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ISSN: (Print) 1744-5647 (Online) Journal homepage: http://www.tandfonline.com/loi/tjom20

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To cite this article: Fernanda Alquini, Duccio Bertoni, Giovanni Sarti, Celso Voos Vieira & João Carlos Ferreira Melo Júnior (2018) Morpho-sedimentological and vegetational characterization of Grande beach at São Francisco do Sul Island (Santa Catarina, Brazil), Journal of Maps, 14:2, 105-113, DOI: 10.1080/17445647.2018.1438317

To link to this article: https://doi.org/10.1080/17445647.2018.1438317

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JOURNAL OF MAPS, 2018
VOL. 14, NO. 2, 105–113
https://doi.org/10.1080/17445647.2018.1438317

Science

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Morpho-sedimentological and vegetational characterization of Grande beach at São Francisco do Sul Island (Santa Catarina, Brazil)

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ABSTRACT
A multidisciplinary study based on several digital (geology, lithology, shoreline evolution, photo-interpretation of aerial and ortho-photographs) and field (topographic and vegetational surveys, grain-size analysis) datasets prompted new insights to a better definition of the processes in action at the Grande beach at São Francisco do Sul Island (Santa Catarina, Brazil). The resulting data enabled us to produce a multi-thematic map at 1:50,000 scale that might be useful in assisting decision-makers to manage the coastal system, taking into account involved factors at once and not separately. In addition, the map may be implemented and integrated with new information, since the database is provided in geographical information system. The results confirmed the importance of addressing coastal systems with a multi-faceted approach that can be applied everywhere, not only in settings similar to São Francisco do Sul Island.

ARTICLE HISTORY
Received 30 May 2016
Revised 2 February 2018
Accepted 5 February 2018

KEYWORDS
Multi-thematic map; beach erosion; sediment grain-size; vegetation; barrier/lagoon system; São Francisco do Sul Island

1. Introduction

The coast is a dynamic environment characterized by a complex interaction between internal and external factors (Andrews, Gares, & Colby, 2002; García-Mora, Gallego-Fernández, & García-Novo, 1999; Ruocco, Bertoni, Sarti, & Ciccarelli, 2014). Local tectonics, topography, vegetation, and soil are the main internal factors driving the evolution of a coastal system. Processes related to wind and wave action, and to a larger extent the eustatism, concur to influence the evolution as external factors. Usually these processes are addressed individually, which is useful to increase the understanding of each (e.g. Devi et al., 2013; Gallego-Fernández & Martínez, 2011; Hesp et al., 2015). But, this does not necessarily add up to an overall comprehension of coastal system dynamics, because it does not take into account the mutual influence these factors have on each other (Bertoni, Alquini, et al., 2014). A lack of knowledge about how these factors interact often leads to poor decisions about coastal planning. A better definition of the relationship between internal and external processes is mandatory for careful management of the naturalistic and administrative facets of littoral areas.

Multi-thematic maps are increasingly becoming more reliable tools to help decision-makers find better choices about several aspects of the management of coastal systems (Ghosh, Kumarb, & Roya, 2015; Sabatakakis, Nikolakopoulos, Papatheodorou, & Kelasidis, 2016). In addition, maps can furnish a lot of different data and can be continuously updated as further information becomes available. This would enable to make instant comparisons and matches among datasets. Mapping might support critical planning decisions about the potential land use, the reduction of areas subjected to any kind of risk related to coastal processes (Coelho, Silva, Veloso-Gomes, & Taveira-Pinto, 2006), and to vulnerability to beach erosion (Alexandrakis & Poulos, 2014; García-Mora, Gallego-Fernández, Williams, & García-Novo, 2001), the identification of areas designated for protection and conservation (De Jong, Keijsers, Riksen, Krol, & Slim, 2014; Fernandes & Amaral, 2013), and for recreation (De Araújo & Da Costa, 2008; Botero, Pereira, Tosic, & Manjarrez, 2015).

The aim of this work is to increase the understanding of the morpho-sedimentological and vegetational characteristics of the Grande beach along with the backing field dune on the Island of São Francisco do Sul (Santa Catarina, Brazil). It provides a multi-thematic map to support decision-making in the management of the coastal area of the island.

2. Study area

2.1. Physical setting

The Island of São Francisco do Sul is located in the northern portion of the State of Santa Catarina,

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which is in the southernmost sector of Brazil (Figure 1). The eastern side faces the Atlantic Ocean, whereas the Babitonga Bay borders the Island to the west and to the north. To the south is the Linguado Channel. In the 1930s the mouth of the channel was artificially silted up to allow for the construction of an access road to the municipality of São Francisco do Sul (Cremer, Morales, & Oliveira, 2006). A series of four small islands, the Tamboretes Islands, are located almost 5 km offshore of the central sector of the Island of São Francisco do Sul (Figure 1). The sea floor is gently sloping, the slope gradient being about 0.01% (Zular, 2011). Only three villages are present on the island: the most important, São Francisco do Sul, is on the western side; the other two settlements, Praia Grande to the north and Praia do Ervino to the south, are on the eastern side. The Acaraí Lagoon occupies the inner portion of the island; a series of hills (about 300 m high) characterize the western side. The Acaraí State Park is situated on São Francisco do Sul Island. The park was established in order to protect an area between the channel and the east coast which is

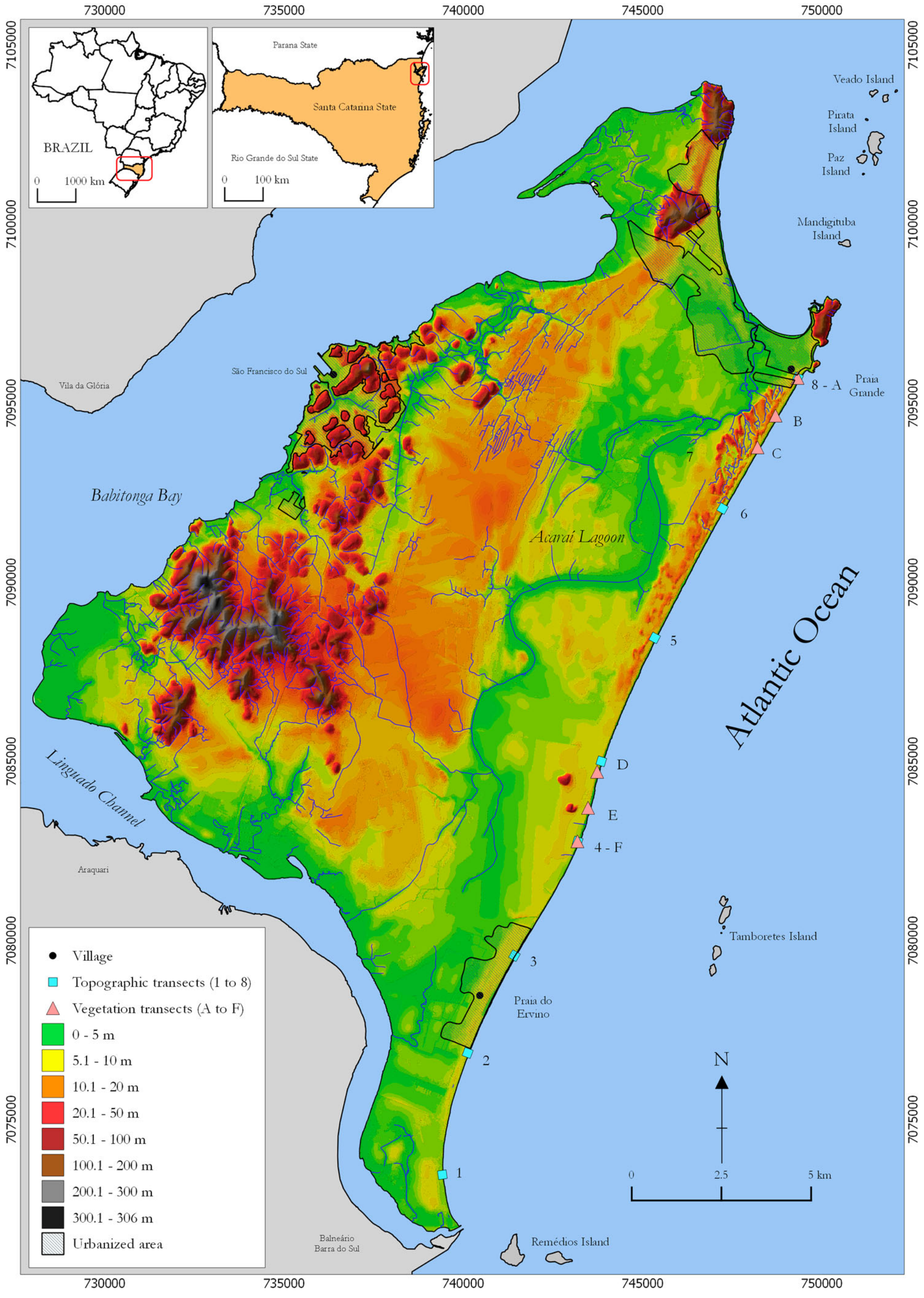

Figure 1. Location of the São Francisco do Sul Island (Santa Catarina, Brazil); the map is derived from a digital terrain model (1 m resolution). The progressive numbers point out the position of the transects where the topographic survey was carried out (cyan squares). The letters represent the position of the transects where the vegetation sampling was carried out (pink triangles). Two sites (4 and 8, F and A respectively) have overlapping symbols because the vegetation sampling and the topographic survey were carried out along the same transect.

home to 'restinga' vegetation, a particular plant association typical of the Brazilian coast. Because of its great importance to conservation of the natural environment of the area, the 'restinga' vegetation required immediate protective actions (Melo Júnior & Boeger, 2015).

São Francisco do Sul Island includes 12 beaches: the longest one, about 25 km, is named Grande and is located on the eastern side of the island. Because it is characterized by a large variety of morphological and sedimentological features and of vegetation species, this is the beach on which the study has been focused. The rest of the beaches are mostly pocket beaches, not comparable to the Grande beach in terms of size (the second longest being about 4 km). Medium sand is the typical grain-size of the sediments that constitute most beaches at São Francisco do Sul (Abreu, 2011).

The width of the Grande beach, which averages about 20 m, is quite constant throughout the entire length of the beach. The beach is subjected to erosion processes that at times produced the destruction of the frontal dune and the generation of a steep scarp at the transition between the backshore and the dunes. The erosion is uniform throughout the length of the beach; no particular accumulation or retreat areas are detectable. The littoral drift is northwards trending (Zular, 2011). Parabolic dunes up to 15 m high characterize the northern sector of the Grande beach (Zone A). They are well developed, but wide blowouts interrupt their regularity (Figure 2(a)). In addition, human interference is significant in this portion of the beach. In the central sector of the beach (Zone B), the dunes are transverse. They are characterized by lower height (hardly over 7 m) and less human impact, likely due to their major distance from the villages (Figure 2(b)). Close to Praia do Ervino village, human interference increases again.

Figure 2. Pictures of parabolic dunes (a) and transverse dunes (b) at the Grande beach, São Francisco do Sul Island. The recognition of large blowouts on parabolic dunes is easily appreciable, as is the difference in vegetation cover between the two dune types.

2.2. Geological setting

The geological elements that characterize the São Francisco do Sul Island were pointed out in accordance with Possamai, Vieira, Oliveira, and Horn Filho (2010) and Vieira (2015). The units, identified based on lithological characteristics, fossil content, absolute dating, and genesis, are listed by age (see geological map, main map):

Paleo-Proterozoic

- São Francisco do Sul Complex (metamorphic unit of the crystalline system) is composed of gneiss with bands defined by intercalations of felsic and mafic minerals characterized by different shades of grey.

Cambrian-Ordovician

- Suíte Morro Inglês (igneous unit of the crystalline system) is composed of porphyritic granitoides with predominant monzogranites, sienogranites, and granodiorites.

Quaternary (undifferentiated)

- Poorly sorted sediments with predominant sand, silt and clay, and variable content of gravel and pebbles; usually the sediments are immature and angular, and can be associated with colluvium deposits (interpreted as colluvial deposits).

Quaternary (Pleistocene)

- Deposits composed of very fine to fine sand, well sorted sediments, low-angle plane-parallel stratification and characterized by series of beach ridges at an elevation of 8–20 m above present mean sea level (interpreted as beach deposits).
- Deposits composed of silty sand sediments, plane-parallel stratification with laminations and lenses of finer sediments; they are usually located at an elevation of 8–12 m above present mean sea level (interpreted as lagoon deposits).

Holocene

- Deposits composed of fine to coarse sand, moderately sorted, low-angle plane-parallel stratification and characterized by series of beach ridges at an elevation up to 6 m above present mean sea level (interpreted as beach deposits).

- Deposits composed of silty sand sediments, moderately to well sorted with organic matter and bioturbation; they are usually located at an elevation of about 4 m above present mean sea level (interpreted as lagoon deposits).
- Deposits composed of fine to medium sands, well sorted; they usually form parabolic dunes, which are active or fixed by vegetation (interpreted as aeolian deposits).
- Deposits composed of silt and fine sand, well sorted sediments; they exhibit flat, elongated surface terraces located along the Acaraì Lagoon (interpreted as lagoon-paludal deposits).
- Deposits composed of silt to fine sand sediments located along the Babitonga Bay and the mouth of the Linguado Channel (interpreted as estuarine-paludal deposits).

According to Possamai, Vieira, Oliveira, and Horn Filho (2010), the pre-Mesozoic metamorphic and igneous units (São Francisco do Sul Complex and Suíte Morro Inglês) outcrop most commonly on the hills on the western side of the island; metamorphic outcrops are also located on isolated elevations, promontories, and on the Tamboretes Islands on the eastern side. During the Quaternary, streams flowing down the slopes formed colluvial deposits at the foot of the hills; these are typical of depositional continental systems. Two strand plain systems can be observed in the central and in the eastern portions of the island: the former is Pleistocenic, the latter Holocenic. The Acaraì Lagoon formed on the back of the Holocenic beach ridges. Paludal deposits can be recognized along several sectors of the present course of the channel and along the Linguado Channel. Large aeolian deposits formed in the northeastern sector, producing high parabolic dunes that covered the Holocene beach ridges in that portion of the island.

3. Materials and methods

The data used in this study consist of digital data (aerial photographs and digital terrain models, DTM; SDS, 2010) and field data collected during topographic and sampling surveys. These data were also used to generate a multi-thematic map (1:50,000 scale) that describes the morphological, sedimentological and vegetational characteristics of the Grande beach. The map can provide information about geomorphology (beach profile topography, type of dune, presence of morphological elements such as blowouts), sedimentology (sediment grain-size), geology (type of deposit), shoreline evolution, and vegetation cover. The data about geomorphology (with the exception of beach profile topography), geology and shoreline evolution are areal, since they cover the whole Grande beach and the backing dune field; the data about beach profile topography are linear along cross-shore transects; data about sediment grain-size and vegetation cover represent the point of collection.

3.1. Digital data

3.1.1. Geological map

The geological map was rendered on a hillshade-generated model from a DTM (SDS, 2010) to emphasize the relief. The geological elements were mapped according to Possamai, Vieira, Oliveira, and Horn Filho (2010) and Vieira (2015). The units are represented in different colors on the map: for São Francisco do Sul Complex, Suíte Morro Inglês, and colluvial deposits the RGB color code is in accordance with the Commission for the Geological Map of the World (CGMW); specific colors were assigned to the units of the same age.

3.1.2. Shoreline analysis

The systematic tracing of the coastline was carried out by analyzing aerial photographs and ortho-photographs, spanning the years from 1938 to 2010 (72 years). The images were properly georeferenced and used to build photo-mosaics of the entire coast for each year of aerial coverage (1938, 1957, 1978, 2010). Shorelines are continuous, except for a short gap in the 1957 coverage. The area where data are missing is limited to the sector fronting the village of Praia do Ervino. For each mosaic, the shoreline was traced out using QGIS vectorization tools at 1:2000 scale. The shoreline is defined by the mean high water line, which is represented by the wet/dry line (Crowell, Leatherman, & Buckley, 1991; Leatherman, 2003; Mazzer & Dillenburg, 2009). The lines were traced in different colors to make direct comparisons easier (1938: red line; 1957: blue line; 1978: green line; 2010: yellow line).

3.1.3. Dune classification

Coastal dunes were identified by photo-interpretation of both the 2010 ortho-photograph mosaic and the DTM. The photo-interpretation was realized mapping the features at 1:3000 scale. Dunes were classified according to Bertoni and Sarti (2011), modified after Hellemaa (1998). The following have been recognized: (i) frontal dunes (still subjected to physical processes and are covered with typical dune vegetation); (ii) semi-mobile dunes (may or may not experience physical processes and are characterized by shrubbery and by blowouts); and (iii) steady dunes (no longer subjected to physical processes and are covered by arboreous vegetation). In addition, parabolic and transverse dunes were traced out following the classification of Hesp (2002). Backshore and blowouts have also been mapped; the backshore seaward limit is represented by the 2010 shoreline.

3.2. Field data

3.2.1. Topographic surveys

The topographic survey was carried out in October 2015 along 8 cross-shore transects (Figure 1). The profiles were uniformly spaced about 3 km apart. Both the anthropized and the natural portions of the beach were surveyed. Each transect starts at the shoreline and ends at the transition to the woody vegetation. The survey was performed using a Leica RTK-GPS (Universal Transverse Mercator projection, Zone 22 S, Datum SAD69); points were recorded at any break-in slope along the cross-shore profile. Instrument accuracy (horizontal and vertical) of about 1 cm was obtained during post-processing of the raw data using the information provided by the nearest fixed station (Araquari Station – SAT 96171). Sea-weather information during the survey was provided by DHN (http://www.mar.mil.br): mean wave height was 1.65 m, with a peak of 1.84 m; the average tide height during the survey was 0.7 m, while the tidal range was about 1.7 m.

3.2.2. Sediment sampling and grain-size analysis

Sediment sampling was carried out at the same time and in the same places as the topographic survey (Figure 1). Samples of about 1 kg each were collected from the surface with a small shovel. The sediment was sampled in specific spots: the beachface, the dune crest, the dune back-toe, and the steady dune. Grain-size analysis was then performed on all the 31 samples collected on the beach. Prior to the sieving procedures, they were treated according to the procedures outlined in Bertoni, Biagioni, Sarti, Ciccarelli, and Ruocco (2014). Once dried and reduced to a quantity still representative of the whole sample (about 100 g), the samples were sieved for 10 min using a mechanical sieve shaker. Sieves from 0.75 to 0.063 mm were used, with a mesh interval of 0.5 phi. The sediment retained on each sieve was weighed with a digital scale (instrument error of 0.01 g). The resulting data were processed by SYSGRAN 3.0 software (Camargo, 2006), which provided the most important (Folk & Ward, 1957) textural parameters such as the mean (Mz). Each grain-size class was then represented along the transects with dots of different colors: cyan (fine sand), yellow (medium sand), and red (coarse sand).

3.2.3. Vegetation sampling

The percentage of vegetation cover was estimated in 2 × 2 m plots along six cross-shore transects (Figure 1). The transects were located in two sectors of the Grande beach characterized by different morphological configurations in order to enable comparison between plant association on the parabolic dunes to the north (Zone A) and on the transverse dunes to the south (Zone B). The plots were placed on specific spots: on the front dune, on the backdune area, and on the fixed dune. The vegetation cover was visually estimated according to the Causton (1988) scale (available as supplemental online material). The phytosociological parameters of absolute and relative cover, of absolute and relative frequencies, and the level of significance of the indicator value were calculated according to Munhoz and Araújo (2011).

The classification of the species followed Christenhusz, Zhang, and Schneider (2011) and APG III (2009). The flora identification was based in the 'restinga' vegetation list of the PEA proposed by Melo Júnior (2015). Species names and authors were in accordance with the Species List of the Botanical Garden of Brazil Flora of Rio de Janeiro (http://floradobrasil.jbrj.gov.br).

4. Results

4.1. Digital data

The shoreline evolution showed that between 1938 and 1957, the coast was subjected predominantly to a progradation of the system, with peaks of more than 60 m in the northern and southern sectors (analytical data are available as supplemental online materials). The central portion of the coast was characterized by a retreat of almost 40 m in that same timespan. During the next timespan (1957–1978) the trend was significantly different, as the erosion processes begun to hit the coast seriously. Evolution trends characterized by accretion and retreat akin to the case at the São Francisco do Sul Island have already been reported in the scientific literature: e.g. Bini, Casarosa, and Ribolini (2008) and Sabato, Longhitano, Gioia, Cilumbriello, and Spalluto (2012).

Retreat peaks of almost 70 m were calculated along the northern sectors of the Grande beach during the second timespan. The central sector was the only portion of the coast that recorded an accretion of almost 40 m as opposed to the previous time interval. During the last timespan (1978–2010) the trend to a progressive retreat of the system continued, in particular in the southern sector of the coast where a retreat of about 30 m was calculated. Conversely, the northern sector experienced accretion of more than 10 m in that same time period. Reasons that explain the retreating tendency of the coastline at the Grande beach are possibly related to anthropogenic factors. In the last decades the Island of São Francisco do Sul has been subjected to increasing human pressure as the villages grew in population and size in response to the development of economic activities mainly related to tourism (Sperb et al., 2004). The need to establish the Acaraí

Table 1. Analytical data about geomorphological (backshore width, frontal dune width and height, and maximum dune height) and sedimentological features (mean grain-size) of the Grande beach, São Francisco do Sul Island.

# Transect	Backshore width (m)	Frontal dune width (m)	Frontal dune height (m)	Maximum height (m)	Mean grain size (phi)
1	15	23	4	4	2.20
2	11	50	4	6	2.08
3	25	59	5	6	1.63
4	11	14	5	5	2.05
5	30	14	6	6	1.48
6	34	22	8	8	1.32
7	26	13	6	8	1.19
8	13	57	7	7	1.75

State Park arose also from the threat of uncontrolled expansion of human activities that could have threatened the 'restinga' vegetation (Melo Júnior & Boeger, 2015).

The photo-interpretation of ortho-photographs allowed the description of the dunes on the eastern side of the Island of São Francisco do Sul. The dune field is continuous along the north–south axis and is composed of an interconnection of frontal and semi-mobile dunes, backed by steady dunes. The semi-mobile dunes are not present in the southern sector of the Grande beach; there, transverse dunes are predominant. The dune field reaches a maximum width of over 1000 m along transect 7 in the northern portion of the beach (analytical data are available as supplemental online materials). Aside from the transects where human activities replaced the steady dunes with buildings and structures (transects 2, 3 and 8), the narrowest portion (about 500 m) is located towards the central sector of the coast. The frontal dunes are the largest where the steady dunes have been wiped out by human activities.

The photo-interpretation confirmed the spatial separation of parabolic and transverse dunes. Parabolic dunes of NNE orientation are located towards the northern sector of the beach, where they are characterized by several large blowouts. The transverse dunes, covered by dense shrub vegetation, are prevalent in the southern sector.

4.2. Field data

The topographic profiles showed that the backshore width was higher in the northern sector of the Grande beach, being consistently over 20 m with the exception of the northernmost transect (Transect 8), which is located towards Praia Grande village (Table 1). To the south, the backshore was generally narrower: the wider transect (Transect 3) was just as wide as the narrowest among those in the northern portion of the beach (about 25 m). The topographic survey also highlighted great variability of width and height of the frontal dunes: the width was higher to the south and lower in the central and northern portions of the beach (Table 1). Again, Transect 8 was an exception, showing a frontal dune width of more than 50 m.

In terms of height, the frontal dunes showed a clear trend to increase northwards; the same tendency was pointed out taking into account the whole dune field, not only the frontal dunes (Table 1). It is worth noting that most transects were characterized by a direct correlation between backshore width and frontal dune height, except for Transect 8, where the frontal dune height was high (7 m) and the backshore was narrow (13 m). Each profile showed evidence of the ongoing erosion process, particularly relevant along the transects showing a steeper scarp relative to the backshore slope.

The grain-size analysis carried out on the sediment samples collected at the Grande beach showed that the average grain-size is medium sand (Figure 3). The grain-size decreases landward along each transect: the

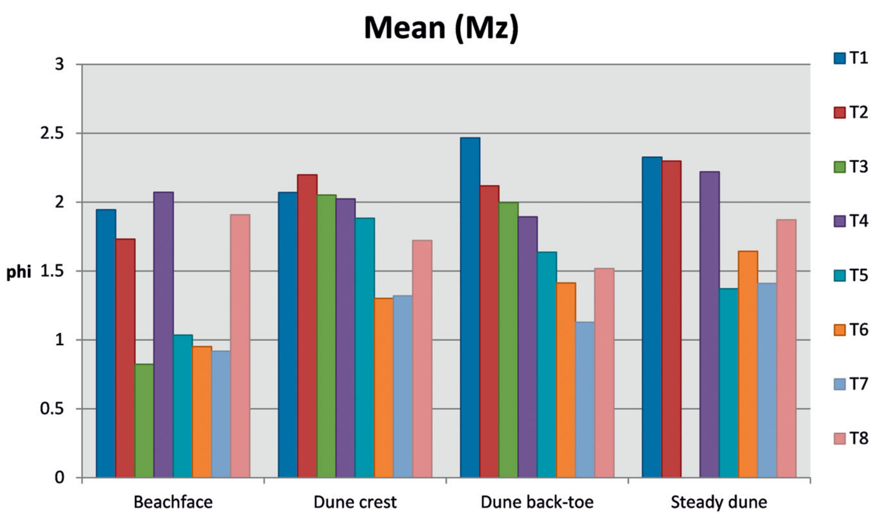

Figure 3. Grain-size distribution (mean, Mz) sorted by the spots where sediment samplings were carried out along each transect: beachface, dune crest, dune back-toe, and steady dune.

mean (Mz) values also evidenced a clear decreasing trend to the north (Table 1). The only exceptions are represented by transects 3, 4 and 8.

With regard to the vegetation, 53 species and 33 families were recorded in the two sites (Zone A and Zone B) where vegetation sampling was carried out. The families with the highest number of recorded species were Poaceae (six species), Fabaceae (five species), Asteraceae (four species), Cyperaceae (four species), and Malvaceae (three species). The most frequent species in the community structure were *Scaevola plumieri*, *Ipomoea imperati*, *Spartina ciliata*, *Hydrocotyle bonariensis*, *Remiera maritima*, *Smilax campestris*, *Aechmea ornata*, *Guapira opposita*, *Varronia curassavica* and *Myrcia pulchra*.

Zone A is characterized by lower species diversity compared to Zone B and by the presence of exotic species (*Centella asiatica*, *Cyperus* sp, *Brachiaria* sp and *Portulaca oleracea*), which are not detected in Zone B. Another factor different in the two sites was the vegetation cover. In Zone A, every transect has higher percentage values in the frontal dune than in the semi-mobile dune. In Zone B, the vegetation cover increases from the frontal dune towards the steady dune, with the exception of transect F, which shows major cover on the frontal dune.

5. Conclusion

The data obtained from the morpho-sedimentological and vegetational analyses carried out during this study provided new insights into the processes in action at the Grande beach at São Francisco do Sul Island (Santa Catarina, Brazil) and about the recent evolution of this barrier/lagoon system. In addition, the datasets allowed the production of a multi-thematic map that includes all the important information collected from field and laboratory activities. The map provides a quick overview of the geology and of the deposits that presently outcrop on the entire island. It also provides an overview of characteristics of coastal morphodynamics. As a matter of fact, the focus on the Grande beach prompts the identification of peculiar tendencies in the evolution of this beach's profile, sediment grain-size, and vegetation.

This study confirms that wise management of coastal systems is achieved when multiple factors are taken into account together. The multidisciplinary approach is often successful because it allows looking at the same aspect from different perspectives and scales, which usually leads to a better, all-around result. Thus, mapping is a valid instrument that is useful for research purposes and as a tool to aid coastal management. The multi-thematic map generated using all the datasets acquired from digital analyses and field surveys will allow all stakeholders to quickly gather information about morpho-sedimentological and vegetational aspects of the Grande beach at São Francisco do Sul Island and will make a legitimate contribution to careful planning of the site. Besides, this approach can be easily replicated elsewhere, because it is not strictly related to specific characteristics of the local area.

Software

QGIS 2.8.2 has been used for map digitization and construction; tables and topographic profile plots have been created using Corel Draw X6. Final rendering and production have been done using Adobe Illustrator CS4.

Acknowledgements

We are thankful to the University of the Region of Joinville (Brazil) for the logistical support we received; sample analysis would not have been as quick without the laboratory instruments they provided. Felipe Tabalipa was very helpful during the fieldwork. FATMA provided bureaucratic support. We are grateful to Dr Daniela Ciccarelli for her useful insights into vegetation aspects and to Dr Serena Giacomelli and Dr Edoardo Grottoli for their patient suggestions about the maps. We also acknowledge the insightful observations made by reviewers prof. Luisa Sabato and Dr Francesco Mascioli, which led to substantial improvements to the final version of the manuscript. Comments by Dr Bieke Cattoor greatly improved the outcome of the maps. We thank Dr Mike J. Smith and Dr Paolo Paron for the editorial support.

Disclosure statement

No potential conflict of interest was reported by the authors.

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