interval range:

$$NDWI=(\rho\_NIR-\rho\_SWIR)/(\rho\_NIR+\rho\_SWIR) \text{ (Equation 3)}$$

Whereby:

ρ_NIR: reflectance in the near-infrared spectral region;

ρ_SWIR: reflectance in the mid-infrared spectral region.

Lastly, the MMRI, proposed by Diniz et al. (2019), was specifically designed to better discriminate mangrove forests from neighboring vegetation, which can be calculated as:

$$MMRI=(MNDWI-NDVI)/(MNDWI+NDVI) \text{ (Equation 4)}$$

Whereby the modified normalized difference water index (MNDWI), proposed by Xu (2006), is described as (equation 5), and [−1, 1] is the interval range:

$$MNDWI=(\rho\_GREEN-\rho\_NIR)/(\rho\_GREEN+\rho\_NIR) \text{ (Equation 5)}$$

Whereby:

ρ_NIR: reflectance in the near-infrared spectral region;

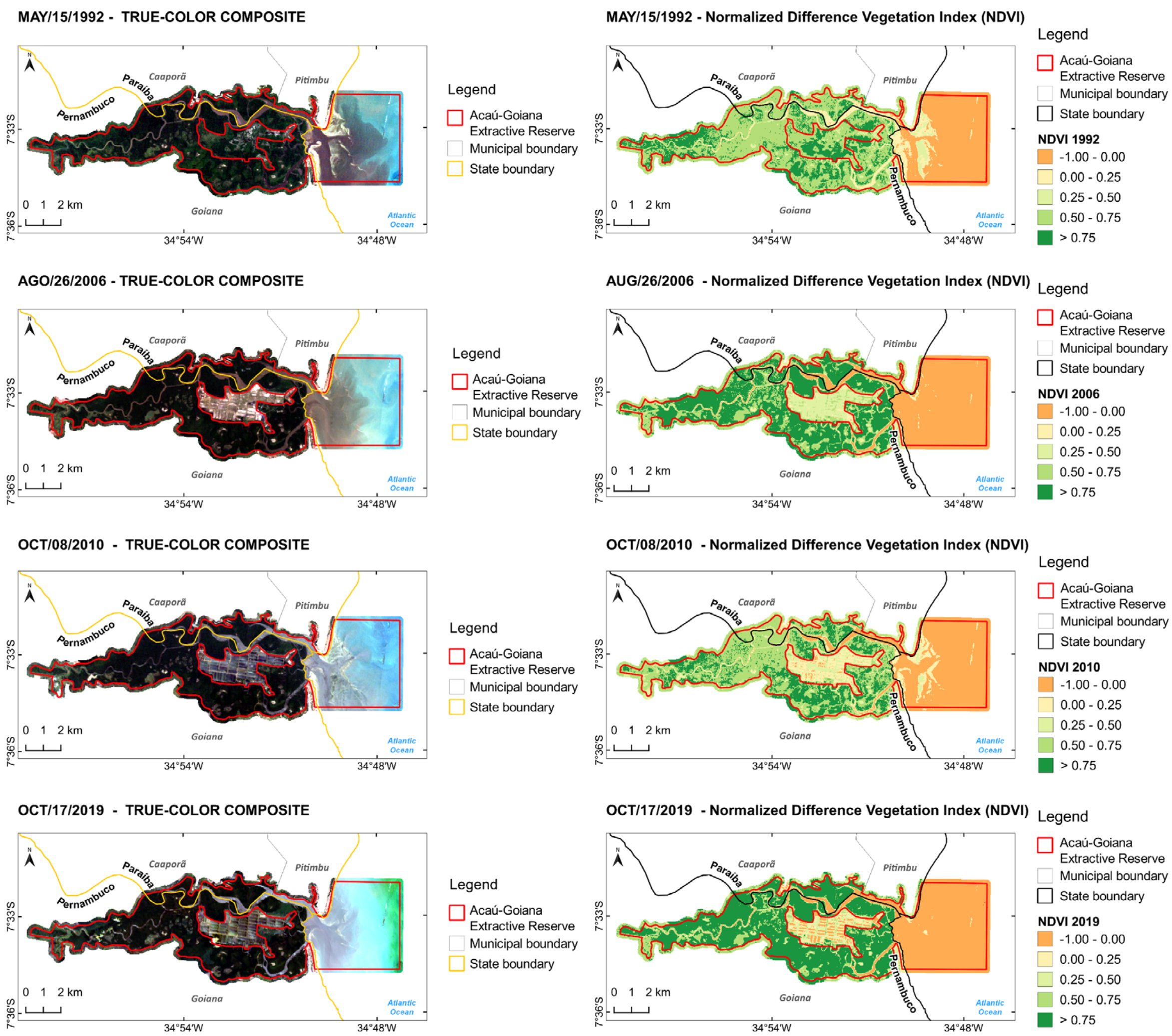
ρ_GREEN: reflectance in the green spectral region.

The results obtained from the analysis of NDVI, NDWI, and MMRI are shown in Figure 1. NDVI values ranged from 0.5 to > 0.75, indicating areas with denser vegetation, whereas those for NDWI varied from 0.25 to 0.75, indicating wet vegetation. MMRI values ranged from −0.6 to −0.3.

An observable trend in land cover is noted, particularly in the center of the region of the reserve, which lies outside the official domain of the reserve. Here, significant vegetation clearance occurred to establish shrimp farming tanks, resulting in the absence of native vegetation since 2006. The operation of these nurseries has raised concerns due to their potential to pollute estuarine waters and contribute to siltation, adversely impacting local biodiversity (Freire-Silva et al., 2020). Notably, the installation of these nurseries predates the establishment of the reserve, dating back to late 1990s, and was contributing factor prompting discussions leading to the inception of the reserve (Fadigas and Garcia, 2010). Shrimp farming emerges as a significant anthropogenic activity driving mangrove deforestation, adversely affecting the quality of the mangrove ecosystem and estuary (Guimarães et al., 2010).

The combination of NDVI and NDWI indices has been employed to identify and monitor the spatial dynamics of mangrove areas, aiding in the detection of anthropogenic impacts (Roy et al., 2019; Faruque et al., 2022). This combined analysis showed environmental improvements following the creation of the Extractive Reserve (RESEX).

Regarding the mangrove areas assessed using MMRI, the values after the creation of the RESEX were closer to 0 (flooded areas), which may suggest the lower quality of the mangrove forests, especially in the western portion of the reserve. The causes that may be subsidizing this reduction include (i) saline stress, which may be the result of siltation along the river from anthropic interventions, interfering with the ideal salinity levels to develop mangrove forests (Jennerjahn, 2017); (ii) agricultural areas. According to the Management Agreement of the reserve, beneficiaries have small areas to develop agriculture to complement their income; (iii) industrial impacts due to the reserve being in an industrial hub (Cidreira-Neto et al., 2020) and (iv) water quality since hypoxia events have been detected in the Goiana River (Costa et al., 2018, Cidreira-Neto et al., 2022). Investigation into these contributing factors is essential for devising effective mitigation strategies to address mangrove area reductions.



True-color composition, Landsat-5/TM and Landsat-8/OLI images, collection-2/level-2. Data sources: IBGE,2020. Earth Explorer, 2022; ICMBio, 2020. EPSG: 4326(WGS84)

Normalized Difference Vegetation Index (NDVI), calculated by band ratio of Landsat-5/TM and Landsat-8/OLI images, collection-2/level-2. Sources: IBGE,2020. Earth Explorer, 2022; ICMBio, 2020. EPSG: 4326 (WGS84)

continued...

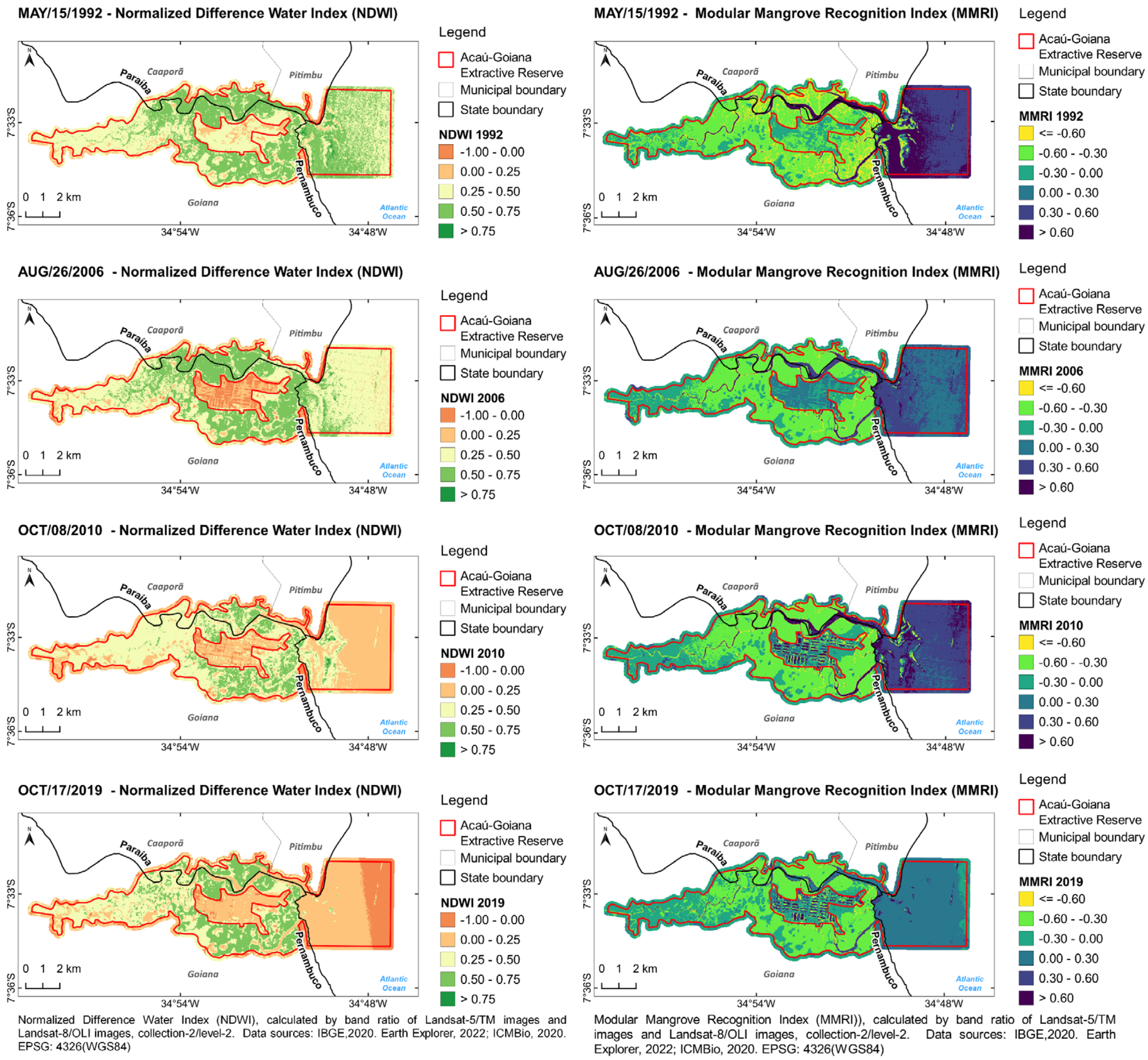


Figure 1. True-color composition, normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and modular mangrove recognition index (MMRI) for 1992, 2006, 2010, and 2019 in the Acaú-Goiana Extractive Reserve, situated between the States of Pernambuco and Paraíba, in Northeast Brazil.

The most notable change in the RESEX Acaú-Goiana territory is the encroachment of shrimp farming tanks. While the observed variations may partially reflect mangrove phenology, further analyses are warranted to accurately discern temporal variations in mangrove coverage. Despite these challenges, this study concludes that mangrove vegetation shows relative stability, indicating the positive impact of local management efforts in preserving the area.

ACKNOWLEDGMENTS

We would like to thank the *Fundo Brasileiro para a Conservação da Biodiversidade* (Brazilian Biodiversity Fund) (FUNBIO) for their support by its research grant (call notice No. 012/021) and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. We thank the reviewers and editors for their comments and suggestions.

AUTHOR CONTRIBUTIONS

I.R.G.C.N.: Conceptualization; Methodology; Investigation; Writing – original draft; Writing – review & editing.

V.D.B.Q.: Conceptualization; Methodology; Investigation; Writing – review & editing.

A.L.B.C.: Supervision; Resources; Project Administration; Funding Acquisition; Methodology; Formal Analysis; Investigation; Writing – review & editing.

B.C.G., G.G.R.: Methodology; Formal Analysis; Investigation; Writing – review & editing.

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