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Multi-temporal analysis of the coastline in the Cocoa Coast, Bahia

Análise multitemporal da linha costeira na Costa do Cacau, Bahia

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Abstract: The Cocoa Coast, located on the southern coast of the state of Bahia, is a very important region from an environmental point of view, as it is home to one of the greatest biodiversities on the planet. However, it has been suffering from the advance and retreat of the coastline, which intensifies the need to carry out studies that aim to understand the dynamics of the coastline in the region, in order to support the maintenance and protection of this environment. This study aims to characterise the spatio-temporal variations of the coastline in this region for the period 1990-2020. A historical analysis of the coastline is carried out using multispectral orbital images from the Landsat series, resulting in a quantitative and qualitative analysis of the dynamics of the coastline in the Cocoa Coast region. The area has been completely modified by accretion and erosion processes, which increased significantly between the first (1990-2000) and the last (2010-2020) interval investigated. It is noteworthy that, considering the social, economic and environmental importance of the Cocoa Coast, there is still a need for continuous monitoring in order to better understand the coastal dynamics of this region.

Keywords: Coastline; Remote sensing; Multitemporal analysis; Cocoa Coast.

Resumo: A Costa do Cacau, localizada no litoral sul do estado da Bahia, é uma região muito importante do ponto de vista ambiental por abrigar uma das maiores biodiversidades do planeta. No entanto, vem sofrendo com o avanço e o recuo da linha de costa, o que intensifica a necessidade da realização de estudos que visem entender a dinâmica da linha de costa na região, como subsídio para a manutenção e proteção deste ambiente. Neste sentido, este trabalho tem o objetivo de caracterizar as variações espaço-temporais da linha costeira desta região entre o período de 1990 a 2020. Realizou-se análise histórica da linha de costa através de imagens orbitais multiespectrais da série Landsat. Concluiu-se que o estudo forneceu de forma quantitativa e qualitativa a análise da dinâmica da linha de costa na região da Costa do Cacau. A área total modificada pelos processos de acreção e erosão aumentou significativamente entre o primeiro (1990-2000) e o último (2010-2020) intervalo investigado. Ressalta-se que, considerando a importância social, econômica e ambiental da Costa do Cacau, há a necessidade de um monitoramento contínuo com a finalidade de melhor compreender a dinâmica costeira desta região.

Palavras-chave: Linha de costa; Sensoriamento remoto; Análise multitemporal; Costa do Cacau.

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1. Introduction

According to Marino and Freire (2013), coastal zones are among the most dynamic environments on Earth, constantly experiencing the advance and retreat of the coastline at various temporal scales. Martins et al. (2004) argued that these constant changes occur in response to natural forces and human activities, making a dynamic study crucial, especially in areas where tourism, driven by the presence of beaches, is a key driver of the local and regional economy.

Magalhães et al. (2017) further emphasised that sandy beaches are particularly susceptible to continuous changes in morphological configuration, which can lead to coastal erosion processes associated with sediment deficit and shifts in the coastline. According to Lelis and Calliari (2003), understanding the evolution patterns of coastal areas and the physical processes controlling morphodynamic equilibrium is essential for planning human use and occupation, with a focus on environmental preservation and quality of life.

To comprehend changes in the coastline's position over time, it is essential to define the coastline for the purpose of this study. However, for practical purposes, the chosen definition is less important than the ability to identify how the chosen indicator for delineating the coastline relates to the physical land-water boundary (YADAV et al., 2017). According to Faye (2010), the coastline should represent the linear division between the maritime and terrestrial domains, although its practical definition can be challenging due to the wide variety of indicators that can be used for its identification.

Yadav et al. (2017) argued that coastline identification can be carried out using various types of data but, in most coastal areas, historical data are limited or nonexistent. Therefore, the choice of data type to be used is often based on the data available for that region. Of this data, the authors highlight historical photographs, coastal maps, aerial photographs, Global Navigation Satellite System (GNSS)-derived coastline data, remote sensing, multispectral and hyperspectral satellite image analysis, and microwave sensors.

Remote sensing data can be very useful in coastal management, when it is processed to generate information for decision-making. According to Toure et al. (2019), remote sensing is increasingly used in coastal monitoring as it allows for the automation or semi-automation of coastline extraction through image processing techniques.

Many indicators can be used to define the coastline. Boak and Turner (2005) published a literature review on the topic, describing the strengths and limitations of potential indicators for determining coastline position. In general, indicators were divided into two categories: those related to mean sea level and those related to visually discernible coastal features. The authors emphasised that, when defining a coastline indicator it should be assumed to be the true representation of its position.

According to Schweitzer (2013), when choosing the indicator to be used, factors such as the continuity of its occurrence and the possibility of good visibility of the indicator on the beach should be considered. Additionally, the scale adopted in the research should be consistent with the chosen indicator. The author also highlights that the quality of coastline position determination is related to the features used as indicators, the recording techniques used, the operator's discernment in identifying the chosen indicator, and the objectives of the study.

According to Hoeke, Zarillo, and Synder (2001), the vegetation line indicator is suitable for studies using remote sensing data. Boak and Turner (2005) pointed out that the use of satellite imagery in coastline identification offers the advantage of broader area coverage, and the detailed spectral information provided allows coastlines to be identified through visually discernible coastal features or by applying digital image processing techniques. According to Yadav et al. (2017), the quality of results will vary depending on the resolution of the images used. Lelis and Calliari (2003) affirmed that understanding the evolution patterns of coastal areas and the physical processes controlling morphodynamic equilibrium is essential for planning human use and occupation, with a focus on environmental preservation and quality of life. In this context, this research aims to conduct a multi-temporal analysis with a decadal interval from 1990 to 2020 for the Cocoa Coast, based on LANDSAT satellite imagery.

2. Methodology

The Cocoa Coast encompasses an area of approximately 6,601 square kilometers, with about 180 km of coastline distributed among the five coastal municipalities. Proceeding from north to south, these municipalities are: Itacaré, Uruçuca, Ilhéus, Una, and Canavieiras (see Figure 1). Among the various coastal areas rich in biodiversity, the region of the Serra do Conduru State Park stands out, primarily located in the municipality of Uruçuca within the Cocoa Coast region. This park is home to the third-largest biodiversity in the world (BAHIA, 2015).

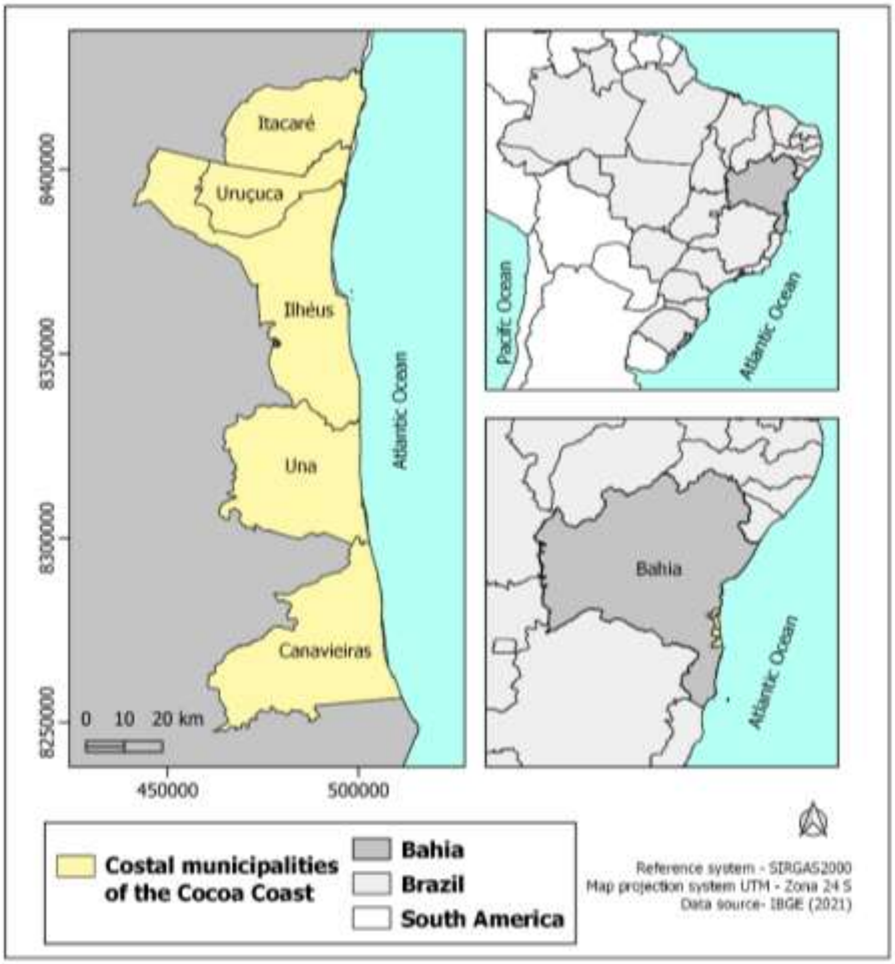

Figure 1 – Location map of the study area, the coastal municipalities of the Cocoa Coast.
Source: The current authors (2023)

In addition to the existing biodiversity, the region attracts significant tourist activity due to the beauty of its beaches, in contrast with the presence of cocoa farming and preserved areas of the Atlantic Forest. According to Oliveira (2006), tourism activities have proven to be an attractive alternative for economic development in the region. It is worth noting that, in most municipalities of the Cocoa Coast, tourism represents the primary driver of the local economy (BAHIA, 2015).

In the methodological procedure, to facilitate the historical analysis of the coastline, a search for multispectral orbital images with low cloud cover was conducted for the study area. For this purpose, images from the LANDSAT satellite series, with a spatial resolution of 30 m, were considered and made available through the United States Geological Survey (USGS) website. LANDSAT Collection 2 Level 2 scenes were used, as these images come with geometric and radiometric corrections, ensuring the minimisation of the effects of electromagnetic radiation reflectance and scattering on the Earth's surface.

For each reference year (1990, 2000, 2010, and 2020), the available scenes were analysed, and the information from these scenes was compiled based on observations of the presence or absence of clouds in the area of interest. It is worth noting that the coastline position identification in this study was performed using the vegetation line analysis method. In this method, it is essential that images from different years are from similar seasons, to ensure that the analyses are conducted during periods with similar climatic conditions. In summary, the entire methodology used can be seen in the research methodology flowchart shown in Figure 2.

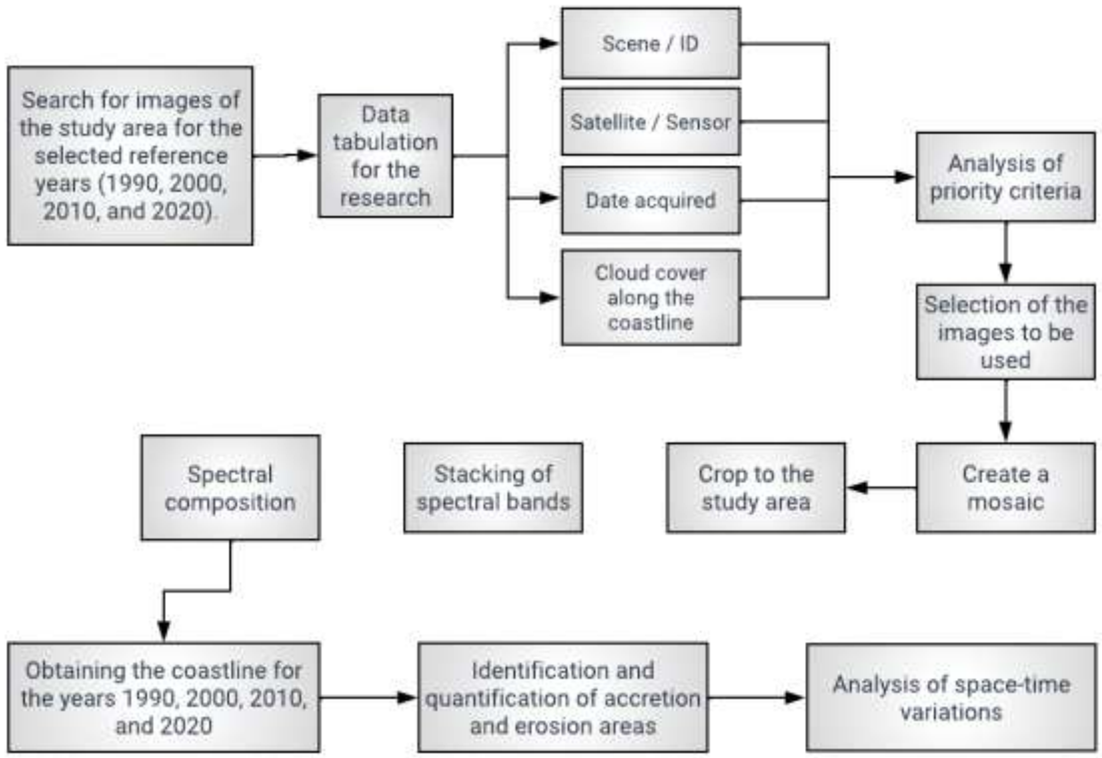

Figure 2 – Research Methodology Flowchart.
Source: The current authors (2023)

The images used were obtained from the following LANDSAT sensors: LANDSAT 4 Multispectral Scanner System (MSS), LANDSAT 5 Thematic Mapper (TM), LANDSAT 7 Enhanced Thematic Mapper Plus (ETM+), and LANDSAT 8 Operational Land Imager (OLI). Two scenes were required to cover the entire study area. In summary, the information about the scenes used is presented in Table 1.

Table 1 – Information about the reference scenes for each year.

Year	Date	Scenes - ID	Satellite - Sensor
1990	December, 27	LT05_L2SP_215070_19901227_20200915_02_T1; LT05_L2SP_215071_19901227_20200915_02_T1	LANDSAT 5 TM
2000	December, 30	LE07_L2SP_215070_20001230_20200917_02_T1; LE07_L2SP_215071_20001230_20200917_02_T1	LANDSAT 7 ETM +
2010	December, 02	LT05_L2SP_215070_20101202_20200823_02_T1; LT05_L2SP_215071_20101202_20200823_02_T1	LANDSAT 5 TM
2020	November, 11	LC08_L2SP_215070_20201111_20210317_02_T1; LC08_L2SP_215071_20201111_20210317_02_T1	LANDSAT 8 OLI/TIRS

Source: The current authors (2023)

The composition used for LANDSAT 5 and 7 satellite scenes was R4G3B2 while, for LANDSAT 8 (OLI), the composition R5G4B2 was employed. Therefore, for LANDSAT 5, bands 4 (0.76-0.90 µm), 3 (0.63-0.69 µm), and 2 (0.52-0.60 µm) were used; for LANDSAT 7, bands 4 (0.76-0.90 µm), 3 (0.63-0.69 µm), and 2 (0.52-0.60 µm) were used, and for LANDSAT 8, bands 5 (0.85-0.89 µm), 4 (0.63-0.68 µm), and 3 (0.53-0.60 µm) were used.

Subsequently, based on these scenes, coastline vectorisation was performed for each observed year. Finally, using the vectorised lines, the necessary spatial analyses were conducted to identify and quantify the variations that occurred in the region over the considered period. It is important to note that the quality and accuracy of vectorisation, as well as the analyses conducted, are limited by the spatial resolution of the input data, which are LANDSAT Collection 2 Level 2 scenes with a spatial resolution of 30 m. Furthermore, all variations identified will be dual-classified as accretion or erosion.

3. Results and Discussion

3.1 Coastline Vectorisation

Figure 3 presents the results of coastline identifications for the years 1990, 2000, 2010, and 2020. In addition, the reference images used for vectorisation, as indicated in Table 1, are also displayed. It should be noted that the images used in the representation below underwent brightness correction to enhance visualisation and presentation. Due to the graphical representation scale, it is not possible to observe the positional differences between the different lines for each year in this image. However, this data was crucial for obtaining the subsequent results.

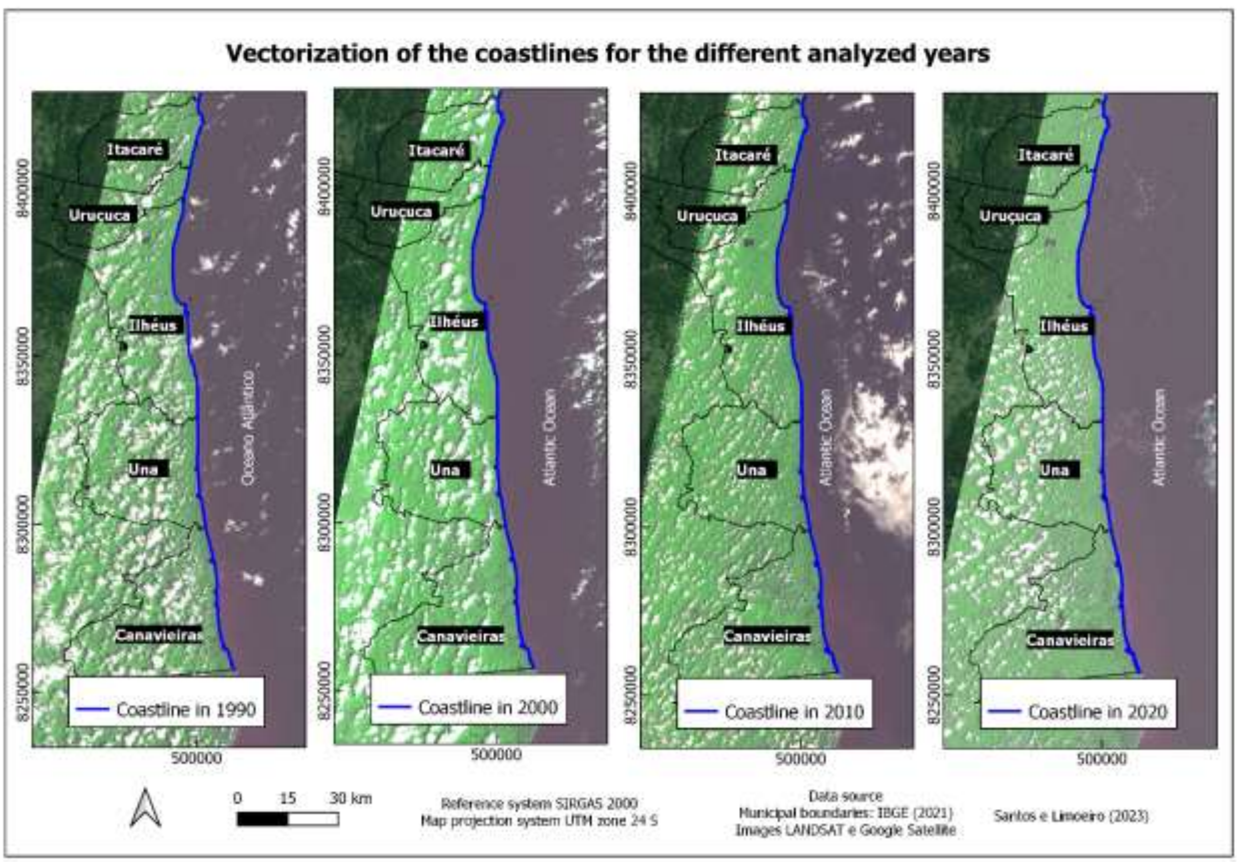

Figure 3 – Graphical representation of the coastlines for the years 1990, 2000, 2010, and 2020.
Source: The current authors (2023)

3.2 Identification of Accretion and Erosion Zones

By comparing the coastline positions from two different years, it was possible to identify accretion and erosion zones. Figure 4 illustrates the dynamics of these coastal processes over the period from 1990 to 2000. For this analysis, the coastline positions from the year 1990 and the year 2000 were taken into consideration.

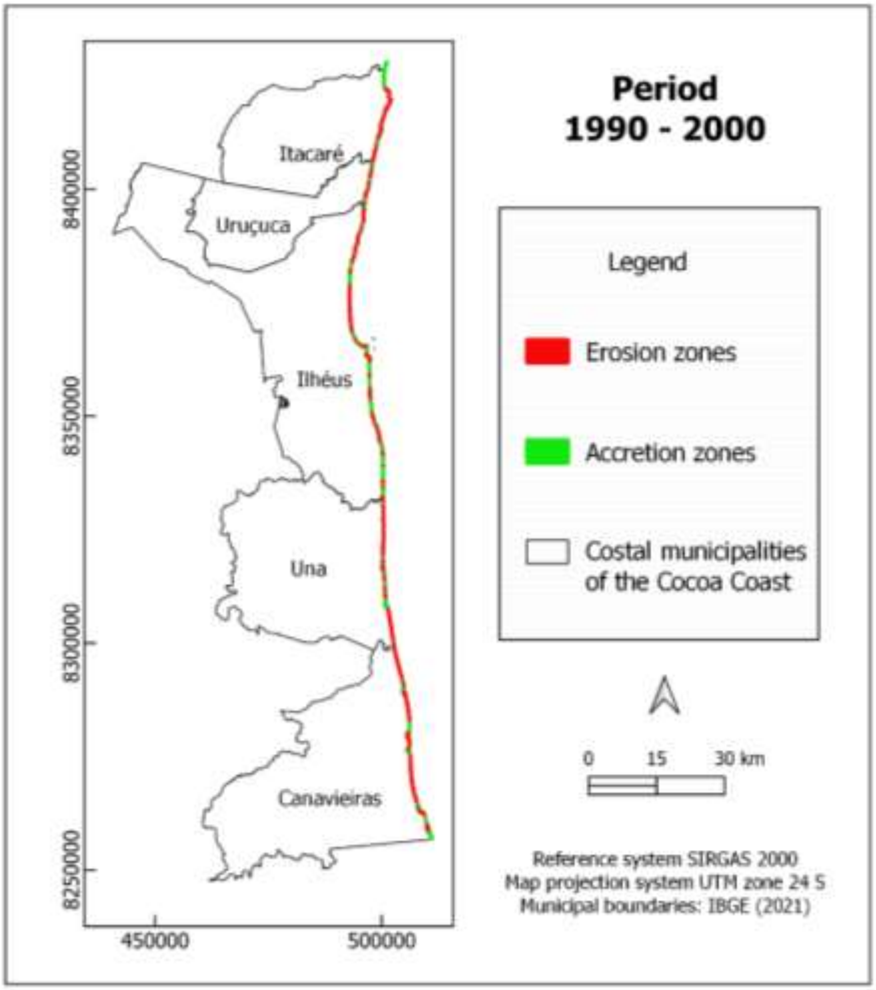

Figure 4 – Accretion and erosion zones of the coastline along the coastal municipalities of the Cocoa Coast for the analysis period 1990-2000.
Source: The current authors (2022)

When observing the variations that occurred during the first analysed time interval (see Figure 4), from 1990 to 2000, it is evident that, considering the entire extent of the Cocoa Coast, there was a predominance of erosion zones. Therefore, in general, a retreat of the coastline can be observed during this period. It should be noted that the erosion process is indicated by the more advanced position of the line representing the year 1990, compared to the line representing the year 2000. According to Teixeira and Bandeira (2022), this process becomes a problem when it threatens areas with human occupation, leading to the emergence of coastal erosion risk areas. Upon closer examination, it should be noted that, in the northernmost region of the municipality of Itacaré, there was a predominance of accretion zones within the period. This is indicated by the more advanced position of the 2000 line compared to the 1990 line in this specific region. This condition demonstrates a trend toward sediment accretion in this segment. However, shortly thereafter, a transition from an accretion condition to an erosion condition begins, which is predominant along the rest of the coastal strip of the municipality of Itacaré. The same predominance of erosive zones can be observed along the municipality of Uruçuca. In general, this trend also occurs in the municipality of Ilhéus; however, in this municipality, it is possible to observe the presence of relatively extensive zones where the accretion process occurred, especially in the southernmost region. In the municipalities of Una and Canavieiras, there is also a predominance of erosion zones. Nevertheless, some alternations can be observed in areas where the accretion process occurs, representing areas with a positive sediment balance.

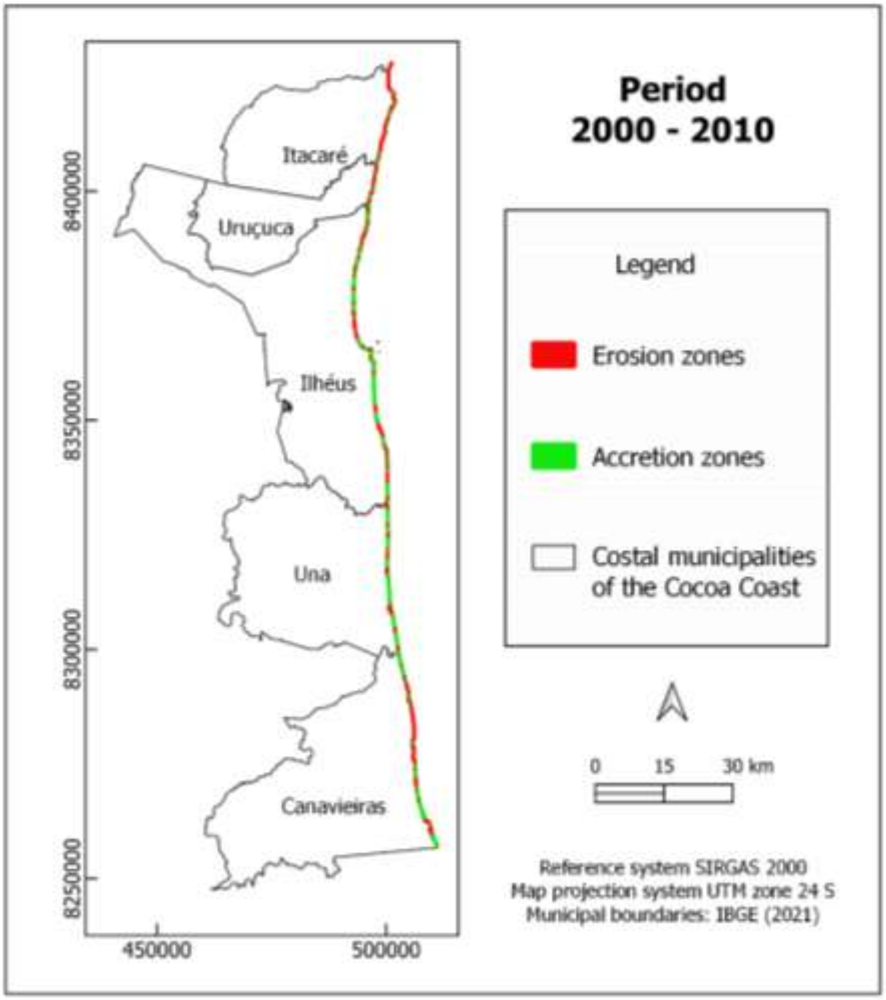

Figure 5 – Accretion and erosion zones of the coastline along the coastal municipalities of the Cocoa Coast for the analysis period from 2000-2010.
Source: The current authors (2023)

When examining the fluctuations that occurred during the second investigated time period, 2000-2010 (Figure 5), and taking into account the entire extent of the Cocoa Coast, it becomes evident that both accretion and erosion processes were active. It should be noted that this analysis considered the coastline positions for the year 2000 and the year 2010. In Itacaré, there is a predominance of erosion zones, indicating sediment loss in this region over the analysed period. Considering that Itacaré is a popular tourist destination, this could be one of the factors contributing to the observed dynamics, as tourism and related human activities are known to stimulate coastal erosion, as noted by Senevirathnaa et al. (2018). In the municipality of Uruçuca, a predominance of erosion zones is also observed, with some transitional zones between accretion and erosion processes along the coastline. The situation is different in the municipality of Ilhéus, where, heading south, the accretion zones become larger than the erosion zones, resulting in a predominance of sediment accretion zones along the municipality's coastline. A similar pattern is observed in the municipality of Una, where sediment accretion zones cover a greater extent, compared to erosion zones. In the municipality of Canavieiras, the accretion zones change over a large stretch of coastline and, further to the south, erosion processes occur. Subsequently, there is a transition to erosion zones.

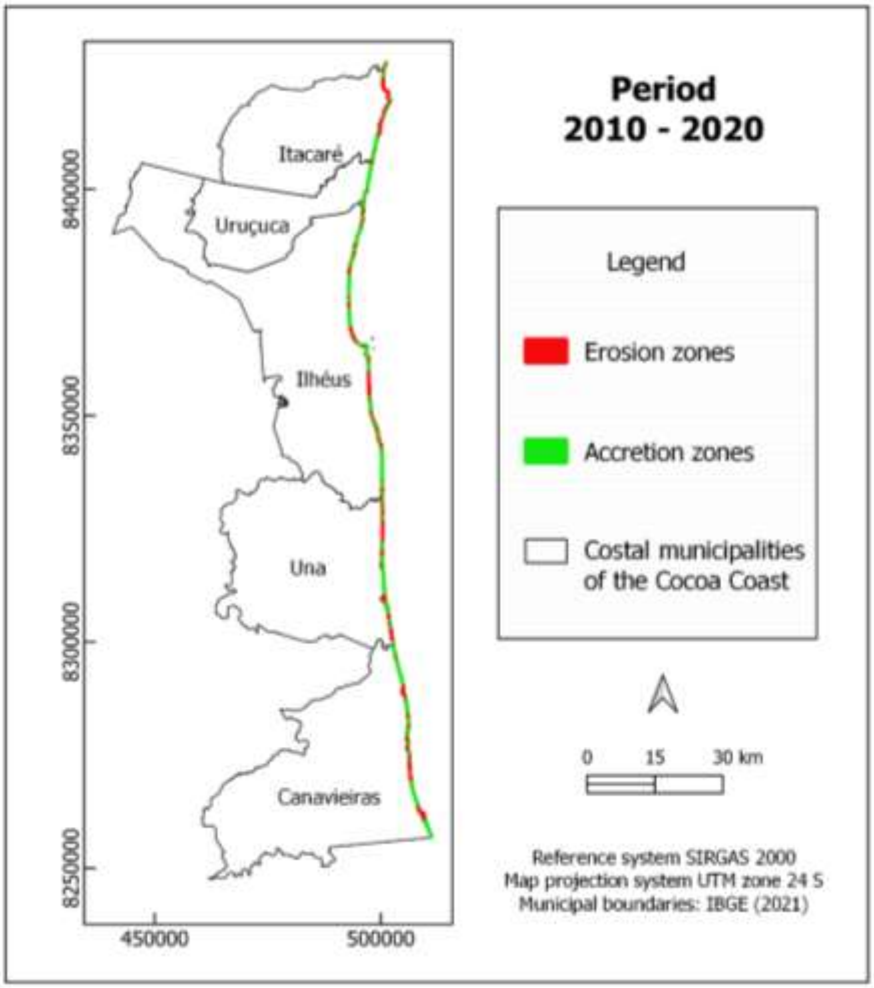

Figure 6 – Accretion and erosion zones of the coastline along the coastal municipalities of the Cocoa Coast for the analysis period from 2010-2020.
Source: The current authors (2023)

In the third time interval, between 2010 and 2020, the coastline positions for the years 2010 and 2020 were considered (Figure 6). When analysing Figure 6, it becomes evident that the presence of accretion zones is predominant throughout the study area. In Itacaré, however, there is a predominance of erosion zones. According to Yincan et al. (2017), this long-term sediment loss can result in the destruction of beaches. However, in the most extreme regions of this municipality, both to the south and north, there is the presence of accretion zones. In Uruçuca, accretion zones predominate, but with very few areas experiencing the accretion process. When examining the municipality of Ilhéus, it can be seen that the accretion zones are more extensive but they alternate with erosion zones, which tend to be more extensive in the central region of the coastal strip of the municipality. In Una, in the northernmost region of the municipality, there is a predominance of erosion zones, while in the southernmost region, accretion zones predominate. In the municipality of Canavieiras, it is noteworthy that most of the sediment erosion zones occur near areas where rivers meet the Atlantic Ocean. However, along the coastal boundary of the municipality, the extent of accretion zones is more extensive, indicating a tendency towards a positive sediment balance.

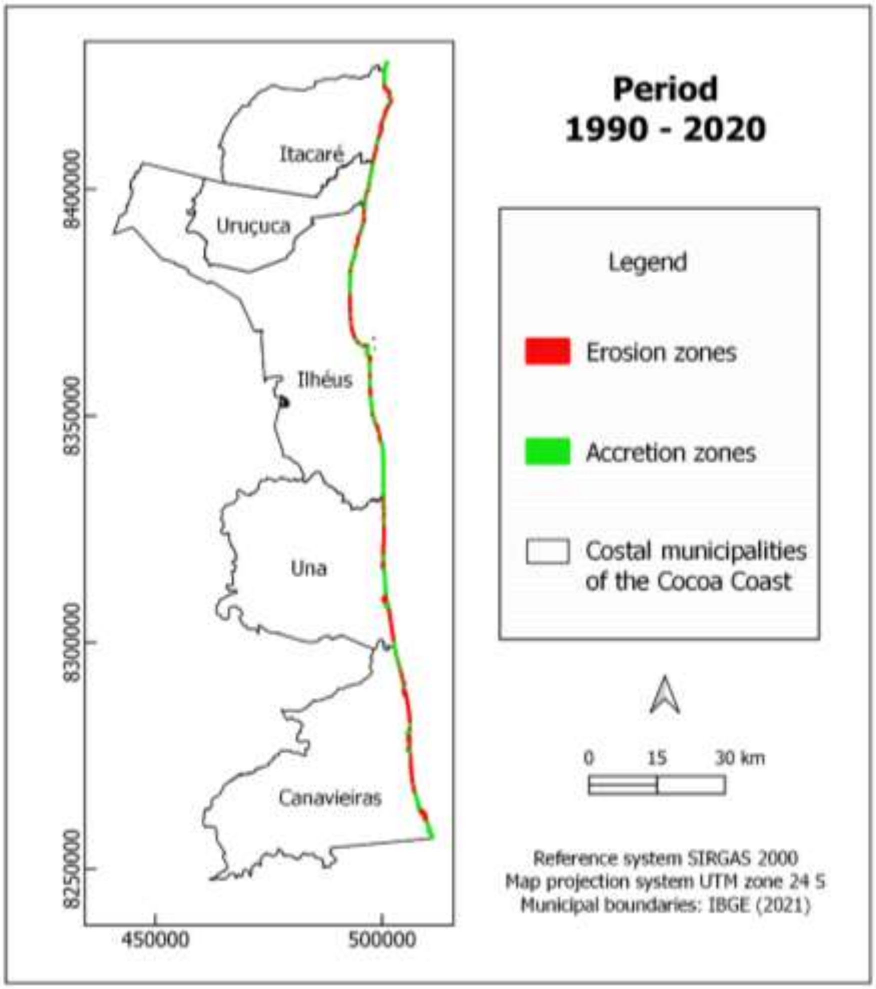

Figure 7 – Accretion and erosion zones of the coastline along the coastal municipalities of the Cocoa Coast for the analysis period 1990-2020.
Source: The current authors (2023)

The fourth observed time interval was between 1990 and 2020 and, in this analysis, the coastline position in 1990 was compared to the coastline position in 2020. Figure 7 evidently shows that, over this period, both the accretion and erosion processes were active. In such cases, as stated by Nehra (2016), detection work requires frequent monitoring of coastlines and is essential for understanding the coastline dynamics and processes related to coastal features. In the municipality of Itacaré, there was a general predominance of erosion zones, with only the northernmost region of the municipality showing a slightly more extensive area where accretion occurred. In Uruçuca, there is a predominance of accretion zones. In Ilhéus, it can be observed that most of the erosive processes occur in the northern region of the municipality's coastline. In contrast, in the southern region, accretion zones are more extensive and continuous. In the municipalities of Una and Canavieiras, a predominance of erosion zones is also noticeable.

3.3 Quantification of accretion and erosion areas

In this section, the results of the quantification of accretion and erosion areas for each municipality, and considering the entire extent of the Cocoa Coast, are presented for the different time intervals studied. These data can be seen in Table 2 below. It should be noted that, for the calculation of the sediment balance, the total accreted area minus the total eroded area was considered. Therefore, a negative sediment balance represents the fact that the total eroded area exceeded the total accreted area, while a positive sediment balance represents the fact that the total eroded area was less than the total accreted area.

Table 2 – Eroded and Accreted Area Values in square kilometers for different analysed periods.

	Area (km^2)							
Period	**1990-2000**		**2000-2010**		**2010-2020**		**1990-2020**	
Process / Region	Accretion	Erosion	Accretion	Erosion	Accretion	Erosion	Accretion	Erosion
Itacaré	0.5158	0.3192	0.1886	0.3013	0.4538	0.2024	0.5814	0.2460
Uruçuca	0.0515	0.1078	0.0433	0.0738	0.2694	0.0109	0.1840	0.0123
Ilhéus	0.6336	0.8390	0.8826	0.3020	1.0614	0.2389	1.5823	0.4345
Una	0.4606	0.6524	0.5025	0.3804	0.8333	0.6733	1.1066	1.0164
Canavieiras	0.9086	1.4689	1.2743	0.9766	1.5151	1.1696	2.1964	2.1136
Total	2.6576	3.6422	2.9208	2.1820	4.3270	2.3710	5.8834	4.1732
Balance	ccretion-0.9846		0.7388		1.9560		1.7102	

Source: The current authors (2023)

Analysing the data in Table 2, it is evident that the action of both processes was intense for all the periods analysed. However, in the period 2010-2020, the dynamics were more intense compared to the previous two periods, with a sediment balance of nearly 2 km^2. In the first period (1990-2000), there was a change of 0.98 km^2, where erosion prevailed over accretion. In the second period (2000-2010), a change in the total area of 0.74 km^2 was observed, and a modification in the dynamics from the previous time interval was noted, characterised by the prevalence of accretion over erosion. However, according to Silva et al. (2015), when the difference between the processes of accretion and erosion is relatively small, considering the entire extent of the study area, it can be inferred that there is a relative balance in the analysed period. For the third period (2010-2020), there is an increase in the total altered area (1.96 km^2), and so accretion is still predominant. In this period, the difference, in terms of the altered areas between both processes, also increased significantly. Finally, the period representing all changes that occurred from 1990 to 2020 provides an overall account of the action and makes it clear that, throughout this period, accretion predominated over the erosion process.

4. Final considerations

The approach used in this study, based on the spatial overlay of coastline vectors extracted from remote sensing images, allowed for the identification of the coastline positions for the years 1990, 2000, 2010, and 2020, as well as the quantification of the variations that occurred over the analysis period. It is worth noting that there is a limitation in the accuracy of this quantification, which is related to the pixel size of the images used, which were from the LANDSAT series with a 30 m pixel. However, considering the entire extent of the study area and the scale of the mapping conducted, the data obtained allowed inferences about the observed dynamics.

The total area modified by the accretion and erosion processes increased significantly between the first (1990-2000) and the last (2010-2020) decades investigated. The analysis of the spatiotemporal dynamics of the coastline in the Cocoa Coast region during the periods considered, allowed us to observe that the accretion process predominated over the erosion process in the periods from 2000 to 2010 and from 2010 to 2020. Only in the first period (1990-2000), did erosion predominate over accretion. Considering the variations that occurred over the entire study period (from 1990 to 2020), there is also a predominance of the accretion process. The results obtained show that the Costa do Cacau region has an intense dynamic and, even with a general trend of accretion, various sections experience erosion processes.

As elucidated by Mazzer and Dillenburg (2009), this observed dynamic demonstrates the importance of conducting studies with temporal scales exceeding decades, to obtain more precise answers regarding the occurrence of these processes. However, for coastal planning and management purposes, both interdecadal and interannual scales are important within the context of historical scale. Therefore, considering the social, economic, and environmental relevance of the Cocoa Coast, it is recommended that future studies analyse short to medium-term variations, to better understand the factors that influence the coastal dynamics of the region, providing support for the maintenance and protection of this environment.

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