IMPACT OF LAND USE ON WATER QUALITY: 20-YEAR BIOGEOCHEMICAL STUDY OF MARANHÃO'S NORTHERN COAST

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ABSTRACT

This study aims to assess the impact of agriculture, livestock, and deforestation on water quality along a section of the northern Brazilian coast in Maranhão state. Biogeochemical descriptors such as Suspended Particulate Matter (SPM), Particulate Organic Carbon (POC), and Chlorophyll-a (CHL-a) concentrations were used to detect changes in water quality. By applying innovative inversion algorithms for MODIS (OC-SMART) data from 2002 to 2022, we generated a biogeochemical time series that was analyzed using Census-X-11 decomposition and trend detection methods. This approach enabled us to explore the temporal biogeochemical changes over the past 20 years, highlighting the impact of anthropogenic pressures in conjunction with climate variability.

Key words **—** water quality, MODIS, biogeochemical changes, anthropogenic pressures.

1. INTRODUCTION

The Brazilian coastline holds significant ecological, societal, and economic importance but is highly vulnerable to both natural processes and human activities, including agriculture, deforestation, urbanization, and dam construction [1]. Changes in land use and land cover have a profound impact on water quality in coastal areas by increasing nutrient runoff, sedimentation, and the introduction of pollutants [2]. In Maranhão state, the primary activities of agriculture and livestock contribute to significant land use and land cover changes, exacerbating ongoing deforestation in the region [3].

The main objective of this study is to assess the impact of land use and land cover changes in Maranhão state on the biogeochemical quality of its coastal waters through the remote sensing of ocean color.

To observe interannual biogeochemical variability in coastal waters, we utilized MODIS satellite at 1 km resolution data from 2002 to 2022, processed with the OC-SMART atmospheric correction. Innovative inversion algorithms, adapted to MODIS and developed based on optical water types, were employed to estimate biogeochemical descriptors such as Suspended Particulate Matter (SPM), Particulate Organic Carbon (POC), and Chlorophyll-a (CHL-a) from water reflectance.

These models were applied to MODIS satellite images to generate a biogeochemical time series over the past 20 years. This series was analyzed using adapted statistical techniques, including classical trend analysis and the Census-X-11 time series decomposition method, to elucidate interannual changes. The results of the statistical analysis were integrated with ancillary data, such as precipitation, river discharge, and currents, to provide a comprehensive understanding of the impact of anthropogenic activities on coastal waters.

2. MATERIAL AND METHODS

2.1. Study area

The State of Maranhão covers an area of 331,983.29 km², making it the second largest in the Northeast and the eighth in Brazil [4]. Its coastline, 640 km long, is the second most extensive in the country. The western coastline belongs to the Amazonian Equatorial Coast, marked by fluvio-estuarine recesses and highly drained river valleys [5]. Our study focuses on the coastal zone between Turiaçu Bay and São Marcos Bay (Figure 1), part of the world's most extensive continuous tidal plain, covering 7,500 km² and 650 km of mangroves [6]. The region, dominated by an equatorial climate with 1,800–2,500 mm of annual rainfall, features high turbidity [7] and intricate ria and estuary formations [8].

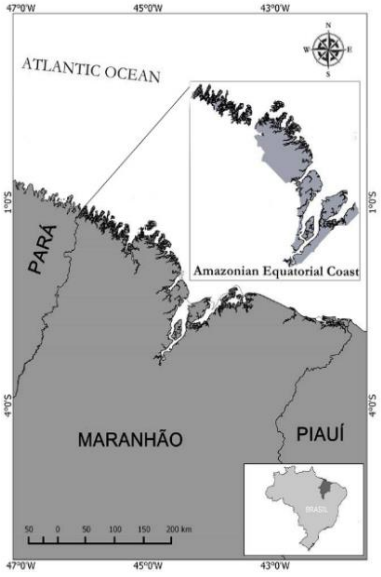

Figure 1. Map of the coast of Maranhão State, Brazil [9].

2.2. Satellite data

To assess water quality over the past 20 years, we used MODIS-Aqua satellite images at a 1 km resolution, the longest continuous time series from a single sensor currently available. MODIS data were processed from level 1 using OC-SMART atmospheric correction for Brazilian coastal waters.

OC-SMART (Ocean Color - Simultaneous Marine and Aerosol Retrieval Tool) is an advanced platform designed to extract aerosol and ocean color information from satellite imagery. It utilizes multilayer neural networks (MLNNs) and extensive radiative transfer simulations based on the AccuRT coupled atmosphere-ocean model. The tool's primary functions are atmospheric correction and retrieving in-water optical properties (IOPs) from satellite data [10].

We generated 20 years of 1 km resolution MODIS OC-SMART data, which will be used in this study.

2.3. Inversion algorithms

To estimate POC from MODIS reflectance, we used a combined approach integrating two models: Tran (2019) [11] and Le (2016) [12], both developed and validated for coastal waters and combined based on optical water classification. Tran (2019) was applied for low and medium POC concentrations using the 488 nm and 667 nm bands, while Le (2016) was used for high POC concentrations, utilizing the 488, 531, 547, and 667 nm bands.

For SPM, we applied a combination of two models: Siswanto (2011) [13] and Han (2016) [14], also validated for coastal waters and combined using optical water types. Siswanto (2011) was used for low SPM concentrations, relying on the blue, green, and red bands. For high SPM concentrations the NIR approach of Han's algorithm was employed.

To estimate CHL-a, we used the CONNECT model [15], which combines two neural networks based on optical water types. One network uses the blue, green, and red bands for clear waters, while the other incorporates blue, green, red, and NIR bands for turbid waters.

2.4. Statistical analysis

We used the seasonal Mann-Kendall test to detect monotonic trends in the time series between 2002 and 2022. This test checks upward or downward trends by comparing two hypotheses: the null hypothesis (H0), which states there is no trend, and the alternative hypothesis (Ha), which indicates a trend exists. The Mann-Kendall test is effective for identifying significant changes [16].

We applied the Census X-11 time series decomposition method to better understand biogeochemical variability and changes in water quality. Following the procedure of Vantrepotte & Mélin (2011) [17], X-11 divides the signal into three main components: interannual, seasonal and irregular variations, using moving average calculations.

Ancillary data:

To explain biogeochemical variability and changes in water quality, we used ancillary data. Land use and land cover information was obtained from the MapBiomas platform, which provides annual land cover mapping, along with monthly monitoring of surface water and fire scars, dating back to 1985. For precipitation data, we used NASA's Integrated Multi-satellite Retrievals for GPM (IMERG), which estimates global surface precipitation rates at a high resolution of 0.1° every 30 minutes, starting from 2000.

3. RESULTS

The seasonal Mann-Kendall test provided the rate of change (RC) for SPM, POC, and CHL-a. This indicates where biogeochemical trends are increasing or decreasing and shows the annual percentage of change.

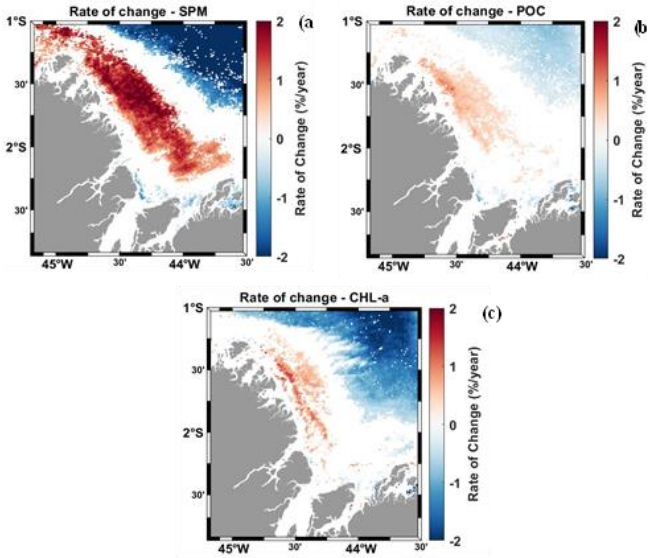

Figure 2. The rate of change of the biogeochemical variables, a: SPM, b: POC and c: CHL-a

We observed an increase in SPM, POC, and CHL-a concentrations in the coastal waters along the western coastline of Maranhão state (figure 2). Between 2002 and 2022, SPM increased by 50%, POC by 30%, and CHL-a by 35%.

The land cover maps of Maranhão state from 2002 to 2022 (Figure 3) show an expansion of pasture areas, replacing green lands and leading to increased deforestation.

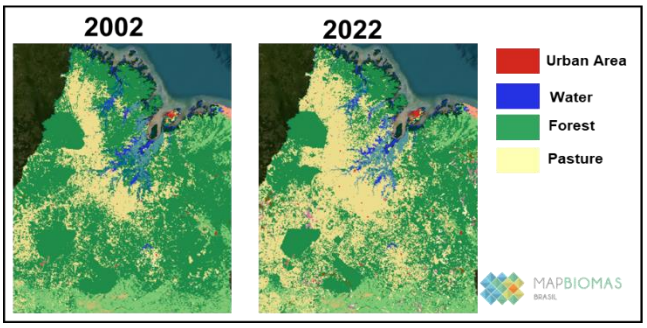

Figure 3. Land cover maps of Maranhão state 2002-2022

The increase in SPM, POC, and CHL-a can be linked to the expansion of pasture and deforestation in Maranhão state. To explain this, we used a simple correlation analysis between the interannual variation of these biogeochemical descriptors and pasture growth from 2002 to 2022 (Figure 4).

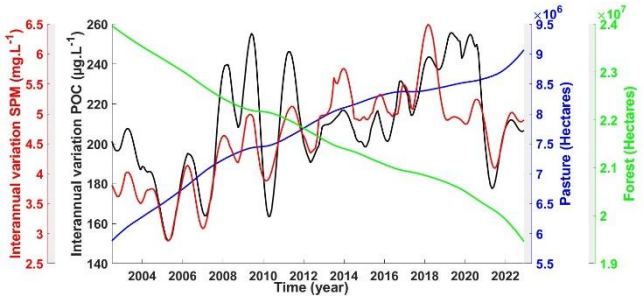

Figure 4. Correlation graphic between interannual variation SPM (red), interannual variation POC (black), Pasture (blue) and Forest (green).

The interannual variation of SPM and POC shows an increasing trend between 2002 and 2022. Pasture areas have expanded over the past 20 years, while forested areas have declined, indicating significant deforestation in Maranhão state over the last two decades.

POC – Pasture	**R^2 = 0.49**
POC – Forest	**R^2 = - 0.46**
SPM – Pasture	**R^2 = 0.76**
SPM – Forest	**R^2 = - 0.70**
Pasture – Forest	**R^2 = - 0.99**
SPM – POC	**R^2 = 0.75**

Table 1. Correlation coefficients between interannual variation of POC and SPM, Pasture and Forest.

Table 1 presents the correlation coefficients (R^2) between the interannual variations of biogeochemical descriptors (POC and SPM) and changes in land use (pasture and forest cover). The positive correlation between POC and pasture (R^2 = 0.49) indicates a moderate relationship, where the increase in pasture corresponds to a rise in POC levels. Conversely, POC shows a negative correlation with forest cover (R^2 =0.46), suggesting that deforestation is associated with higher POC concentrations.

The correlation between SPM and pasture is notably strong (R^2 = 0.76), reinforcing the link between expanding pastureland and elevated SPM levels. Similarly, SPM shows a strong negative correlation with forest cover (R^2 = -0.70), implying that deforestation contributes significantly to the increase in suspended particulate matter.

The inverse relationship between pasture and forest cover (R^2 = -0.99) confirms the clear trade-off between these two land uses over the study period, with pasture expansion directly contributing to forest loss. Finally, the strong positive correlation between SPM and POC (R^2 = 0.75) indicates that these two biogeochemical descriptors are closely associated and likely influenced by the same land use changes.

The interannual variability of SPM and POC shows modulations that are not entirely linked to land cover changes. To account for these variations, we compared the interannual variability of SPM and POC with that of precipitation between 2002 and 2022 (figure 5).

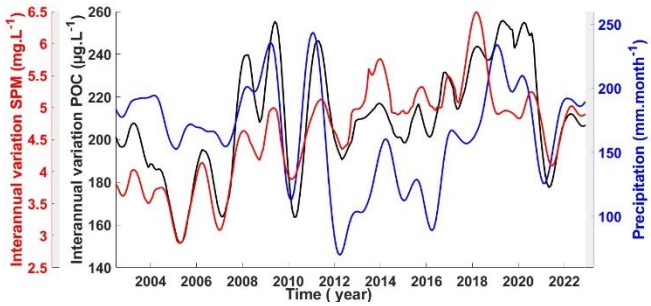

Figure 5. Correlation graphic betwenn interannual variation SPM (red), POC (black) and precipitation (blue).

Over the last two decades, the interannual variability of precipitation has not shown a significant trend. However, periodic fluctuations in precipitation appear to influence POC exports, likely through variations in the intensity of land surface flushing.

Land cover changes are not the only drivers of biogeochemical dynamics in the study area; climatic modulations also have a significant impact on these processes.

4. DISCUSSION

The observed increases in SPM, POC, and CHL-a concentrations in the coastal waters of Maranhão state are closely linked to significant land use changes, particularly the expansion of pasture areas and deforestation. As highlighted by Watanabe and Ortega (2014) [18], Abrupt land-use changes such as deforestation, agriculture, and urbanization, are cumulatively a major driver of global environmental change and can significantly disrupt biogeochemical processes.

Human activities over the past century, including intensive agriculture, deforestation, and waste discharge, have significantly perturbed coastal oceans, leading to widespread eutrophication. This has degraded water quality and altered marine food webs and community structures [19]. The relationships identified between land use changes and biogeochemical descriptors (R^2 values) indicate that pasture expansion and deforestation are associated with increases in SPM and POC. This aligns with findings from previous studies that emphasize the perturbational effects of human activities on carbon and nutrient cycling in coastal margins [20, 21, 22].

Furthermore, climatic factors, particularly precipitation variations, contribute to the interannual variability of POC and SPM, suggesting that both land cover changes and climatic modulations play crucial roles in biogeochemical dynamics. Changes in precipitation and temperature, along with their interactions with land use and vegetation, are significant climate-related stressors expected to impact sediment transport in the future [23]

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5. CONCLUSIONS

The study highlights the significant impact of land use changes, particularly the expansion of pasture areas and deforestation, on the biogeochemical dynamics of coastal waters in Maranhão state. The observed increases particulate matter pool and CHL-a concentrations are closely linked to these land use transformations.

Additionally, climatic factors, especially precipitation variations, contribute to the interannual variability of these biogeochemical indicators, emphasizing the intricate interplay between land cover changes and climate-related stressors. Understanding these dynamics is crucial for effective management and conservation of coastal ecosystems, which are increasingly threatened by human activities and climate change.

Finally, remote sensing of ocean color, combined with adapted statistical analysis, enhances our ability to analyze and understand long-term biogeochemical variations.

6.ACKNOWLEDGMENTS

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