Résumé

Bioindicateurs de la dynamique érosive de la mer dans les systèmes de plage et dune à la côte continentale Portugaise

Les écosystèmes psammophilic littoraux, sont organisés selon les gradients de la mer environ les zones plus à l'intérieur. Ces gradients révèlent une succession de communautés végétales distinctes, qui progressivement se particularisent de la plage jusqu'à les dunes intérieures stabilisées. Du point de vue de la composition structurelle, physionomique et floristique, ces communautés forment diverses associations phytosociologiques, qui définissent les différents biotopes, selon leur géomorphologie, le sol et les caractéristiques écologiques. Aux plages de sable stables du point de vue de la balance d'érosion, les différentes communautés végétales ont tendance à occuper de empreintes zonales relativement larges, avec des transitions claires. Toutefois, quand les processus érosifs sont forts, ils impliquant le démaigrissement de la plage, les retraites du littoral, et l'avance des sables mobile vers à l'intérieur. Dans les cas les plus sévères, le gradient zonal (entre la plage, les dunes instables, et les dunes relativement stabilisées), est souvent comprimé, et les distinctes communautés végétales tendent à se chevaucher. Puisque les hemicryptophytes herbacés de la plage et des dunes instables, ont des compétences intrinsèques de colonisation, haute tolérance (ou même de préférence) à l'enterrement, et les taux élevés de croissance, ils peuvent s'adapter rapidement à l'instabilité de la surface topographique, et émigrer à l'intérieur de l'écosystème. Cependant, le taux de croissance de la végétation ligneuse chamaephitic, caractéristique des dunes relativement stables (dunes gris) sont plus lents, ainsi que la capacité des plantes à résister à la mobilité des sables et à l'ensevelissement. L'avance de la mer à l'intérieur, combinée à la dissemblance dans la résilience des différentes associations de plantes, résultant en la diminution de la vigueur des taxons chamaephitic, et l'amalgamation de plantes des différentes communautés. L'objectif principal de ce travail était d'étudier des tendances générales d'érosion le long de la côte continentale portugaise, basée dans l'analyse de la végétation dominante le long du gradient psammophilic. Il a été concentré dans le rôle joué par certaines plantes comme bioindicateurs de la célérité des processus d'érosion, causés par le transport des sables pour le vent, la dynamique de la mer et le recul côtière. L'intensité du phénomène, exprimée par la présence d'espèces hemicryptophitic typiques des secteurs de la arrière plage et des dunes blanches, mélangés à des associations végétales dominants aux dunes grises, est analysée. Les plantes qui peuvent être utilisées à des bioindicateurs fiables sont identifiées, un total de 10 *taxa* : *Ammophila arenaria* subsp. *australis, Cakile maritima, Calystegia soldanella, Elymus farctus*, *Eryngium maritimum*, *Euphorbia paralias* , *Medicago marina*, *Otanthus maritimus, Pancratium maritimum* et *Polygonum maritimum*. Les corrélations entre les changements observés dans le modèle théorique d'un gradient psammophilic en situations d'équilibre et d'érosion sont établies. L'intensité du phénomène est analysée et quantifié le long des différents secteurs de la côte portugaise. Une valeur maximum de 14,9 % de couverture pour des bioindicateurs (espèces psammophilic en les relevés de la dune gris) a été enregistrée au Nord d'Aveiro, en tombant à 10,9 % entre Aveiro et Figueira da Foz. Les valeurs continuent à baisser dans l'association *Armerio welwitschii-Crucianelletum maritimae* (de transition entre l'antérieur et la association Méditerranéenne), avec 9,6 %. Cette tendance à la baisse est confirmée en *Artemisio crithmifoliae-Armerietum pungentis,* avec 6,4 % dans la côte du Sud-ouest et le record le plus bas dans la côte Sud d'Algarve (5.9 %). Donc, les plus hautes valeurs se produisent dans le Nord de Portugal descendant vers le Sud, résultats cohérents avec les caractéristiques physiques de la côte portugaise, et les hypothèses de travail.

Abstract

Bioindicators of erosive dynamics in beach and dune systems in the Portuguese mainland coast

The littoral psammophilic ecosystems are organized according gradients leaning from the sea to interior areas, including a succession of phytosociological associations, correspondent to well discriminate biotopes, according their geomorphologic, soil and ecological characteristics. In the stable sandy shores (in terms of erosion balance), the different communities occupy relatively wide zonal tracks, with clear transitions. However, in situations of beach downwasting and coastline retreat, the mobile sands tend to advance inland, often compressing the zonal gradient, and distinct communities tend to overlap. Since the herbaceous hemicryptophitic flora typical from the beach and instable dunes has intrinsic colonization skills, high tolerance (or even preference) to burial, and elevated growing rates, it can quickly adapt to the instability of the topographic surface, accompanying its movement to the interior. Yet, the growing rates of the woody chamaephitic vegetation, characteristic of the more interior and relatively stable dune (gray dune) are slower, in addition to a lower capability to resist to burial. Thus, sea advance and inherent sands mobility inland, combined with the dissimilar resilience of plant associations, results in the in the overlap of the chamaephitic *taxa* and in the amalgamation of species from different communities. The main objective of this work was to study general trends of erosion along the Portuguese softline mainland coast, based in the analysis of the dominant associations that occur along the psammophilic gradient. It was focused in the role played by some plants has bioindicators of the velocity of erosional processes caused by wind transportation, sea dynamics and coastal retreat. Plants that can be used has reliable bioindicators are identified. Correlations between the observed alterations in the theoretical model of a coastal psammophilic gradient, and the intensity of erosion are established. The intensity of the phenomenon is analyzed and quantified along different sectors of the Portuguese coast.

Bioindicators of erosive dynamics in beach and dune systems in the Portuguese mainland coast.

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Introduction

The Portuguese coastal natural ecosystems are included in three main types: beaches and dunes, cliffs, and marshes (MOREIRA 1984; COSTA 2001). Coastal beaches and dunes usually are formed in soft shorelines of sand, gravel or cobble. Although the retreat and advance of the shoreline position can occur naturally (BROWN *et al.* 2011), soft cliffs and sedimentary coasts are far less resilient than hard rock coasts, that barely erode (EUROSION 2004).

Erosion dominates over accretion on at least 70% of the world's sandy shorelines, resulting in an inland displacement of the shoreline (BIRD 1985). Erosion in soft shorelines can be a normal environmental response to cyclic climatic conditions, that slowing goes on for several years, or take place in fast and dramatic episodes, like following catastrophic storm events (SOPAC 2007; BROWN *et al.* 2011). Yet, commonly considered as problematic, since it jeopardizes human development along the coast, having high costs (economic, in property, land, infrastructures and transports), erosion is indeed a natural process of sediment redistribution (VELOSO-GOMES *et al.* 2004; BROWN *et al.* 2011); the problem lies in erosion being amplified or stimulated by human interferences in the usual sands movement and budget patterns (CARTER 1991). Direct causes include hard engineering techniques of coastal defence, inefficient or inappropriate protection structures, dredging for navigational purposes, and coastal artificialization (e. g. harbour development), that have high impacts on natural sediment processes (EUROSION 2004).

Plus, vegetation clearing as well as related land use changes, river damming and water regulation works, land reclamation, water extraction, sands and gas mining, are all factors that contribute to land subsidence and lost. An indirect, but significant cause is the sea-rise and its sources, the economic activities that increase CO_2 concentration in the atmosphere contributing to global warming (CARTER 1991; EUROSION 2004; FEAGIN *et al.* 2005a; IPCC 2007; BROWN *et al.* 2011).

Rising sea level over the next century will affect coastal regions in several ways: land loss, shoreline retreat from erosion and inundation, increased frequency of storm-related flooding, intrusion of salt water into freshwater aquifers (CCSP 2009). Sea level rise can be considered the ultimate vulnerability exposure factor (WILSON *et al.* 2005) to coastline erosion (MARTINS *et al.* 2012), since the sensitivity of a coastal region depends on the physical aspects (shape and composition) of a coastal landscape and also in its ecological setting (CCSP 2009).

In many locations of the Portuguese coast, dramatic land use changes, such as the abandonment of agriculture and the construction of dams that retain the sediments upstream, are probable causes to coastal erosion (MARTINS *et al.* 2012). Still, those causes are poorly studied (EUROSION 2004).

In the Portuguese west coast the predominant annual wave direction is from the northwest, with episodic winter storm waves from the southwest (COSTA & PINTO 2011; SILVEIRA *et al.* 2011). From Aveiro to the north, the coastal exposure to the sea dynamics is higher than in other areas, being the coast of Algarve (southeast) sheltered from the predominant wave and winds direction of northwest. Main natural factors related with coastal erosion are the waves, winds, storms, tides, near-shore currents and slope processes (landslides) (EUROSION 2004). The impact of the turbulent energy of waves is particularly significant in open straight sectors of the coast, like in Vagueira and Costa da Caparica (Cova do Vapor) (DIAS & NEAL 1992; FERREIRA 2006). Wave formation is also related with stronger wind patterns, which cause aeolian erosion of the sands. Extreme storm are common along the coast, sometimes triggering several meters of retreat in a short amount of time. The importance of the tides as an erosion factor is also high along the macrotidal Atlantic coasts (tidal ranges superior to 4 meters), thus, in the Portuguese west coast (EUROSION 2004).

In the last three decades, erosion has been studied in a number of points of the Portuguese mainland coast, by several authors (e.g. OLIVEIRA *et al.* 1982, ANDRADE *et al.* 1989, FERREIRA *et al.* 1990, ÂNGELO 1991, MARQUES 1991, BETTENCOURT & ANGELO 1992, DIAS & NEAL 1992, FERREIRA & DIAS 1992, DIAS *et al.* 2000, FERREIRA 2006, MENDES & PINHO 2008 and COSTA & PINTO). In general, their outcomes indicate that, combined, the orientation of the coast, the predominant wave direction and the diminution of the wave energy to the South, results in a general progressive diminution of erosion in that direction, except for a few well known problematic locations like Costa da Caparica (FERREIRA 2006). This is confirmed by IA (*Instituto do Ambiente,* Environment Institute, Portugal) in a report made in 2005, so as to concluded that the erosive effect is more intense in the stretches to the north of Nazaré, particularly between Espinho and Ovar (which shows the higher rate of retreat). According to the same study, the average rates of retreat ranged from 0.2 meter/year to 9 meters/year, and all the values superior to 1meter/year were localized in the north of Figueira da Foz.

However, despite all the studies about erosion of the Portuguese coast, there is only a reduced number of recent works specifically dealing with the relations between the coastal erosion phenomenon, and the natural vegetation distribution and behavior along the coastal beaches and dunes. Some exceptions are the works of ARAÚJO *et al.* 2002, SOARES DE CARVALHO *et al.* 2002, LOMBA *et al.* 2005 and LOMBA *et al.* 2008.

Still, most of the works relying on the important bioindication potential (ISERENTANT & DE SLOOVER 1976) of the sands' flora and vegetation (FAVENNEC 2002) are focused in restricted areas of the north Portuguese coast, in the Atlantic (Eurosiberian) Biogeographic Region, like GRANJA *et al.* 2000, SILVA 2006 and HONRADO *et al.* 2010.

This lack of information is concerning, considering future scenarios of sea-rise in which coastal erosion can derail or block the coastal dunes' accommodation landwards, since there will be no available space (PSUTY & SILVEIRA 2010). If there is space, in low intensity scenarios, plant communities may fully developed over five years; in moderate and high, may became too stressed to grow, leading to smaller dunes and eventual breakdowns of dune formation. In the higher water scenarios, they will no longer provided wind blocks, elevated dune structures, or added to the sand and soil fertility (FEAGIN *et al.* 2005a).

Native psammophilic flora and vegetation plays a vital role in the resilience and vitality of coastal social-ecological services (FEAGIN *et al.* 2010; MARTINS *et al.* 2012), for instance biodiversity maintenance (TIL & KOOJMAN 2007; HOWE *et al.* 2009), subsurface water retention, sand fixation and dune construction. Sandfixing plants (e.g. *Atriplex* sp.) are responsible for stabilizing surfaces and sand-building (e.g. *Ammophila* sp. and *Elymus* sp.) are involved in accumulating material (CARTER 1991). Time and space relationships between the beach and the dune systems' sediment budget, are the foundation for foredune (mobile dune or white dune) development and geomorphological evolution across the beach-dune profile (PSUTY & SILVEIRA 2010). Coastal dunes develop as accumulating systems with very positive sediment budgets (i.e. input far exceeds output). Thus, a negative budget leads to a dissected dune system by erosion landforms: blowouts, deflation hollows and plains, reactivation dunes and scarping (CARTER 1991).

In conditions of dynamic equilibrium (erosion equals accretion) psammophilic communities occur in well-defined geomorphological and ecological gradients (FEAGIN *et al.* 2005b) mostly determined by environmental factors, has sea dynamics, sea proximity and sands mobility, that are expressed in specific plant associations, coverage and species compositions (KIM & YU 2009).

Along the coastal *geopermasigmetum* (RIVAS-MARTÍNEZ 2005), plant specialization to the substrate is high, the different communities can be clearly identified (in terms of species, composition, and coverage), and usually do not contact except in narrow border areas (MARTINS *et al.* 2012). Since, facing severe erosive sea processes, very often the beach sands and the foredune advance inland (PSUTY & SILVEIRA 2010) overlapping the relatively stabilized dunes (gray dunes), in such situations their vegetation can mingle and coexist for a period of time.

Work hypothesis

The presence of dune constructors (CARTER 1991), hemicryptophitic species typical from the high beach and foredune communities, in the secondary (or gray) dune, can be interpreted to provide information on the intensity of sea erosion.

According to the position they occupy along the psammophilic gradients (RIVAS-MARTÍNEZ 2005), these species have high bioindication potential of sea erosion (ISERENTANT & DE SLOOVER 1976; NETO *et al.* 2010; MARTINS *et al.* 2012), and a special importance for conservation concerns.

So, considering the geographical and physical characteristics of the mainland Portuguese coast, the global percentage of exclusive psammophilic plant species in the gray dune is to be maximum at North of Aveiro (MARTINS *et al.* 2012) where the sea erosion is higher, diminishing to South. It should be lowest in the Oriental Algarve's coasts (EUROSION 2004).

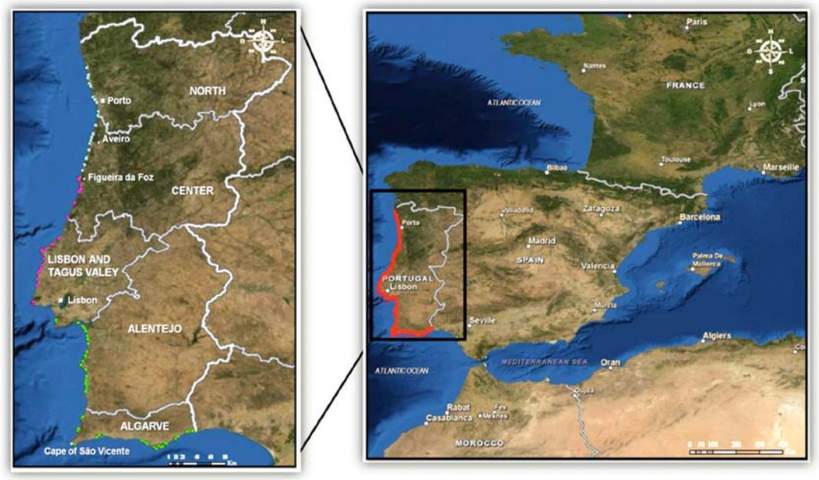

Figure 1

Study area, the Portuguese continental coast. (Source: Orthophotomaps from ESRI. Maps created in a GIS Open Source Programe).

Study area

The study area of this work is the Portuguese continental soft coastline, which shows a tended linear configuration (Figure 1) in result of the mineral nature of the rocks and sea erosion intensity (RIBEIRO *et al.* 1987). It is composed by four main types of coasts: low sandy beaches, cliffs, littoral wetlands - estuaries and deltas -, and artificialized coasts, with about 591 Km of beaches that alternate irregularly with sea cliffs (ANDRADE *et al.* 2002). To the north of Espinho until the Portuguese north end, between Nazaré and the mouth of the Tagus River, and in southwest of Alentejo and western Algarve (Costa Vicentina, that goes from the south of Sines until Cape of São Vicente), the coasts are mainly tall and rugged, with some small beaches limited by cliffs, in many areas. From Espinho to about a third of the territory (Figueira da Foz), the shore is mainly low and sandy (ANDRADE *et al.* 2002). Where the sea contacts with soft rocks, or the line of contact is predominantly low (due to the emerging of a narrow strip of coastal area during the marine regression), exist most sandy beaches and dune formations. Sometimes they are promoted by the deposition of sands in crevices (e. g. some coastal areas between Espinho and São Pedro de Moel, or in the Eastern Algarve), or along continue formations of significant extension, like in the arch Tróia-Sines (DAVEAU 1995; RIBEIRO *et al.* 1987).

Material and Methods

This work was based in the analysis of 209 phytosociological inventories made according the sigmatist landscape phytosociological approach (BRAUN-BLANQUET 1979; GÉHU & RIVAS-MARTÍNEZ 1981; RIVAS-MARTÍNEZ 2005). The relevés were randomly picked (RUXTON & COLEGRAVE 2006.) from several bibliographic fonts: BRAUN-BLANQUET *et al.* 1972; DÍEZ-GARRETAS 1984; RIVAS-MARTÍNEZ *et al.* 1990; NETO 1993; COSTA *et al.* 1994; COSTA *et al.* 1997; CALDAS *et al.* 1999; COSTA *et al.* 2000; PINHO 2001; NETO 2002; PAIVA-FERREIRA & PINTO-GOMES 2002; LOMBA 2004; SILVA 2006. Concerning the occidental coast from Lisbon to Algarve, some original unpublished relevés, from the authors, were analyzed. To perform the statistical analysis, the abundance classes of BRAUN-BLANQUET 1979 were transformed into numeric values, using the middle value of each class.

Botanical nomenclature is according MCNEILL *et al.* 2006, IPNI 2011 and CASTROVIEJO et *al.* (1986 – 2007, plus more recent revisions of Flora Iberica published on-line). Phytosociological nomenclature respects WEBER H. *et al.* 2000, and sintaxonomy follows RIVAS-MARTÍNEZ *et al.* 2001, RIVAS-MARTÍNEZ *et al.* 2002 and RIVAS-MARTÍNEZ 2005.

Concerning geomorphology, beaches and dunes' psammophilic gradient, follows BIRD 1965, and ecology is according MOREIRA 1984.

Results and Discussion

- The studied relevés correspond to the three dominant chamaephitic plant associations which occur in the gray dunes along the continental Portuguese coast. These communities are:

1. *Iberidetum procumbentis* Bellot 1968, an Iberian-Atlantique association that, in Portugal, only occurs to the North of Aveiro. Such communities are differentiated by the presence of the Portuguese endemic *taxa Jasione lusitanica* A.DC. (only distributed by Minho, Douro Litoral and Beira Litoral) and *Coincya monensis* (L.) Greuter & Burdet var. *johnstonii* (Samp.) Leadlay (that only exists in Douro Litoral). It is also characterized by the absence of the genus *Armeria* Willd. A total of 88 relevés were analyzed.

2. *Armerio welwitschii-Crucianelletum maritimae* Br.-Bl., Rozeira & P. Silva in Br.-Bl., G. Br.-Bl., Rozeira & P. Silva 1972. Characterized by the presence of the Portuguese endemism and exclusive to this association, *Armeria ciliata* subsp. *welwitschii* Boiss., it can be considered a transition between the Eurosiberian (*Iberidetum procumbentis*) and the Mediterranean association (*Artemisio crithmifoliae-Armerietum pungentis* Rivas Goday & Rivas-Martínez 1958). It is distributed by the soft coastline between Aveiro and Lisbon.3. *Artemisio crithmifoliae-Armerietum pungentis* Rivas Goday & Rivas-Martínez 1958. This Mediteranean association only occurs to the South of Tagus River, being dominated by *Armeria pungens* Hoffmanns. & Link., and possessing the Southwest Portuguese endemic *taxon Herniaria maritima* Link ex Nyman (present in Algarve, Baixo Alentejo, Portuguese Estremadura and Ribatejo), plus *Thymus carnosus* Boiss. and *Linaria lamarckii* Rouy, two species that are distributed by Algarve, Baixo Alentejo and Portuguese Estremadura, recently also given to Huelva (Spain), second Flora Iberica.

• According to their life types and fidelity to specific beach and mobile dune plant associations, when found in the relevés identified has gray dunes' communities, the next *taxa* were considered has bioindicators of sea erosion (see Figure 2):

1. *Ammophila arenaria* (L.) Link subsp. *australis* (Mabille) M.Laínz.
2. *Cakile maritima* Scop. (subsp. *integrifolia* Hyl. ex Greuter & Burdet and subsp. *maritima* Scop.)
3. *Calystegia soldanella* (L.) Roem. & Schult.
4. *Elymus farctus* (Viv.) Runemark ex Melderis
5. *Eryngium maritimum* L.
6. *Euphorbia paralias* L.
7. *Medicago marina* L.
8. *Otanthus maritimus* (L.) Hoffmanns. & Link
9. *Pancratium maritimum* L.
10. *Polygonum maritimum* L.

The justification for choosing these *taxa* as bioindicators relies in the following:

Cakile maritima subsp. *integrifolia*, *C. maritima* subsp. *maritima*, and *Polygonum maritimum*, are characteristic *taxa* in the sparsely covered first vegetation strip, that occurs in the medium-high beach

Figure 2
Bioindicators of sea erosion:

1. *Ammophila arenaria* subsp. *australis*;
2. *Cakile maritima*;
3. *Calystegia soldanela*;
4. *Elymus farctus*;
5. *Eryngium maritimum*;
6. *Euphorbia paralias*;
7. *Medicago marina*;
8. *Otanthus maritimus*;
9. *Pancratium maritimum*;
10. *Polygonum maritimum* L.

transition area (medium covers of 25.78% for the Eurosiberian association - *Honkenyo-Euphorbietum peplis* Tüxen ex Géhu 1964 - and 19.11% to the Mediterranean - *Salsolo kali-Cakiletum aegyptiacae* Costa & Mansanet 1981, according the study of MARTINS *et al.* 2012. These plant communities are floristically poor and dominated by therophitic pioneers, halo nitrophilous, has *Cakile maritima*, which are dispersed by sea, transported during the high tides, and deposited in the debris accumulation areas, especially during spring. Due to the sands instability, high salinity and constant inundation, perennial species do not have the capacity to establish in this beach sector.

In Portugal, the two associations are separated in "Cabo da Roca" (within the influence of Serra de Sintra, Lisbon). In the North is found *Cakile maritima* subsp. *integrifolia*, and in the South *C. maritima* subsp. *maritima*. Both communities are included in the "Nature 2000" habitat "Annual vegetation of drift lines" ["Vegetação anual das zonas de acumulação de detritos pela maré"], with the habitat code number 1210 (code EUNIS 2002: B2.1; Paleartic 2001: 17.2; Corine Land Cover: 3.3.1.). They have suffered a decrease in its area, over the last twenty years (ALFA 2006).

When found in the gray dunes's relevés, these species can be interpreted has reliable bioindicators of swift sea advance or of the occurrence of strong storms, and waves' penetration landwards, thus being related with erosive dynamics in the coastline.

Elymus farctus and *Eryngium maritimum* are species that typically appear in the high beach, where the flat areas can suffer a periodic penetration of the waves, especially during winter. In Portugal, this beach sector is mainly colonized by perennial hemicryptophitic grasslands dominated by *Elymus farctus*, receiving the sea water through a laminar flow and may suffering wind deflation. Separated in "Cape Mondego" (Quiaios beach - Figueira da Foz), it is possible to identify the associations *Euphorbio paraliae-Elytrigietum boreoatlanticae* Tüxen in Br.-Bl. & Tüxen 1952 corr. Darimont, Duvigneaud & Lambinon 1962 nom. mut. (Eurosiberian), and *Elytrigietum junceo-boreoatlantici* J. C. Costa, C. Neto, Lousã, J. Capelo & Rivas-Martínez 2004 (Mediteranean). Besides *Elymus farctus*, *Eryngium maritimum* is a colonizer also frequent in these grasslands.

Included in "Nature 2000", with the habitat code number 2110 (EUNIS 2002: B1.3/P-16.211; Paleartic 2001: 16.211; Corine Land Cover: 3.3.1.), corresponding to the "mobile embryonic dunes" (or "dunas móveis embrionárias" in Portuguese), the have suffered a decrease in its distribution area in the last two decades, showing different conservation status along the Portuguese coast. Best levels of conservation are correlated with lower human pressures (ALFA 2006; MARTINS *et al.* 2012).

When found in more advanced positions inward, namely mingled in the gray dunes, those species indicate that the sea water was able to penetrate in the secondary dunes, indicating recent sea erosion episodes.

Otanthus maritimus, *Euphorbia paralias*, and *Medicago marina*. In the more inland sector of the high beach, plants and other obstacles constitute barriers to the wind carried sand grains, which are then deposited and tend to aggregate around it. These micro-irregular areas formed by a gradual sand accumulation, originate the embryonic dunes or "nebkas", dominated by *Otanthus maritimus*, that tend to grow, and by coalescence of several, may originate the primary mobile dunes that are then dominated by *Ammophila arenaria* subsp. *australis*. *Euphorbia paralias* and *Medicago marina* (usual species in the embryonic dunes). The "nebkas" to the North of Quiaios are formed by *Otantho maritimi-Ammophiletum australis* Géhu & Tüxen 1975 corr. Rivas-Martínez, Lousã, T.E. Díaz, Fernández-González & J.C. Costa 1990, and by *Loto cretici-Ammophiletum australis* Rivas-Martínez 1965 corr. in the South.

Hence, when found in the gray dunes, they reveal that dune formation is taking place in a displaced position in the interior, and can be used has a bioindicator.

Ammophila arenaria subsp. *australis*, *Pancratium maritimum* and *Calystegia soldanella*. Commonly known as "marran grass", *Ammophila arenaria* is a harsh perennial that spreads locally and mainly reproduces by vegetative rhizome fragments. It prefers psammophilic substrates well drained and with low contents of organic matter, but has elevated ecological ranges for soil pH and temperature, is tolerant to wind, air salinity, sands mobility, burial and oligotrophic conditions. Yet, it does not tolerate high concentrations of salt in the soil. Most vigorous growths are found in the mobile or semi-stable dunes, since this *taxon* is well adapted to sands movement, requiring sand burial to maintain vitality and avoid senescence (RUSSO *et al.*1988, BUELL *et al.* 1995. Burial promotes elongation of the leaves and the development of adventitious roots (RANWELL 1959), which is important to obtain soil nutrients and water.

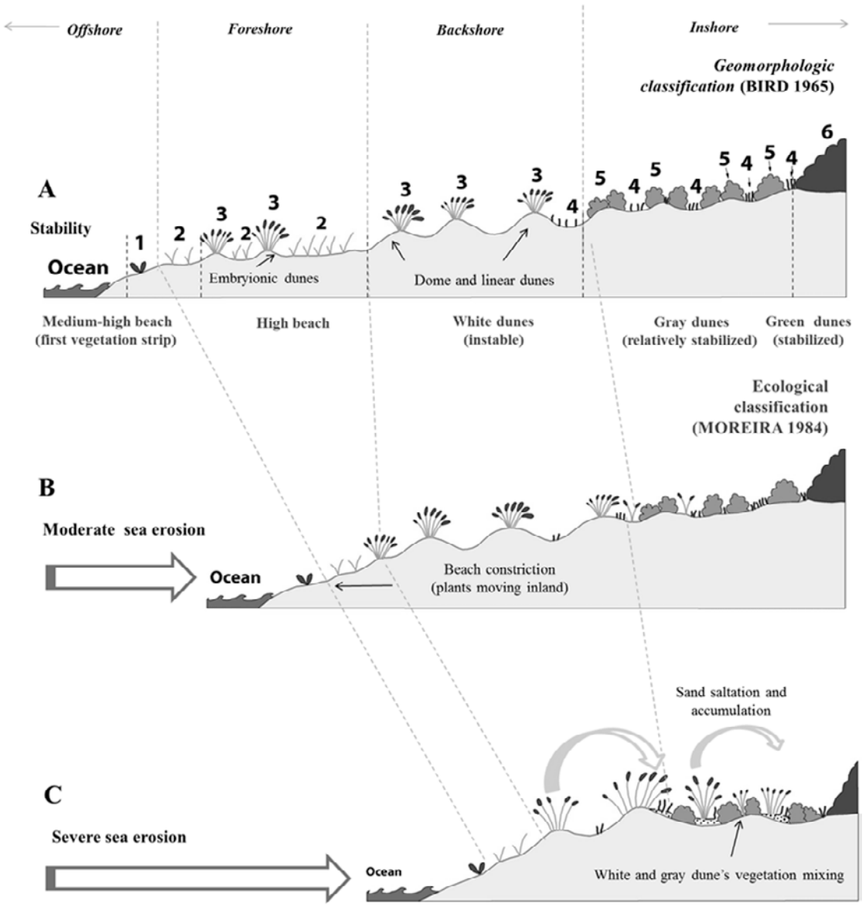

Figure 3
Typical ocean–interior dunes psamophilic communities in different dynamic conditions. [1. Halo nitrophilous therophitic scrubs (annual), 2. Hemicryptophitic grasslands (perennial), 3. Hemicryptophitic communities (embryonic and mobile dunes), 4. Therophitic grasslands (clearings of the chamaephitic vegetation), 5. Chamaephitic vegetation (relatively stabilized dunes), 6. Phanaerophitic vegetation (stabilized dunes)].

Due to its strong colonizer skills, resistance and resilience to environmental perturbations and stress conditions, "marran grass" is a competitor, considered one of the worst invasive species in other parts of the world (RUSSO *et al.*1988). In its native range, the *taxon*'s ecological optimum is in the white dune communities (NETO 1991; MARTINS *et al.* 2012), where is the dominant species (RUSSO *et al.*1988), usually accompanied by *Othanthus maritimus*. In mainland Portugal "marran grass" structures the associations *Otantho maritimi-Ammophiletum australis* Géhu & Tüxen 1975 corr. Rivas-Martínez, Lousã, T.E. Díaz, Fernández-González & J.C. Costa 1990 (Eurosiberian), and *Loto cretici-Ammophiletum australis* Rivas-Martínez 1965 (Mediterranean). These communities are included in the "Nature 2000" habitat 2120 (EUNIS 2002: B1.3/P-16.212; Paleartic 2001: 16.212; Corine Land Cover: 3.3.1.), with the designation "Shifting dunes along the shoreline with Amophila arenaria ("white dunes")" ["Dunas móveis do cordão dunar com Ammophila arenaria ("dunas brancas")"]. Their conservation status across the Portuguese coast is globally medium to bad, in the more touristic areas, having suffered a serious decrease in the last two decades (ALFA 2006). *Calystegia soldanella* is a psammophilic species, also common in the high beach and foredune sectors.

Opposing to the mobile dunes, further inland, in conditions of stabilization of the sands movement, other species and communities are able to establish, forming the gray dunes' vegetation, and *A. arenaria* subsequently begins to senesce (RUSSO *et al.*1988). When *A. arenaria* appears mingled with the gray dune's communities (that are directly dependent of a relative stabilization of the substrate), reveals a state of landscape dynamics where the sands from the foredune advance inland, overlapping the more stable sands. Since accommodation space is a key requirement for the continued functioning of the foredune morphologies during periods of sea-level rise and land loss (PSUTY & SILVEIRA 2010), and this space does not always exists, or the time for accommodation is not sufficient, the presence of those species is an unequivocal bioindicator of shoreline retreat.

• In conditions of stability (A, Figure 3), the coastal *geopermasigmetum* is well defined, and the different geomorphological beach sectors (BIRD 1965) are easily identified, having understandable correspondences with the different ecological types (MOREIRA 1984). When the sea advance and coastline retreats, resulting in beach constriction and plants moving inland, the hemicryptophitic vegetation (high beach grasslands of *Elymus farctus* and embryonic dunes with *Ammophila arenaria*) constricts, suffering a reduction in its area (B, figure 3). When erosion is more severe, the foreshore and the backshore almost disappear. Since the hemicryptophitic vegetation has the ability to accompany the sands movement landwards, the inshore sector (where the gray dune's vegetation develops) suffers the carried sands accumulation, being buried by them. By intrinsic biological characteristics, the gray dunes' communities (dominated by chamaephitic vegetation and therophitic grasslands in its clearings) have a much slower reaction time. Thus, vegetation can mingle and coexist for a certain period of time, until the gray dune plants are totally buried, ending up to disappear in many cases, especially if there is no accommodation space landwards (PSUTY & SILVEIRA 2010). In most severe situations, even the stabilized dunes (phanaerophitic green dunes) are affected.

Figure 3 illustrates what succeeds with the vegetation, along the psammophilic ocean-interior dunes' gradient, in different dynamic conditions: A. Sedimentary budget equilibrium, B. Moderate sea erosion, and C. Severe erosion caused by sea advance. In Figure 4 it is possible to see a typical situation from condition B (or C).

Figure 4

Bioindicators mixed with typical species from the grey dune (partially covered by mobile sands).

Figure 5

Location of the 209 studied relevés and cover (%) of species with optimum in the beach and white dune, used as bioindicators, present in the gray dune's associations in the different coastline sectors.

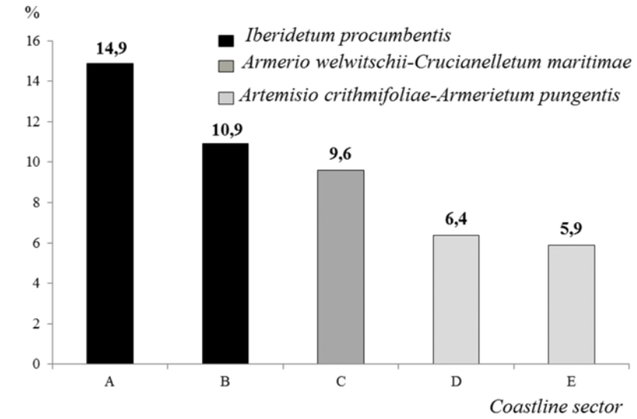

Figure 6

Percentages of cover by bioindicator species found in the gray dunes relevés, along the Portuguese mainland coast. Coastline sectors: A. Aveiro to North, B. Figueira da Foz to Aveiro, C. Lisbon to Figueira da Foz, D. Cape of São Vicente to Lisbon and E. South coast of Algarve.

• According to the physical and geographical characteristics of the coast, the Portuguese mainland coast was divided in 5 sectors: A. Aveiro to North and B. Figueira da Foz to Aveiro (*Iberidetum procumbentis*); C. Lisbon to Figueira da Foz (*Armerio welwitschii-Crucianelletum maritimae*); D. Cape of São Vicente to Lisbon and E. South coast of Algarve (*Artemisio crithmifoliae-Armerietum pungentis*) (see Figure 5).

• The calculus of the medium coverage rates by psammophilic species with their ecological optimum in the beach and instable dune sectors, found in the gray dune's relevés (in relation to the total coverage rates) has showed that the highest values occur in Northern Portugal, in the association *Iberidetum procumbentis*, descending to South, like showed in Figure 6.

• A maximum value of 14,9 % of coverage has been registered to sector A. (North of Aveiro), dropping to 10,9% between Aveiro and Figueira da Foz. Values continue to downward in the association *Armerio welwitschii-Crucianelletum maritimae*, with 9,6% in sector C. This trend is confirmed in the Mediterranean association, *Artemisio crithmifoliae-Armerietum pungentis*, with 6,4% in the Southwest coast, and the lowest record in the South coast of Algarve with only 5.9 %. Those results were obtained, using the mean value for all the inventories analyzed in each sector. Figures 7 to 10, show different situations registered along several sectors of the Portuguese coast.

To be significant at a broad scale, a representative study of the entire Portuguese sandy coast'S, needed a large amount of data. The use of phytossociological relevés guaranteed that accurate records, obtained by a normalized and robust method of vegetation analyses with strong emphasis on plant relations and environmental variables (PAIVA-FERREIRA & PINTO-GOMES 2002; RIVAS-MARTÍNEZ 2005; GÉHU 2006).

The results obtained have permitted to enlighten the physical process underlying the bioindication of sea erosion processes given by characteristic species from the beaches and white dunes, when mingled with the gray dune's vegetation.

Besides the erosive power of the sea, related with the predominant sea drift and wind's power, other factors can be pointed as a cause of the Portuguese soft coastline retreat. In fact, human actions as river damming and construction in the littoral, affect the sand supply and beach nourishment, and also the effects of climatic change, like the progressive sea level raising and the increasing in storms and surge, among others. Nevertheless, the major trend in the decreasing of sea erosion, observed by bioindication, from North to South, showed by maximum values in Minho and minimum in Algarve, is according and corroborates the work hypothesis.

Like in other works, general results indicate that the interpretation of phytossociological data (relevés), in the particular context of bioindication of sea erosion, can provide valuable information in the diagnosis of such situations. At finer scales, applied coastal management and ecosystem conservation, can benefit with the use and development of such methodologies and studies.

Figure 7
Micro cliff caused by sea erosion in the front of the beach (Aveiro).

Figure 8
Typical plants from the beach and white dune, with *Elymus farctus* and *Ammophila arenaria* subsp. *australis*, invading the gray dune and overlapping the chamaephitic vegetation (Tróia).

Figure 9
Severe erosive processes and white dune collapse, caused by sea advance, near Lagoa da Sancha (North coast of Sines).

Figure 10
Extensive gray dune in Armação de Pêra (Algarve). This relatively stabilized coastal does not show evident sea erosion (or coastal retreat).

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