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Potential Use of Mangroves as Nature-Based Solutions to Improve Navigation Conditions in a Port in Southern Brazil

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ABSTRACT: Mangroves and the associated shoal forest known as 'restinga' are ecosystems of great ecological relevance that play a significant role in the protection of the coastline in tropical regions. In Brazil, the coastal region has been severely affected by urban expansion. The Paranaguá Port, located in Paraná State (Brazil), is the fourth most important Brazilian port in throughput, and is located in an estuarine region which features large mangrove forests. An historical assessment of its inner access channel dredging rates was made to assess the impacts that the expansion of the Port in the last 30 years may have caused to the ecosystem. In the following, the historical data concerning the dredged volume in the inner access channel was compared to the mangrove and the shoal forest associated variation, aiming to establish a potential correlation between vegetation and siltation in the inner access channel to show as the preservation or restoration of specific ecosystems has potential to Nature-Based Solutions.

1 INTRODUCTION

Mangroves and the associated shoal forest known as 'restinga' are ecosystems of great ecological relevance that also play a significant role in the protection of the coastal line in tropical regions, reducing the erosive effects of marine processes as well as decreasing the deposition of fluvial siltation in estuaries [1, 2]. They are also highly productive and capable of storing large amounts of carbon, serving as sinkholes [3]. Brazil features the third largest extension of mangroves in the world, covering approximately 9,900 km2, only surpassed by Indonesia and Australia. The total area of Brazilian mangroves remained relatively stable between 1985 and 2018, despite the urban and real-estate developers' pressure to occupy these ecosystems [4], which are legally protected by the Brazilian Forest Code and labelled as 'Permanent Protection Areas' (APP). During this period, around 75% of Brazilian mangroves forests remained unchanged for two decades or more [4]. This trend is in opposition to those observed in most tropical countries. For instance, Ecuador lost around 50% of its mangrove forests to aquaculture between 1980 and 2000. The Philippines converted nearly 279,000 ha from 1951 to 1988 [5]. The data concerning these 2 countries is comparable to Brazil because all of them present similar social and environmental characteristics, as well as similar sources of deforestation pressures [5].

In Brazil, mangroves are found between latitudes 04o 30′ N and 28o 30′S, ranging from the Amazonian state of Amapá to Santa Catarina, beyond the Tropic of Capricorn. Of the coastal Brazilian states, only Rio Grande do Sul doesn't feature mangroves. The distribution of the Brazilian population along the coastline isn't homogeneous, therefore the risks to which mangroves and the associated shoal forest are exposed differ from region to region considering that the primary driver of land conversion is anthropogenic activities. The proportion of mangrove loss due to climate causes, however, has been increasing worldwide in the last 20 years in comparison to human-driven causes [6]. Figure 1 illustrates a typical mangrove environment in Brazil.

Figure 1. A typical healthy mangrove vegetation. The trees are submitted to the periodical tidal flood conditions in which their roots act like riparian structures, entrapping sediments and reducing the silt up of water bodies.

Additionally, it is important to highlight that, even though in the grand scale Brazilian mangroves are stable, locally they are subjected to dynamics that are not well measured in monitoring reports that rely only on remote sensing [7].

The usage of mangroves, the ‘restinga' and other coastal ecosystems as Nature-Based Solutions can prove to be a reliable mechanism to both promoting climate adaptations to vulnerable regions and restoring natural areas that provide ecosystem services which impact directly in the maintenance of biodiversity, which already has an inherent value [8]. In the case of wetland replacement, however, it is indicated that the ‘green infrastructure’ be used alongside conventional engineering structures, such as dykes, to protect the newly placed sediments and vegetation so they have enough time to consolidate [9].

The main purpose of this research is to delimitate the importance of mangroves and the shoal forest around Paranaguá and Antonina Ports (PAP) inner access channel to evidence how the preservation or restoration of specific ecosystems has the potential to be used as Nature-Based Solutions.

2 CHARACTERIZATION OF THE AREA OF INTEREST

In the Southern Brazilian state of Paraná lies one of the largest harbour areas in the country, the Paranaguá Port and, further upstream the channel, lies the smaller Antonina Port. The Paranaguá Port is the fourth largest port in throughput in Brazil (58,399,109 t in 2022), and the third in container shipping (607,070 TEUs in 2022). It is also the most important Brazilian port for exporting agricultural products such as soybean and soybean meal. The Antonina Port, on the other hand, is much smaller and mostly used for cabotage and it can be considered as an auxiliary structure to the Paranaguá Port. Both are in the Paranaguá Estuarine Complex (PEC). The area is part of one of the largest continuous Mata Atlântica (Atlantic Rainforest) remainings, especially due to the presence of the Serra do Mar (Sea Chain), a system of mountain ranges and escarpments that stretches for approximately 1,500 km neighbouring the Brazilian coastline that has hampered human settlements. Figure 2 shows the location of the PEC.

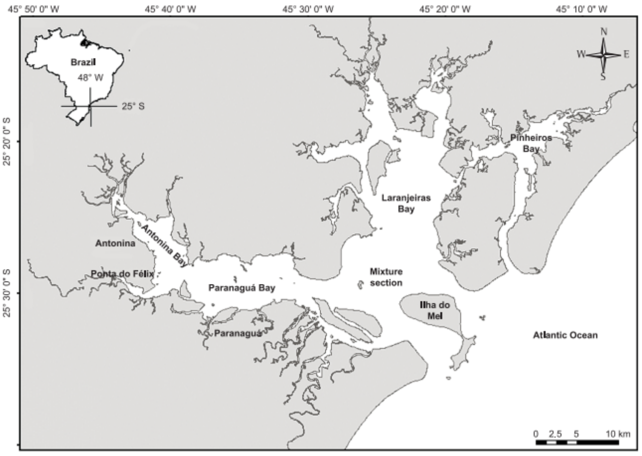

Figure 2. The PEC in the Brazilian State of Paraná [10]. The region is one of the most ecologically important estuaries in the Brazilian subtropical region, which is encompassed by five municipalities (Guaraqueçaba, Antonina, Morretes, Paranaguá and Pontal do Paraná).

The Mata Atlântica has been severely deforested elsewhere and is considered a biodiversity hotspot due to the presence of several threatened and endemic species. The Paranaguá and Antonina Port areas and their activities are, thus, inserted in this context and are part of a delicate balance that involves economical activities, social improvement, sustainable development, and nature maintenance. In the current study, it was analysed the correlation between the mangrove and the shoal forest associated area and the dredged volume in the inner access channel to the Paranaguá and Antonina Ports (PAP), thus establishing a potential synergic effect between nature conservancy and infrastructure performance. Figure 3 presents the area of interest.

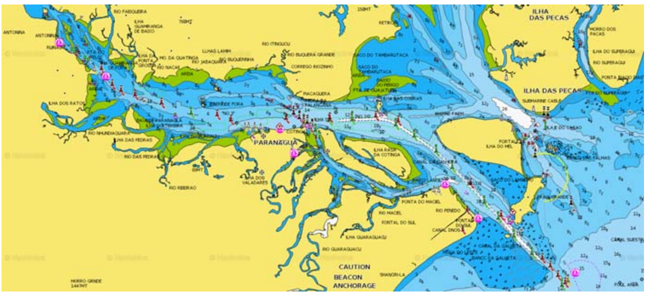

Figure 3. Depiction of the area of interest in the Southern portion of the PEC. The access channel corresponds to the central talweg, right southern the island known as Ilha do Mel, depicted in the eastern portion of the figure.

The area of interest comprises only the inner access channel, thus, although the area as whole is relatively well preserved, the Southern portion of the Bay, where the channel is located, as well as the main cities and coastal infrastructure, is more severely impacted by urban settlements and the pollution and silting up of water bodies.

The inner access channel drains several watersheds whose flow rates and sedimentary inputs are fundamental parameters to comprehend the sedimentation processes in the internal portion of the Bay. The watersheds that drain towards the area of interest are identified by the following main rivers: Cachoeira, Nunes, Nhundiaquara, Pinto, Marumbi and Sagrado. All of the aforementioned rivers have hydrologic historical data series provided by Agência Nacional de Águas – ANA (National Waters Agency) that enable the calculation of suspended fine sediments discharge.

The sector of the channel between the Paranaguá and Antonina Port, known as Delta 1 and which corresponds to the Zone of Maximum Turbidity (ZMT), has been continuously presenting, in the last decades, a problem related to the presence of a fluid mud layer near the bottom (layers up to 0.5 m), which is associated to the concentration of fine cohesive sediments that feature colloidal behaviour and a high percentage of clay particles [9]. The rapid formation of fluid mud deposits reduces channel depths and negatively impacts the navigation of vessels, silting up water bodies and increasing the costs associated with dredging the channel to navigable depths [11]. Figure 4 illustrates the internal divisions of the channel.

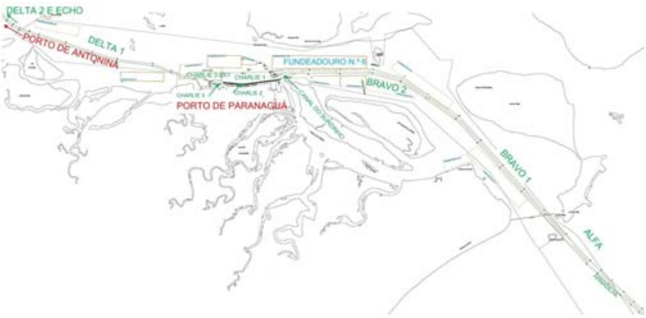

Figure 4. Internal divisions of the access channel to the PAP. The Delta 1 region, between the Antonina and Paranaguá Ports, is where the fluid mud is concentrated and, consequently, where silting up is more frequent.

Table 1 indicates the nautical dimensions of each segment of the inner access channel.

Table 1. Dimensions of each segment of the inner access channel in the PEC as of 2015.

Segment	Depth (m)	Length (m)	Width (m)
Alfa	15.00	8,600	200.00
Bravo 1	13.50	6,052	200.00
Bravo 2	13.50	14,448	200.00
Charlie 1	12.00	3,000	600.00
Charlie 2	12.00	3,300	50.00
Charlie 3	12.00	2,500	400.00
Charlie - Internal	11.00	900	135.00
Delta 1	8.00	12,300	110.00
Delta 2	8.00	980	400.00
Surdinho	13.00	900	220.00

3 MATERIAL

In the following, it is presented the data used in this research to assess potential variables that could impact the dredged volume in the channel.

3.1 *Soil Use and Occupation in the Southern Portion of the PEC*

The data used to determine the long-term soil use and occupation in the Southern Portion of the PEC (Paranaguá, Antonina and Morretes) was taken from the MapBiomas v.7.0, a collaborative network that produces yearly mapping of soil use, water surface and fire scars, starting from 1985 until the current date. The platform uses Landsat images, which have an average resolution of 30 m. The calibration of the system made by a group of experts and the reliability of the platform is such that MapBiomas is used extensively by a wide range of political and social agents to substantiate public policies.

3.2 *Hydrologic Data*

The data used to determine the flow rate and sedimentary input from all of the watersheds that are drained to the area of interest were obtained in the Hidroweb website maintained by the Agência Nacional de Águas – ANA (National Waters Agency). Based on the provided information, it was possible to calculate the rating curve of liquid and sedimentary flows of the rivers Cachoeira, downstream to the UHE Governador Parigot de Souza - ANA Station 82121003, Nunes - ANA Station 82140700, Nhundiaquara - ANA Station 82170000, Marumbi - ANA Station 82195002, Pinto - ANA Station 82198000 and Sagrado - ANA Station 82198300.

3.3 *Pluviometry Data*

The pluviomety data for the Paranaguá region was obtained in the Instituto Nacional de Meteorologia – INMET (National Meteorologic Institute) database. The historical series ranges from 1961 to 2021.

4 RESULTS

In the graph depicted in Figure 5 it is presented the yearly deforestation rate of primary vegetation in the Southern portion of the PEC from 1987 to 2020. The surface of the vegetation loss is measured in hectares.

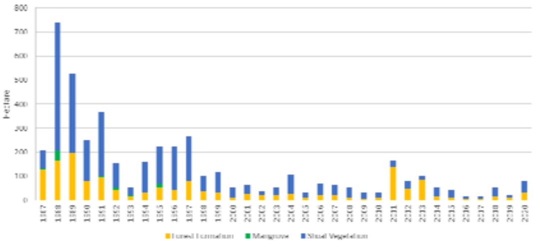

Figure 5. Deforestation rate of primary vegetation from 1987 to 2020. Except for some years, shoal vegetation (in blue) was the most deforested ecosystem in the Southern PEC.

The results indicate that the deforestation rates of primary vegetation in the Southern PEC have experienced a sharpened decrease since its historic series peak in 1988. In comparison to forest formations and shoal vegetations, mangrove is the least deforested ecosystem in the region. Except for some specific years during the historic series, shoal vegetation was the most deforested ecosystem in the region, whose suppression represented more than 50% of most yearly deforestation rates, especially when they were higher. That is expected, since most urban settlements and infrastructure are in the coastal plain, where shoal vegetation prevails, such as the one illustrated by Figure 6.

Figure 6. A typical shoal vegetation in the Southern Atlantic coast of Brazil. These trees are lower and bushier than the forests that cover the Serra do Mar slopes and are adapted to sandy environments.

Forest formations, on the other hand, dominate the hilly terrain of the Serra do Mar, improper for land occupation, which is also protected by its legal status as a Conservation Unit. It is also important to note that, after 1995, mangrove deforestation in the region was mostly irrelevant, smaller than 1 hectare.

In the graph depicted in Figure 7, it is presented the yearly deforestation rate of secondary vegetation, therefore regrown, in the Southern portion of the PEC from 1987 to 2020. The surface of the vegetation loss is measured in hectares.

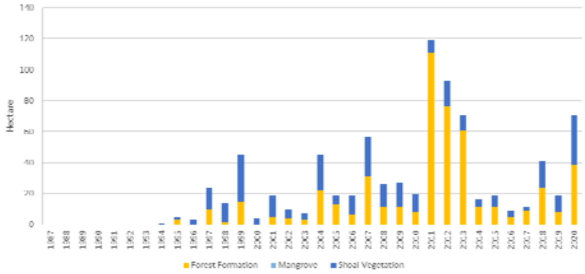

Figure 7. Deforestation rate of secondary vegetation from 1987 to 2020.

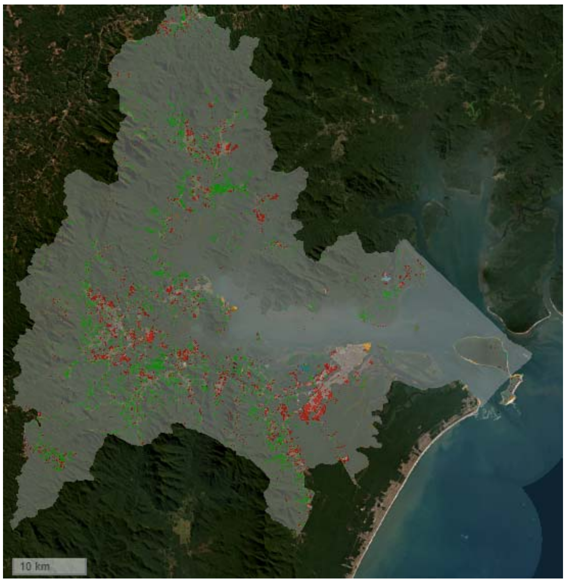

Figure 8. Historical transition map of the Southern portion of the PEC, between 1987 and 2020. In red it is represented the secondary vegetation suppression and, in green, vegetation growth. The Serra do Mar range is located in the outer borders of the highlighted region.

The deforestation rate for secondary vegetation follows a significantly different trend than that observed for primary vegetation. In the first period of the historic series, from 1987 through the mid-nineties, secondary vegetation deforestation was mostly irrelevant. Since then, however, there has been a continuous increase in the vegetation suppression, mostly in forested environments. It is important to note that the deforestation of secondary vegetation was predominantly made for urban expansion and agricultural activities near water bodies, as depicted in red in Figure 8.

The graph depicted in Figure 9 presents the average yearly pluviosity for the region from 1961 to 2021.

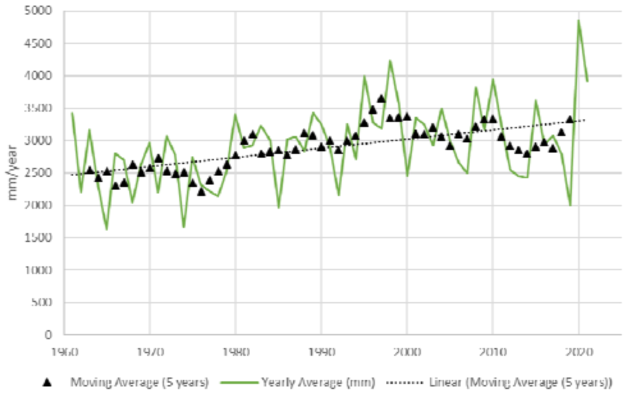

Figure 9. Average yearly pluviosity in the Paranaguá region from 1961 to 2021. The Paranaguá rainfall station is located near the Port, thus it is more representative of the phenomena that are taking place in the lowlands, near the estuary.

The pluviosity trend between 1961 and 2021 indicates an increase in the average rainfall in the Paranaguá region. This may be related to climate change since the Southeastern South America sub-region is expected to experience a surge in mean precipitation, as already observed in some other regions, such as São Paulo and Rio de Janeiro [12]. An increase in the precipitation is likely to affect the salinity of the estuary, which may be detrimental to the mangrove ecosystem that lies in the coastal interface. These effects, however, will also be influenced by the expected sea-level rise in the internal regions of the PEC [13].

Besides the increase in the yearly average pluviosity, there has also been a surge in the maximum daily precipitation, indicating that more intense climate phenomena are happening in the PEC. The current situation already poses a risk to the population exposed to vulnerable conditions, such as people living near water bodies, and an intensification of these events will likely affect a larger percentage of the population. It is expected that the current infrastructure will also be severely affected by damage and floods.

Figure 10 presents the location where bottom sediment samples were collected in the access channel from 2014 to 2020.

The graph presented in Figure 11 shows the results of d50 (mm) for each sample.

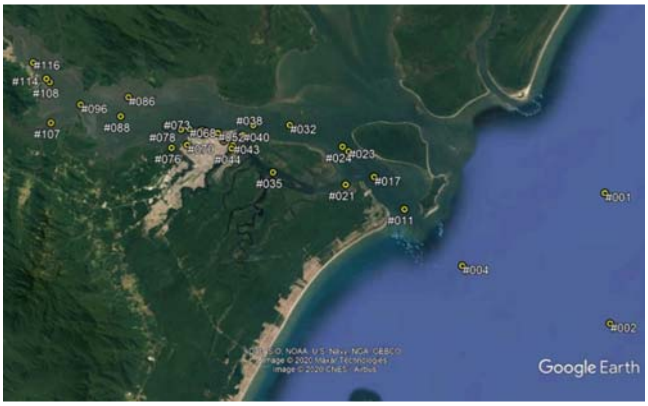

Figure 10. Location where bottom sediment samples were collected in the access channel between 2014 and 2020.

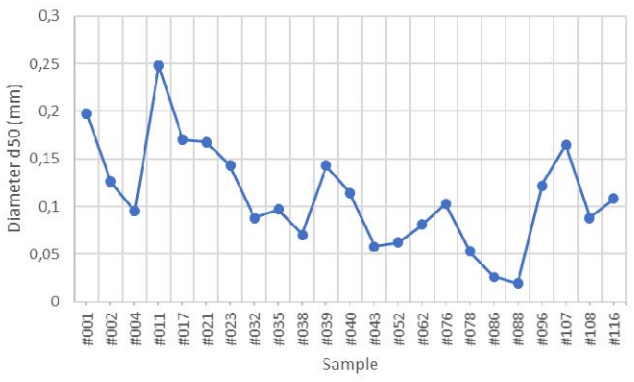

Figure 11. Results of sample diameter size d50 (mm) collected in the access channel from 2014 to 2020. The results clearly indicate that the smallest sediment particles were obtained in samples #086 and #088, both collected in the Delta 1 sector.

Table 2 indicates the sedimentation input and the dredged volume in the sectors Delta 1 and Delta 2/Echo between 2000 and 2017, based on the data provided by the Hidroweb website and information disclosed by the administration of the PAP.

Table 2. Sedimentation input and dredged volume in the sectors Delta 1 and Delta 2/Echo from 2000 to 2017.

	Delta 1		Delta 2/Echo	
Year	Sedimentation Input (m³)	Dredged Volume (m³)	Sedimentation Input (m³)	Dredged Volume (m³)
2000	558,333	52,485.3	497,883	16,098.7
2001	321,505	149,516.0	278,108	45,860.8
2002	410,786	99,677.4	420,031	30,573.8
2003	389,074	-	349,487	-
2004	328,913	3,136.1	304,617	961.9
2005	470,878	-	395,935	-
2006	426,961	-	377,548	-
2007	181,298	92,542.6	342,822	28,385.4
2008	85,976	-	313,064	-
2009	824,975	-	367,304	-
2010	327,697	-	353,150	-
2011	1,121,519	-	783,257	-
2012	1,682,242	-	401,531	-
2013	213,440	675,240.0	326,618	417,789.0
2014	381,626	886,416.0	297,735	105,384.0
2015	99,809	-	291,307	-
2016	94,779	2,677,317.0	284,969	777,039.0
2017	83,676	-	372,590	-

Figure 12 presents a comparison in trend between the yearly sedimentation input given to the main Delta 1 sector by the affluent watersheds, the deforestation rates in the Paranaguá municipality and the volume dredged from the sector. The data used to compile the yearly sedimentation input was obtained from the ANA database in the Hidroweb website. The deforestation rates are limited to the Paranaguá municipality due to its participation in the sedimentation input to the Delta 1 sector, mostly affected by the rivers within its borders.

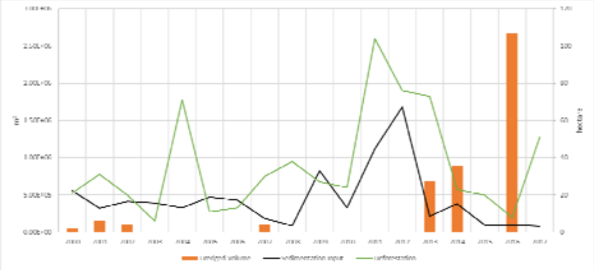

Figure 12. Comparison in trend between the sedimentation input (in black), deforestation rates in Paranaguá (in green) and the volume dredged in the Delta 1 sector (in orange). It is observable that the sedimentation input is correlated to the deforestation rates in the watershed encompassed by the Paranaguá municipality and also with the dredging rate (with a time lag).

Figure 13 presents a comparison in trend between the yearly sedimentation input given to the main Delta 2 and Echo sectors by the affluent watersheds, the deforestation rates in the Morretes and Antonina municipalities and the volume dredged from both sectors. The data used to compile the yearly sedimentation input was taken from the ANA database in the Hidroweb website. The deforestation rates were limited to Morretes and Antonina due to the participation of the watersheds encompassed by both municipalities in the sedimentation input to the Delta 2 and Echo sectors.

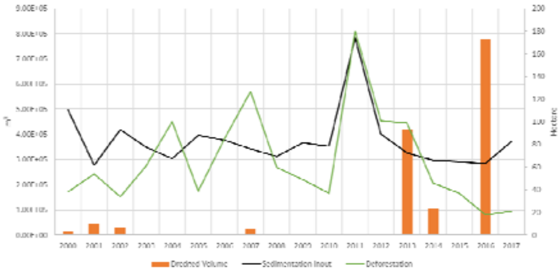

Figure 13. Comparison in trend between the sedimentation input (in black), deforestation rates in Antonina and Morretes (in green) and the volume dredged in the Delta 2 and Echo sectors (in orange). As observed in the Delta 1 sector, the sedimentation input is correlated to the deforestation rates in the watershed encompassed by both cities and with the dredging rate (also with a delay).

5 CONCLUSIONS

The results summarised in Figures 12 and 13 show the correlation of deforestation increase in the hydrographic basins and maintenance dredging over a given threshold. That is evidenced by the increase in maintenance dredging in the sectors of the main access channel where most rivers discharge. The lags between the peaks occurring with both parameters are related to the administrative efficiency of the Port Authority's concerning the response time required to schedule dredging.

It can also be inferred that the mentioned threshold depends on the natural cleaning capacity of tidal currents in the bay versus the silting rate associated with deforestation.

The importance of mangroves and the shoal forest indicate that their preservation or restoration may be considered a Nature-Based Solution to improve the management of the port's infrastructure.

The deforestation rates of primary vegetation in the PEC have been constantly dropping since the start of the historic series, in 1987. The major drivers for these changes are probably associated with the creation of several Conservation Units in the Serra do Mar hills and bordering the estuary. The trend of secondary forest loss, on the other hand, has dramatically increased in the last 25 years. This type of vegetation stems from the shallow cut of a former primary forest and is not as nearly complex as the original vegetation. Considering the transition map presented on Figure 7, most of the deforestation was made for urban expansion or agricultural activities in the lowlands of the PEC. Considering that deforestation was concentrated in areas near water bodies, combined with the high pluviosity that is characteristic of the region, it may have led to an increase in sedimentation input to the estuary, which, in the long term, is detrimental to the navigation in the inner access channel, especially in the Delta 1 sector, majorly dependent on the watershed encompassed by Paranaguá city.

The silting up of the inner access channel requires much more maintenance dredging to provide the design depth of navigation, which is a costly operation that also impacts directly in the maintenance of the port and its related activities.

It is noteworthy that, despite the contrary trends observed for primary and secondary vegetation, mangrove forests have never been majorly deforested in the region during the historic series. This may be related to the protection imposed by the Brazilian Forest Code to this type of ecosystem. Even the expansion of the Paranaguá Port hasn't directly led to mangrove loss because, since 1997, no deforestation of this vegetation was observed in the historic series. Shoal vegetation, however, has been continuously affected by deforestation, which led to impacts in the sedimentation input to the estuary. It is possible to assume that there is an interaction between both estuarine ecosystems and, when one of these vegetation is destroyed, there is a decline in the ecosystem services provided by them.

The data concerning the pluviosity in the Paranaguá estuary indicate that the mean rainfall has been constantly increasing in the last 50 years, a phenomenon that is probably closely related to climate change. The prognostic elaborated by the last IPCC report states that the Southeastern South America sub-region will experience a dramatic surge in the average pluviosity and in the intensity of extreme climatic events, which will be harmful both to infrastructure and to populations exposed to vulnerable conditions. Furthermore, it is expected that the increase in pluviosity may have a significant impact in the volume of sediment entrainment, thus, again, impacting the navigation of the inner access channel.

The results point out to the importance of preserving the riparian forests in the shoal lowlands, where Conservation Units are lacking, in comparison to the slopes of the Serra do Mar, and, if needed, the recomposition of areas that are currently deforested and occupied by shrubs, agricultural activities or exposed soil, especially in view of climate change. In addition to the interrelation between deforestation and sedimentation input, which negatively affects the design depth of navigation in the estuary, requiring the employment of costly dredging activities, the recomposition of vegetation may prove to be a dynamic agricultural activity in itself, considering the opportunities that are arising from the implementation of the Nationally Determination Contributions (NDC) of the Paris Agreement and the discussions related to carbon marketing.

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