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Editorial note / *Nota editorial*

COASTAL EROSION AND POLLUTION IN DEVELOPED COASTS

Francisco Taveira-Pinto[1], Paulo Rosa-Santos[1], Tiago Fazeres-Ferradosa[1], A. Rita Carrasco[2]

Increased human activities and coastal development are quickly affecting most of the world's coastlines. Therefore, it is still critical to assess at the regional level, how various coastal pressures will impact distinct landscapes (Taveira-Pinto *et al*., 2022a). The current issue explores two main pressures in the coastal systems: coastal erosion and human induced pollution.

While Taveira-Pinto *et al*. (2022b) invoke the main causes of shoreline retreat and coastal erosion (natural and anthropogenic) in the northern Portuguese coast of Portugal, Isa *et al*. (2022) describe analytically the focused impacts of urban expansion in the southern sandy temperate dunes of Argentina.

The work of Taveira-Pinto *et al*. (2022b) is a benchmarking study to define the past and current vulnerability of a highly developed coast, with crucial importance for the Portuguese economic and cultural contexts. The authors proposed the use of state-of-art methods (set-back lines) to assess local vulnerability due to coastal storms and envisage its adoption in large-scale coastal management plans. Selected examples are provided by the authors to demonstrate the potential of this methodology in supporting the development of coastal zone management plans, but also to highlight the limitations and uncertainties related to the complexity of the phenomena under analysis.

Based on lessons learned from dune afforestation in Buenos Aires sandy barriers, Isa *et al*. (2022) highlight the consequences of the systematic replacement of native vegetation by fast-growing exotic species in dune ecosystems, concluding that the observed fixation of dunes generates a sedimentary imbalance and induces local erosion, among other negative effects. This work evaluates environmental milestones on urban expansion on local dune fields and concludes that local revegetation should be made by means of native species corresponding to the original landscape of the dunes of about a century ago.

Such as erosion, coastal pollution is an emerging issue of the present-day world, attempting to unbalance the natural equilibrium in coastal and terrestrial ecosystems. This journal issue presents two works that address the topic. Almeida *et al*. (2022) establish a methodological portfolio for the characterization of marine microplastic-pellets whereas the work of Aguiar *et al*. (2022) describes the eutrophication status at the entrance of a tropical urbanized estuary in Guanabara Bay (Brazil).

Almeida *et al*. (2022) conducted sampling surveys along a stretch of the Brazilian coast to collect and assess microplastic-pellets metrics and typology. The authors propose a standard-basis scheme for pellets classification likely of being applied worldwide as a tool to identify and evaluate human pollution sources based on plastic.

Aguiar *et al*. (2022) assess pollution levels in the water column and sediment, by employing the trophic index (TRIX) that encompasses four main environmental variables: saturation of dissolved oxygen, chlorophyll-a, dissolved nitrogen, and phosphorus. Obtained results were further compared with other locations and classified accordingly to anthropogenic pressures and raising awareness about the need to develop public policies at the local scale to suppress pollution sources.

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EROSÃO COSTEIRA E POLUIÇÃO EM ZONAS COSTEIRAS DESENVOLVIDAS

O aumento das atividades humanas e o desenvolvimento económico estão a afetar, rapidamente, a maioria das zonas costeiras no mundo. Por conseguinte, torna-se importante avaliar localmente os impactos que as várias pressões costeiras poderão ter em ambientes costeiros distintos (Taveira-Pinto et al., 2022a). O presente número apresenta contributos relativos a dois dos principais problemas dos sistemas costeiros: a erosão costeira e a poluição induzida pelo homem.

Taveira-Pinto et al. (2023) analisam as principais causas do recuo e da erosão costeira (natural e antropogénica) na costa norte de Portugal e Isa et al. (2022b) descrevem analiticamente os impactos da expansão urbana nas dunas temperadas arenosas do sul da Argentina.

O trabalho apresentado por Taveira-Pinto et al. (2022b) é um estudo de benchmarking que procura definir a vulnerabilidade presente e passada de uma costa altamente desenvolvida, com importância crucial para os contextos económicos e culturais portugueses. Os autores propõem a utilização de métodos reconhecidos no estado-da-arte (set-back lines) para avaliar a vulnerabilidade local causada por tempestades costeiras e analisam a importância da sua aplicação em planos de gestão costeira de grande escala. Os autores demonstram e exemplificam o potencial desta metodologia no apoio ao desenvolvimento de planos de gestão costeira, destacando ainda as limitações e incertezas relacionadas com a complexidade dos fenómenos em análise.

Com base nas lições aprendidas no que respeita à florestação de dunas em Buenos Aires, Isa et al. (2022) realçam as consequências da substituição sistemática da vegetação nativa por espécies exóticas de crescimento rápido nos ecossistemas dunares. Os autores concluem que a fixação de dunas gera um desequilíbrio sedimentar e incrementa a erosão local, entre outros efeitos negativos. Este trabalho avalia diversos marcos ambientais relativos à expansão urbana nos campos de dunas locais e conclui que a re-vegetação local deve ser feita através de espécies nativas que correspondam à paisagem original das dunas, isto é, de há cerca de um século.

Tal como a erosão, a poluição costeira é uma questão emergente do mundo atual, com impacto no equilíbrio natural nos ecossistemas costeiros e terrestres. Este número da revista apresenta dois trabalhos que abordam este tópico. Almeida et al. (2022) estabelecem um portfolio metodológico para a caracterização de micro-plásticos marinhos enquanto Aguiar et al. (2022) descrevem o estado de eutrofização à entrada de um estuário tropical urbanizado na Baía de Guanabara (Brasil).

Almeida et al. (2022) realizaram levantamentos por amostragem ao longo de um trecho da costa brasileira para recolher e avaliar a métrica e a tipologia de micro-plásticos presentes no local. Os autores propõem um esquema padrão para a classificação de plásticos que pode ser aplicado a nível mundial, como uma ferramenta para identificar e avaliar fontes de poluição humana com base na amostragem de micro-plásticos.

Aguiar et al. (2022) avaliaram os níveis de poluição na coluna de água e nos sedimentos, através do índice trófico (TRIX) que engloba quatro variáveis ambientais principais: saturação de oxigénio dissolvido, chlorophyll-a, azoto dissolvido e fósforo. Os resultados obtidos foram ainda comparados com outros locais e classificados em conformidade com as pressões antropogénicas e a crescente necessidade de sensibilização para o desenvolvimento de políticas públicas à escala local que promovam supressão de fontes de poluição.

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ASSESSMENT OF EUTROPHICATION THROUGH ECOLOGICAL INDICATORS AT THE ENTRANCE OF A TROPICAL URBANIZED ESTUARY

Valquiria Maria de Carvalho Aguiar[@ 1], José Antônio Baptista Neto[1], Estefan Monteiro da Fonseca[1]

ABSTRACT: Dissolved nutrients, phytoplankton biomass and other ancillary variables, were obtained at two sub-embayments at the entrance of Guanabara Bay (Rio de Janeiro, Brazil) and a composite trophic status index (TRIX) was used to assess the water quality of the study area. The role of bottom sediments in nutrient dynamics was also investigated through the evaluation nutrients, phytoplankton biomass and other sedimentary variables, since this compartment acts as a geological record of anthropogenic input. Jurujuba Sound, at the east margin, and Flamengo-Botafogo Sounds, at the western margin, were sampled during neap and spring tides in the dry season. Signs of eutrophication were detected through the extreme variations of dissolved oxygen concentrations at both margins, being more accentuated at Jurujuba Sound (2.20-14.07 mg.l^{-1}). Dissolved inorganic nitrogen was elevated at both margins and mostly composed of ammonium, surpassing 87% at Flamengo Botafogo Sounds, which suggests a continued input of raw sewage at the western margin of the bay. TRIX revealed poor water quality for most stations at the study area, varying from 4.53 to 7.29 at Jurujuba Sound and from 5.67 to 7.87 at Flamengo-Botafogo Sounds. The increase of TRIX from neap to spring tide was registered at both margins, revealing decrease of water quality. The differences in grain size between both margins played a key role in nutrient dynamics, with predominance of fine sediments at Jurujuba Sound and coarser particles at the opposite margin. Accumulation of high concentrations of TOC (0.87-6.57%) and inorganic phosphorus (154.34-1516.82 µg.g^{-1}) were favored by the predominance of fine sediments at Jurujuba Sound. The assessment of eutrophication in water column and bottom sediments revealed the maintenance of this process at the entrance of Guanabara Bay sustained by the recurrent anthropogenic input, what demands urgent action from public policies to mitigate this situation.

Keywords: nutrients, estuary, trophic index (TRIX), sediments.

RESUMO: *Nutrientes dissolvidos, biomassa fitoplanctônica, e outras variáveis auxiliares, foram obtidas em duas enseadas na estrada da Baía de Guanabara (Rio de Janeiro, Brazil) e um índice trófico composto (TRIX) foi utilizado para avaliar a qualidade da água na área de estudo. O papel dos sedimentos de fundo na dinâmica dos nutrientes também foi investigado através da avaliação de nutrientes, biomassa fitoplanctônica e outras variáveis sedimentares, já que este compartimento atua como um registro geológico de aporte antropogênico. A Enseada Jurujuba, na margem leste, e as Enseadas de Flamengo-Botafogo, na margem oeste, foram amostradas durante as marés de quadratura e sizígia na estação seca. Sinais de eutrofização foram detectados através da variação extrema de oxigênio dissolvido em ambas as margens, sendo mais acentuada na Enseada Jurujuba (2.20-14.07 mg.l^{-1}). O nitrogênio orgânico dissolvido foi elevado em ambas as margens e majoritariamente composto de amônio, ultrapassando 87% nas Enseadas Flamengo-Botafogo, o que sugeriu aporte contínuo de esgoto bruto na margem oeste da baía. O TRIX revelou baixa qualidade da água para a maioria das estações da área de estudo, variando de 4.53 a 7.29 na Enseada Jurujuba e de 5.67 a 7.87 nas Enseadas Flamengo-Botafogo. O aumento do TRIX entre quadratura e sizígia foi registrado em ambas as margens, revelando a piora da qualidade da água. As diferenças granulométricas entre ambas as margens tiveram papel fundamental na dinâmica dos nutrientes, com predominância de sedimentos finos na enseada Jurujuba e grãos mais grossos na margem oposta. A acumulação de elevada concentração de carbono orgânico total (TOC) (0.87-6.75%) e fósforo inorgânico (154.34-1516.82 µg.g^{-1}) foram favorecidos pela predominância de sedimentos finos na enseada Jurujuba. A avaliação da eutrofização na coluna d'água e sedimentos de fundo revelou a manutenção deste processo na entrada da Baía de Guanabara mantido pelo aporte antropogênico recorrente, o que demanda ação urgente do poder público para mitigar essa situação.*

Palavras-chave: *nutrientes, estuário, índice trófico, sedimentos.*

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1. INTRODUCTION

In the freshwater to ocean continuum, estuaries are crucial areas for the study of land-ocean interactions concerning marine biogeochemistry. Mixing of seawater and freshwater at ebb and flow tides in an hourly scale has a determinant role on nutrient dynamics as well as changes of physico-chemical properties. The extent of these effects is conditioned by tidal state and amplitude of coastal water (Anand *et al*., 2014; Barletta *et al*., 2019). The input of macronutrients in estuaries occurs naturally through riverine discharge and the understanding of their cycling depends on a series of factors including hydrodynamics, morphology, freshwater inflow and flushing time, microbial activity, particle and dissolved phases interactions and benthic exchanges. Apart from the aforementioned factors, the biogeochemistry of urbanized estuaries can also be influenced by anthropogenic input, leading to eutrophication, which can become a permanent condition and cause the degradation of the aquatic environment (Statham, 2012, Freeman *et al*., 2019).

Guanabara Bay has a long record of pollution of its waters and sediments, particularly discussing organic pollutants and trace metals, and the northwest portion of the bay is considered one of the most polluted areas of the estuary (Rebello *et al*., 1986; Machado *et al*., 2004; Farias *et al*., 2008; Borges *et al*., 2009; Aguiar *et al*., 2011; Abuchacra *et al*., 2015). Studies concerning macronutrients in the water column of Guanabara Bay are scarce (Aguiar *et al*., 2013; Abuchacra *et al*., 2015; Brandini *et al*., 2016; Guimarães and Mello, 2006; Júnior *et al*., 2006), especially concerning tidal variations. This estuary comprises harbors, oil and gas, fishing and tourism activities, and dredging of the harbor channel often takes place in this coastal area. The bay receives a heavy load of anthropogenic material mostly composed of raw sewage and industrial effluents. Approximately 50% of the urban households in the drainage basin of the bay are connected with sewage treatment stations, however, there has always been a deficit between produced and treated sewage, around 13%. The most recent estimation is that 18 $m^3.s^{-1}$ of untreated sewage is released into the bay (Coelho, 2007; Fistarol *et al*., 2015). With respect to macronutrients, the input of nitrogen and phosphorus into Guanabara Bay is estimated to be $6.2x10^{10}$ tonnes N/yr and $3.2x10^9$ tonnes P/yr, respectively, originated mostly from raw sewage (Wagener, 1995). Eutrophication is a condition often related in the inner portions of the bay (Soares-Gomes *et al*., 2016), associated with very elevated productivity and bottom hypoxia (Aguiar *et al*., 2011; Abuchacra *et al*., 2015; Brandini *et al*., 2016; Guenther and Valentin, 2008). Despite its huge economic importance to Brazil, the anthropogenic impact on Guanabara Bay is notorious and several attempts to reduce and control pollution have been discussed since 1994, when PDBG (Program for Remediation of Guanabara Bay) began through an international cooperation program between BID (Inter-American Development Bank) and JBIC (Japanese Bank for International Cooperation). New attempts to clean up the bay were discussed shortly before 2016 due to the fact that the city of Rio de Janeiro was chosen to host the Olympic Games in that year. However, very little results have been achieved with respect to cleaning up its waters, monitoring policies and sewage treatment, and Guanabara Bay continues to suffer the effects of huge loads of anthropogenic inputs.

The present study aims to assess pollution levels at the entrance of Guanabara Bay using a simple tool, a trophic index (TRIX) developed by Vollenweider *et al*. (1998) that is based on a linear combination of the log of four state variables (saturation of dissolved oxygen, chlorophyll-a, dissolved nitrogen and phosphorus), an approach that allows comparison with other urbanized coastal systems and widely used in eutrophication studies (Jayachandran and Nandan, 2012; Jungxiang *et al*., 2014; Brugnoli *et al*., 2019). Neap and spring differences were considered to check any significant differences between tidal flushes. Considering the fast dynamics of water column, especially in a semi-diurnal estuary, the assessment of eutrophication through sediment quality was also considered, since this compartment plays a key role as a geological record for the anthropogenic input. The northwest part of Guanabara Bay has always been considered a hot spot for pollution and this study attempts to show that the recurrent anthropogenic inputs also affect other parts of this estuary.

2. MATERIAL AND METHODS

2.1. Study Area

Guanabara Bay has an area of approximately 384 km^2 (Figure 1) with a drainage basin that has 4.080 km^2 and 45 rivers and channels, among which, six are responsible for approximately 85% of the total mean annual volume of freshwater discharged into the bay: Guapimirim, Iguaçu, Caceribu, Estrela, Meriti and Sarapuí (Coelho, 2007; Fistarol *et al*., 2015; Kjerfve *et al*., 1997).

Guanabara Bay is considered a mixed semidiurnal estuary with a microtidal range tidal range between 0.7 and 1.3 m.

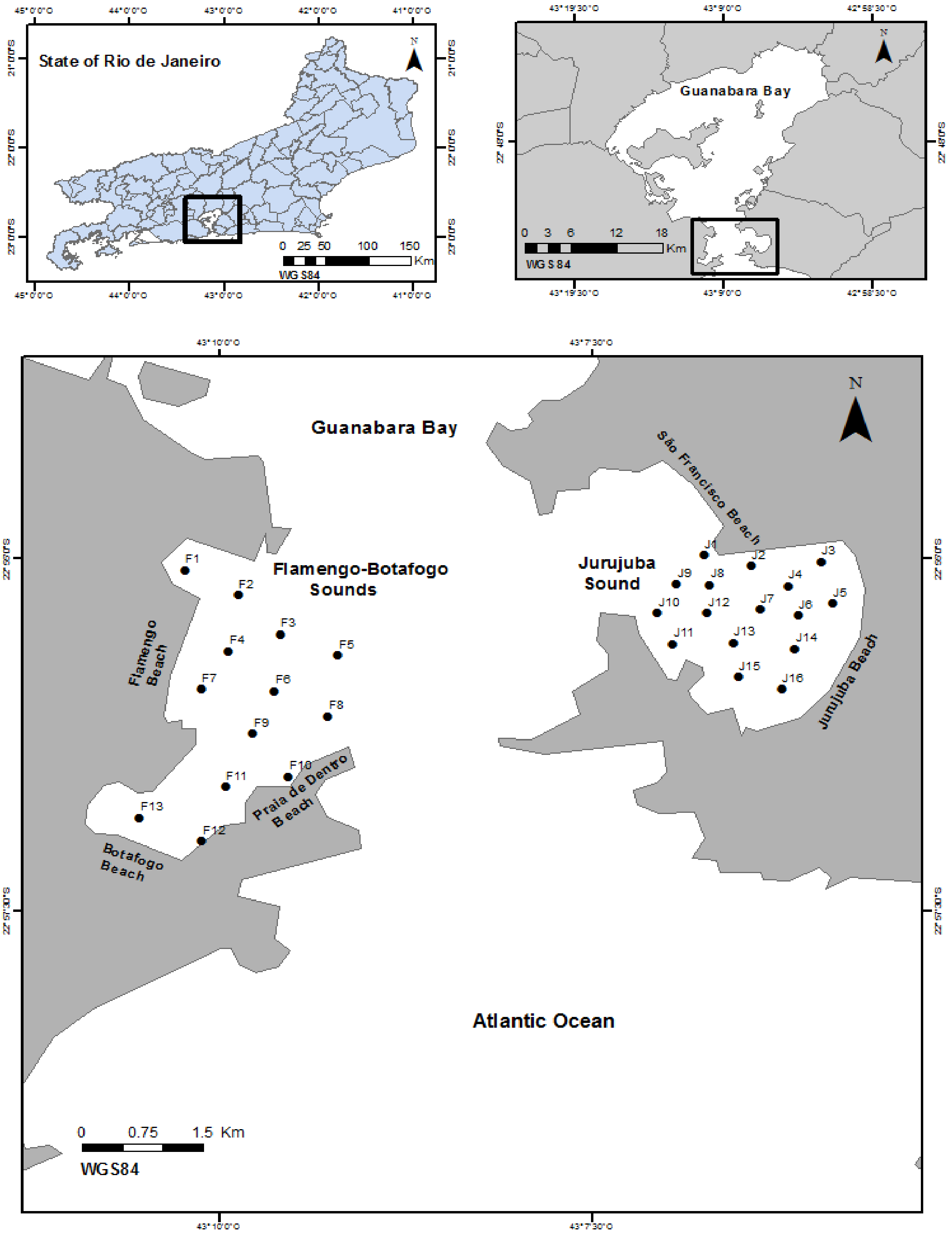

Figure 1. Study area and sampled stations.

The bay is tidally dominated, due to the predominance of shallow depths and slightly hypersynchronous, therefore the tidal range is greater at the landward margins than at the mouth of the bay. The input of fresh water into the bay is smaller than the inflow waters from the ocean, which means that fresh water inflow is not enough to affect the circulation pattern (Fries *et al*., 2019). Circulation inside the bay is a composition of gravitational (bidirectional) and residual tide circulation, both affected by prevailing winds, and the time estimated to renew 50% of its waters is 11.4 days (Kjerfve *et al*., 1997). The short residence time is not equal all around the bay; however, it prevents the water quality from getting worse in spite of the constant anthropogenic input. Sedimentation rates are high varying from 0.6 cm/year near the mouth to 4.5 cm/year in the inner part of the bay, and bottom sediments are composed of sand, muddy sand, sandy mud and mud (Amador, 1980; Kjerfve *et al*., 1997; Soares-Gomes *et al*., 2016).

The flux of anthropogenic input to Guanabara Bay is intense and constant, and dredging of the harbor area is frequent due to shipping and docking activities. Most of the watercourses in the drainage area are affected by high levels of pollutants, a consequence of domestic and industrial effluents from around 10.000 industries and 10 million population (Brandini *et al*., 2016), characterizing Guanabara Bay as one of the most polluted coastal areas in Brazil. Within the cities situated at the northeast portion of the bay, around 48% of the sewage is collected. However, almost 97% of the collected sewage is discharged *in natura* into the bay. The situation around other parts of the bay is not better, and most of the sewage discharged into the bay is not treated at all. According to Soares-Gomes *et al*. (2016) previous environmental studies in Guanabara Bay, allow the identification of some pollution hot spots: (i) the area of Rio de Janeiro Harbor, mainly contaminated by trace metals and receiving the discharge of River Maracanã, one of the most polluted rivers of the drainage basin (Aguiar *et al*., 2016; Cordeiro *et al*., 2015); (ii) the northwestern area, where the main oil refinery is located and some of the most polluted rivers discharge (Estrela, Sarapuí, Meriti, Iguaçu); (iii) The eastern area in the proximities of the city of São Gonçalo and Niterói Harbor (Aguiar *et al*., 2011; Neto *et al*., 2005), considered the second biggest urban concentration of the metropolitan area; (iv) Jurujuba Sound, one of the most polluted sites (Abuchacra *et al*., 2015; Baptista Neto *et al*., 2000; Sabadini-Santos *et al*., 2014).

2.2. Sampling and Analysis

Samplings occurred during the dry season of 2014, in July and August during daylight period. Jurujuba Sound and Flamengo-Botafogo Sounds were sampled twice during neap and spring tides each, therefore the data set corresponds to a total of four samplings. The tide range for neap and spring tides were between 0.5-0.9m and 0.0-1.2m, respectively. Water column was sampled near surface and bottom, in 16 stations at Jurujuba Sound and 13 at Flamengo-Botafogo Sounds (Figure 1). A multi probe YSI® 556 (Yellow Springs Instrument Company) was used to measure temperature, salinity, pH and dissolved oxygen (DO). Water samples were collected with a horizontal Van Dorn bottle and stored in polyethylene bottles pre-washed with HCl 10% (v/v) and rinsed with Milli-Q water. Bottles were immediately refrigerated in ice until arrival at laboratory. Bottom surface sediments were collected with a stainless steel Van Veen grab and samples were stored in plastic bags and immediately stored in ice.

At the laboratory water samples were filtered for determination of dissolved nutrients and suspended particulate material (SPM) with GF/F glass microfiber filters. Filtered samples for determination of dissolved inorganic phosphate (DIP) and dissolved inorganic nitrogen (DIN) were frozen at -20°C until the moment of analysis. After filtration GF/F membranes were used in the gravimetric determination of SPM according to Strickland and Parsons (1972). Determination of DIP and DIN was made through spectrophotometry as described in Grasshoff *et al*. (1999). Water samples were also filtered for the determination of chlorophyll-a (chlo-a) and phaeophytin-a (phae-a) with 0.45μm cellulose membranes which were frozen at -20°C in the dark for posterior analysis using 90% ketone extraction according to Strickland and Parsons (1972). Freeze-dried sediment samples were used for sediment analysis. Grain size analysis was performed through laser light scattering using a particle analyzer-Malvern series 2600, after elimination of organic matter and calcium carbonate with the method proposed by Suguio (1973). Total organic carbon (TOC) and total nitrogen (TN) were determined after elimination of carbonates with HCl 10% (v/v) in a Perkin Elmer Elemental Analyzer CHNS/O using acetanilide as a standard. Inorganic and organic phosphorus in sediments were determined following the method described in Aspila *et al*. (1976).

The software Statistica 7.0 was used to perform Mann Whitney test to evaluate significant differences for each sound between neap and spring tides and also between the sounds concerning the tides.

The Trophic Index (TRIX) initially proposed by Vollenweider *et al*. (1998) for costal marine areas is widely used in several coastal areas around the world. The index is a linear combination of four variables concerning nutritional factors and primary production and allows the comparison of different coastal areas concerning eutrophication. The calculation of TRIX uses concentrations of chlorophyll-a ($mg.m^{-3}$); oxygen as an absolute deviation from saturation D%O, TP-total phosphorus ($mg.m^{-3}$) and DIN-dissolved inorganic nitrogen (mg/m^3).

$$TRIX = \frac{1}{1.2}\left(log(Chla.|D\%O|.DIN.TP) - (-1.5)\right)$$

The classification of coastal water by TRIX defines four categories of trophic state in terms of quality: (i) high, 2<TRIX<4; (ii) good- 4≤TRIX<5; (iii) moderate- 5≤TRIX<6 and (iv) poor- 6≤TRIX<8.

In the present study, TRIX was calculated for each station for surface and bottom waters.

3. RESULTS

3.1. Water column

Field work occurred in the dry season in the State of Rio de Janeiro in 2014. Precipitation during the sampling month was obtained from the meteorological station installed at Universidade Federal Fluminense (UFF) in Niterói-RJ and reached maximum values of 25 and 8 mm in July and August, respectively. Table 1 presents the ranges of variables registered in Jurujuba and Flamengo-Botafogo Sounds during neap and spring tides.

At Flamengo-Botafogo Sounds differences between neap and spring tides were significant for temperature (*p=0.00004*) and salinity (*p=0.00378*). Salinity varied between 25.90-27.69 and small stratifications were registered among the sampled stations during neap tide. During spring tide no haline stratifications were observed.

At Jurujuba Sound pH variation was higher during neap tide and was significantly different (*p=0.0000*) from spring tide (Tab. 1). At Flamengo-Botafogo Sounds, pH values were typical for marine waters, varying from 8.05 to 8.64 and from 8.28 to 8.55 during neap and spring tides, respectively.

Dissolved oxygen at Jurujuba Sound varied between 4.51-14.07 $mg.l^{-1}$ and 2.20-10.73 $mg.l^{-1}$ in neap and spring tides, respectively, with significant differences between them (*p=0.00001*). During spring tide, with the exception of J10, every station at Jurujuba Sound presented DO values below 5 $mg.l^{-1}$, at bottom waters, characterizing poor oxygenation and reaching saturation levels as low as 38%. Some stations presented DO levels under 5.00 $mg.l^{-1}$ at surface and bottom waters (J11, J14 and J16). The lowest DO concentration was registered at bottom water of J3, 2.20 $mg.l^{-1}$.

Concentrations of DO at Flamengo-Botafogo Sounds were low during neap tide, maintaining saturation values under 80% and reaching values as low as 41.51% at F1, in the marina area. With tidal change, water oxygenation improved significantly (p=0.00116) during spring tide, with only a few inner stations (F1, F12 and F13) presenting DO<5.00 $mg.l^{-1}$. Saturation of the water column was around 80% for most stations, however, values as low as 38.47% were registered during spring tide, close to Botafogo Beach (F13). The marina area (F1) also presented a low saturation value, 53%.

Table 1. Neap-spring variations of depth (m), temperature (oC), salinity, pH, dissolved oxygen ($mg.l^{-1}$), saturation of dissolved oxygen (%), chlorophyll-*a* ($\mu g.l^{-1}$), phaeophytin-*a* ($\mu g.l^{-1}$), dissolved inorganic phosphorus (µM) and dissolved inorganic nitrogen (µM) at Jurujuba and Flamengo-Botafogo Sounds

Tide		Depth (m)	T	S	pH	DO	%DO	Chl-a	Phae-a	DIP	DIN
					Jurujuba Sound						
Neap	Min	2.5	22.72	27.11	7.31	4.51	11.60	0	0	0.05	1.11
	Max	6.0	23.71	28.44	8.97	14.07	207.30	24.72	126.56	0.71	7.43
Spring	Min	2.0	22.33	27.34	7.48	2.20	33.90	0.59	0.06-	0.22	1.02-
	Max	6.1	23.79	28.65	7.89	10.73	167.30	32.04	43.65	1.09	5.63
					Flamengo-Botafogo Sounds						
Neap	Min	6.7	19.80	20.44	8.05	3.00	41.51	0.36	0.21	0.33	2.92
	Max	19.0	20.80	28.76	8.64	5.18	71.26	7.12	11.84	1.73	28.79
Spring	Min	4.0	20.68	25.90	8.28	2.78	38.47	0	1.09	1.16	7.52
	Max	30.0	23.30	27.59	8.55	6.11	88.61	45.39	74.83	4.63	48.52

Phytoplankton biomass at Jurujuba Sound was low at most stations during neap tide, varying from zero to 24.72 $\mu g.l^{-1}$, whereas phaeophytin-*a* varied between zero and 126.56 $\mu g.l^{-1}$. During spring tide chlorophyll-*a* peaked at Jurujuba Sound and reached the highest value at surface water of J4 (32.04 $\mu g.l^{-1}$). Other peaks of chlorophyll-*a* were also registered during spring tide at surface waters of J1, J3, J8 and J9 with values between 9.49 and 26.11 $\mu g.l^{-1}$. Neap-spring tide differences were significant (*p=0.026946*), and concentrations of chlorophyll-*a* were lower during neap tide.

At Flamengo-Botafogo Sounds, concentrations of chorophyll-*a* during spring tide were significantly different from neap tide (*p=0.000627*), since phytoplankton biomass was only detected at some inner stations F7, F11, F12 and F13. The elevated chlorophyll-*a* concentration found at F13 at surface and bottom waters (35.04-45.39 $\mu g.l^{-1}$), suggested a local phytoplankton bloom at Botafogo Beach. Phaeophytin-*a*, on the other hand, was detected in every station, during spring tide, with the exception of F13, revealing a massive presence of degraded phytoplankton biomass. During spring tide, concentrations of phaeophytin-*a* were significantly different from neap tide (*p=0.001235*) and ranged from 1.09 $\mu g.l^{-1}$ (F12) to 74.83 $\mu g.l^{-1}$ (F6).

Dissolved inorganic phosphorus presented significant differences (*p=0.00001*) between neap and spring tides at Jurujuba Sound. Higher concentrations of DIP (>0.70µM) were registered during spring tide at stations J11-J16, closer to a marina area. At Flamengo-Botafogo Sounds concentrations of DIP during neap tide varied from 0.33 to 1.73µM, with higher values at the inner stations F1, F12, F13 and also at F3 and F5. During spring tide, DIP concentrations increased significantly (*p=0.00001*), varying from 1.16 to 4.63 µM, and higher concentrations were registered again at F1, located at the marina area in Flamengo, F12 and F13, at Botafogo beach, and F10, close to Praia de Dentro.

DIN did not present significant differences between neap and spring tides (*p=0.428238*) at Jurujuba Sound. During neap tide, the percentage of ammonium in DIN was between 37 and 99%. With change to spring tide, ammonium was not detected at several stations (J7, J10, J11, J12, J13, J14, J15) and its fraction in DIN varied between 1 and 58%. DIN varied significantly between neap and spring tides (*p=0.000963*) at Flamengo-Botafogo Sounds. The highest fraction of DIN at Flamengo-Botafogo Sounds was composed of N-NH4 during neap (87-97%) and spring (88-98%) tides.

During neap tide, with the exception of salinity and chlorophyll-*a*, all the variables were significantly different between Jurujuba and Flamengo-Botafogo Sounds (Tab. 2). In spring tide, differences between both margins at the entrance of the bay were also considered significant for most variables, except for dissolved oxygen, saturation of DO and chlorophyll-*a*.

Table 2. Mann-Whitney analysis (p<0.05) between Jurujuba and Flamengo-Botafogo Sounds for neap and spring tides.

Variables	**Neap tide** *p*	**Spring tide** *p*
Temperature	0.000000	0.000000
Salinity	0.266958	0.000000
pH	0.000000	0.000000
DO	0.000000	0.139812
%sat DO	0.000000	0.777842
Chl-*a*	0.669816	0.011669
Phae-*a*	0.000001	0.000083
DIN	0.000001	0.000000
DIP	0.000000	0.000000

3.2. Sediments

Bottom sediments at Jurujuba Sound exhibited predominance of pelitic sediments, with concentrations of silt and clay over 50%. Stations J3, J5, J7 did not reach 50% of silt and clay, but surpassed 40%, and J16 presented less than 10% of silt and clay. At Flamengo-Botafogo Sounds grain size analysis revealed the predominance of sandy sediments at the bottom of the sounds (Figure 2).

The total content of calcium carbonate at Jurujuba Sound (Figure 2) varied between 3.80 to 43.38% (Figure 2) and results classified stations J6-J14 as litobioclastics (>30%) whereas the rest of them was classified as litoclastic (Larssouner *et al*., 1982). On the other side of the bay, Flamengo-Botafogo Sounds presented carbonate contents that classified bottom sediments as litoclastics, with the exception of F11, with more than 40% of $CaCO_3$ (litobioclastic).

At Flamengo-Botafogo Sounds TOC contents were low, mostly under 0.5%, except for F4 and F11, with 3 and 8.26%, respectively (Figure 2). Contrasting results of TOC were found at Jurujuba Sound, with most concentrations elevated between 0.87 and 6.57% (Figure 2).

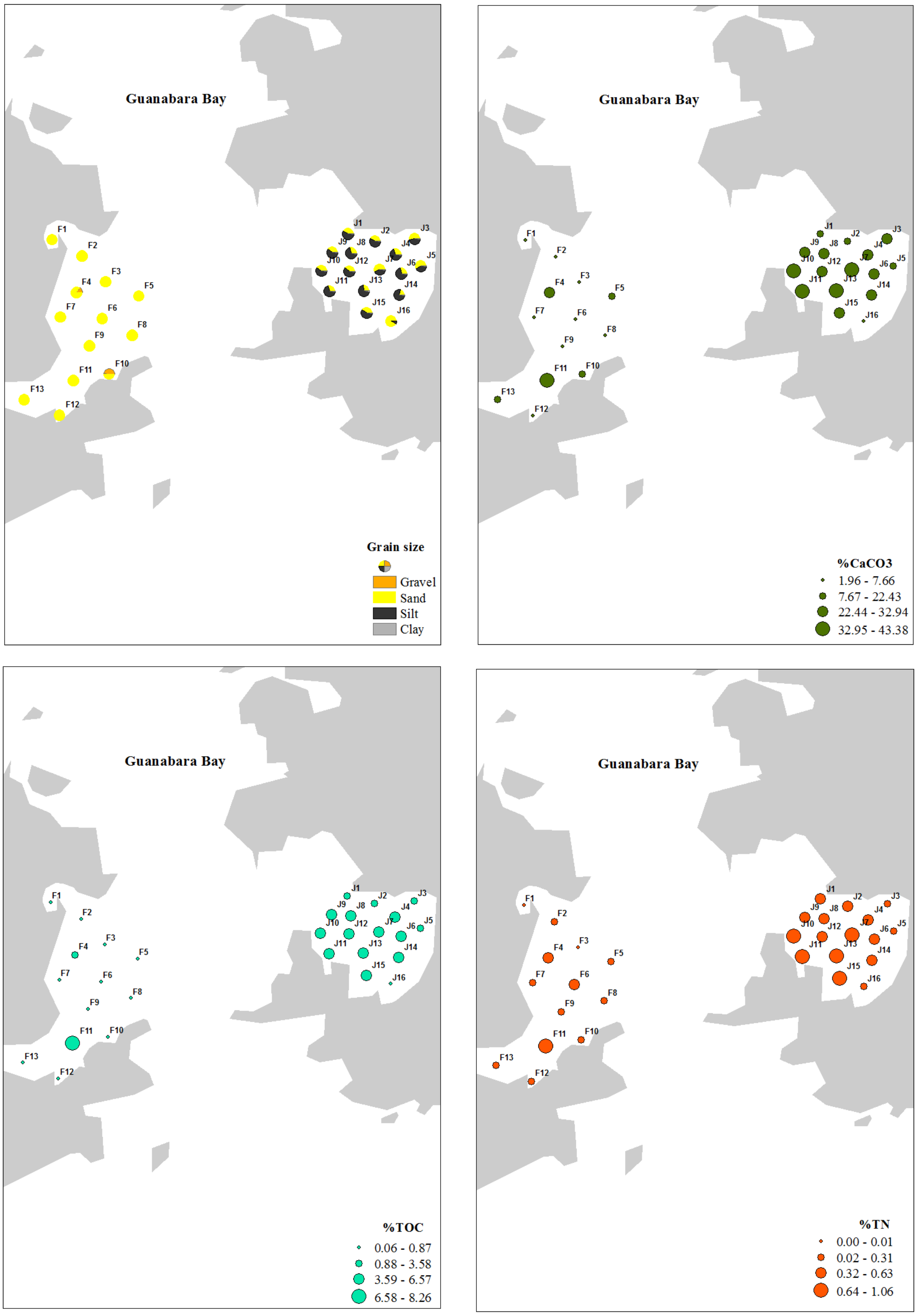

Figure 2. Grain size, calcium carbonate ($CaCO_3$), total organic carbon (TOC), total nitrogen (TN) for bottom sediments at Jurujuba and Flamengo-Botafogo Sounds.

Chorophyll-*a* was not detected in the sediments of Jurujuba Sound (Figure 3), except for J16 with a low value, 0.67 $\mu g.g^{-1}$, whereas phaeophytin-*a* was registered in every station, varying from 6.85 to 34.12$\mu .g^{-1}$. Chlorophyll-*a* was detected only at a few stations in Flamengo-Botafogo Sounds and the highest concentration was registered at F11, 1.47 $\mu g.g^{-1}$ (Figure 3). Results of chlorophyll-*a* and phaeophytin-*a* suggest the predominance of degradation process at both sub-embayments (Figure 3).

Concentrations of inorganic phosphorus (IP) at bottom sediments at Jurujuba Sound presented a range (Figure 3), from 154.34 (J16) to 1516.82 $\mu g.g^{-1}$ (J9). The concentrations of organic phosphorus at Jurujuba Sound, were markedly smaller than the inorganic form, varying from 20.34 to 965.61 $\mu g.g^{-1}$ (Figure 3). In contrast to the opposite margin, the accumulation of phosphorus on Flamengo and Botafogo Sounds was predominantly under the organic form. Concentrations of IP were mostly under 600 $\mu g.g^{-1}$, varying between 69.80 to 1699.63 $\mu g.g^{-1}$. whereas organic phosphorus varied from 2.45 to 20.232.14 $\mu g.g^{-1}$ (Figure 3).

Differences between the two sub-embayments at the entrance of Guanabara Bay were considered significant for the sediment variables, with the exception of chlorophyll-*a* and gravel (Table 3).

Table 3. Mann-Whitney analysis ($p<0.05$) for bottom sediment variables between Jurujuba and Flamengo-Botafogo Sounds.

Variables	*p*
IP	0.000702
OP	0.043053
$CaCO_3$	0.001006
TOC	0.000193
TN	0.003302
Chl-*a*	0.160531
Phae-*a*	0.000055
gravel	0.982507
sand	0.000014
silt	0.000005
clay	0.000005

4. DISCUSSION

4.1. Water column

Results proved to be significant differences of anthropogenic inputs and nutrient dynamics between the two opposite margins at the entrance of Guanabara bay. Depth variations between the two sub-embayments can account for marked differences concerning some physical variables. Smaller temperature ranges at Jurujuba Sound during both tidal periods, can be justified by it shallowness (up to 6 m) and darker waters favoring higher temperatures, whereas at Flamengo-Botafogo Sounds depths can reach more than 20 m. Fries *et al*. (2019) described that water column at the entrance of the bay is well mixed, and this mixed water reaches up to 15-20 km inside the bay, with current velocities around 0.5 $m.s^{-1}$ in deeper areas, reducing to approximately 0.1 $m.s^{-1}$ in shallower depths. According to Kjerfve *et al*. (1997), haline stratifications at Guanabara Bay are weak or moderate never exceeding 4 salinity units. Indeed, this was the case of Flamengo-Botafogo Sounds during neap tide, with differences between surface and bottom waters up to 2 units, except for F1 where differences in salinity from top to bottom reached 6 units. Station F1 is an inner one located in a marina area; therefore, this stratification could probably be caused by anthropogenic discharge in this area.

Concentrations of DO below 5.00 $mg.l^{-1}$ are the beginning of biological stress for many aquatic species with lower tolerance to anoxic conditions, especially the ones in higher levels of the food chain (Bricker *et al*., 2003; Kadiri *et al*., 2014). Moreover, hypoxia/anoxia conditions can also be reached during the night period, due to predominance of respiration and decomposition processes and excess of organic matter. Hypoxia is a matter of concern when it comes to Jurujuba Sound in particular since it comprises local fishing communities and mariculture. Previous studies have detected hypoxia at Jurujuba Sound (Aguiar *et al*., 2013; Abuchacra *et al*., 2015), with values as low as 0.86 $mg.l^{-1}$ at bottom waters. Despite the fact that low concentrations of DO were observed at both sub-embayments, concentrations did not characterize hypoxia during sampling, that occurred during daylight. The differences in the levels of dissolved oxygen between the two margins were highlighted, especially during neap tide (Figure 4). The degradation of excess organic matter drives the consumption of dissolved oxygen, which was mainly observed at waters adjacent to bottom sediments, with DO levels $<5.00\ mg.l^{-1}$. In the case of Jurujuba Sound, lower concentrations of DO were accompanied by lower pH values, especially during spring tide, corroborating the hypothesis of mineralization of organic matter. Higher values of DO during neap tide were also accompanied by higher pH values, suggesting intense primary production at Jurujuba Sound (Figure 4).

At Flamengo-Botafogo Sounds, the levels of DO slightly increased from neap to spring tide, except for the most inner stations F1 and F13 which maintained low concentrations of dissolved oxygen.

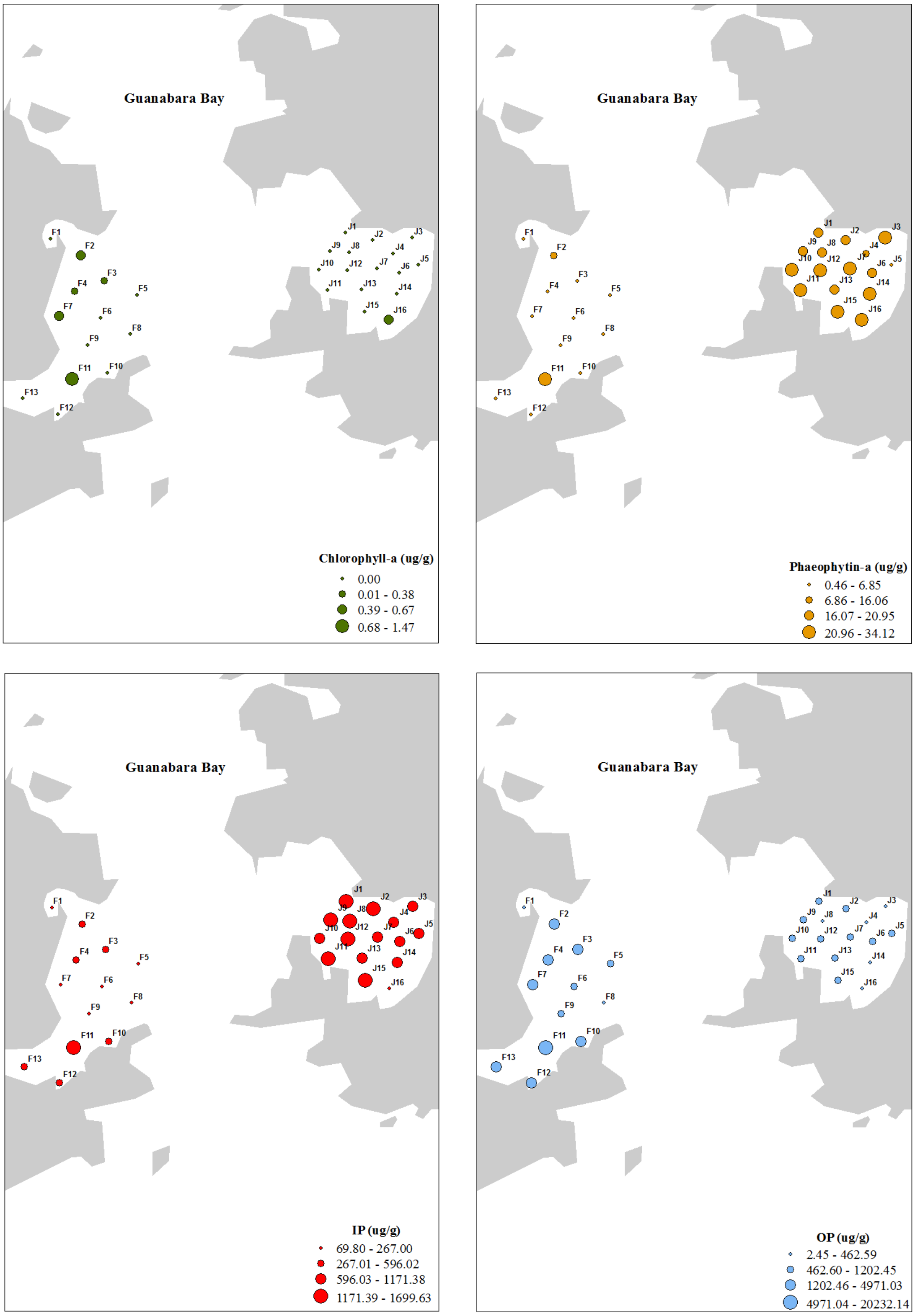

Figure 3. Chlorophyll-a, phaeophytin-a, inorganic phosphorus (IP) and organic phosphorus (OP) at bottom sediments from Jurujuba and Flamengo-Botafogo Sounds.

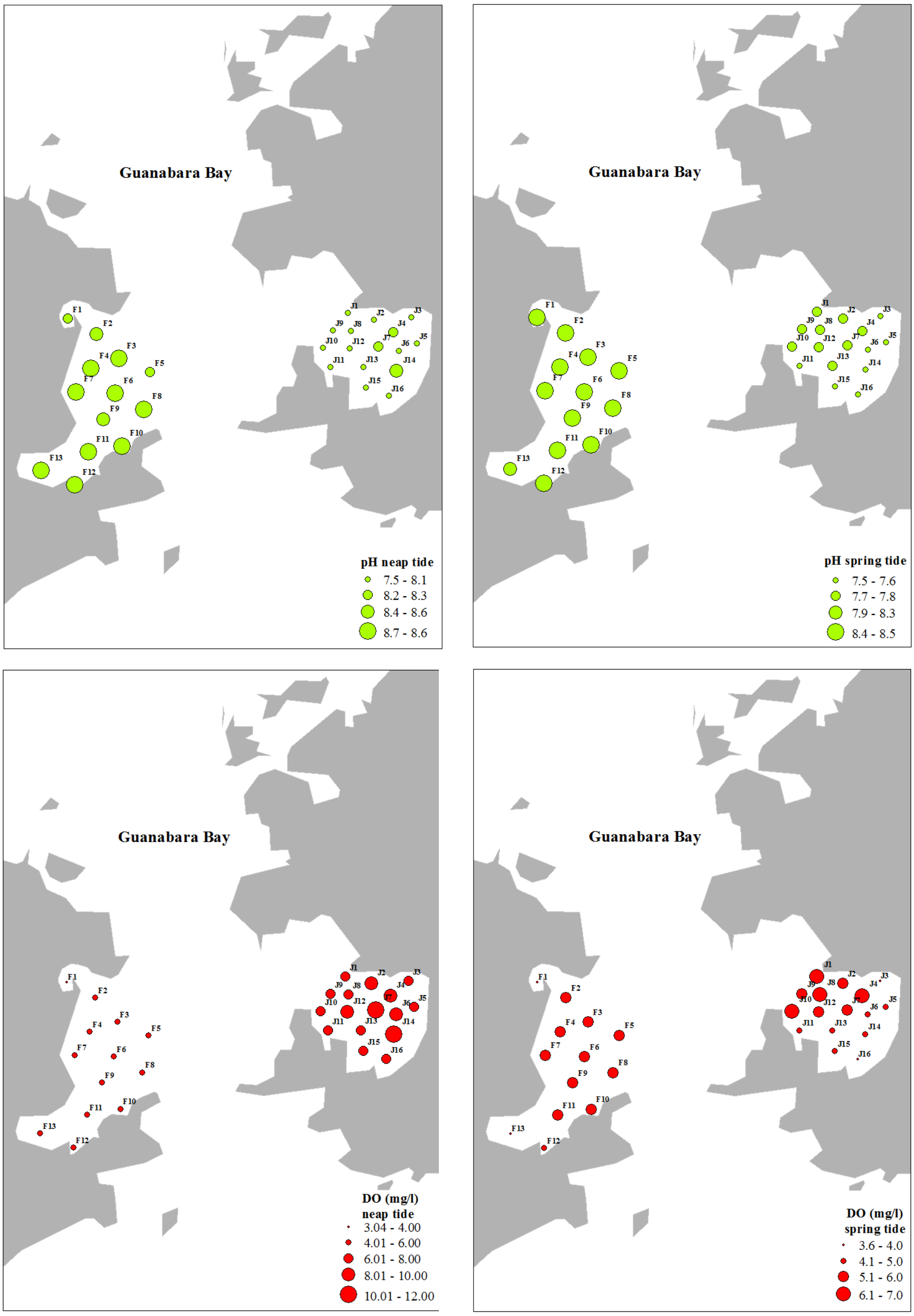

Figure 4. Mean values (surface and bottom) for pH and dissolved oxygen (DO) at Jurujuba and Flamengo-Botafogo Sounds during neap and spring tides.

This is probably caused by the restricted circulation at these areas, as well as smaller depth and the input of fresh water and sewage at these locations. The main fluvial influences at the study area are the Berquó and Banana Podre rivers, both channeled. These rivers receive municipal untreated wastewater and converge before reaching Botafogo Sound (F13). Station F1, on the other hand is located inside Marina da Glória under the direct influence of sewage input, presenting strong septic smell and dark waters.

The differences in the contents of phytoplankton biomass between the opposite margins were also striking, with chlorophyll-*a* concentrations clearly higher at Jurujuba Sound (Figure 5). The peaks of chlorophyll-*a* were consistent with concentrations of DO higher than 5 $mg.l^{-1}$ during spring tide (J1, J3, J8, J9), suggesting predominance of production processes, which was corroborated by chlorophyll-*a*/phaeophetyin-*a*>1 at these sites. However, at most stations during spring tide, chlorophyll-*a*/phaeophytin-*a* was <1, in accordance with low values of DO and pH, suggesting the occurrence of degradation processes. Only at F7, F11 and F12 chlorophyll-*a* and phaeophytin-*a* were both detected in spring tide with a ratio chlorophyll-*a*/phaeophytin-*a* >1, pointing to production at these stations.

Concentrations of dissolved inorganic phosphorus were significant different between the two margins, and lower concentrations of DIP at Jurujuba Sound (Figure 6) may be attributed to sorption processes of phosphorus on fine sediments. At Flamengo-Botafogo Sounds, on the other hand, the sorption of phosphorus by bottom sediments is lessened by the predominance of coarser particles at the bottom. Ammonium is usually the most abundant form of nitrogen in surface waters after phytoplankton blooms remove most of nitrate and phosphate, and is also excreted by organisms along with urea and peptides. The decrease in DIN concentrations, including ammonium, at Jurujuba Sound in spring tide coincided with the peaks of chlorophyll-*a*, suggesting that phytoplankton could have alternatively assimilated $N\text{-}NH_4^+$ for primary production which has a lower energetic cost for cells associated with protein synthesis (Parker *et al*., 2012).

High percentages of ammonium in DIN composition can also be originated from anthropogenic input of raw sewage, through the hydrolysis of urea, and decomposition of other nitrogen organic compounds. During both tides, peaks of DIN with high concentrations of $N\text{-}NH_4^+$, occurred at stations F7 and F9, in front of Flamengo Beach and also at F12 close to Botafogo Beach. This confirms a continuous input at this location, probably trough domestic effluents which are maintained in the water column for a longer time due to restricted circulation patterns of the area. The increase in DIN at most stations during spring tide was accompanied by the depletion of phytoplankton biomass at most stations. Some studies relate inhibition of primary production due to excess $N\text{-}NH_4^+$. The increase of nutrients drives eutrophication, however, high concentrations of chlorophyll-*a* are only achieved once the larger dissolved inorganic nitrogen pool is accessed.

Concentrations of ammonium above a threshold value may inhibit the assimilation of NO_3^-. Dugdale *et al*. (2007) and Dugdale *et al*. (2012) described concentrations of ammonium above 4μM as inhibitory by for assimilation of nitrate by phytoplankton for primary production in a study at San Francisco estuary. Overall concentrations of $N\text{-}NH_4^+$ were elevated during both tides at Flamengo-Botafogo Sounds, higher than 4μM, which may justify the low concentrations of chlorophyll-*a* especially in spring tide. It is therefore, reasonable to infer that DIN with ammonium concentrations under 4μM at Jurujuba could be used to enhance primary production, whereas the excess of this nutrient would inhibit primary production at Flamengo-Botafogo Sounds.

Table 4 compares concentrations of DIP, DIN, DO and chlorophyll-*a* from the present study with past ones at Guanabara Bay. Except for Fistarol *et al*. (2015), who presented data from the entrance of the Guanabara Bay, results from past studies were obtained from different locations inside the bay. Overall, results obtained in the present study fell within the range registered in previous studies at Guanabara Bay, revealing a continuous anthropogenic impact of its waters over the last decades.

4.2. Trophic index (TRIX)

Figure 7 shows results of trophic index (mean±SE) at the entrance of Guanabara Bay. Overall, TRIX values did not present a wide range of throphic conditions, revealing a mostly degraded environment at both sub-embayments, varying from good (4≤TRIX<5) to poor (6≤TRIX<8).

At Jurujuba Sound the increase of TRIX from neap to spring tide was clear in every station. During neap tide, water condition of over 50% of the stations was considered good, and the rest of them moderate. With tidal change, water quality decreased to poor condition at most stations. At Flamengo-Botafogo Sounds, the calculation of TRIX was not possible at some stations, mostly for spring tide, since chlorophyll-*a* was not detected at several stations. Despite the fact that water quality at Flamengo-Botafogo Sounds was already considered poor at most stations, it was noticeable that TRIX also increased from neap to spring tide, and the stations classified with moderate

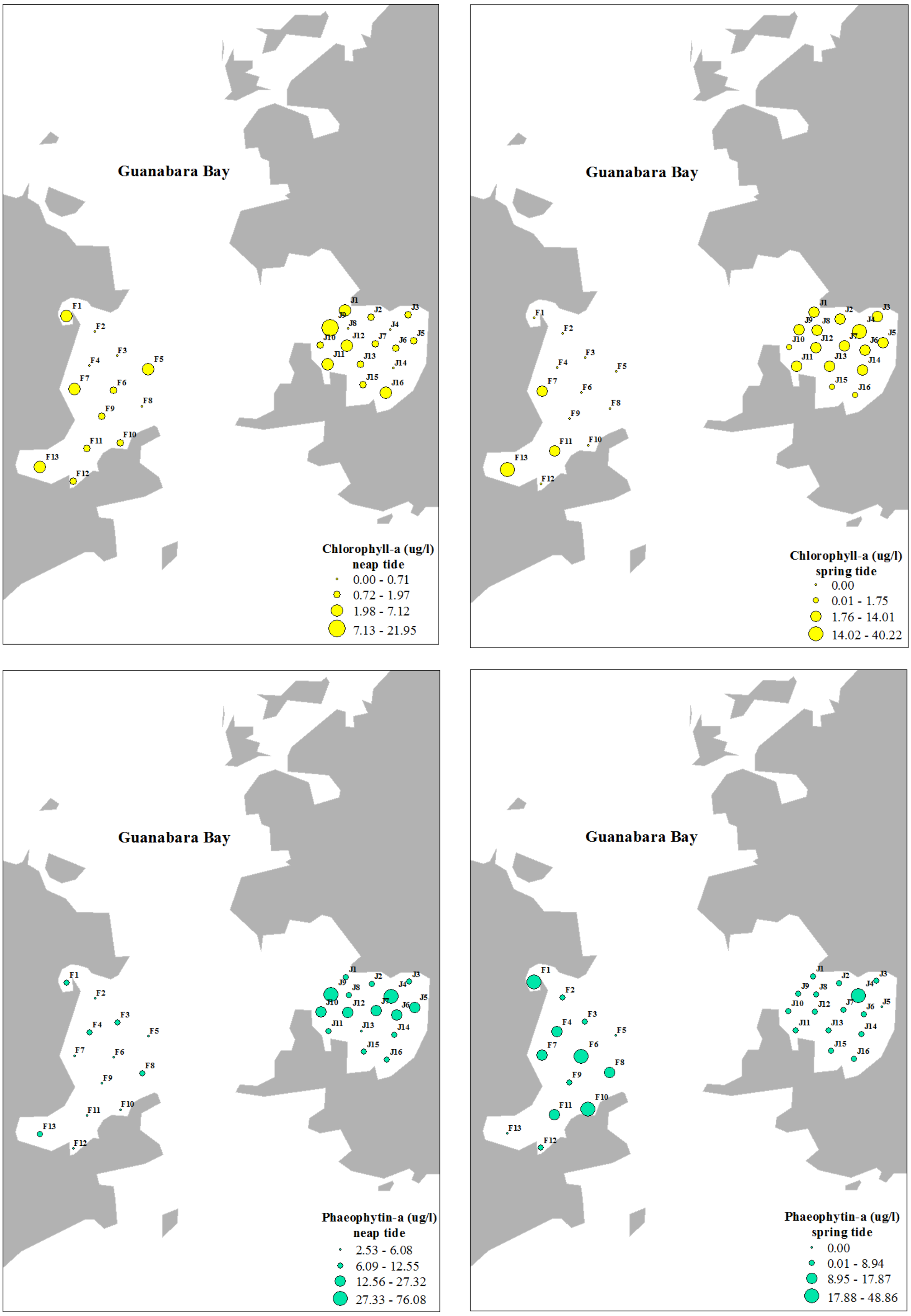

Figure 5. Mean values (surface and bottom) for cholophyll-a and phaeophytin-a at Jurujuba and Flamengo-Botafogo Sounds during neap and spring tides.

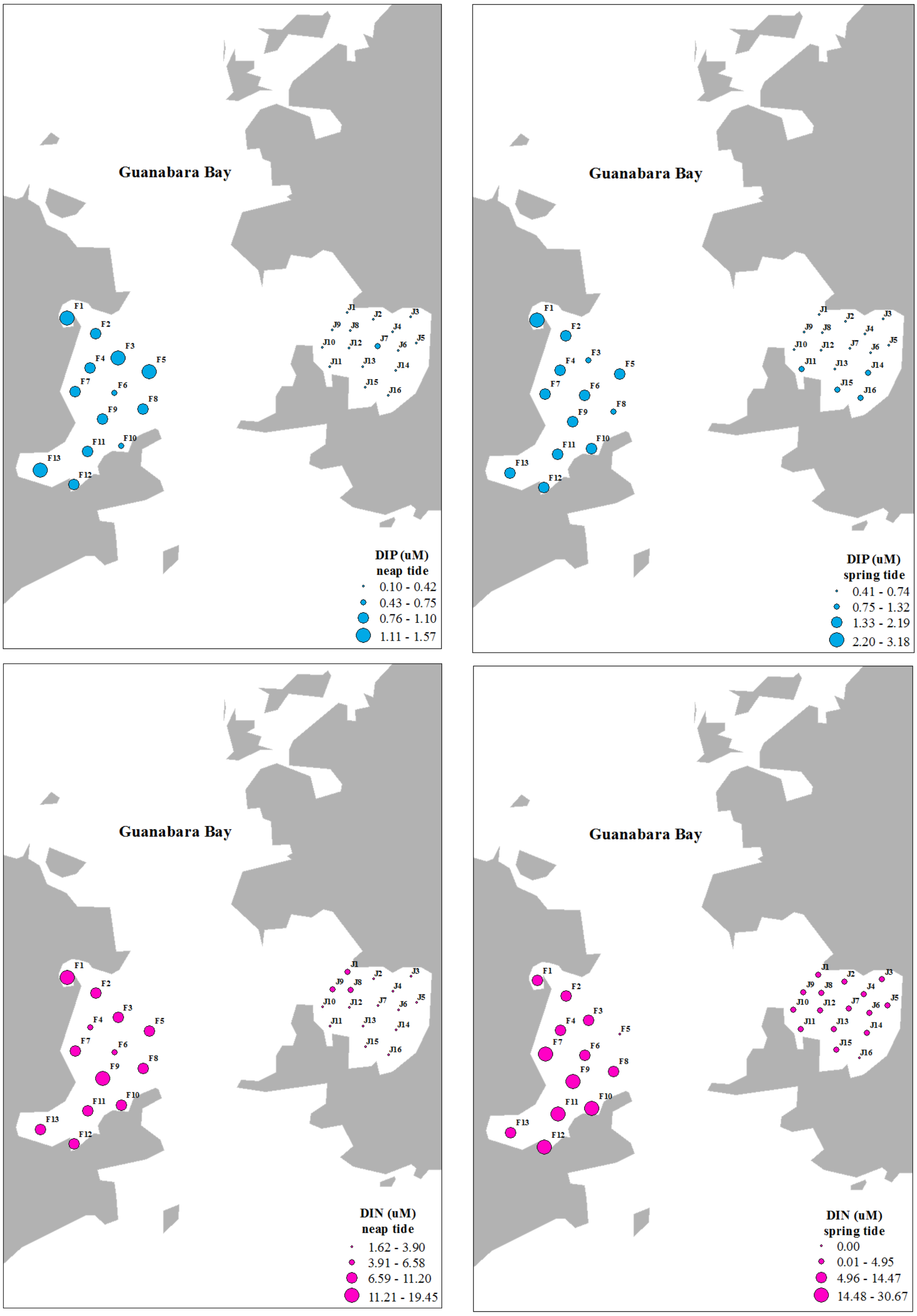

Figure 6. Mean values (surface and bottom) for dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN) at Jurujuba and Flamengo-Botafogo Sounds during spring tide.

Table 4. Concentrations of dissolved inorganic phosphorus (DIP), dissolved inorganic nitrogen (DIN) chlorophyll-*a* (Chl-*a*) and dissolved oxygen (DO) in the water column, from past studies at Guanabara Bay and the present one.

Study	**DIP** (μM)	**DIN** (μM)	**Chl-*a*** (μg.l-1)	**DO** (mg.l-1)
*Kjerfve *et al*. (1997)	0.003-0.12	0.13-7.07	20.6-102.7	3.1-11.1
Gonzalez *et al*. (2000)	0.86	10.36	26.03	6.1
*Fistarol *et al*. (2015)	0.05-7-4	0.60-68.3	0.5-8.2	0.28-3.97
*Brandini *et al*. (2016)	3.4	124	82.8	9.1
This study, Flamengo-Botafogo Sounds	0.33-4.63	2.92-48.52	0.36-45.39	2.78-6.11
This study, Jurujuba Sound	0.05-1.09	1.02-5.63	0.59-32.40	2.20-14.07

*mean values

water quality decreased to poor. The shift from neap to spring tide seemed to decrease water quality at the entrance of Guanabara Bay. One of the main factors that could decrease water quality at Guanabara Bay is fluvial discharge, however, no significant differences in precipitation were registered between sampling periods to affect anthropogenic input at the sounds. The fluctuations of flood and ebb tide during sampling certainly influences TRIX since Guanabara Bay is a semi-diurnal estuary and biogeochemical processes in the water column are very dynamic. Nevertheless, most of the stations were sampled during flood tide. The index is quite sensitive and even little fluctuations of nutrients, chlorophyll-*a* or dissolved oxygen are enough to shift water quality. Raw data proved that there was indeed an increase in the variables used for TRIX calculations from neap to spring tide at Flamengo-Botafogo Sounds (Figure 5 and Figure 6). For Jurujuba Sound, the increase of DIP and chlorophyll-*a* from neap to spring tide was enough to decrease water quality. According to Fries *et al*. (2019), the ocean waters from beaches located outside Guanabara Bay, like Copacabana and Ipanema, can enter the bay during flood tide. This entrained water brings along the untreated sewage from the Ipanema marine outfall, which certainly affects the water quality at the entrance of the Bay. TRIX results for Guanabara Bay were close to the values of impacted coastal areas, such as Mediterranean Ecoregion and Youngsan River at South Korea (Tab. 5) and presented the highest values among them.

4.3. Bottom sediments

Results of the present study concerning bottom sediments show that they play a crucial role in biogeochemistry at the entrance of the bay. The accumulation of high concentrations of organic matter at Jurujuba Sound bottom sediments is favored by its small depths and predominance of fine sediments. TOC results at Jurujuba Sound were higher than the results obtained by and by Baptista Neto *et al*. (2000) (TOC<5%) and Abuchacra *et al*. (2015) in the same area (TOC<5.06%), suggesting the increase of anthropogenic input at the east margin in the past years. In a study conducted in six eutrophic estuaries at north-eastern Brazil, Silva *et al*. (2017), found average TOC values between 0.42 and 2.69%, much lower than the ones found in the present study, suggesting a high anthropogenic pressure at the entrance of Guanabara Bay, especially at Jurujuba Sound.

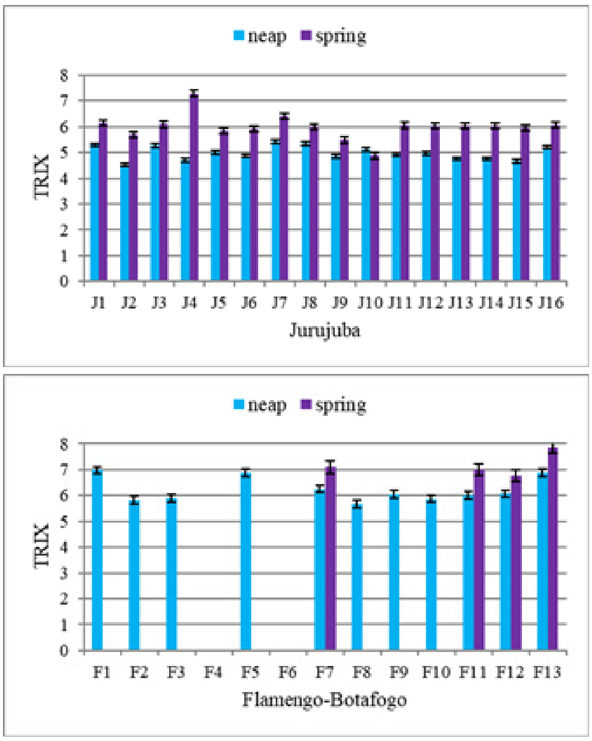

Figure 7. Mean values of trophic index (TRIX) calculated for Jurujuba and Flamengo-Botafogo Sounds, for neap and spring tides.

Table 5. Trophic Index (TRIX) calculated according to Vollenweider *et al.* (1998) for different coastal areas.

	TRIX
Mediterranean Ecoregion, Italy (Pettine *et al*., 2007)	2.99-6.03
Gulf of Riga, Baltic coast (Boikova *et al*., 2008)	3.48-5.83
Coastal area of Sicily, Italy (Caruso *et al*., 2010)	0.99-6.02
Youngsan River Estuary- Korea (Sin *et al*., 2013)	5.9-6.5
Portuguese Continental Exclusive Economic Zone (Cabrita *et al*., 2015)	4.2-6.3
Eastern Mediterranean (Simboura *et al*., 2016)	1.31-6.02
This study, Jurujuba Sound	4.53-7.29
This study, Flamengo-Botafogo Sounds	5.67-7.87

At both sub-embayments, anthropogenic inputs of nutrients enhance the production of organic matter as shown by the results of C/N ratios. At Jurujuba Sound, organic matter OM was considered of mixed origin tending to marine (8.1<C/N<9.7) (Bader, 1955). At Flamengo Botafogo Sounds, C/N<6 for most stations revealed OM of marine origin. The exceptions were F2 and F11 with OM classified as mixed origin tending to marine (6<C/N<12). Results at Flamengo-Botafogo Sounds were higher than the ones found by Eichler *et al*. (2003) (TOC<4.6%) for Guanabara Bay.

Elevated concentrations of chlorophyll-*a* and phaeopigments in sediments are commonly found in the sediments of eutrophic estuaries under anthropogenic pressure, suggesting high primary production (Venturini *et al*., 2012; Silva *et al*., 2017). In the present study, chlorophyll-*a* was hardly detected in the sediments, on the other hand phaeophytin-a was elevated, especially at Jurujuba Sound. The inhibition of primary production by high turbidity levels is the probable cause of low levels of chorophyll-*a* in the bottom sediments of Jurujuba Sound, which, despite low depths presents very dark waters. Phytodetritus accumulation can also account for high concentrations of phaeopigments in the study area.

The evaluation of the trophic state of a marine environment only through the concentrations of nutrients in the water column may be masked by its dynamics. In comparison, sediments are natural nutrient sinks and can be very reliable to assess eutrophication aspects since they act as a geological register throughout time. Therefore, sediments play a key role in interpreting the environmental health of a coastal ecosystem, especially in relatively shallow environments. When it comes to phosphorus, the sorption of this nutrient by sediments is a crucial factor influencing its transport, degradation and fate in the aquatic system. The efficiency of coastal sediments in retaining phosphorus as well as the buffering effect between bottom sediments and water column concerning DIP is well documented and the preservation of P in the sediment compartment depends on a number of factors, such as DO at bottom waters, sedimentation rate, bioturbation, nature of P compounds supplied to the sediment/water interface and diagenetic processes (Boers *et al*., 1998; Froelich, 1988; Gardolinski *et al*., 2004). The sediments of urbanized coastal areas usually receive a mixture of labile and refractory organic and inorganic phosphorus, and some of these compounds are harder to degrade and thus behave as inert material and end up buried in their original form (Sundby *et al*., 1992). The internal contribution, in the form of released P adsorbed on bottom sediments can equally contribute or even exceed the contribution from external sources for the maintenance of eutrophication (Boers *et al*., 1988). Bottom sediments from Jurujuba Sound revealed a strong anthropic influence and the ability of retaining P, what is justified by the presence of fine sediments. The values of IP found in the present study are similar to the range of P concentrations registered at different sites at Guanabara Bay, such as the ones found by Carreira and Wagener (1998) around the Ipanema submarine outfall, 309-1498 $\mu g.g^{-1}$ and Borges *et al*. (2009) that found up to 1196 $\mu g.g^{-1}$ of total phosphorus with a contribution of ~90% of IP.

At Flamengo-Botafogo Sounds the predominance of OP suggests an elevated contribution of organic matter composed of refractory compounds such as humic substances, and probably not completely mineralized. Station F11, near Botafogo Beach, stood out with the highest concentrations of carbonate, TOC, IP, chlorophyll-*a* and phaeopigments, revealing a direct anthropogenic input at this location, probably due to Banana Podre and Berquó rivers that discharge directly into Botafogo Sound.

Eutrophication signs at bottom sediments of Jurujuba Sound were made explicit by elevated contents of TOC and inorganic phosphorus, both of them interacting with adjacent water to enhance this process and perpetuate this cycle as long as the anthropogenic supply of nutrients is maintained. At Flamengo-Botafogo Sounds bottom sediments cannot absorb most of the anthropogenic input due to the predominance of coarser particles, however the presence of elevated concentrations of organic phosphorus is also an indication of eutrophication.

5. CONCLUSIONS

The entrance of Guanabara Bay showed distinct characteristics regarding nutrient dynamics, mostly responding to two main factors: heavier nutrient loading through sewage input at Flamengo Botafogo Sounds, and differences between bottom sediments of the two areas influencing adsorption processes on nutrient dynamics.

Heavier anthropogenic input at Flamengo-Botafogo Sounds was evidenced by a higher concentration of dissolved inorganic phosphorus and dissolved inorganic nitrogen, mainly in the form of ammonium, probably derived from raw sewage. High concentrations of ammonium also seemed to play a key factor in phytoplankton biomass production at Flamengo-Botafogo Sounds, with primary production inhibited by elevated concentrations of this nutrient. Lower oxygenation of Flamengo-Botafogo waters compared to Jurujuba Sound also corroborated the hypothesis of heavier anthropogenic load at this location, with organic matter being mineralized along the deeper water column, decreasing dissolved oxygen levels.

Differences between grain size of bottom sediments from Jurujuba and Flamengo-Botafogo Sounds greatly influence nutrient dynamics at the entrance of Guanabara Bay. Fine sediments at Jurujuba Sound act as a trap for nutrient and organic matter absorbing excess anthropogenic discharge, helping to mask some eutrophication signs in the water column. At Flamengo-Botafogo Sounds coarser sediments retain less organic matter and inorganic nutrients; therefore, eutrophication signs are more evidenced in the water column. Overall, TRIX ranges were similar, revealing poor water quality at the entrance of Guanabara Bay, with a noticeable decrease from neap to spring tide. Results generated in the present study show the necessity of urgent public policies in order to mitigate eutrophication at Guanabara Bay.

AUTHORS CONTRIBUTION

Valquíria Aguiar: aquisição de dados primários, análises formais, escrita do artigo.

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ESTABLISHING A STANDARD-BASIS FOR THE CHARACTERIZATION OF MARINE MICROPLASTIC-PELLETS

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ABSTRACT: Plastic pellets are small granulated microplastics (diameter ranging from 1-5 mm), which are considered as emerging pollutant in aquatic environment. Currently, the literature provides a poor database for classification and standardization of plastic pellets, impairing the comparison of environmental impacts assessed by several studies. Thus, in this work, a classification related to pellet characteristics was proposed in order to establish a standard of identification. Four sampling surveys were carried out in the Pecém-CE port area in the year of 2017 (northeastern coast of Brazil). The pellets were characterized according to its size, shape, transparency, and color. From the characterization of the 1,411 pellets collected, granules with different morphologies were observed. Most classes of pellets had light colors (white 37%, yellow 22% and amber 12%). The classification of the granules resulted in a catalog with 155 classes, divided into four blocks. The standardization of the characteristics of the pellets in classes, provided a documentation of the types of granules produced and found near the port area, making it possible to quantify and characterize the granules manually and with the naked eye. This type of classification can be used anywhere in the world as a tool to assist research on the presence of pellets in the marine environment and the impacts caused by them.

Keywords: beach survey, environmental pollution, plastic pellets, standardized characterization.

RESUMO: *Pellets de plástico são pequenos microplásticos granulados (diâmetro variando de 1-5 mm), que são considerados como poluentes emergentes no ambiente aquático. No entanto, a literatura fornece um banco de dados insuficiente para classificação e padronização de pellets plásticos, dificultando a comparação dos impactos ambientais avaliados por diversos estudos. Assim, neste trabalho, foi proposta uma classificação relacionada às características do pellet a fim de estabelecer um padrão de identificação. Quatro coletas foram realizadas na área do porto de Pecém-CE (litoral nordeste do Brasil) em 2017. Os pellets foram caracterizados quanto ao tamanho, forma, transparência e cor. A partir da caracterização dos 1.411 pellets coletados, foram observados grânulos com diferentes morfologias. A maioria das classes de pellets apresentou cores claras (branco 37%, amarelo 22% e âmbar 12%). A classificação dos grânulos resultou em um catálogo com 155 classes, divididas em quatro blocos. A padronização das características dos pellets em classes, permitiu a documentação dos tipos de grânulos produzidos e encontrados junto à zona do porto, permitindo quantificar e caracterizar os grânulos manualmente e à olho nu. Este tipo de classificação pode ser utilizado em qualquer parte do mundo como ferramenta para auxiliar nas pesquisas sobre a presença de pellets no meio marinho e os impactos causados por eles.*

Palavras-chave: *Pellets plásticos, pesquisa de praia, caracterização padronizada.*

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1. INTRODUCTION

Plastics are synthetic organic polymers (Barnes *et al*., 2009; Worm *et al*., 2017), whose world production between the years of 1950 and 2019 increased from one and a half million ton to three hundred and sixty-eight million tons (PlasticsEurope, 2010; 2020). According to their size, plastics are classified into megaplastics, macroplastics, mesoplastics, microplastics and, nanoplastics (Barnes *et al*., 2009; Dris *et al*., 2015; Bhuyan *et al* 2021; Kershaw and Rochman, 2016). In particular, microplastics with diameters between 1 and 5 mm are most preferred for marketing and transportation (Fred-Ahmadu *et al*., 2020; Cai *et al*., 2018; Galloway *et al*., 2017; Wessel *et al*., 2016).

The microplastics can originate from primary sources such as pellets (raw material to produce plastic goods) (Andrady, 2011; Cai *et al*., 2018; Underwood *et al*., 2017; Wagner *et al*., 2014; Worm *et al*., 2017) or secondary ones, resulting from the fragmentation and degradation by photo-oxidation or physical abrasion of larger plastics (Avio *et al*., 2017; Veerasingam *et al*., 2016; Wagner *et al*., 2014). In turn, plastic pellets, also referred as granules or thermoplastic resins (Epa, 1992; Takada, 2006; Wilcox *et al*., 2015; Worm *et al*., 2017) are generally cylindrical or spherical granules with a diameter normally between 2 and 5 mm (Costa *et al*., 2010; Epa, 1992). The most produced resins are those composed of polyethylene (PE), polypropylene (PP), polystyrenes (PS), polyvinyl chloride (PVC) and polyethylene terephthalate (PET) (Ivar Do Sul and Costa, 2014; Lebreton *et al*., 2017; Wright *et al*., 2013).

These plastic pellets can enter the aquatic environment through different pathways (Dris *et al*., 2015). For example, dispersion from the mainland to the marine environment can occur through stormwater runoff, discharges from sewage treatment plants, wind, river runoff, and accidental spills (Dris *et al*., 2015; Underwood *et al*., 2017). In addition to natural toxic substances added to the pellets, other chemical compounds present in the aquatic environment can be adsorbed/adhered, such as: persistent organic pollutants (POPs), aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) (Endo *et al*., 2005; Mato *et al*., 2001; Ogata *et al*., 2009; Rios *et al*., 2007; Takada, 2006). Unfortunately, due to the small size, density and color, pellets can be ingested by aquatic animals (Acampora *et al*., 2017; Cole *et al*., 2013; Lusher *et al*., 2013; Miranda and de Carvalho-Souza, 2016), causing serious toxicity effects due to the bioaccumulation/biomagnification at various food chain levels (Costa *et al*., 2019; Le *et al*., 2016; Worm *et al*., 2017). Interestingly, some studies showed how the growth of biofilm adhered to microplastics increase the incorporation of pollutant metals (Richard *et al*., 2019). However, the wide variety of pellet contents found in the environment makes it difficult to standardize scientific studies regarding the real effects of these materials directed to the type of material.

Until the beginning of 21st century, research on pellets focused on quantifying and qualifying the sampled material (Fernandino *et al*., 2015). At the beginning of this century, studies began on the quantification of POPs in pellets (Mato *et al*., 2001) which gained relevance with the implementation of the International Pellet Watch (IPW) global monitoring program in 2001 (Takada, 2006). In addition, many studies have been carried out to identify pellet intake by marine animals (Acampora *et al*., 2017, Bellas *et al*., 2016, Choy and Drazen, 2013, Cole *et al*. al., 2015). However, according to Fernandino *et al*. (2015), there is no standard to classify these resins and this impairs the standardization of information provided by several studies characterizing this material for the scientific community. Therefore, the objective of this work is to establish a standard classification related to the pellet characteristics visible to the naked eye for future scientific works.

2. MATERIAL AND METHODS

2.1. Sampling area and pellets sampling

For this work, the study area comprised beach strips near the port of Pecém (offshore, built in an industrial-port complex), located on the west coast of Ceará, in São Gonçalo do Amarante city, Brazil.

Four monthly samples were carried out near to the port of Pecém (Table 1), in portions of the previous sand strip (PA), east of the port with initial latitude 3°33'23.14'' S initial length 38°48 '8.05 " W and final latitude 3° 33'27.56" S and final longitude 38°48'5.46 " W, based on the influence of ocean current. It was also sampled in the posterior sand strip portion (PP), west to the port, initial latitude 3°32'42.13' 'S initial longitude 38°49'2.6'' O, final latitude 3°32'43.87" S and final longitude 38°49'7.09'' O, having as reference the geographic north (Figure 1).

For sediment sampling, it was used the methods with adaptations (Lippiat *et al*., 2013; Sivadas *et al*., 2022). The adaptations consisted in determining a sample area of 150 m (the initial points being 0 m and final 150 m) parallel to the coastline and dividing it by 10 equidistant sections of 15 m in length.

In the present study, it was possible to determine sampling pellets at the post-beach (Fernandino *et al.*, 2015) in 10 quadrats in each sampling area (Figure 1), using a square transect (1 m²). Pellets visible by the naked eye were manually removed from the surface layer of the sediment. Then, a sediment layer was collected from the entire transect area from one to three centimeters deep. The sediment was immersed several times in 10 L-buckets, until all sediment was immersed, with approximately 8 L of sea water and the floating pellets were separated from the plastic fragments and removed one by one manually.

Table 1. Date and tidal regime of sediment sampling in PA e PP in the adjacencies of port of Pecém.

Date (2017)	Time (h:min) (Start - end)	Tide Regime	Tidal range (m)
May 7-8th	9:00 - 11:30	Spring tide	2.5 – 0.5
June 4th	8:00 - 10:30	Spring tide	2.2 – 0.7
July 7th	9:00 - 12:30	Spring tide	2.4 – 0.6
August 20th	09:00 - 12:00	Spring tide	2.8 – 0.0

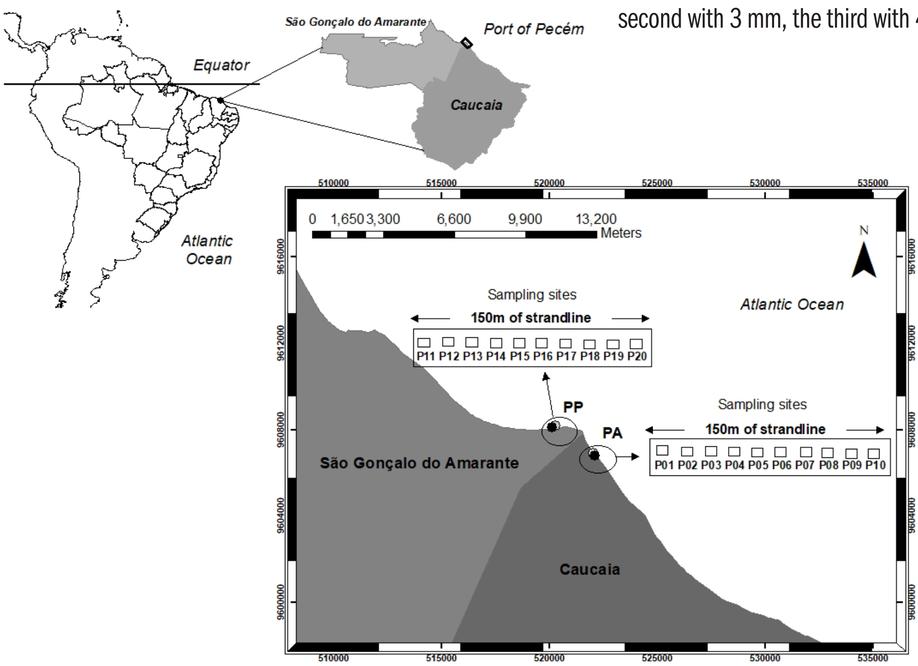
Source: Directorate of Hydrography and Navigation (DHN) (2017).

2.2. Pellets characterization

The granules were stored in plastic containers and transported to the Effluent and Water Quality Laboratory (EQUAL) of the Federal University of Ceará, (UFC) city of Fortaleza, Brazil, where they were duly quantified and later characterized by the naked eye according to size, shape, transparency and color. The pellet size was measured with pachymeter with an accuracy of 0.05 mm. In relation to the shape, the pellets were divided in spherical, flat, cylindrical, cylindrical flat, rectangular, cubic, and irregular (those that did not present any of the previous forms). The color characterization was performed from the RGB universal color table (R-red, G-green and B-blue), one of the most widely used color standards for image data processing and storage (Vezhnevets *et al.*, 2003).

The color was determined by a single researcher so that there was no distortion in the results and the pellets was divided into: white, yellow, amber, red, turquoise, blue, light blue, lime green, yellowish green, gray, black, brown, brown yellows and violets. The transparency degree was divided into three categories: opaque, translucent, and transparent.

After the characterization, the pellets were separated and organized in blocks according to the diameter of the granules, also considering the other characteristics (color, shape and transparency). The first block was pellets with diameter 2 mm, the second with 3 mm, the third with 4 mm and the fourth with 5 mm.



Note: PA: Previous sand strip (E); PP: Posterior Sand strip. WGS 1984 coordinate system UTM zone 24 S. Projection Transverse mercator.

Figure 1. Area and sampling site on the beach strip adjacent to the port of Pecém, Ceará, Brazil.

3. RESULTS

Pellets characterization

From the characterization of the 1,411 pellets collected, granules with different morphologies were observed (Supporting material). It was also observed that in most samples, most of the pellets had light colors, but also dark colored resins were found. The classification of the granules resulted in a catalog with 155 classes, divided into four distinct blocks, considering four factors: size, shape, color, and transparency. Figure 2 show the cluster pellets by size (2, 3, 4 and 5 mm) for the 155 classes group found. The Classification and characteristics of pellets by size are separately discriminated in Supplementary materials (Table 2 to Table 5).

When the different classes and blocks were analyzed, granules with diameters of 6 and 8 mm were found with characteristics that classify them as thermoplastic resins. However, these granules are not considered microplastics standards, due to their size (> 5 mm) (Costa *et al*., 2010; Dris *et al*., 2015; Fernandino *et al*., 2015; Mato *et al*., 2001; Underwood *et al*., 2017). The percentage to general characteristics of the pellets found are shown in Figure 3.

4. DISCUSSION

4.1. Intrinsic aspects of color

Not surprisingly, most of pellets classes found (37%) were white followed by yellow pellets, as being an issue resulting from the industry's tendency to produce white pellets (Figure 2). Since it is known that industries produce more light-colored pellets (Epa, 1992), because thus, chemical additives and plasticizers can be added when manufacturing the final product from the resins, modifying the initial coloration (Andrady and Neal, 2009).

The additives optimize the performance and give other properties to the resins (*e.g.*, change the original density of the granules) (Bellas *et al*., 2016; Talsness *et al*., 2009), which can increase resistance to heat, oxidative damage, and microbial

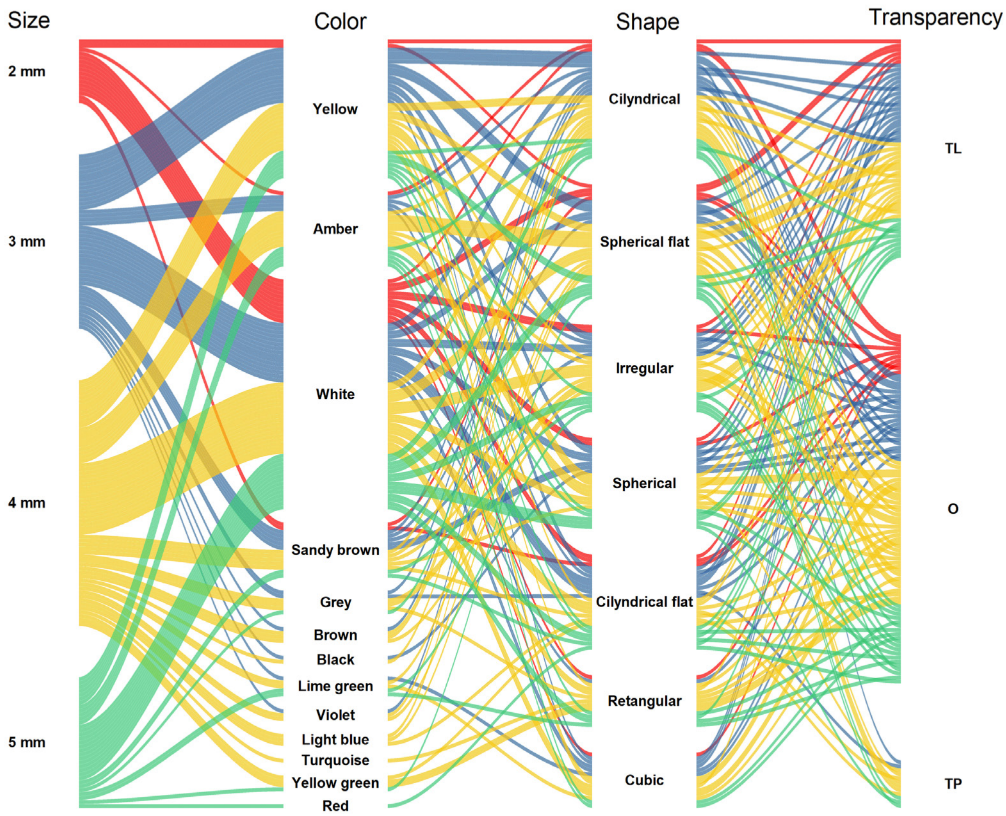


Figure 2. Cluster of characterization and classification for all 1,411 pallets by size, color shape and transparency. The 155 classes are shown in supplementary material.

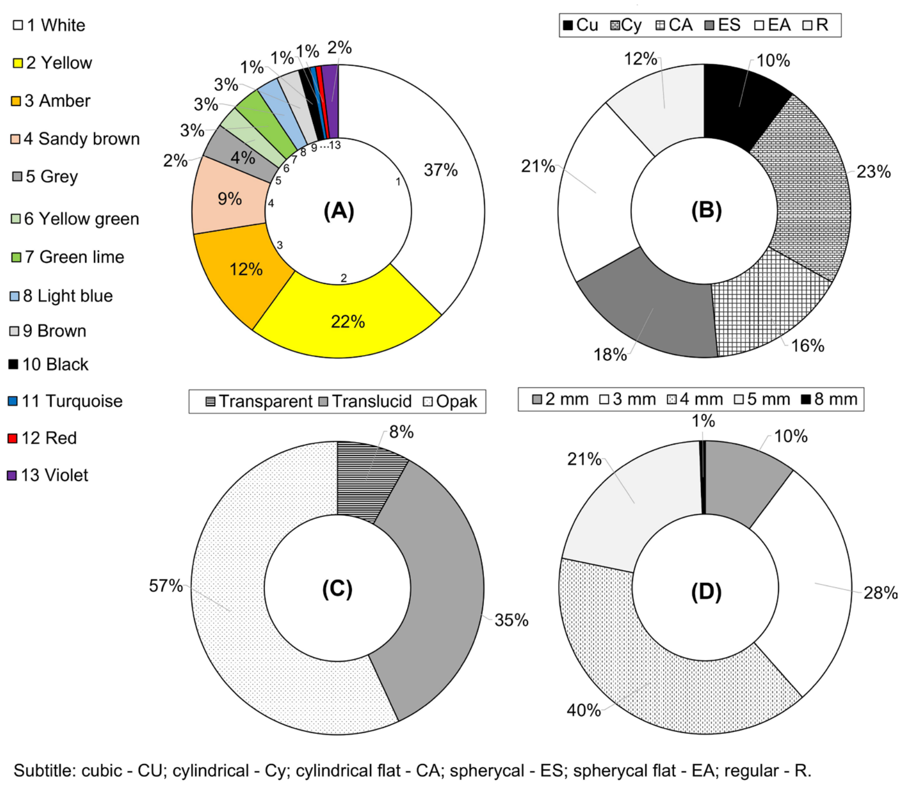


Figure 3. Percentage of the 155 classes by color (A), shape (B), transparency (C) and size (D).

degradation, making them stay longer in the environment (Browne *et al*., 2007; Lithner *et al*., 2011; Thompson *et al*., 2009).

On the other hand, yellow and brown, in their different shades may have originated from the photo-oxidation process by ultraviolet radiation (UV) or by physical weathering (Ismail, 2009; Karapanagioti and Klontza, 2007; Turner and Holmes, 2011). The degradation of pellets exposed to UV rays can vary according to environmental conditions. Therefore, it is fundamental knowing the process of photo-oxidation in different environments to calculate the dwell time and degradation, as well as to provide a basis for assessing the situation of plastic pollution in the environments (Cai *et al*., 2018). For instance, Cai *et al*. (2018) carried out a laboratory experiment in which they used three types of plastic resins (PP, PE and PS). The samples were placed on glass plates and submerged in pure water and simulated sea water and subjected to a UV light bulb (UVA340).

According to Cai *et al*. (2018), the degradation of all analyzed plastic resins was significantly higher in air-exposed condition than in aqueous solution environments (*e.g.*, sea water and ultrapure water). This may be related to the higher oxygen content in the air, as well as to the higher rate of UV radiation incident on the pellets. Therefore, knowing the origin of the pellets in relation to the collection site (whether water or soil) is important, as there may be places where there is a higher incidence of UV radiation, as well as contact with sea water or air, changing the rate their degradation. Thus, polymer discoloration can be caused by several factors (Endo *et al*., 2005), such as type and concentration of additives, environmental condition, and elapsed time after polymer production. In addition, the different colors or shades of yellow and brown suggest that the pellets underwent different degrees of weathering (Turner and Holmes, 2011).

Many studies classify the pellets by color, shape, size (Corcoran *et al*., 2020; Li *et al*., 2020; Wessel *et al*., 2016), but there is no standardization as proposed here. According to Corcoran *et al*. (2020), identifying these characteristics can be useful for pellet manufacturers and processors who want to determine whether their products are contributing to pellet pollution in different beach places. Thus, when organizing by numeric classes, it would not be necessary to place all the characteristics of the pellets, just the number being sufficient.

4.2. Marine microbiota and the presence of microplastics

Some studies suggest that the color of the resins may influence their ingestion by the aquatic animals because, together with the small size, they resemble the prey (Choy and Drazen, 2013; Hidalgo-Ruz *et al*., 2021; Wright *et al*., 2013). According to Fotopoulou and Karapanagioti (2012), there is evidence that seabirds select specific plastic shapes and colors and are generally white or yellow in color; behavior also common among other animals, such as fish and turtles.

As a result of the selective ingestion of food, by color, by some organisms, the characterization and separation of granules in color may be ecotoxicologically important (Bellas *et al*., 2016; Endo *et al*., 2005; Neves *et al*., 2015). Depending on the color of the pellet ingested by the animal, it would be possible to assume the presence or not of organic pollutants *e.g.*, yellow pellets. However, as light colors (white, yellow, amber) are the most observed in the stomachs of animals, the prevalence of these resins may reflect the pellets availability of these colors in the environment, rather than a selectivity colors (Lusher, 2015) as described by Wright *et al*. (2013) and Fotopoulou and Karapanagioti (2012). With the classification detailed here, it would facilitate the organization of pellets that are found in animals, allowing a standardization in future results.

4.3. Size and morphology shape

The size of pellets is another important factor, because of their small size, they are more readily available to organisms throughout the food chain. Size allows pellets to be ingested by a wide range of marine animals, both in benthic and pelagic ecosystems (Lusher, 2015). Wright *et al*. (2013) stated that resins with diameters <0.5 mm are ingested 37 times more than the larger ones. The ingestion of pellets causes negative effects on animals, from physical intestinal blockage to organ damage caused by the release of toxins (Wilcox *et al*., 2015).

Most of the classes found were 4 mm in size, followed by the 3 mm size. The size of the pellet directly impacts availability for the animal, because the smaller, the more easily ingested, whether by larger or smaller beings. Conversely, few papers morphologically describe the pellets addition, the behavior and fate of microparticles of different types and forms of polymers also need to be established. Additionally, the description and inclusion of the morphology for the characterization of the pellets complements the other data (color, shape, size, and transparency). The division and characterization of the classes of this work provide data on various types of resins produced by the industry, since, although many researches make identifications about the occurrence (Corcoran *et al*., 2020; Fotopoulou and Karapanagioti, 2012; Holmes *et al*., 2012; Lozoya *et al*., 2016; Miranda and de Carvalho-Souza, 2016; Moreira *et al*., 2016; Choong *et al*., 2021; Tavares *et al*., 2016; Turner and Holmes, 2011; Turra *et al*., 2014; Wright *et al*., 2013), colors, shapes and sizes, in the literature raised for this work, no classification of this type was found. Therefore, monitoring programs in the study region are needed to assess the temporal trends of pellet accumulation on sandy beaches and are decisive for evaluating possible strategies to reduce their entry into the oceans.

In addition, other physical factors must be considered because they change the distribution of pellets such as waves, tides, speed and direction of the winds (Izar *et al*., 2019). The assessment of the physical and biological processes that influence the accumulation of pellets, especially on land and in depth, would help in the interpretation of data and the understanding of the establishment of zones of accumulation.

5. CONCLUSIONS

The standardization of the characteristics of the pellets in classes, provided a documentation of the types of granules produced and found near the port of Pecém, Ceará, Brazil, making it possible to quantify and characterize the granules manually and with the naked eye, with a classification in four blocks and 155 different classes of pellets. Yellow, amber, and brown (yellowish brown and light brown) pellets are the most frequent.

Since these colors are produced by photo-oxidation they indicate a longer travel time and presence of the respective pellets in the environment. Thus, a ratio of fresh-colored pellets divided by the number of bleached pellets can be used as an indicator for the proximity of the beach to the sources of the emitted pellets and can easily aid in estimating the time spent in the environment, either at sea or in sediment.

This type of classification can be used anywhere in the world as a tool to assist research on the presence of pellets in the marine environment and the impacts caused by them, since one of the biggest problems in the scientific community today is that there is no standardization in relation to the characteristics of resins, thus hindering in-depth studies on the subject.

In addition, more research is recommended to evaluate patterns of pellet accumulation in the Brazilian coast, which lacks data. The classification made in this work may help in future studies, in relation to the characteristics of the pellets and a possible standardization of the resins in other works.

AUTHORSHIP CONTRIBUTION STATEMENT

Clara Cabral Almeida Conceptualization, methodology validation, field sampling, laboratory analysis, manuscript writing; **Willame Araújo Cavalcante**, manuscript writing, data interpretation, validation; **Camila Dourado Alves Brito**. Field Sampling and investigation; **Lucas Nogueira Guerra** investigation; **Mathias Bochow** resources, manuscript writing and review; **Sandra Tédde Santaella** resources, manuscript writing and review, supervision.

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SUPPORTING MATERIAL

ESTABLISHING A STANDARD-BASIS FOR THE CHARACTERIZATION OF MARINE MICROPLASTIC-PELLETS

Pellets characterization

From the characterization of the 1,411 pellets collected, granules with different morphologies were observed. It was also observed that in most samples, most of the pellets had light colors, but also dark colored resins were found. The classification of the granules resulted in a catalog with 155 classes, divided into six distinct blocks, considering four factors: size, shape, color, and transparency. Tables 2 to 5 show the classes of pellets by size (2, 3, 4 and 5), respectively.

Table 2. Classification and characteristics of pellets with 2 mm.

Class	Color	Shape	Transparency
1	Yellow	Cilyndrical	TL
2	Yellow	Spherical flat	TL
3	Amber	Cilyndrical	0
4	White	Irregular	TL
5	White	Cilyndrical	0
6	White	Spherical flat	TL
7	White	Spherical	TL
8	White	Cilyndrical flat	0
9	White	Irregular	0
10	White	Retangular	0
11	White	Cilyndrical flat	TL
12	White	Spherical flat	0
13	White	Cubic	0
14	White	Spherical	0
15	Sandy brown	Cilyndrical flat	0
16	Sandy brown	Spherical flat	0

Transparency: 0 = opak, TL = translucent.

Table 3. Classification and characteristics of pellets with 3 mm.

Class	Color	Shape	Transparency	Class	Color	Shape	Transparency
17	Yellow	Spherical flat	0	39	White	Cilyndrical flat	TL
18	Yellow	Cubic	TL	40	White	Cilyndrical flat	TL
19	Yellow	Cilyndrical	0	41	White	Cilyndrical flat	0
20	Yellow	Cilyndrical	TL	42	White	Cubic	0
21	Yellow	Spherical flat	TL	43	White	Spherical	0
22	Yellow	Spherical	0	44	White	Cilyndrical	0
23	Yellow	Cilyndrical	0	45	White	Irregular	0
24	Yellow	Irregular	TL	46	White	Retangular	0
25	Yellow	Spherical flat	0	47	White	Spherical	TL
26	Yellow	Spherical	TL	48	White	Spherical flat	0
27	Yellow	Cilyndrical	TP	49	White	Cilyndrical flat	TP
28	Yellow	Cilyndrical flat	TL	50	Grey	Cilyndrical flat	0
29	Yellow	Irregular	0	51	Grey	Cilyndrical	0
30	Yellow	Cilyndrical flat	0	52	Sandy brown	Spherical	TL
31	Amber	Cilyndrical flat	TL	53	Sandy brown	Irregular	TL
32	Amber	Cubic	TL	54	Sandy brown	Cilyndrical	0
33	Amber	Cilyndrical	TL	55	Sandy brown	Spherical	0
34	Amber	Irregular	TL	56	Sandy brown	Spherical flat	0
35	White	Spherical flat	TL	57	Brown	Cilyndrical	TL
36	White	Cilyndrical	TL	58	Black	Spherical	0
37	White	Irregular	TL	59	Lime green	Cubic	0
38	White	Cubic	TL	60	Violet	Cilyndrical	0

Transparency: 0 = opak, TL = translucent, TP= transparent.

Table 4. Classification and characteristics of pellets with 4 mm.

Class	Color	Shape	Transparency	Class	Color	Shape	Transparency
61	Lime green	Cubic	O	92	White	Cilyndrical flat	TP
62	Yellow	Spherical	TL	93	White	Cilyndrical flat	O
63	Yellow	Spherical flat	TL	94	White	Irregular	O
64	Yellow	Cilyndrical flat	TL	95	White	Spherical	O
65	Yellow	Cilyndrical	O	96	White	Retangular	O
66	Yellow	Cilyndrical	TL	97	White	Spherical flat	O
67	Yellow	Retangular	O	98	White	Irregular	TL
68	Yellow	Spherical	O	99	White	Cubic	O
69	Yellow	Spherical flat	O	100	White	Cubic	TL
70	Yellow	Irregular	TL	101	White	Retangular	TL
71	Yellow	Cubic	O	102	White	Irregular	O
72	Yellow	Cubic	O	103	White	Cubic	O
73	Yellow	Spherical	O	104	Grey	Retangular	O
74	Amber	Spherical	TL	105	Grey	Irregular	TL
75	Amber	Cilyndrical	O	106	Grey	Irregular	TL
76	Amber	Spherical flat	O	107	Brown	Cilyndrical	O
77	Amber	Spherical	O	108	Brown	Cilyndrical	TL
78	Amber	Spherical flat	TL	109	Brown	Irregular	TL
79	Amber	Spherical	TP	110	Sandy brown	Spherical	O
80	Amber	Irregular	O	111	Sandy brown	Cilyndrical	O
81	Amber	Spherical flat	O	112	Sandy brown	Spherical flat	O
82	Amber	Spherical flat	TL	113	Sandy brown	Irregular	O
83	Light blue	Cilyndrical	O	114	Sandy brown	Cilyndrical flat	O
84	Light blue	Cilyndrical flat	TP	115	Black	Cilyndrical	O
85	Light blue	Spherical flat	TP	116	Turquoise	Retangular	O
86	White	Cilyndrical flat	TL	117	Yellow green	Retangular	O
87	White	Cilyndrical	TL	118	Yellow green	Retangular	O
88	White	Spherical	TL	119	Yellow green	Cilyndrical flat	O
89	White	Spherical flat	TL	120	Lime green	Spherical flat	TP
90	White	Spherical flat	TP	121	Violet	Cilyndrical	O
91	White	Cilyndrical	O	122	Violet	Spherical flat	TP

Transparency: O = opak, TL = translucent, TP= transparent.

Table 5. Classification and characteristics of pellets with 5 mm.

Class	Color	Shape	Transparency	Class	Color	Shape	Transparency
123	Yellow	Spherical	0	140	White	Irregular	0
124	Yellow	Cilyndrical flat	TL	141	White	Spherical flat	TL
125	Yellow	Spherical flat	TL	142	White	Retangular	TL
126	Yellow	Cilyndrical	0	143	White	Cilyndrical	TL
127	Yellow	Irregular	0	144	White	Spherical	TP
128	Yellow	Spherical flat	0	145	White	Spherical flat	TP
129	Yellow	Cubic	0	146	White	Cilyndrical flat	0
130	Amber	Spherical	TL	147	White	Spherical	TL
131	Amber	Cubic	0	148	White	Cilyndrical	0
132	Amber	Cilyndrical	0	149	Grey	Cilyndrical	0
133	Amber	Retangular	0	150	Sandy brown	Irregular	0
134	Amber	Cilyndrical flat	0	151	Sandy brown	Cilyndrical flat	TL
135	White	Irregular	TL	152	Yellow green	Spherical flat	TP
136	White	Spherical	0	153	Lime green	Irregular	0
137	White	Retangular	0	154	Lime green	Retangular	0
138	White	Spherical flat	0	155	Red	Cilyndrical flat	0
139	White	Cilyndrical flat	TL				

Transparency: 0 = opak, TL = translucent, TP= transparent.

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ENVIRONMENTAL EVOLUTION OF COASTAL AFFORESTATIONS: MANAGEMENT STRATEGIES FOR DUNE FIXATION IN THE SANDY BARRIERS OF BUENOS AIRES, ARGENTINA

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ABSTRACT: Tourism in the southern sandy temperate barriers has historically been one of the drivers of coastal development in Buenos Aires, Argentina. This process, which has been accompanied by dune fixation and a subsequent urbanization, began in the 1930s and occurred in the absence of coastal management policies causing several environmental problems. This work aims to analyze the historical development of two dune afforestation projects with the objective of characterizing their main environmental issues. These projects, which started almost simultaneously, are currently at completely different levels of development. For this purpose, a literature and relevant legislation review was carried out, allowing us to characterize them and generate comparisons. At the same time, it is intended to propose new strategies for dune fixation. One of the peculiarities of these afforestation projects is that two brothers carried them out: Carlos and Ernesto Gesell. Carlos initiated an afforestation that led to the sprawl of Villa Gesell. This city reached historical records of urban growth and it is actually one of the most popular bathing resorts of Argentina. Ernesto founded Dunamar on a more restricted dune field and it is currently at a significantly lower stage of development than Villa Gesell. Coastal erosion, surface runoff increase, decrease of foredune areas and replacement of native dune vegetation are some of the reported problems. Currently, there are projects for the expansion of the urban area of these villages under different strategies for dune stabilization. Although their effects have been extensively documented, they propose fixations with fast-growing exotic species. This work proposes the revegetation by means of native species corresponding to the original landscape of the dunes of about a century ago. To this end, certain aspects must be taken into account within the framework of integrated coastal management.

Keywords: urban development; coastal tourism; native dune vegetation; dune fixation.

RESUMO: *O turismo nas barreiras arenosas do Sul em Buenos Aires, Argentina, tem sido um dos motores históricos de expansão costeira local. O seu desenvolvimento iniciou-se na década de 1930, na ausência de políticas de gestão costeira, sendo acompanhado por mecanismos de fixação dunar e uma subsequente urbanização, que causaram vários problemas ambientais. Este trabalho pretende analisar o desenvolvimento histórico de dois projetos locais de florestação dunar, por forma a enquadrar o seu contexto ambiental. Os projetos, que começaram quase simultaneamente, encontram-se atualmente em níveis de desenvolvimento técnico completamente diferentes. Foi realizada uma revisão bibliográfica e de legislação relevante, que nos permitiu caracterizá-los e compará-los. Ao mesmo tempo, foram propostas novas estratégias para a fixação das dunas. Uma das peculiaridades destes projetos de florestação é que foram levados a cabo por dois irmãos: Carlos e Ernesto Gesell. Carlos iniciou a reflorestação que levou à expansão de Villa Gesell. Esta cidade atingiu recordes históricos de crescimento urbano e é na realidade uma das estâncias balneares mais populares da Argentina. Ernesto fundou a cidade Dunamar num campo de dunas mais restrito e o projeto encontra-se atualmente numa fase de desenvolvimento significativamente inferior à de Villa Gesell. Fenómenos de erosão costeira, aumento do escoamento superficial, diminuição da área natural de dunas e substituição da vegetação nativa das dunas, são alguns dos problemas relatados para estes locais. Atualmente, existem projetos para a expansão da área urbana destas cidades assumindo diferentes estratégias para a estabilização das dunas. Embora os seus efeitos tenham sido amplamente documentados, estes projetos propõem fixações com espécies exóticas de crescimento rápido. Este trabalho propõe a revegetação de espécies nativas correspondentes à paisagem original das dunas há cerca de um século atrás. Para o efeito, certos aspetos técnicos deverão ser tidos em conta no âmbito da gestão costeira integrada do troço litoral.*

Palavras-chave: *desenvolvimento urbano; turismo costeiro; vegetação nativa das dunas; fixação de dunas.*

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1. INTRODUCTION

Sand barriers caused by a Holocene fluctuation of the sea level dominate temperate Southern Hemisphere. The sand availability at the maximum sea level high stand permitted that onshore winds help accumulated sand to establish barriers of about 3 km width (Isla, 2017). The afforestation of these barriers could be performed where the wind-blown sand can be dominated into fixed dunes. For success, it was necessary that the roots of the introduced trees could reach the depth of the water table (Rodrigues-Capítulo *et al*., 2018).

One of the main drivers of coastal development has been and continues to be tourism (Da Silva and Schwingel, 2019). This process is accompanied by the location of infrastructures and services that promote diverse land use and land cover (LULC) changes over coastal areas (Roig-Munar, 2018). Several authors place coastal urbanization and dune afforestation among the most relevant LULC changes resulting from tourism development over dune systems (Mollema *et al*., 2015; Okello *et al*., 2015).

In the Buenos Aires Province, Argentina (Figure 1), several resort villages were developed in relation to anthropogenic forests that were later managed into parks (Juarez and Isla, 1999; Isla, 2013). In some of these coastal areas, the process of tourism development occurred with poor planning strategies and in the absence of coastal management policies, resulting in environmental problems (Dadon, 2011).

This work aims to analyze the historical development of two dune afforestation projects carried out in the province of Buenos Aires, Argentina, which have become important coastal tourist villages, with the objective of analyzing their main environmental problems. Although they are almost contemporaneous, these projects are currently at completely different levels of development. A review was based on previously bibliography and relevant legislation or regulations over the study sites, allowing a characterization and comparison of these two projects.

At the same time, taking into account the existence of current projects for the expansion of these developments on dune areas, this work aims to generate proposals for new dune fixation processes within the framework of Integrated Coastal Management.

One of the particularities of these projects is that they were carried out by two brothers. Carlos Idaho Gesell initiated the Villa Gesell project in 1931. His brother Ernesto Gesell forested Dunamar a few years later. Although both towns were settled on a coastal barrier of dunes, their beginnings and later development were different.

2. THE SANDY BARRIERS OF BUENOS AIRES

Villa Gesell, on the one hand, is located on the Eastern Barrier of Buenos Aires in the homonymous county; Dunamar, on the other hand, is located on the Southern Barrier and in the Tres Arroyos County (Figure 1). Both sites were developed over barriers dominated by transverse dunes. In Villa Gesell, winds from the north dominate slightly; however, the asymmetry of the transverse dunes indicates that the sand transport is towards the NNE. In Dunamar, westerly winds prevail causing an asymmetry of the transverse dunes (Cortizo and Isla, 2007; Cortizo, 2010). Annual precipitations are higher in Villa Gesell (844 mm) than in Tres Arroyos (766 mm).

Since the origin of these touristic projects, groundwater availability for the inhabitants and for the afforestation purposes were completely different in both barriers. On the one hand, in Villa Gesell the water table has a lenticular shape and the aquifer comprises the 3 km of the sand barrier (Bértola *et al*., 2002). Another aquifer was discovered below the Villa Gesell sand barrier within sandy silts of Upper Pleistocene age (Violante *et al*., 2001). In detail, at the neighboring Pinamar County, three aquifers were discriminated: one comprising Pleistocene rocks, while two aquifers within the Holocene sediments (Rodrigues-Capítulo and Kruse, 2017). On the other hand, at Dunamar, the sand barrier is on top of cliffs, 7 m above mean sea level (Cesare, 2016).

3. HISTORICAL DEVELOPMENT AND ACTUAL ENVIRONMENTAL PROBLEMS

3.1. The Villa Gesell of Carlos Gesell

In 1930, estimates of federal property indicated that there were 3089 ha to be incorporated into the Argentine heritage; 1648 of these ha were bought by Carlos Idaho Gesell in 1931 (Juarez and Mantobani, 2006; Benseny, 2011). In 1946, he bought more fields to Astengo Morando, who kept the ownership of the southern sand-dune field of the current Villa Gesell County. The Morando's property today comprises the localities of Mar de las Pampas, Las Gaviotas and Mar Azul (Figure2).

Carlos Gesell works were very difficult as the sand-dune fields were very dynamic and the plants specimens did not adapt easily. Despite this, by the early 1940s, he successfully stabilized the dunes by means of wooden sand fences followed by artificial afforestation with rapid-growth exotic species (Figure 3). The city grew in three stages. During 1931-1940, the main purpose was the fixation of the dunes. In the second stage (1941-1970) the

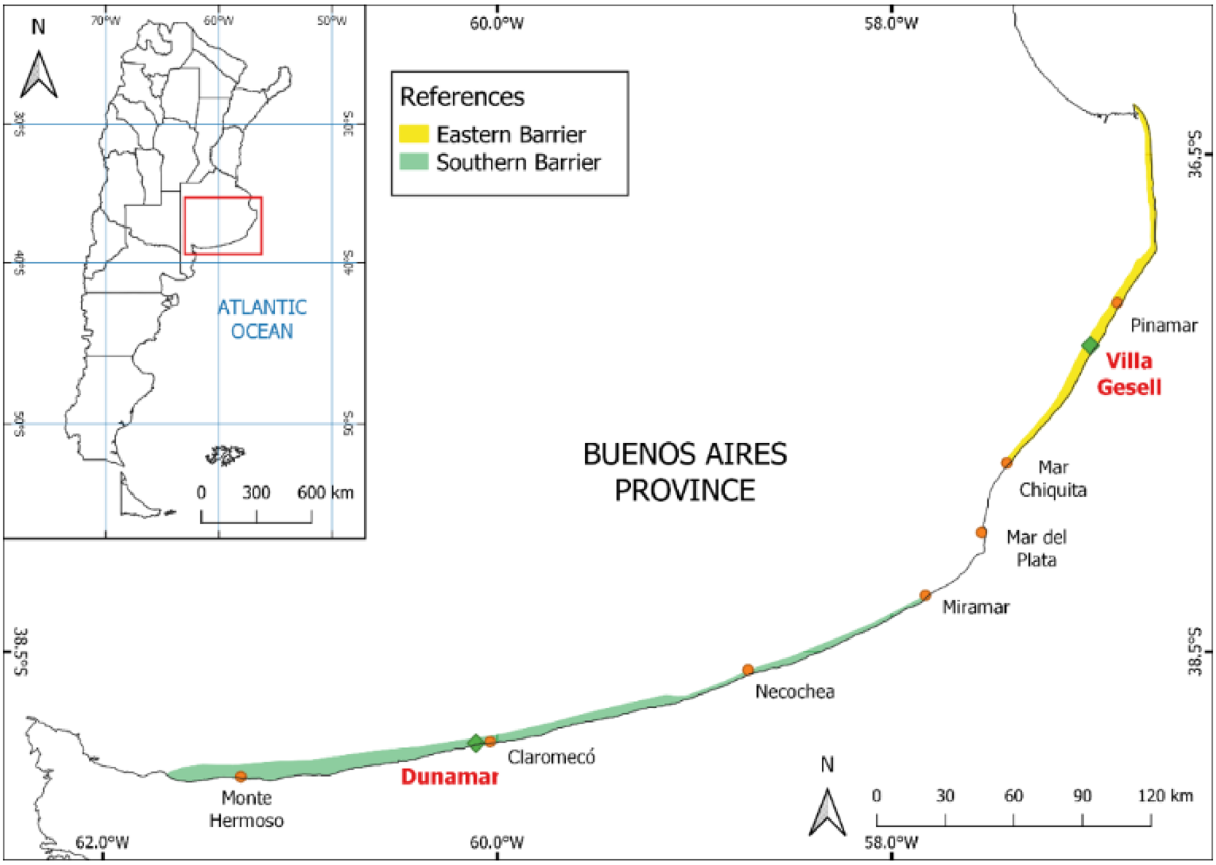

Figure 1. Location of Villa Gesell (Eastern Barrier) and Dunamar (Southern Barrier), in the Buenos Aires Province, Argentina. [Modified after Isla *et al.* (2001)].

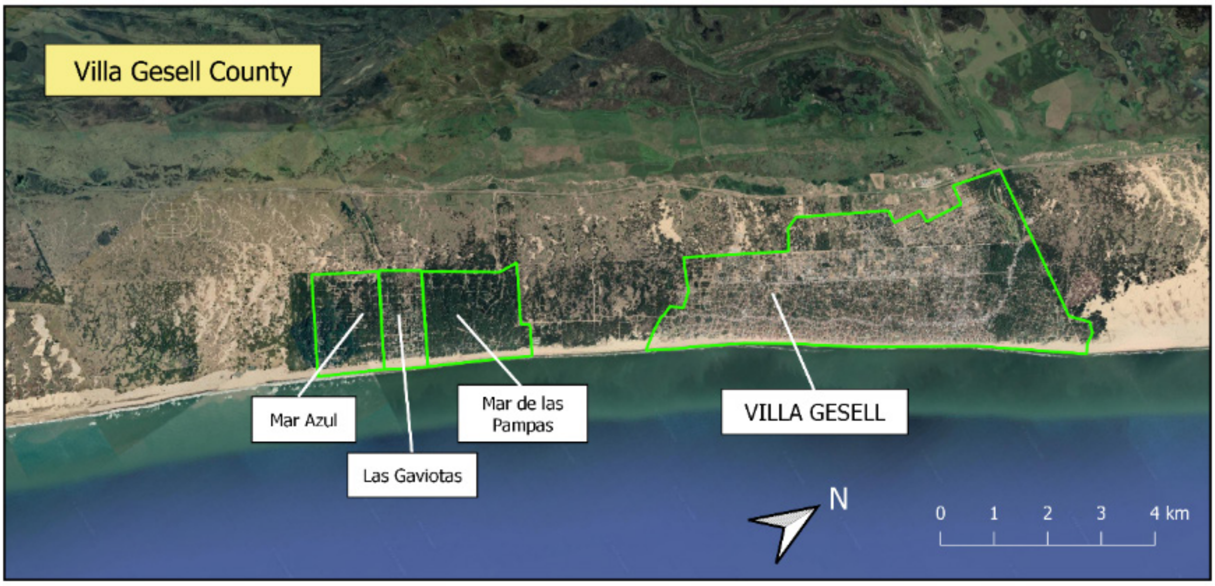

Figure 2. Coastal villages of the Villa Gesell County: Mar Azul, Las Gaviotas, Mar de las Pampas and Villa Gesell.

consolidation of the village occurred, with avenues parallel to the beach and streets (called "paseos") normal to the coast but oriented preferentially to the inter-dune depressions and respecting the original morphology of the dunes. During the third stage (1971 to present), the village became a city restricted to the width of the sand barrier. Due to the promotion of access to land and construction, during 1974 and 1975 Villa Gesell reached the highest urban growth rate in Argentina (Juarez and Isla, 1999). In this way and due to conflicting interests, the urban county became independent from General Madariaga, its historical rural municipality. Some characteristics inherited from the resort village evolved into the problems of a densely populated city (Isla, 2013; Isla and Isla, 2020).

In spite of the enormous work done to fix and forest the dunes and the advantages that this brought for the urban expansion, the northern sector of Villa Gesell has been deforested in the last decades (Figure 4). A reduction in the forested area in the first 300 m closer to the beach has been observed at the expense of an increase in the density of urban surfaces (building, asphalted streets, parks and gardens). One of the few areas where dense woods are still preserved are the neighborhood of the Carlos Gesell's foundational house, known as "Pinar Del Norte". In both cases, urbanized and densely forested sectors, the width of the beach diminish drastically. However, in the first of these the setback was greater than in the second.

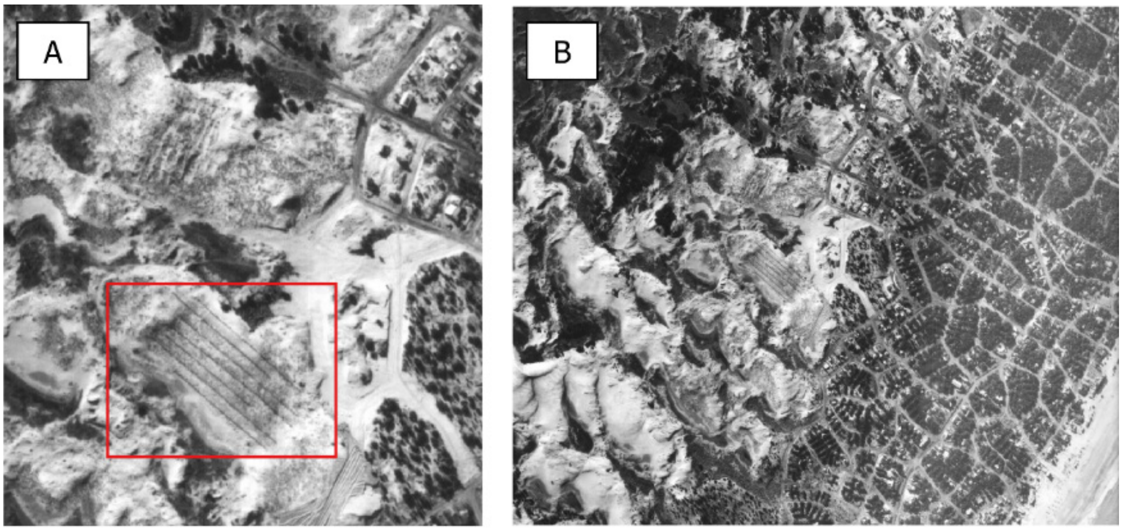

Figure 3. Aerial photographs from Villa Gesell in the 1960s. Sand fences in the transverse dune fields before tree establishment (A). Urbanization of the dune fields after fixation with sand fences and afforestation. Streets respecting the original morphology of the dunes (B).

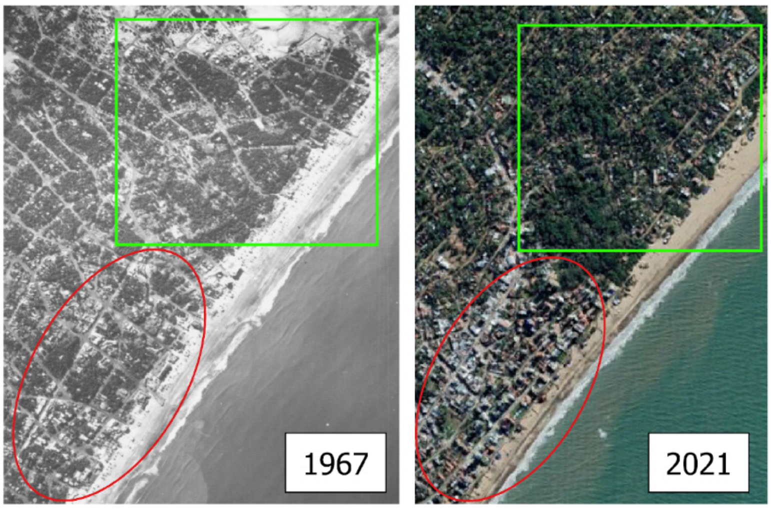

Figure 4. Land use/land cover comparison in northern Villa Gesell between 1967 and 2021. It is observed a decrease in the afforestation in the first 300 m from the beach (circle). In Pinar Del Norte (square) the tree cover grew but beach widths diminished. Lots are approximately 100 x 100 m.

Foredunes are retreating faster at the city center (located in the north sector) mostly due to the episodic impact of storms arriving from the SSE (Isla *et al*., 1998 and 2018). This erosion has increased due to the pluvial runoff induced by the pavement of the streets normal to the coast (Figure 5). The channeling of stormflows towards the beaches generates scarps and canals. To the south of the county, in Mar de las Pampas, Las Gaviotas and Mar Azul, the retreat is less than 0.5 m/yr. but may certainly increase if the forecasted sea-level rise (Oppenheimer *et al*., 2019).

Comparing oblique photographs from the sixties to recent ones, it is evident the decrease of the foredune areas. The areas with shrubs (mainly *Tamariscus*) were replaced by bathing-resort facilities (Figure 6).

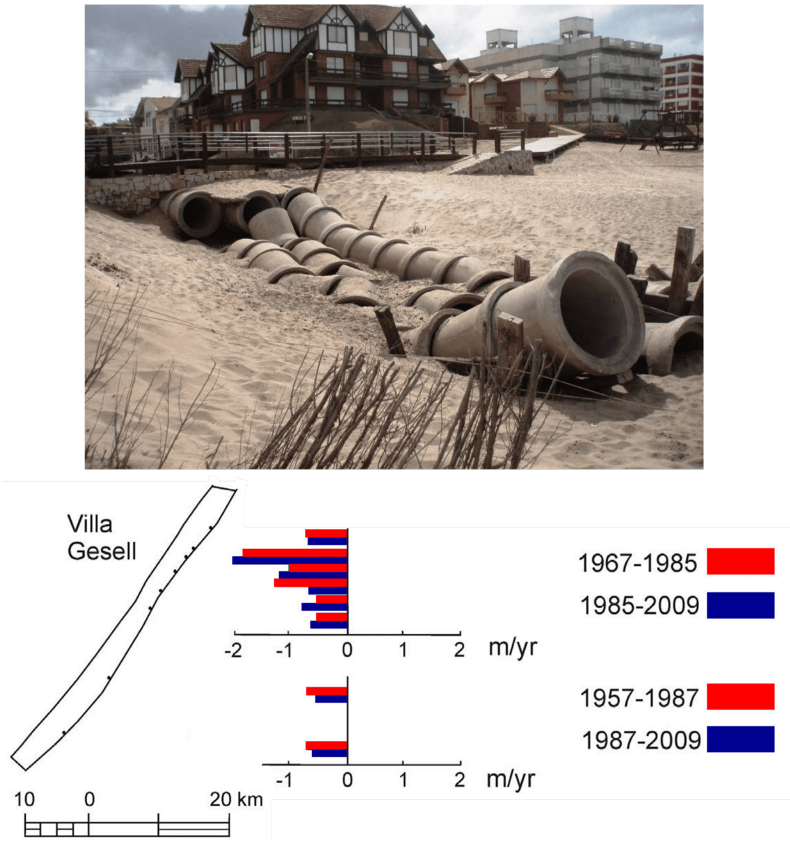

Figure 5. Up: storm flows discharge over beaches in Villa Gesell city centre. Down: Retreat of the Villa Gesell County coastline between 1967-1985 and 1985-2009 [Modified after Isla *et al.* (2018)].

Figure 6. The original village grew to be transformed in a coastal city with tall buildings. Left photo: Mid '70s, right photo: 2010 [Modified after Isla (2013)].

The urban growth of Villa Gesell has generated a systematic replacement of the dune fields with their native vegetation by urban areas and exotic forests (Faggi and Dadon, 2010). This urbanization parallel to the coast had its maximum development in the second half of the century (Figure 7). However, in the last 20 years the urban surface of Villa Gesell has not expanded. Instead, there has been a densification of buildings, increasing the establishment of impermeable covers over the sandy substratum (Figure 7). This led to an increase of runoff processes causing beach erosion.

3.2. The Dunamar village

The Dunamar bathing resort grew associated to the Claromecó village. This village was originated by a proposal of the Bellocq family to the Federal authorities (Juarez and Mantobani, 2006). In 1945, Ernesto Gesell bought 1600 ha of the dune fields immediately to the west of the Claromecó creek (Figure 8). The first problem was the access to these dunes. Bridges across the creek were constructed twice and destroyed by floods. Since 1980, a bridge assure the access of cars. Although precipitation in this region was significantly less, Ernesto Gesell's experience gained from working with his brother was applied to an improved strategy. At the same time, the terrace below the dunes were an easy access of the trees to the water table.

The sand fence and afforestation of Dunamar generated three subsequent urban subdivisions between 1947 and 1949, defining 753 lots. Subsequently, in 2002, two grandchildren of

Figure 7. Urban development of Villa Gesell, mainly parallel to the coast (1957-2021) (A). Densification of buildings between 2003 (B) and 2021 (C). [Modified from Juarez and Isla (1999); Isla (2017); Isla and Isla (2020)].

Eduardo Gesell promoted the inclusion of 80 new lots, raising to the actual number of 832 lots (Cesare, 2016). As in Villa Gesell, the urban area of Dunamar has not increased in the last 20 years. However, buildings have densified and the forest cover has expanded towards the west (Figure 9).

The afforestation and subsequent stabilization of the dunes has generated changes in the morphological characteristics because of the decrease in the availability of sand. At Médano Verde, next to Dunamar, transverse dunes migrated at rates of 5-6 m/yr. between 2003 and 2013. These migration rates diminished drastically to 1.5 m/yr. in the last years (Isla *et al*., 2021). This has generated that, today, the main problem in Dunamar continues to be the sedimentary excess and the dune mobility.

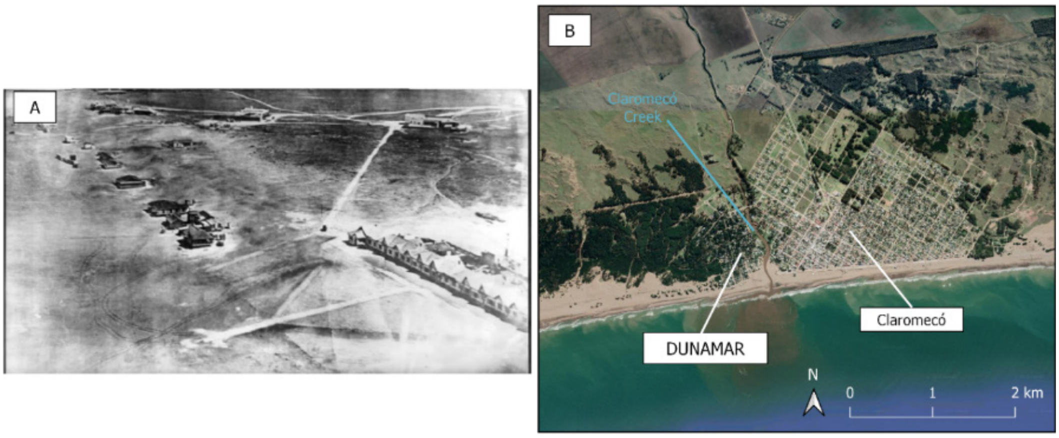

Figure 8. From the beginnings, the Claromecó village was urbanized on a terrace where the dunes were eliminated (Photo of the '40s decade) (A). In contrast, Dunamar dunes were afforested and the village is expanding to the west (B).

Figure 9. Dunamar densification and advance of afforestation (2003-2021).

4. CURRENT PROJECTS FOR URBAN DEVELOPMENT

In the whole territory of the Buenos Aires Province, according to Decree No. 3202/06 the foredunes cannot be removed, forested or urbanized. At the same time, according to Decree No. 8912/77, in order to develop new urbanization in dune areas, the dunes must be previously fixed and forested and the density of urbanization will be that which allows the permanence of fixation and afforestation works. The Decree No. 10081/1983 establishes that the Federal Government is able to expropriate public and private properties in dune areas in order to fix them. Taking into account the provincial decrees together with other normative that regulate the action at municipal level, there are current projects for the expansion of the urban area and the vegetation of new dune sectors in Villa Gesell and Dunamar.

4.1. The Villa Gesell City Assessment Plan

Villa Gesell grew at rates without antecedents in Argentina that led to several unsolved growing problems (water provision, coastal-dune retreat, beach erosion, runoff episodes, and domestic-sewage disposal). Nowadays it is one of the main destinations of domestic tourism in Argentina with more than 1.15 million tourists registered in Villa Gesell during January 2022 (Source: Villa Gesell Touristic Office). The complexity of the different areas of the Villa Gesell city led to propose an Assessment Plan for coastal urbanization (*Plan de Ordenamiento Municipal*; Decree No. 13621/21) discriminating at least 6 sectors of the county. The city has 13,257 lots of which 18% are vacant, only taking into account authorized and declared constructions. Its stable population was 29,600 inhabitants by 2010 but with a high growth rate; 40,800 inhabitants were projected to 2025. At the same time, the potential tourist population of the city taking into account its hotel vacancies is 180,000 inhabitants, meaning 600% of its stable population at times of maximum occupancy.

The municipal plan proposes reaching a potential tourist population of 300,000 inhabitants by 2030 and 590,000 inhabitants by 2045. To this end, it is proposed to extend the linear extension of the waterfront that can be urbanized from 8.05 km to 17.36 km. This means restructuring in six stages about 870 of the 1170 ha of the city center to reach an urban density of 400 inhabit/ha; and expanding urban development linked to tourism by approximately 1,300 ha divided into the south (“Colonia Marina”) and the north of the city center and with an average urban density of 30 inhabit/ha (Source: *Plan de Ordenamiento Municipal*; Decree No. 13621/21) (Figure 10).

The same plan proposes a “reconversion” of urban forests due to the age of the existing trees since the initial forestation of Carlos Idaho Gesell, which occurred almost a century ago. To this end, reseeding strategies are planned. At the same time, new dune fixation and forestations are planned in those areas where the urban area will be expanded. For this purpose, the municipality

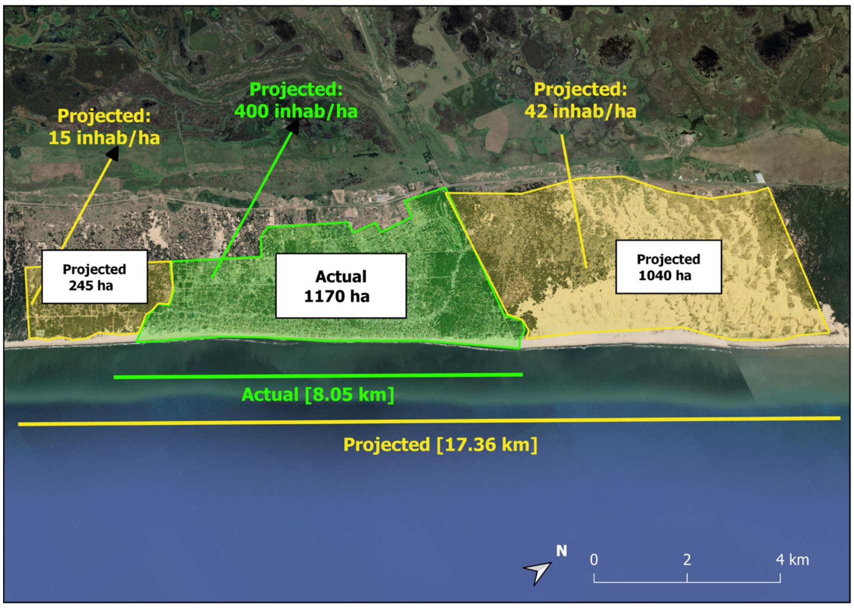

Figure 10. Actual and projected urban surface, population density and alongshore urban waterfront coverage in Villa Gesell.

plans to fix the dunes with grasses and low shrub species, avoiding landscaping with lawn and fixing with large species that consume a lot of water.

4.2. The Dunamar forest urbanization

Ernesto Gesell's descendants are proposing the urbanization of the afforestation towards the west of Dunamar taking care about the new procedures and rules stated by the environmental authorities of the Buenos Aires Province (Figure 12). For this purpose, 120 ha will be urbanized in a first stage, keeping a remaining 40 ha for future expansions. 610 lots will be assigned to low-density family housing and only 3 lots will be destined to hotels, projecting a density of 40 inhabit/ha (Cesare, 2016). This means and urban waterfront increase from 670 m to 2320 m. The project anticipates new fixation and afforestation of dunes, consolidating the areas without forests. In this way, the project intends to guarantee a reserve zone of 56.9 ha covering the first 250 m inland from the shoreline, granting 39.6 ha to the public domain and keeping 17.3 ha of the private domain undeveloped (Cesare, 2016) (Figure 11).

5. CONTEMPORARY AFFORESTATIONS

In order to compare the afforestation strategies employed and the historical development of Villa Gesell and Dunamar, Table 1 summarizes the characterization and data collected through the literature and legislation review.

According to the Decree No. 3202/06, Dunamar has 670 m of urbanized coastline, while Villa Gesell has 8,050 m. This shows that the project initiated by Ernesto Gesell is currently at a significantly lower stage of development than the one initiated by his brother Carlos. The afforestation process in Dunamar was carried out following the guidelines developed in Villa Gesell, however, the current projections and forestation policies of Dunamar do not seem to take in account the subsequent experience of the urbanization process in the project of Carlos Gesell. Villa Gesell is currently facing several environmental issues due to the lack of management. The importance of approaching the future urbanization of Dunamar under integrated coastal management strategies and environmentally efficient management of coastal resources is reinforced. In Villa Gesell, it is important not to continue with the mistakes of the past and the lack of planning that led to serious environmental problems and coastal erosion. In Dunamar, being in a less advanced stage of urban development and planning, it is important to take the failed experience of Villa Gesell as a lesson to avoid repeating this paradigm of uncontrolled urbanization.

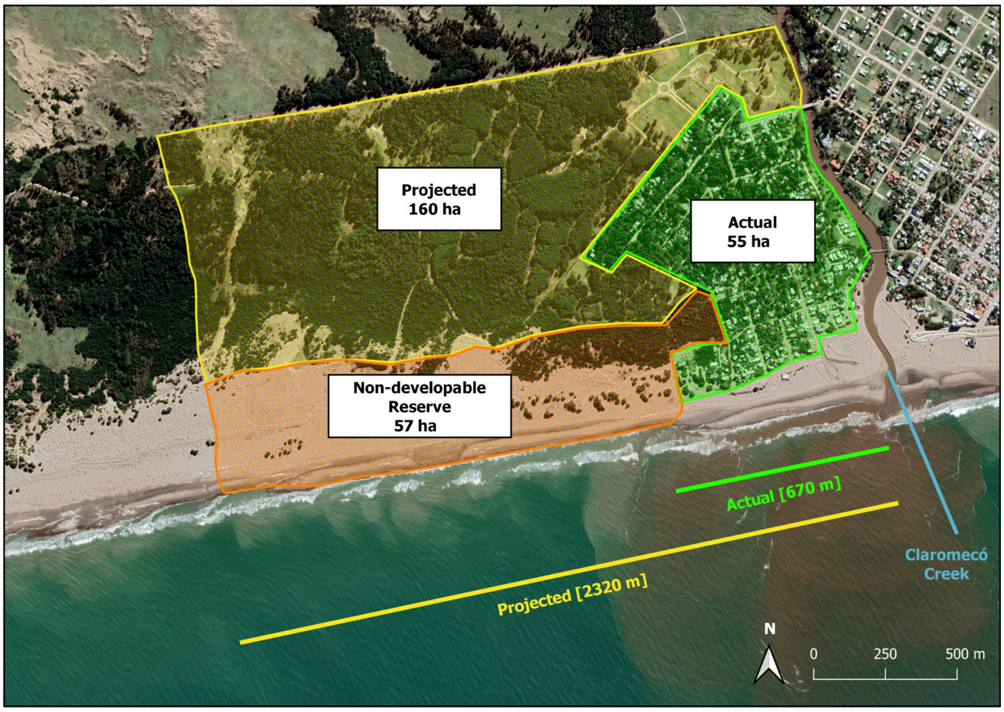

Figure 11. Actual and projected urban surface and alongshore urban waterfront coverage in Dunamar.

Table 1. Comparison between Villa Gesell and Dunamar. Historical development, dune afforestation strategies and future planning.

Criteria/Coastal Village	**VILLA GESELL**	**DUNAMAR**
Start of afforestation works	1931. Successful from 1942 onwards.	1945
Dune stabilization strategy	Wooden sand fences	
Nature of vegetation used for dune fixation	Rapid-growth exotic species	
Main species used for dune fixation	*Carpobrotus chilensis* <Uña de gato> *Acacia melanoxylon* <Acacia Negra> *Tamarix gallica* <Tamarisco> *Myoporum laetum* <Siempre Verde> *Yuca spp.* *Pinus spp.*	
Pre-planning for dune fixation	Trial and error approach (1931-1942)	Based on previous experience in Villa Gesell
Original dune landscape	Respected in the original conception of the urban development plan and in the dune founding forestations	Restricted by the morphology of the Claromecó Creek that made access to Dunamar difficult
Development of the subsequent urbanization	Reached the highest urban growth rate in Argentina between 1975 and 1975. Currently is one of the most popular bathing resort places of the whole country	The current urbanization covers only 55 ha, which means a stable population of less than 2000 people. It presents an incipient degree of development.
Main current environmental problems derived from dune fixation	- Coastal erosion - Sedimentary imbalance - Surface runoff increase - Diminish of foredune areas - Replacement of native dune vegetation - Spread of invasive exotic species	- Changes in dune morphology - Dune mobility - Diminish of foredune areas - Replacement of native dune vegetation - Spread of invasive exotic species
Current regulations associated with dune fixation	Decree No. 8912/1977 Decree No. 10081/1983 Decree No. 3202/2006	
Future planning of dune fixation and urban development	Assessment Plan for Coastal Urbanization Decree No. 13621/2021	Private initiatives carried by the grandchildren of Ernesto Gesell
Projected extension of the waterfront that can be urbanized	From 8.05 km to 17.36 km (115.7% increase)	From 0.67 km to 2.32 km (246.3% increase)
New urbanized area	1285 ha	160 ha
Nature of the proposed fixation	Native dune vegetation	Rapid-growth exotic species
Proposal for reforestation of historic forests	Yes	No

6. DISCUSSION

Forested coastal settlements progress in relation to the availability and quality of freshwater resources. Drought periods can change the mineralization of the groundwater when evaporation dominates over precipitation. At the same time, vegetation diversity can also change depending on the ground water quality. Significant changes linked to anthropogenic threats (afforestation, farming, intensive grazing, tourist urbanization and military activities, among others) were reported between the Belgian and Netherlands coastal dunes (Martens *et al*., 2013).

Several authors have identified afforestation in coastal areas as having a major impact on the local hydrological balance. These fast-growing exotic species evaporate and transpire large amounts of water from infiltrating rain, increasing the concentration of solutes in groundwater and modifying water table levels (Cozzolino *et al*., 2017). These variations have been recognized in the Mediterranean coast of Italy (Mollema *et al*., 2013), the Netherlands (Stuyfzand, 2016) and even in Pinamar County, neighboring Villa Gesell (Rodrigues-Capitulo *et al*., 2018). In a similar way, urbanization processes induce significant decrease in evaporation due to the reduction of green areas and the development of artificial stormwater infiltration (Locatelli *et al*., 2017).

One of the main doubts regarding the forested sand barriers is the transpiration effects in the water budget. Comparing forested and non-forested segments of the Pinamar barrier, the water table is 3 m lower at the forested sector (Rodrigues-Capítulo *et al*., 2018). Another issue to consider is whether the urban growth in altitude at coastal cities can alter the wind dynamics and annual temperature differences within the dune field (Isla, 2010a).

At the same time, coastal problems resulting from dune stabilization have been extensively documented. Dolan and Lins (1987) have identified large-scale fixation of the Outer Banks, United States, sandy barrier as the main cause of coastal erosion. Illenberger (1993) has recognized similar patterns in Port Elizabeth, South Africa. In Denmark, the impacts of afforestation in coastal areas have led to the evaluation of deforestation for the recovery of natural areas with landscape value (Jensen, 1994). In Rio Grande do Sul, Brazil, preservation areas were deliberate occupied by fast dispersion Pinus afforestation, acting as a physical barrier against winds and affecting the sedimentary imbalance. Actually, is recommended to eradicate pine trees in these dune systems in order to preserve the original landscape (Lipp-Nissinen *et al*., 2018). In Costa da Caparica, Portugal, the dune stabilization by mean of tree species turned worthless fields into profitable lands for tourist urbanization but promoting further coastal erosion processes (Palma *et al*., 2021).

According to documented afforestation in 50 years, these forests can sequester 400 tons of C/ha (Turno-Orellano and Isla, 2004). At the same time, some authors identified that afforestation processes promote thermal comfort in public areas of Itapirá, San Pablo, Brazil (Martelli and Santos, 2015) and can improve the local microclimate significantly (Leal *et al*., 2015).

Although the dune afforestation has allowed the subsequent process of tourist urbanization and economic development of these villages, some authors have identified a systematic replacement of native dune vegetation during the process of dune fixation (Faggi and Dadon, 2010; Marcomini *et al*., 2017). These dunes were originally dominated by sparse vegetation of the Panicum genus resistant to the conditions of the environment (Cabrera, 1941). The implantation of fast-growing exotic species and the production of gardens and green spaces in residential areas generated a decrease in the availability of sand. This altered the original morphology and the beach-dune sedimentary exchange, inducing coastal erosion problems (Isla *et al*., 1998).

At the same time, the strategies for dune fixation are intimately connected to perceptions. Historically, dunes were considered a danger for human property and housing. Carlos Gesell has even been widely recognized and awarded as “the dune tamer” for his afforestation works (Benseny, 2011). Nowadays, dunes have an intrinsic value for their ecosystem services, which are to be preserved through new integrated management strategies (Palma *et al*., 2021). In Torres, Rio Grande do Sul, Brazil, the Itapeva State Park was exclusively created in order to protect the dune fields and its native vegetation from the encroachment and impacts of tourist development, being dune fixation one of the most relevant (Rockett *et al*., 2018).

Dune afforestation can have both benefits and disadvantages. Although it is recommended for arid and semi-arid zones where the aim is to increase species richness and improve soil fertility, there is evidence that the introduction of exotic species has caused irreversible damage to the environment at the local level. For this reason, dune stabilization with forestation has been discontinued in some countries such as England, Wales and Denmark (Defra, 2007). In spite of their documented environmental impacts, in some localities such as Villa Gesell, coastal forests are valued as community heritage and are part of the local cultural identity (Dadon, 2002).

There is abundant evidence of urbanization as a driver of vegetation dispersion. This process can be accompanied by the extinction of native species and the spread of highly invasive exotic species (Faggi and Dadon, 2010). Tourist activities gradually spread from the urban environments towards the more remote and preserved beaches, including conservation areas. This generates a gradient of anthropogenic impact and a process of vegetation dispersion, such as that observed towards the western sector of Dunamar (Figure 9). Thus, the impacts of artificial afforestation are not strictly restricted to the boundaries of touristic coastal urbanizations (Garzo and Dadon, 2021).

Numerous studies identify urbanization and tourism as two of the main factors that alter and destroy coastal dune systems (Nordstrom, 2000). The economy of coastal tourist villages is strongly based on urban development, but is highly dependent on the preservation of coastal landscapes and the bathing quality of their beaches (Klein and Osleeb, 2010). In this way, it is highlighted that coastal development and tourism promotes environmental changes but are also vulnerable to these changes (Li *et al*., 2016).

These initiatives are only two examples of several coastal urbanization plans that are evolving in relation to anthropogenic modifications of the coastal dune fields with different restrictive issues. Gesell and other foresters initiated a touristic "industry" that comprises stages of tree thinning, parking strategies and urban plans (Isla, 2013; Isla and Isla, 2020). Buenos Aires Province has stated new models for the growth of urban settlements: field clubs ("clubes de campo"; Decree No. 9404/86), and neighborhoods of restricted accesses ("barrios cerrados"; Decree No. 27/98). These urbanization models flowered during the nineties although they were criticized for giving more initiatives for the private owners, coastal barriers included (Vidal-Koppmann, 2015).

The Gesell brothers promoted the afforestation of sand barriers in Buenos Aires Province. Carlos Gesell imagined transforming those high-altitude dunes into a touristic city. His brother Ernesto faced lately a similar task afforesting the dunes west of the Claromecó. The current dune fixation plans for these bathing resorts differ significantly from those originally proposed almost a century ago by Carlos Gesell and his brother. Not only thanks to the regulations that govern these projects and the activities related to dune afforestation and coastal urban development; but also thanks to the knowledge of the environmental processes that these fixations with fast-growing exotic species have promoted over time.

The future dune-fixation plans for Villa Gesell and Dunamar present important differences with different approaches: forests re-conversion, meaning de-forestation and afforestation, and dune fixation with both native and exotic dune species. For Villa Gesell, on the one hand, a forest re-conversion is proposed meaning the replacement of almost centennial trees for new individuals in those sectors where forests are already established. This approach is primarily intended to reduce the hazard related with frequent tree falls during extreme climate events. Although the environmental impacts of coastal afforestation were extensively documented (Yang *et al*., 2006; Ratas and Rivis, 2008; Weston, 2014; Luo *et al*., 2015), the de-forestation and introduction of new trees will not led to a significant change in coastal dynamics. Some authors have also identified de-forestation as a useful strategy for coastal dune restoration (Lithgow *et al*., 2013).

On the other hand, new dune fixation areas with native dune species are proposed. However, Novoa *et al*. (2013) identified the impacts of exotic species over the re-vegetation of costal dunes with native species and difficulties on its re-introduction. Zaloumis and Bond (2011) showed that forest restoration over coastal dunes follows a linear increase in woody species over time but restoring native grasslands may represent efforts that are more considerable.

In contrast, new dune fixation areas with exotic rapid-growth tree species are projected for Dunamar. As mentioned previously, this strategy promotes several impacts over coastal dynamics and beach equilibrium. Although it promotes an increase in species richness, the introduction of exotic species means several problems for dune conservation (Castillo and Moreno-Casasola, 1996). Malavasi *et al*. (2013) proposed to strictly regulate the afforestation's area in order to preserve natural dune fields. Avis (1989) recommended to only stabilizing those areas when it is absolutely necessary but only by using native species.

Strategies for future dune fixation

As mentioned above, LULCs resulting from urban and tourism development associated with afforestation projects are usually recognized as the main driver force behind impacts on hydrology, sediment balance and biodiversity change in dune areas (Lemauviel and Rozé, 2003). The stability of the dunes is greatly threatened when changes in land use occur, such as forestation with exotic trees and shrubs (Curr *et al*., 2000). These species can generate favorable conditions to the new establishment of exotic vegetation from other sources of dispersal.

One of the consequences of the urbanization of fixed dune sectors is the introduction of ornamental species and the production of gardens and urban green spaces. This generates a change in the species assemblages from the residual natural vegetation that may remain standing, also generating the introduction of exotic shrub and grass species related to gardening (Pauchard *et al*., 2006).

Historically, the vegetation of the sandy barriers of the Buenos Aires province was an open grassland composed of about 70 species, dominated by *Panicum racemosum* and other grasses that withstand being buried with sand and dispersed by seawater (Faggi and Dadon, 2011). Cabrera (1941) described this grassland community in detail. This can be considered as the typical plant community prior to the arrival of massive sea-and-sun tourism.

Faggi and Dadon (2010) compared the species assemblages between urban and non-urban dune areas. They found that the number of exotics increased substantially towards the urban centers. At the same time, the areas located 10 km away from urban centers presented a high similarity with pristine original communities obtained from the plant inventories made in the 1940s (Cabrera, 1941).

The plant associations described in the early 20th century are still present today, although some species have disappeared and the percentage cover of many species has changed (Faggi and Dadon, 2011). The spread of exotics, either introduced into the surroundings from pastures or as weeds from the rural environment (*Dactylis glomerata*, *Festuca arundinacea*) together with ornamentals escaped from gardens (*Gazania longiflora*, *Lagurus ovatus*) changed the composition of the original vegetation.

Based on this, the fixation of native species with high colonization power of dune environments is proposed as a management strategy. This would avoid the new introduction of exotic species with their subsequent changes in coastal morphodynamics, as well as the impact on coastal aquifers and changes in local biodiversity. To this end, certain relevant aspects must be taken into account:

1. The species to be used should tend to reestablish the original dune system or at least an environment with a high percentage of floristic similarity. For this purpose, surveys from the 1940s are available (Cabrera, 1941) (Table 2, Figure 12).
2. It should be taken into account that not all plant species colonize all the spaces present in dune environments. In active dunes, vegetation will tend to establish in the shallows, being the most humid sectors. On the continental side of the foredunes, establishment will be more successful than on the seaward sides. Likewise, the vegetation may differ with respect to the semi-fixed and fixed dunes, as well as their dune faces and crests (Table 2).
3. The use of properly constructed and installed sand fences would allow the sediment retention necessary for the establishment of incipient vegetation. Adequate sand management is a key aspect for revegetation of the dunes.
4. Dune revegetation zones should be protected from being affected by tourist traffic, off-road vehicles and other urban-tourist activities that may affect the development of plant species.
5. To this end, it is important to have signage and delimitation to alert and to make people aware of the process carried out, its relevance and the care that must be taken into account.
6. A monitoring plan should be established to evaluate the fixation strategies used from the point of view of the success of plant species establishment, as well as various environmental variables related to the sediment balance and coastal aquifers.
7. The proposed management plan should foresee permanent evaluations in order to be able to adapt the next steps according to the results obtained throughout the dune fixation process.
8. It is necessary to work with adequate planning to ensure the establishment of native vegetation in the dunes. Under this premise, the Integrated Coastal Management tools that guarantee an adequate execution of the plan become relevant. Therefore, it is proposed and promoted that all the aforementioned aspects be framed in a constant process of public participation, contemplating the opinions and interests of civil society, academia, coastal managers and private actors.

Table 2. Dominant native species for each of the dune sub-environments and level of dune coverage. Status of each species: ntv = native; ntz = naturalized; end = endemic [Adapted and modified from Faggi and Dadon, 2010; Faggi and Dadon, 2011; Marcomini *et al.*, 2017]

Dune type	Sub-environment	Dominant species and status	Level of dune coverage
Active dune fields	Crests	*Panicum racemosum* [ntv] *Cortaderia selloana* [ntv]	Low
	Lows	*Panicum racemosum* [ntv] *Calycera crassifolia* [ntv] *Cakile maritima* [ntz] *Sporobolus coarctatus* [ntv]	Low
	Incipient dunes	*Panicum racemosum* [ntv] *Cakile maritima* [ntz] *Sporobolus coarctatus* [ntv]	Low
	Continental faces	*Baccharis genistifolia* [ntv] *Tessaria absinthoides* [ntv] *Androtrichum trigynum* [ntv] *Cortaderia selloana* [ntv] *Solidago chilensis* [ntv] *Cyperus prolixus* [ntv] *Achyrocline satureioides* [ntv]	Intermediate - High
	Seaward faces	*Panicum racemosum* [ntv] *Calycera crassifolia* [ntv] *Cakile maritima* [ntz] *Sporobolus coarctatus* [ntv]	Low
Semi-active dune fields	Crests	*Panicum racemosum* [ntv] *Calycera crassifolia* [ntv] *Hydrocotyle bonariensis* [ntv]	Low
	Lows	*Adesmia incana* [ntv] *Tessaria absinthoides* [ntv] *Cortaderia selloana* [ntv] *Panicum racemosum* [ntv] *Androtrichum trigynum* [ntv]	Intermediate - High
	Slip faces	*Senecio crassifolius* [ntv] *Panicum racemosum* [ntv]	Intermediate
	Stoss faces	*Panicum racemosum* [ntv] *Calycera crassifolia* [ntv] *Hydrocotyle bonariensis* [ntv]	Low
Stable dune fields	Crests	*Achyrocline satureioides* [ntv] *Panicum racemosum* [ntv] *Ambrosia tenuifolia* [ntv] *Cortaderia selloana* [ntv] *Hydrocotyle bonariensis* [ntv] *Adesmia incana* [ntv] *Schoenoplectus californicus* [ntv]	Intermediate - High
	Faces	*Achyrocline satureioides* [ntv] *Tessaria absinthoides* [ntv] *Cortaderia selloana* [ntv]	Intermediate
	Lows	*Hydrocotyle bonariensis* [ntv] *Cortaderia selloana* [ntv] *Ambrosia tenuifolia* [ntv] *Conyza blakei* [ntv] *Typha sp.* [ntv] *Mikania parodii* [end] *Eleocharis viridans* [ntv]	Very High
	Dune margins	*Ambrosia tenuifolia* [ntv] *Cortaderia selloana* [ntv] *Melilotus albus* [ntz] *Hydrocotyle bonariensis* [ntv] *Equisetum giganteum* [ntv] *Melilotus indicus* [ntz] *Eleocharis viridans* [ntv]	Very High

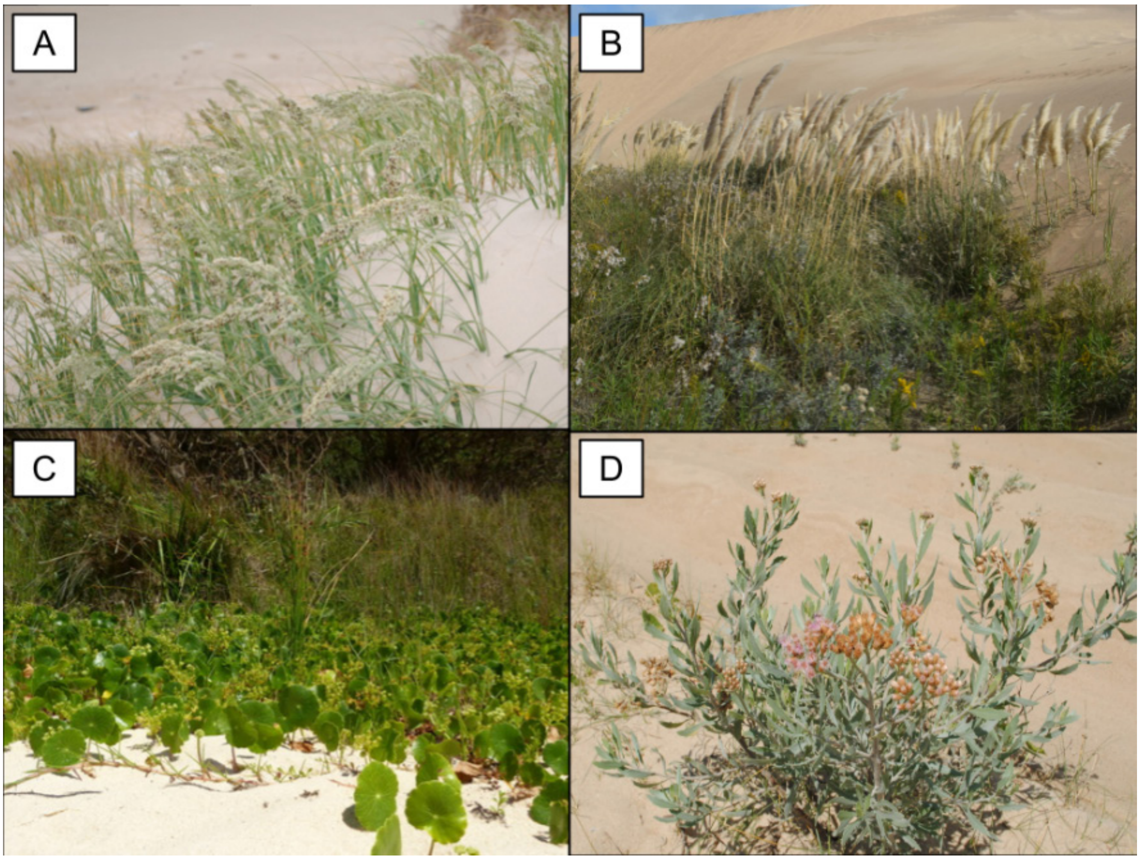

Figure 12. Native species proposed for dune fixation. *Panicum racemosum* (A), *Cortaderia selloana* (B); *Hydrocotyle bonariensis* (C); *Tessaria absinthoides* (D).

7. CONCLUSIONS

The Gesell brothers faced similar afforestation challenges, but with different physical conditions inherited from the spatial intervals and the environmental conditions of two different sand barriers. Although the dune afforestation has allowed the tourist and economic development of Villa Gesell and Dunamar, the systematic replacement of native vegetation by fast-growing exotic species has induced several environmental problems. Coastal erosion, surface runoff increase, diminish of foredune areas and spread of exotic plant species are some of these impacts. In this way, afforestation projects over coastal areas could have a major impact on the local hydrological balance. At the same time, the fixation of dunes generates a sedimentary imbalance that induces coastal erosion processes, among other impacts.

The urban development of the studied villages was substantially different. Villa Gesell grew at rates without precedent in Argentina that led to several unsolved growing problems (water provision, coastal-dune retreat, beach widths, runoff episodes, domestic sewages). Dunamar is still being planned in stages and present incipient problems due to the abundance of sand. Recent plans propose the urban development of Dunamar and Villa Gesell, taking into account the increase in the urbanized surface and the tourist capacity of these villages, as well as different strategies linked to dune fixation. Re-conversion (de-forestation and afforestation) and dune vegetation with native species are proposed for Villa Gesell; afforestation with exotic woody species is proposed for Dunamar.

These strategies present different levels of complexity for their implementation as well as diverse environmental impacts. Re-conversion may not signify several changes over coastal sedimentary imbalance; despite of that de-forestation is recommended in order to restore natural dynamics over dune areas. New dune fixations with woody exotic species is not recommended, especially taking into account negative experiences in the region. Dune stabilization with native species is strongly recommended, even representing more effort in order to reach a success in the implementation of the strategy.

This review propose a series of measures as a guideline for the implementation of the future dune fixation strategies. Besides the plant species to use, the implementation of sand fences and other specific measures proposed in this work, it is important to face the future development of coastal villages over dune areas under the orbit of an Integrated Coastal Management.

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AUTHORS CONTRIBUTION

Conceptualization, F.I.I; Methodology, F.I.I, P.A.G. and L.S-C; Formal Analysis, F.I.I, P.A.G. and L.S-C; Investigation, F.I.I, P.A.G. and L.S-C; Resources, F.I.I; Data Curation, F.I.I, P.A.G. and L.S-C; Writing – Original Draft Preparation, F.I.I, P.A.G. and L.S-C; Writing – Review & Editing, F.I.I, P.A.G. and L.S-C. All authors have approved the submitted version.

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HAZARD MAPPING BASED ON OBSERVED COASTAL EROSION RATES AND DEFINITION OF SET-BACK LINES TO SUPPORT COASTAL MANAGEMENT PLANS IN THE NORTH COAST OF PORTUGAL

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ABSTRACT: Coastal zone management plans need to consider scenarios of coastline evolution and associated uncertainties. In this paper, the main causes of shoreline retreat and coastal erosion (natural and anthropogenic) in the north coast of Portugal are discussed. The importance of increasing knowledge on coastal dynamics to improve long-term predictions of coastline changes is highlighted since it is essential to establish proper management tools. It is also shown that the Portuguese coastal ecosystems are not resilient enough to extreme events and that the Portuguese coastal zone, like very many others worldwide, and will be severely affected by the effects of climate change. It is concluded that extreme events need to be properly characterized and their impacts assessed since they have important implications in terms of uses of either the coastal zone or the coastal waters. Without that analysis, coastal management plans will be lacking technical and scientific information and data that could help decision-makers define the best strategies to control erosion levels and the impact of extreme events related to climate change effects. Finally, a detailed assessment of the coastline evolution was performed for the new *Caminha-Espinho* coastal management program, for the time horizons 2050 and 2100, based on historical data. The methodology used for the evaluation of the rates of shoreline change, hazard mapping and definition of set-back lines is presented. Selected examples are given to demonstrate the potential of this methodology in supporting the development of coastal zone management plans, but also to highlight the limitations and uncertainties linked to the complexity of the phenomena under analysis.

Keywords: coastal management programs, climate change, set-back lines, extreme events, *Caminha-Espinho* stretch.

RESUMO: *Os planos de gestão da zona costeira devem considerar os cenários de evolução da linha costeira e as incertezas associadas. Neste artigo, são discutidas as principais causas do recuo da linha de costa e da erosão costeira (naturais e antropogénicas) na costa norte de Portugal. A importância de aumentar o conhecimento sobre a dinâmica costeira de forma a melhorar as previsões a longo prazo das alterações costeiras é realçada, uma vez que este é essencial para estabelecer ferramentas de gestão adequadas. Mostra-se, também, que os ecossistemas costeiros portugueses não são suficientemente resilientes a eventos extremos e que a zona costeira portuguesa, à semelhança de muitas outras no mundo, será severamente afetada pelos efeitos das alterações climáticas. Conclui-se que os eventos extremos necessitam de ser devidamente caracterizados e os seus impactos avaliados uma vez que têm implicações importantes em termos de usos, quer da zona costeira, quer das águas costeiras.*

Sem essa análise, os planos de gestão costeira terão em falta informação e dados técnico-científicos fundamentais para ajudar os decisores a definir as melhores estratégias para controlar os níveis de erosão e o impacto de eventos extremos relacionados com os efeitos das alterações climáticas. Por fim, foi realizada uma avaliação detalhada da evolução da linha de costa para o novo programa de gestão costeira Caminha-Espinho, para os horizontes temporais 2050 e 2100, com base em dados históricos. É apresentada ainda a metodologia utilizada para a avaliação das taxas de alteração da linha de costa, mapeamento de perigos e definição de linhas de recuo. Exemplos selecionados são apresentados para demonstrar o potencial desta metodologia no apoio ao desenvolvimento de planos de gestão da zona costeira, mas também para destacar as limitações e incertezas associadas à complexidade dos fenómenos em análise.

Palavras-chave: *programas de gestão costeira, alterações climáticas, linhas de recuo, eventos extremos, troço Caminha-Espinho.*

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1. INTRODUCTION

The Portuguese continental coastline is approximately 987 km long, mostly sandy, with around 60% of its extension composed of sandy dunes. Several estuaries, small river discharges, rocky areas, cliffs, urban areas, ports and coastal aquifers can also be found along the coast, Figure 1. In some stretches, nearshore rocky outcrops provide natural shelter to the coast (Rosa-Santos *et al.*, 2009).

Since the 1970's, Portuguese coastal areas experienced rapid and significant economic growth and development. Nowadays, about 75% of the Portuguese population lives in the coastal zone and about 14% less than 2 km from the coastline at high tide (APA, 2017). This number is still growing, which leads to important impacts in both estuarine and coastal waters, as it is shown in Figure 2 and Figure 3, for, respectively, Pedra Alta and Pedrinhas.

It is important to note that around 14% of the Portuguese continental coastline is artificialized due to the presence of coastal structures (*e.g.*, groins, revetments or port breakwaters), 25% is affected by coastal erosion and there is a potential risk of loss of territory in circa 67% of the coastline (Lança, 2020).

The Portuguese coastline is divided into coastal stretches having each one a coastal management plan associated, namely the *Planos de Ordenamento da Orla Costeira* or the more recent *Programas da Orla Costeira*. These management plans have not always been effective in controlling the multiple impacts of the very many activities that are carried out in coastal areas and putting into practice measures to protect, preserve and improve the quality of coastal waters, namely as per stipulated in the Water Framework Directive (EC, 2000). Notwithstanding, a significant length of the Portuguese coastline is still in a relatively natural state.

Some coastal areas have today a better management strategy in terms of conservation and development. An increased interest of national and local authorities in protecting coastal areas and waters from human activities has been observed, especially close to beaches and urban areas at risk. São Bartolomeu do Mar is a good example of a planned retreat respecting the history, social, cultural and economic aspirations of local communities, Figure 4. The interventions carried out in São Bartolomeu do Mar included the demolition of existing buildings (27 in total) and the nature restoration in degraded and/or unoccupied areas, with soil decompaction, dune recovery, planting of

Figure 1. Examples of coastal stretches from the Portuguese coast.

Figure 2. Pedra Alta, Viana do Castelo: evolution from 1965 to 2021 (Google Earth images).

Figure 3. Pedrinhas, Esposende: evolution from 1965 to 2021 (Google Earth images).

autochthonous species and the installation of sand-retention fences. The interventions also included the requalification of the urban seafront and the consolidation of structural elements that were degraded, considering local cultural and religious heritage and traditions.

Climate change is important to consider in future coastal zone planning, mainly because it is associated to extreme events (*e.g.* more frequent storms, higher wave heights and periods, changes in wave direction, increased mean sea level and changes in wind direction) that will cause relevant impacts on coastal waters and coastal aquifers, with increased erosion rates, salt water intrusion and water quality deterioration (Taveira-Pinto *et al*., 2021a). Due to those extreme events, several coastal areas will face higher risks, due to increasing overtopping and issuing flooding, more rapid erosion at higher erosion rates and other related phenomena, all combined with ongoing sediment starvation from natural and human-induced causes. For these reasons, the management of coastal areas needs to adapt to present challenges, in order to allow the required increase in coastal resilience and safety against extreme events (Taveira-Pinto *et al*., 2021b).

Coastal erosion, *i.e.*, the advance of the sea in relation to a reference coastline, with generally known causes, should be evaluated and analyzed as an average over a given period of time. This period should be long enough to eliminate seasonal variations related to tidal range, weather, storms and local sediment dynamics. Nowadays, the analysis of historical aerial photographs using tools such as the DSAS – Digital Shoreline Analysis System (an add-in software within the Environmental System Research Institute – ESRI, ArcGIS©) (Nave and Rebelo, 2022), eventually combined with topo-hydrographic and LiDAR surveys (Bio *et al*., 2020), allows to assess the coastline evolution and to calculate a range of statistical parameters that characterize that change.

Recently, during the revision of *Caminha-Espinho* coastal management program, the rates of shoreline change were assessed considering historical coastline evolution data and anecdotal evidence of areas prone to overtopping and flooding. While developing this coastal management program, which encompasses a coastal stretch with a length of approximately 120 km, the influence of extreme storm events, expected mean sea level rise, overtopping and flooding were considered, as

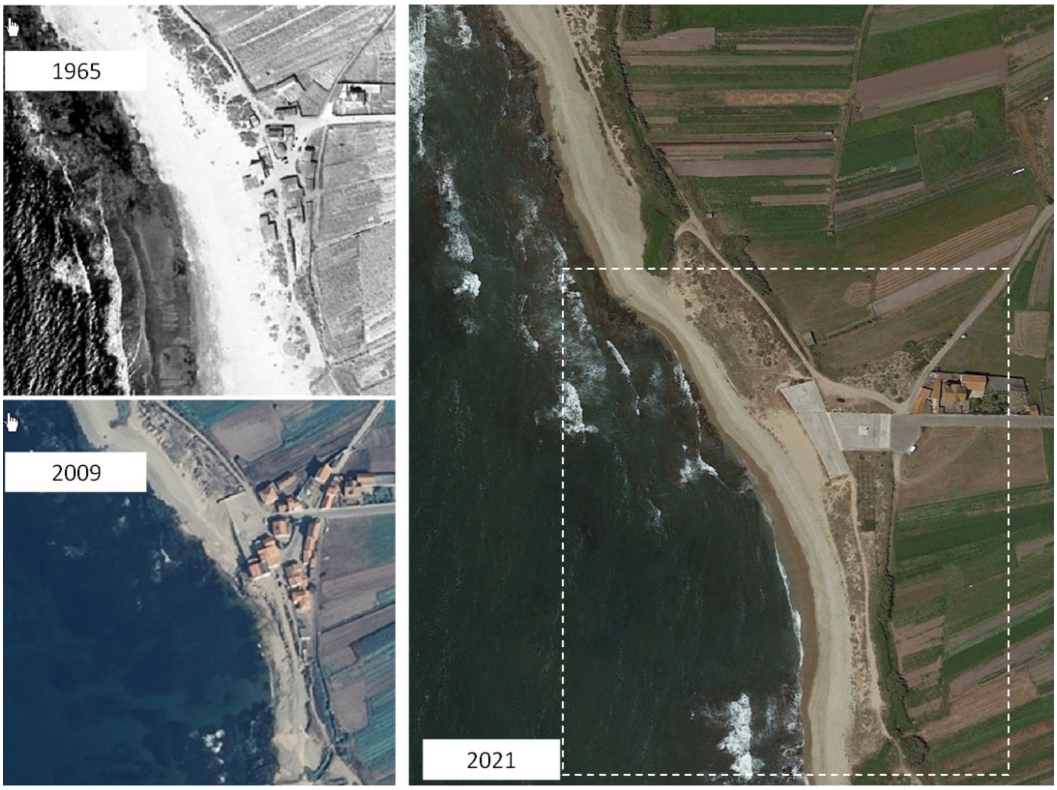

Figure 4. São Bartolomeu do Mar, Esposende: Evolution from 1965 to 2021 (Google Earth images).

well as precautionary measures for safeguarding of people and assets in vulnerable areas.

Following this introduction, an overall characterization of *Caminha-Espinho* coastal stretch is presented in section 2. The main anthropogenic effects on the Portuguese shoreline are discussed in section 3 whereas the methodology used in the calculation of the rates of shoreline change, hazard mapping and definition of set-back lines the for 2050- and 2100-time horizons are described in section 4. The latter includes as well the obtained results and discussion.

In this paper, selected examples are presented to show the potential of the methodology used for hazard mapping based on set-back lines in supporting the development of coastal zone management programs, but also to highlight the limitations and uncertainties related to the complexity of the phenomena under analysis. The goal is to show the importance of increased knowledge on local coastal dynamics to improve long-term predictions of coastline change, to establish proper management tools, and to handle present and future coastal management challenges. As a matter of fact, recent extreme events have revealed that Portuguese coastal ecosystems are not resilient enough and therefore should be severely affected by the effects of ongoing climate changes.

2. GENERAL CHARACTERIZATION OF THE PORTUGUESE NORTHWEST COAST

The coastal zone is the interface between land and sea. Its significance and value are particularly relevant, namely in what concerns natural, human, economic and cultural assets. Its management is highly complex, due to natural hydro- and morpho-dynamics, diversity and vulnerability, as well as the interconnectivity of natural, economic and environmental systems. The following characteristics can be highlighted along the Portuguese NW coastal zone:

- beaches having a high recreational value, as well as delivering important coastal protection services;
- well-preserved beaches and dune ridges in some stretches;
- strong pressure for urban construction near the shoreline;
- generalized coastal erosion processes.

The wave regime in the NW Portuguese coast is of high energy, with offshore mean significant wave heights of circa 2-3 m, and mean wave periods of 8-12 s. In winter, storms generated in the North Atlantic are frequent and can persist for up to 5 days, with significant wave heights reaching 8 m (Veloso Gomes *et al*., 2006). In Leixões buoy, maximum waves higher than 14 m are often recorded during the winter season for wave directions between W and NW. Local storms can produce SW waves with up to 4 m of height, but the dominant wave regime is from W-NW (Veloso Gomes *et al*., 2006). Tides are semi-diurnal, with tidal ranges varying approximately from 2 m to 4 m, from neap to spring tides, respectively.

The sediment transport in the NW Portuguese coast is mostly associated with the littoral drift currents, originated from the waves that propagate to shore with a certain angle in relation to the coastline. Hence, waves, usually coming from NW, induce a dominant drift current directed from North to South (Rosa-Santos *et al*., 2009). This current may be inverted in some areas due to the presence of obstacles, namely south of estuary mouths protected by coastal structures (*e.g.*, breakwater, jetty, groin). At those locations, the sediment transport direction can change or be reversed by refraction and diffraction phenomena. Nevertheless, the annual mean balance is predominantly from North to South, as it can be verified directly through the accumulation of sediments in the northern zones of existent coastal structures, in contrast with the erosion that occurs in southern zones.

The coastal wind regime presents high seasonal variability. From April to August, WNW and NW winds are predominant, while in the other periods of the year the E-SSE wind is more frequent. W-SW winds are not frequent, although important during storm events. These local winds generate maritime currents and sea states with intensities and directions directly related to their velocity, persistence and direction. Even though important, those currents remain relatively small when compared to the currents associated with the wave action. The direct wind action is more significant on the emerged areas of the beach, namely on dunes.

In the Portuguese NW coast, erosion is mainly the result of the weakening of river sediment sources in recent decades (Santos *et al*., 2017). Less sediment is now being supplied to the coast due to damming in rivers of Portugal and Spain, regularization of the river banks and maintenance dredging to maintain service draughts in existing navigation channels and sand mining for construction, as well as land use change and urbanization.

Portuguese sandy coasts are thereby eroding because the potential transport capacity of waves – between 1 and 2

Mm^3/year – is much higher than the annual sediment volume supplied by the rivers – now up to 0.2 Mm^3/year (Veloso Gomes *et al.*, 2006). Sea level rise due to global eustatic effects associated with climate change, at an average rate of approximately 1.5 mm/year (observed during the 20th century), also contributes to the decrease of the sedimentary supply of the rivers to the coast by the induced change in their equilibrium profile. Regional effects, related to climate change and coastal subsidence are also accepted causes of shoreline retreat (Bruun, 1962). Erosion along the Portuguese coast can also be traced back to the construction of sea ports, not just because of maintenance dredging taking sediment out of the system, but also because of long enough outer breakwaters intercepting the littoral transport and inducing erosion problems in adjacent shorelines due to the lack of natural nourishment.

3. SHORELINE AND COASTAL RESPONSE TO ANTHROPOGENIC FACTORS

To adequately manage the coastal zone, it is necessary to understand the effects of both relevant physical processes and anthropogenic factors, since these effects will allow defining short and long-term scenarios for shoreline change and risk analysis (Dean, 2008). The impact of anthropogenic factors on the Portuguese coastal zone has become significant in recent decades. Furthermore, both spatial and temporal scales of such impacts are anticipated to increase in the near future (Santos *et al.*, 2017).

Erosion rates have been increasing during the last decades (mean shoreline retreats of up to 8 m/year in some stretches), with the exception of areas immediately updrift of existing transverse hard structures. More recently, this phenomenon has reached coastal stretches where there have been no records of erosion problems in the past. Hence, the extrapolation of historical erosion data to predict permanent loss of land in coming decades or centuries has to be carried out with caution, due to the complexity and nonlinearity of the involved physical processes.

Winters in the North Atlantic Ocean are often very severe (several strong storm events) and the shoreline of the Portuguese NW coast, during those periods, experiences several problems, mainly in the stretches where there is no natural protection (*e.g.*, rock outcrops). For example, a storm on January 3-7, 2014, caused damages in more than 40 locations along a coastal stretch of circa 120 km (Figure 5). Causes for said problems in several urban waterfronts, which are now more vulnerable to erosion and direct wave action, are often linked to:

- sandy beaches that are generally very narrow and dunes often presenting erosion bluffs;
- sandy beaches located updrift groins that have started losing sand (retreated) and downdrift in which erosion problems have aggravated;
- a high number of coastal protection structures (*e.g.*, groins and revetments) that are damaged or in bad condition.

Urban development (buildings, promenades, etc.) along waterfront in recent decades, sometimes on top of beaches and dunes, also contributed to changing morphological conditions, at least locally, increasing coastal risks. It should be noted here that in the 120-kilometre coastal stretch in analysis, *Caminha-Espinho*, there are 45 km of urban seafront and about 30 important beaches. The risk management in the past has been to construct groins or/and seawalls following disasters due to the exposure to ocean environmental conditions, however, more often than not, these coastal protection works have accelerated erosion problems further downdrift and have not precluded the continual process of coastal urban development. Quite the opposite, construction on top of dunes and sometimes beaches has assumed alarming proportions in some coastal municipalities, and uncontrolled urban expansion in coastal areas continued despite known and identified vulnerabilities. Urban development has also introduced changes to the natural coastal landscape, that has had detrimental impact on aesthetic ecosystem services. Unprotected beaches in *Caminha-Espinho* remain naturally dynamic and offer a big contrast to that. Recent efforts to deal with observed coastal environmental degradation through well-thought planning are encouraging; however, the level of land occupation in areas at risk and the need for restoring valuable coastal ecosystems may require more urgent measures and more difficult decision-making. This highlights the need to make a new revision of the coastal management plans supported by high spatial resolution data on erosion rates and exposure – *i.e.*, uses and land occupation on the hinterland – as well as on likely climate change scenarios.

4. COASTAL EROSION RATES AND HAZARD MAPPING

4.1 Introduction

Coastal management plans should be based on a detailed understanding of coastal dynamics, predictions of the shoreline positions for several spatial and temporal scenarios of climate

Figure 5. Damage in the NW coast of Portugal due to the storm of January 3-7, 2014. Examples from Matosinhos, Porto, Gaia and Furadouro (source: Público Newspaper).

variability, climate change and direct anthropogenic influencing factors, but also consider the state of vulnerability of beaches, dunes and coastal structures to storms and other extreme events, as well as the impact of these onto coastal infrastructure and environmental degradation and change (Taveira Pinto, 2004). Therefore, management plans need to be revised periodically.

Uncertainty and pressure caused by challenges of continued growth in coastal areas require new management approaches to maintain and restore the integrity and functioning of coastal ecosystems, as well as to regulate the use of land in response to ever-growing coastal risks, thereby avoiding making the same mistakes again and having to take decisions in the aftermath of coastal disasters.

As it was mentioned before, there is strong evidence that in large extensions of the NW coastal zone of Portugal, a generalized shoreline retreat is occurring causing worrisome concerns. For example, some areas are at high hazard levels from erosion, as is the case of Bonança Beach, located downdrift of the groin of Ofir. Figure 6 presenting the coastline evolution (vegetation line) at Bonança Beach, between 1965 and 2017, clearly demonstrates that persistent retreat trend.

Anthropogenic factors determine, to a greater or lesser extent, erosive patterns along the Portuguese coast. Nevertheless, a reduction of the influence of these factors in coastal ecosystems is technically possible only in a few and well identified cases and its impacts are mostly local.

Coastal risk drivers are intrinsic to natural coastal dynamics and the occurrence of physical processes that bring about relevant morphological changes, especially in coastal zones characterized by low-lying sandy beaches, such as the area under analysis. Depending on the information available, the processes usually considered are long-term erosion (in this case for the time horizons of 2050 and 2100), erosion due to the occurrence of extreme storms, erosion due to the mean sea level rise and occurrence of flooding. All processes are somehow associated to climate change (Coelho *et al*., 2009).

In this context, for defining set-back lines associated with coastal hazards for different periods of interest, it is advised to use methods based on a worst-case scenario approach, that consider shoreline evolutionary trends (basis for the initial determination of set-back lines) and changes associated with the acceleration of sea-level rise as well as the consequences

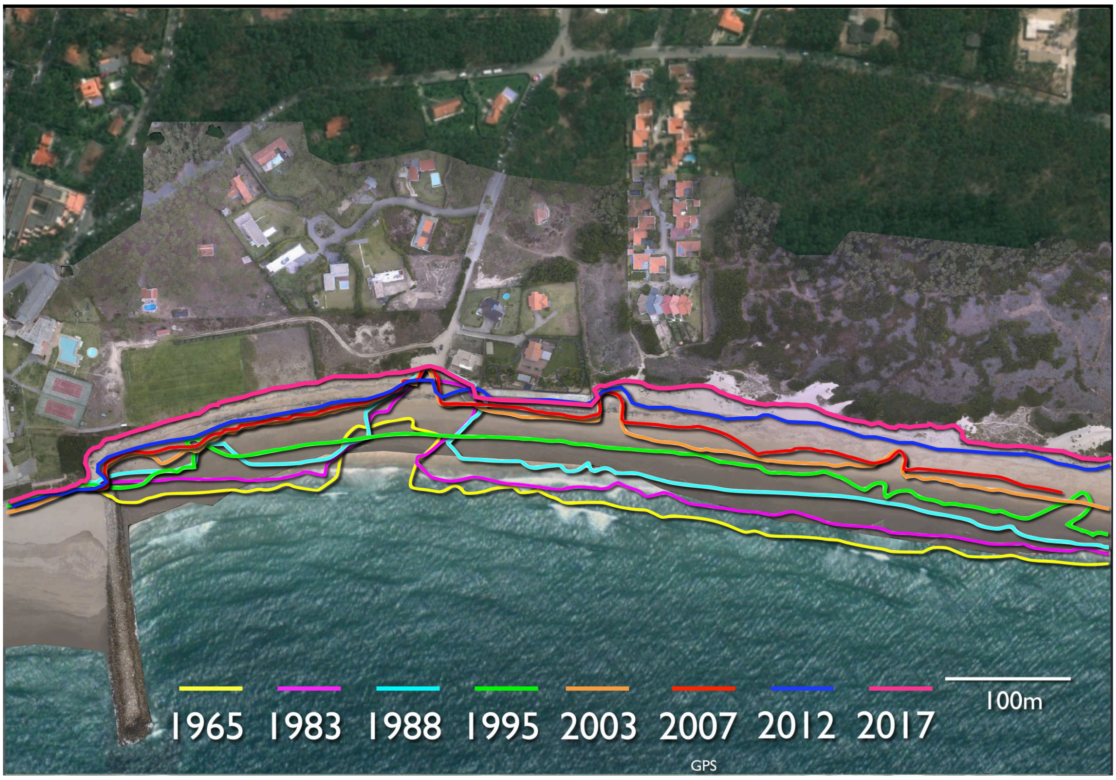

Figure 6. Coastline evolution (vegetation line) at Bonança Beach between 1965 and 2017.

of extreme storms (*e.g.*, instantaneous shoreline retreat and overwash), as the one presented in Ferreira *et al*. (2006).

In the most recent revision of *Caminha-Espinho* coastal management program of 2022, set-back lines were determined considering the vulnerability arising from the occurrence of each of the previously referred coastal processes and their expected evolution in time. Due to the high uncertainty associated to field data measurements and numerical modelling results, the definition of the set-back lines associated with each coastal process involved some expert judgment, as well as conservative principles, since the vulnerability of each coastal process and the associated set-back line may overlap. However, in this paper, only erosion trends are analyzed and briefly discussed.

The set-back lines are defined to enforce restrictions on the use and occupation of the soil, aiming at reducing projected coastal risks to 2050 and 2100, based on the extrapolation of historical coastline evolution trends. This approach has some limitations, as will be discussed in the next section.

4.2 Methodology

Coastal hazards along *Caminha-Espinho* stretch, in the northwest coast of Portugal, were assessed by comparing historical coastlines, at several years for which aerial photos were available. The retreat or the accretion rates for each profile were calculated from the changes observed in coastlines in those surveys. The final coastline evolution rate, $TELC_{(50/100)}$, was then defined assuming, for each profile and for the time horizons of 2050 and 2100, the average annual rates of shoreline change previously calculated for the *Caminha-Espinho* stretch. Then, using this rate, it is possible to project future coastline evolution, $PELC_{(50/100)}$ (erosion/accretion), as well as to define the coastline erosion set-back lines for the time horizons of 2050 (Level I, +35 years) and 2100 (Level II, +85 years). Projections are from the year 2012.

The coastline erosion set-back lines, $FSEC_{(50/100)}$, are defined as:

$$FSEC_{(50/100)} = PELC_{(50/100)} + TE_{(50/100)} + SNAM_{(50/100)} \qquad (1)$$

where $TE_{(50/100)}$ represents the direct influence of extreme storms and $SNMAM_{(50/100)}$ the direct influence of the sea level rise. The values of sea level rise considered in the assessment were +0.35 m and +1.50 m for the time horizons of 2050 and 2100, respectively.

The zone threatened by sea, $ZAM_{(50/100)}$, is defined as:

$$ZAM_{(50/100)} = TE_{(50/100)} + SNMAM_{(50/100)} \quad (2)$$

The limits of the frontal dune, represented in the field by the beach crest berm, were used as proxy for the shoreline position. When absent, the outer limit of the vegetation was used for that purpose. In general, the base of the foredune presents a more time-conservative positional nature with respect to the beach-dune border, constituting an advantage over other indicators (such as the *runup* limit and the berm crest) that are strongly influenced by daily, seasonal and interannual variations in beach morphology related to the forcing agents (*e.g.*, waves, currents, tides). The vegetation line is, usually, clearly visible in aerial photographs, providing an easily distinguishable boundary. In addition, this limit is an excellent indicator of the *runup* limit because vegetation usually disappears in flooded areas. When dune erosion buffs with a high slope are present, the limit considered was its top. In armored coastlines (*i.e.*, where seawalls, revetments, etc. are present), the limit assumed was the foot of those structures, considered as the maximum limit of potential wave run-up (Henriques, 2006).

The use of two-dimensional migration indicators, in the form of lines, is an useful approach from which straightforward information can be derived (Ferreira *et al.*, 2006). Unlike other indicators derived from the application of mathematical models, these lines effectively materialize an actual coastline change. However, this approach does not allow determining sedimentary budgets, which calculation is essentially three-dimensional. For example, this approach is not suitable to identify areas where the beach width is decreasing or where the frontal beach is eroding (as is typically the case in front of armored shorelines), even though the coastline retreat (*i.e.*, the vegetation line) is insignificant. Notwithstanding, the set-back lines have the advantage of having intrinsically incorporated factors influencing coastal dynamics locally, including storm impact, sedimentary shortages and mean sea level rise. Even though the cumulative effect of all coastline change influencing factors are present, this approach does not allow to distinguish the contribution of individual processes and thereby the hazard intensity associated with each one of them.

The coastlines used in the assessment of the rates of shoreline change were always defined using the criteria described above. The reference coastline is a coastline dated from the year 1958, provided by the Portuguese Environment Agency (APA). However, because of light overexposure in some sectors leading to a low quality of the aerial photography of 1958 for the purpose of deriving coastlines, this reference coastline does not cover the entirety of the area under analysis. The wider implication of this was that the time interval used in those sectors to compute the rates of shoreline change had to be shortened. Similarly, while some of the coastlines used in the assessment cover fully the whole area, others only partially cover it. The coastlines of 2012 and 2006, obtained from aero photographic surveys carried out for those years, fall under the former. The latter concerns the coastlines of the following years: 1948 (only for the beach of Aguçadoura North), 1965, 1973, 1983, 1987, 1994 and 1995. All imagery datasets were georeferenced using known coordinate control points, perfectly visible in the photographs and materialized in the field.

The coastline evolution trends were analyzed by quantifying its mobility, as extracted from aerial photography of different dates, with the application of the Digital Shoreline Analysis System (DSAS), developed by the USGS (Danforth *et al.*, 1992; Thieler *et al.*, 2009).

The differences in position of the coastline were measured in relation to a common baseline and using a sequence of 50 m equidistant transects, Figure 7. The common baseline, from which the transects that intersect the various coastlines were obtained, was defined as far as possible in the sea and parallel to the coastlines under analysis. Since the transects are perpendicular to that common baseline, it is ensured that the intersection of these with the different coastlines occurs as close as possible to an angle of 90°, therefore reducing the possibility of underestimating or overestimating the rates of shoreline change. A 200 m buffer was defined for all available coastlines and the obtained offshore limit was chosen as the origin of the transects. This buffer was deemed adequate considering the current trends of retreat, which are mostly erosive. Therefore, it also ensures that in future work to update this data, it will not be necessary to modify the position of the common baseline, thereby assuring that the new data is consistent with previously calculated rates of shoreline change.

The DSAS automatically calculates the intersection of the transects with the various coastlines available, resulting in the calculation of a set of statistical parameters. In this paper, the

Least Mean of Square (LMS) rate was considered. End Point Rate (EPR) was used when only two shorelines were available. The EPR is defined as the ratio of total shoreline movement (*i.e.*, the distance between the earliest and the latest measurement) and the number of elapsed years, providing a yearly rate of change. Furthermore, the rates of shoreline change were obtained using the best regression line adjusted to the retreat values determined, filtering out the effect of outliers (extremes) or residual values.

The calculated rates of change are expressed in distance of variation per year (m/year). This represents the total observed coastline displacement in the time interval under analysis. Positive values represent accretion and negative values represent erosion. In order to make a correct interpretation, one must always check which temporal instants were used at each point for the calculations, by analyzing the intersected coastlines. In some cases, a high coastline mobility (distance) is observed due to a long-time interval of analysis during which low rates of shoreline change occurred, while in other cases, this coastline mobility presents similarly high values but obtained in a shorter time interval of analysis, as a result of high rates of shoreline change.

In fact, the analysis of rates of shoreline change is strongly dependent on the time interval under analysis. Sometimes a long interval masks recurrent short-term tendencies that are more important and have been maintained over the last few years. This is particularly relevant, for example, in situations where the older coastline was inland, coastline recovery has been observed in a given time period by natural causes or due to the construction of a coastal defense intervention and, in recent years, a retreat trend is occurring. In this case, the analysis of the entire time interval will lead to accretion when, in fact, the sector has been eroding in recent years. The same holds true for the opposite case in which sectors in erosion may have changed, in recent years, to a situation of accretion resulting, for example, from the construction of coastal defense works or nourishments. All statistical data obtained for each transect was expressed numerically and graphically.

To allow a more accurate analysis, trends in rates of shoreline change have been computed for several time intervals. Firstly, those rates were calculated for the entire time interval under analysis, *i.e.* between 1958 and 2012, wherever these coastlines were available. At the same time, the rates of shoreline change were estimated for the time interval between 1994 and 2012,

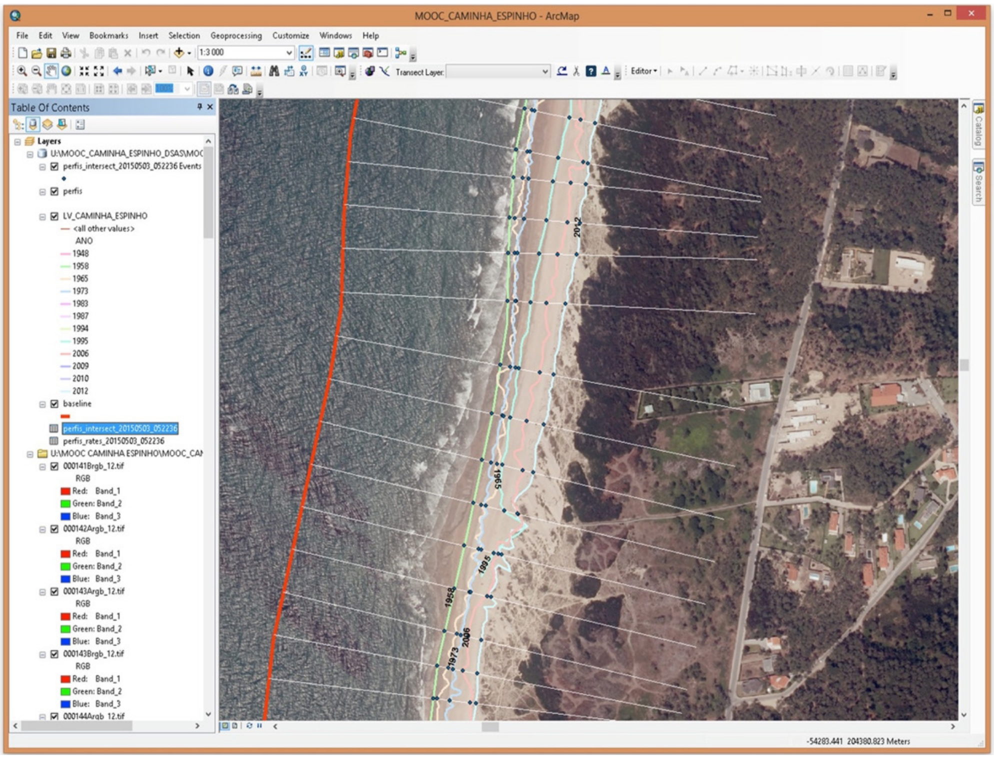

Figure 7. Example of the GIS project used to calculate the rates of shoreline change from the coastline variation, showing the intersection of the transects with the various coastlines available, which allows the calculation of the rates of shoreline change.

representing the trend in recent coastline evolution over 20 years in which information was available. Then, observed differences in the computed trends were compared, allowing a better interpretation of the past tendency to predict future evolution. For example, in some instances, there is an inversion of the evolution trend in the period from 1994 to 2012 compared to when the time interval from 1958 to 2012 is considered.

For the assessment of the overall retreat along the 120 km of the *Caminha-Espinho* coastal management program, the following sectors were analyzed:

- Mouth of Minho River (Cabedelo Beach) – Mouth of Âncora River;
- Mouth of Âncora River – Mouth of Lima River;
- Mouth of Lima River – Mouth of Neiva River;
- Mouth of Neiva River – Mouth of Cávado River;
- Mouth of Cávado River – Mouth of Ave River;
- Mouth of Ave River – Mouth of Leça River;
- Mouth of Leça River – Mouth of Douro River;
- Mouth of Douro River – Barrinha de Esmoriz.

The hazard mapping for coastal erosion considered three levels and associated thresholds: low (green) – up to 0.6 m/year; moderate (yellow) – between 0.6 and 1.3 m/year; and high (red) – above 1.3 m/year. The assessment has been carried out for both of the above-mentioned time intervals (1958-2012, and 1994-2012), any observed differences are discussed.

4.3 Results and final remarks

There is a lot of uncertainty in future coastlines predicted from the linear extrapolation of historical coastline evolution. Hence, decision-making on the long-term planning of coastal areas should cautiously and critically consider computed historical rates of change. In this paper, the average annual rates of shoreline change estimated for the overall 52/56 years (*i.e.*, $TELC_{(50/100))}$ are considered for the definition of the long-term set-back lines due to coastal erosion (Equation 1). In parallel, $TELC_{(50/100)}$ was also defined using only short-term shoreline changes for the last 20 years. The final set-back lines were established taking into account the lines obtained for these two periods. Hence, it is possible, given the uncertainty associated with long forecast intervals and using a cautious approach, to define those lines as representing a "best estimate" based on the historical coastline data available and as a "worst case scenario" in terms of local coastline evolution.

Figure 8 presents the results on rates of shoreline change for the two time periods considered, long-term and short-term, obtained for Moledo beach. It is possible to observe that in Moledo several transects show important changes in erosion hazard magnitude from the larger period of analysis to the last 20 years, being that level aggravated in recent decades (*i.e.*, between 1994 and 2012). Figure 8 also includes the coastal set-back lines for 2050 and 2100.

Because of the limited number of datasets available for the analysis, the predictions of the long-term coastline position have important limitations. The projected coastlines to the 2050 and 2100 time horizons based on observed historical trends calculated for a time interval that includes, at best, 56 years of observations is deemed high uncertainty, associated with both the mathematical approach itself and the maintenance or variance of the coastal processes influencing coastline evolution over time.

For some coastal transects, such as those in the sector from Mouth of Minho River (Cabedelo Beach) – Mouth of Âncora River (Figure 9), the integrated analysis of short- and long-term evolution trends revealed that the average of short-term changes was lower than the long-term changes (1958-2012 *versus* 1994-2012). For other profiles, the opposite behavior is observed (Figure 9).

In general, the evolution trends obtained for *Caminha-Espinho* coastal stretch agree with the ones earlier reported by Ponte Lira *et al*. (2016). The differences observed may be due to the spatial and temporal discretization used in both studies and the methodologies adopted to assess the shoreline evolution trends.

5. CONCLUSIONS

As part of the work efforts associated to the new *Caminha-Espinho* coastal management program (POC-CE), an assessment of the past shoreline changes was carried out considering historical data to derive coastline positions and determine observed erosion trends, along with the identification of the coastal areas prone to be overtopped and flooded. However, this paper intended only to present and discuss the methodology used to estimate the coastline evolution in the *Caminha-Espinho* coastal stretch, for the 2050- and 2100-time horizons. Selected results were used to show not only the potential of the applied methodology as support of coastal management plans, but also to highlight the main limitations and uncertainties when dealing with coastal erosion phenomena.

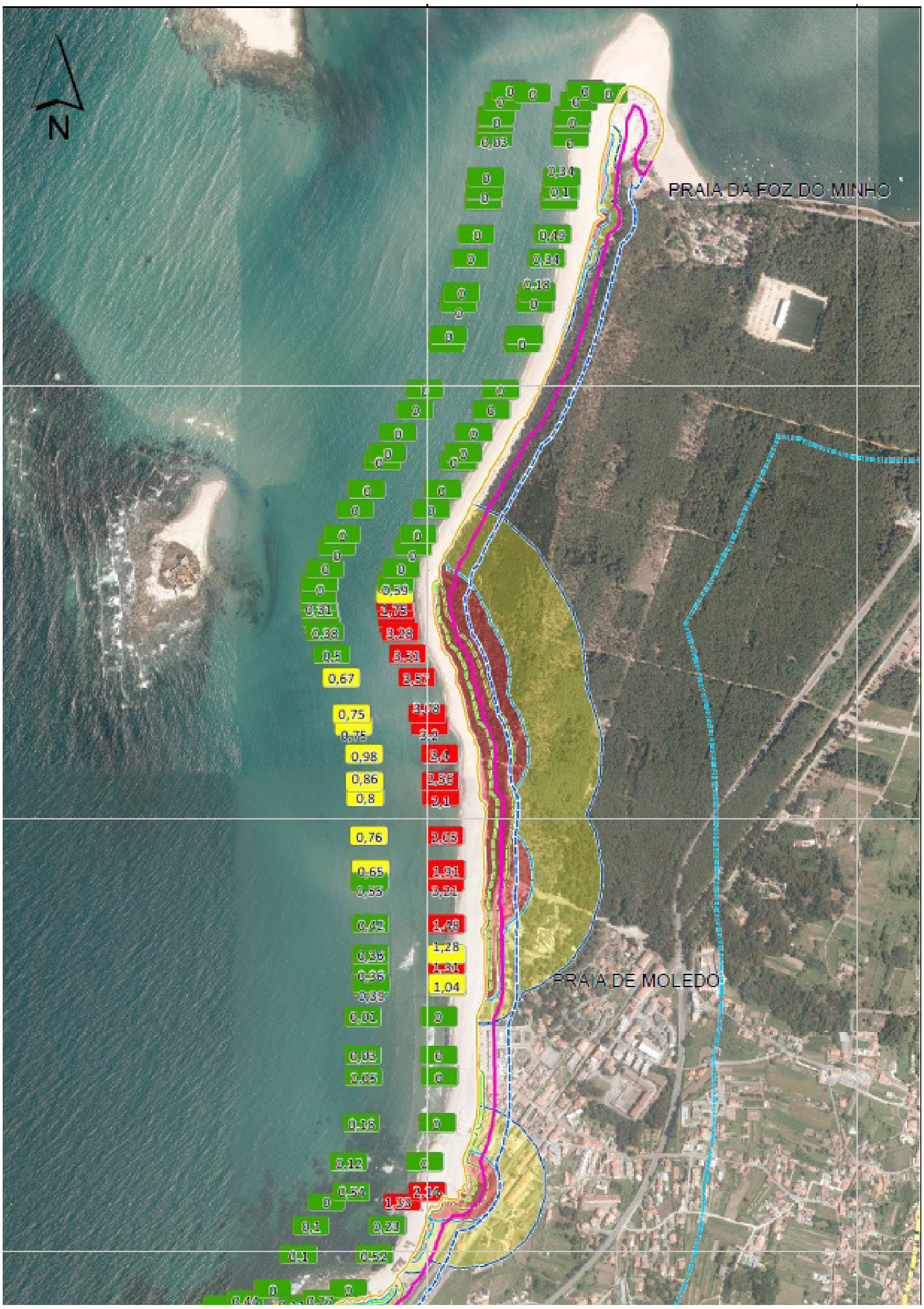

Figure 8. Analysis of Moledo beach (left squares – erosion rates 1958-2012; right squares – erosion rates 1994-2012; green – lower than 0.6 m/year, yellow – between 0.6 and 1.3 m/year, red – higher than 1.3 m/year; red area – projection for 2050; yellow area – projection for 2100).

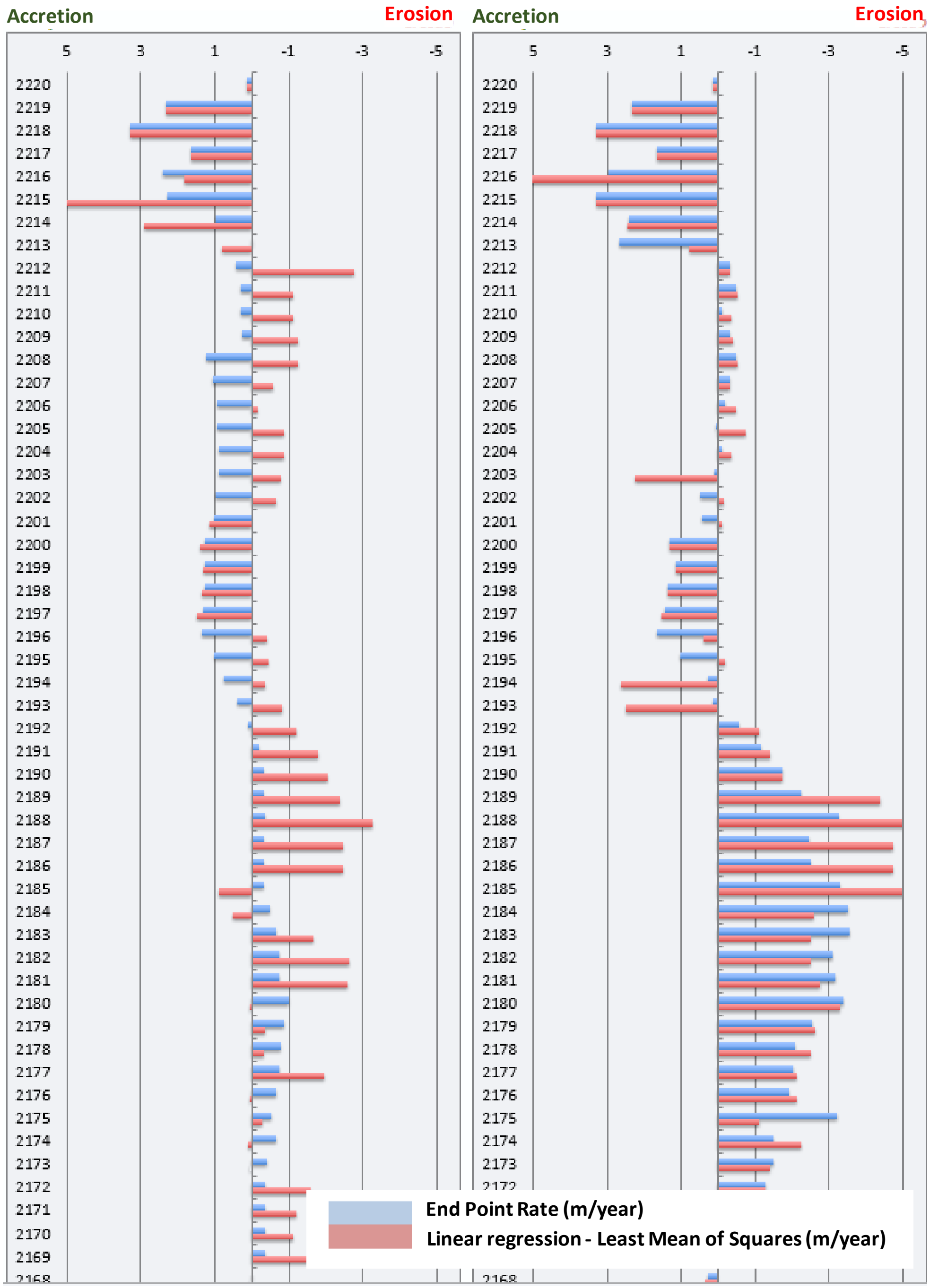

Figure 9. Example of average annual migration rates (m/year) per transect (profile) estimated for the time intervals “1958-2012” (left) and “1994-2012” (right).

The main natural and anthropogenic causes of shoreline retreat and coastal erosion on the north coast of Portugal were identified, of which insufficient sediment supply is among the most important ones. It was concluded about the importance of increasing knowledge on coastal dynamics to improve long-term predictions of coastline changes, since this knowledge is essential to establish proper management tools. To enforce consistent efforts of regulating coastal development and restoring coastal ecosystems, coastal zone management planning needs to be developed considering potential scenarios of coastline evolution – including projected effects of climate change – as well as economic growth and development, which has tremendous impact on uses and land occupation on the hinterland. The former drives the hazard components of coastal risk, whereas the latter affects exposure and vulnerability drivers. Coastline evolution patterns and trends, expressed in, *e.g.*, coastline erosion rates, are key to any coastal risk assessment because they help define areas where permanent losses of land can be expected.

The methodology used to evaluate those retreat rates for the northwest coast of Portugal, in the scope of the revision of *Caminha-Espinho* coastal management program, allowed for the evaluation of erosive trends and patterns, and thereby identify several critical areas with high coastline retreat rates, as well as areas subject to frequent overtopping/flooding events (not presented in this paper). This coastal hazard assessment considered sea level rise projections. It has shown that the Portuguese coastal ecosystems are not resilient enough to extreme events and that the Portuguese coastal zone, like very many others worldwide, will be severely affected by the effects of climate change.

Summing up, the extreme events, somehow related to climate change effects, overall need to be better characterized and their expected impacts on uses in the hinterland and coastal waters better assessed and analyzed. More specifically, risk attribution, *i.e.*, the specific contribution of each risk component (hazard, exposure, or vulnerability) to the overall risk of the coastal stretch, needs to be further considered when drafting coastal management plans because it is not enough to look only at hazard levels without taking into account uncontrolled urban expansion (risk driver for exposure) or coastal environmental degradation (both a risk driver and a consequence of poor planning). Without that analysis, coastal zone management plans will be lacking technical and scientific information and data that could help decision-makers define the best strategies to control erosion and the impact of extreme events related to climate change effects.

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