COASTAL SAND DUNES AND BARRIER ISLANDS

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Summary

Coastal sand dunes develop along any coast where there is enough sediment supply that can be transported by the wind. Barrier islands are linear sandy elements aligned along the coast. Both ecosystems occur throughout the coasts of the world. Because they are found in all latitudes, with many different climates, the biomes developed on these topographic features are very diverse.

Coastal dunes and barrier islands are always changing in shape and location because of the wind action. Their complex and changing topography generates a high environmental heterogeneity. The flora and fauna found in coastal dunes and barrier islands are greatly affected by the substrate mobility, extremely high temperatures, drought, flooding, salinity and a scarcity of nutrients. They show morphological, physiological and behavioral responses to these limiting conditions. The vegetation is very diverse: lichens and bryophytes abound in Europe and the polar regions, while plants with seeds (especially palms) are more diverse in the tropics. Arthropods, mollusks, amphibians, reptiles, birds and mammals are the animal groups best represented. The biotic interactions between the organisms that live on these ecosystems range from positive to negative and a combination of both.

Coastal sand dunes and barrier islands act as a buffer against intense winds and waves; facilitate water catchment; and are heavily used in tourism. They are often severely degraded due to excessive exploitation, chaotic urban growth, trampling, invasion of species, sea level rise and climate change. The need for management and conservation policies that consider the natural dynamics of these systems is evident. Several strategies are described.

1. Introduction

Coastal sand dunes are eolian landforms that are developed along any coast where there is enough supply of loose sediments that can be transported by the wind (Figure 1). Barrier islands are normally linear sandy elements aligned along the coast. These unique ecosystems are widely distributed throughout the coasts of the world.

Figure 1. Coastal sand dunes found in the central region of the Gulf of Mexico

The term dune is used in many different languages. The English word is related to “down”. It is assumed that the Celts, who lived in the coastal area of Holland and Flanders were the first people to use the dunes intensively, and used the word *dûn*. The Romans met human settlements on the dunes in The Netherlands and used the word *dunum*, which led to the Italian, Spanish and Portuguese *duna*. Probably, the Celtic word reached the Germanic languages through the Greek äïýíïí (doúnon) and derived into German *Düne*, French *dune*, Swedish *dyn*, Norwegian and Danish *dyne* and modern Dutch *duin*.

The environmental factors that affect the flora and fauna on sand dunes and barrier islands are very similar, thus, many of the dominant plant species on sand dunes are also dominant on barrier islands. Because they are found in all latitudes, the climate, vegetation types and fauna of these systems are very diverse. In terms of biodiversity the wide variety of biomes adds to the ecological relevance of these communities.

Coastal sand dunes and barrier islands act as a buffer against intense winds and waves. They also protect landward communities and oftentimes facilitate the retention of the water table. On a worldwide basis, these coastal ecosystems have been severely degraded as a result of an excessive exploitation of natural resources, chaotic demographic expansion, industrial growth and tourism. Also, mineral and water extraction, trampling, invasive species, grass encroachment, sea level rise and climate change have had a deleterious impact. As a consequence, many dune systems are already irreversibly altered and lost. The need for management and conservation policies of dry coastal ecosystems such as dunes and barrier islands has become evident since the 1980s (and earlier in some countries), resulting in the implementation of different strategies and technologies throughout the world.

2. General features

2.1. Worldwide distribution

2.1.1. Sand dunes

Coastal sand dunes are found above the high water mark of sandy beaches and occur on ocean, lake and estuary shorelines, as well as river mouths. They are most common along coasts exposed to strong winds and with abundant sediment supply. They occur in any climatic zone, from the Arctic to the Equator, meaning they are distributed almost worldwide (Figure 2).

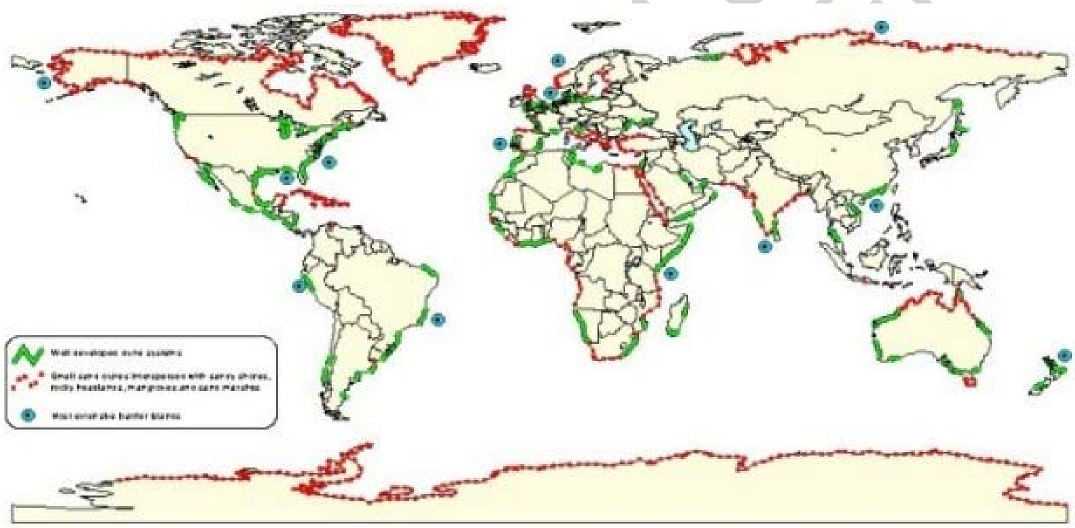

Figure 2. Distribution of coastal sand dunes and barrier islands of the world

Some examples of well developed dune systems in the world are found along the Great Lakes, the Pacific and Atlantic coasts of USA and Mexico, the Gulf of Mexico, central America, Brazil, Europe (Great Britain, Ireland, western France, southern Spain, Denmark, The Netherlands and Poland), the Mediterranean, southeastern Australia, South Africa and even Sri Lanka where nearly 300 km of low dune coasts have been described. In some places extensive coastal dune systems are lacking, but much of these coasts are comprised of long stretches of sandy shores interspersed with estuaries and rocky headlands.

2.1.2. Barrier islands

Barrier islands are elongated sandy islands aligned parallel to the coast, and separated from the mainland by a lagoon which is usually shallow. Barrier islands are found all over the world (Figure 2). They account for 10 to 15% of the world's total shorelines. Usually, barrier islands develop along coasts of low profile, with gentle offshore gradients, low to moderate tidal range and an abundant supply of sediment. Such islands are normally much longer than they are in width. Important chains of barrier islands can be found along Alaska, the Colombian Pacific coast, Ecuador, Peru, Brazil, Africa, The Netherlands, Germany, Denmark, Siberia, India, Sri Lanka, the southern coast of China, and Australia. The longest stretches, however, are located along the eastern and gulf coast of North America, where their total length reaches 4500 km.

3. Environmental characteristics

3.1. Geological origin, typology and topography

3.1.1. Sand dunes

Coastal dunes can be of many different ages. What it means is that the processes supporting the creation of coastal dunes were repeated many times . There can be episodes of dune development, dune stabilization, dune mobilization, and a repetition of the sequence several times.

Many coastal sand dunes first appeared in association with stable beaches. That is, when sediment supply was adequate along the margin of some water body that was not transgressing rapidly. There are geomorphologic features which are considered as coastal sand dunes in the geologic record from the early Tertiary period (65 million years ago), although some authors suggest that coastal dunes existed back in the Cambrian period (500 millions years ago). However, present-day coastal dune systems are confined to the geological time when the ocean level was at its present position to allow dunes to form, and sediment supply was sufficient. According to this, most present coastal dunes are relatively young because the shoreline system is relatively young. For example, most of the dunes in northern Europe, USA and Canada formed from shelf debris moved onshore as glaciers retreated and sea level stabilized during the Late Pleistocene and Early Holocene (ca. 10 000 years ago). The earliest dunes in the British Isles are around 5000 to 6000 years old, while the Dutch dunes date from about 4000 to 5000 years before present. A similar chronology has been suggested for the dunes in North America (e.g. Oregon). The Australians claim that the sea level around their continent has been stable for the last 5000 to 6000 years and that the oldest coastal landforms are of that age. The modern shoreline at the Gulf of Mexico is of the order of 3000 ± 500 years.

Sand dunes are highly variable in terms of their size, longevity and mobility. They range from small and ephemeral to massive and persistent sand accumulations. They may extend inland for up to 10 km although their width may also be only a few meters. In terms of substrate mobility, dunes may be considered as mobile, semi-mobile or stabilized. When they are mobile, they may be either gaining or losing sand. Semi-mobile dunes are partially covered by vegetation and the stabilized ones are totally covered. The more plant cover the dunes have, the less mobile becomes the substrate. Often, dune systems display a complex mosaic of stabilized and mobile dunes over relatively small areas.

When their position relative to the shoreline and stability are considered, the following typology has been provided: a) embracing or incipient foredunes (or primary or yellow or embryo dunes), which are closest to the sea, and relatively low; b) secondary (or gray) dunes, which are farther inland, may have different degrees of stability and may be higher; and c) a range of stabilized or mobile forms.

As dunes migrate inland, they assume different shapes, which are the result of depositional and accumulation processes: foredunes, blowouts, parabolic dunes, barchans and transgressive dunefields. Foredunes run parallel to the shore and are located at the landward edge of the beach. Blowouts are wind hollows or basins—a result of erosive processes. Blowouts are classified as either saucer (semi-circular) or troughs (elongate), depending on their shape. Parabolic dunes (also termed U-dunes), are roughly shaped like a parabola or a U, when viewed from above in a windward direction.

They have elongated trailing ridges that terminate downwind in U-shaped depositional lobes. Barchans are very similar to parabolic dunes. However, in this case the trailing ridges extend downwind. The windward and the leeward slopes of these two types of sand dunes are different. In parabolic dunes, the windward slope is less steep than the leeward slope, while the contrary occurs in barchans.

Finally, transgressive dunefields are large-scale sand deposits formed by the downwind movement, transgressing over vegetated or semi-vegetated terrain. They are also known as mobile dunes, sand drifts or migratory dunes. Such a moving substrate gives rise to a considerable variety of landforms. Usually, the upper part of the dune is termed the crest. The trailing ridges (or arms) are located on the sides of the crests.

Often, slacks, seasonal wetlands, ponds and occasionally inter-dune lagoons occur. Depending on their proximity to the water table, slack depressions may be classified as wet (when they become flooded after the water table rises) or dry (when flooding does not occur).

3.1.2. Barrier Islands

Barrier islands are also relatively new geomorphological features (rarely older than 6000 to 7000 years before present). Thus, there has been little time for soil development, species immigrations and evolutionary adjustments to the barrier island environment. The barrier islands along the coast of Eastern USA were formed during the Holocene, 5000 to 4000 years ago, and it has been suggested that the formation of most of the present day barrier islands in the Gulf coast of USA began between 5000 and 3500 years ago. Typically, barrier islands include a beach facing the ocean, a foredune, sometimes a secondary dune and on the landward side, a saltmarsh or a mangrove swamp.

3.2. Formation and movement

Dunes form from marine sand that is delivered to the beach by the nearshore waves. When this sand is exposed to the air and dries, it becomes vulnerable to aerodynamic processes. The critical factors in dune formation are sediment supply, grain size, windspeed at the sand surface, topography and surface roughness. There is a minimum threshold wind speed for sand transport which depends on the grain size. After reaching this threshold speed, the windblown sediments travel close to the ground as a result of saltation, during which individual grains move in a series of small jumps. Wind velocity near the surface increases up the windward slope and reaches its maximum value at the crest of the dune; then it decreases rapidly down the leeward slope (or slip face), which has an angle of about 31 to 33°.

According to this, erosion will usually be highest on the windward slope and the crest of the dune, while the crest and leeward face will be primarily a zone of sand deposition. As a result of such differential erosive-depositional processes, dunes may migrate downwind, while retaining their general shape. This only holds true while the wind regime and substrate availability remain relatively constant.

Another important factor affecting the movement of sand dunes is the presence of obstacles that will affect wind speed. Bare sand has a low surface roughness, and wind speeds slightly higher than the critical speed, will induce sand movement. Surfaces with either vegetation or other obstacles (e.g. tree trunks, fences, buildings) will reduce the wind speed thus inducing sand deposition and dune growth.

Some dune vegetation can keep pace with accreting surfaces, which means that plants can continue to grow through the rising depth of sand and thus, the dune grows and more of the sand becomes gradually stabilized. Depending on the presence and type of obstacles, mobile dunes move at different rates.

Parabolic dunes and transgressive dunefields migrate inland at rates depending on their morphology, size, slope, general terrain and the vegetation across which they are moving, and wind velocity and direction. In the North Island of New Zealand rates of dune migration can be as low as 1 to 2 m per year, when advancing over tall forest, 2 to 5 m year^{-1} over shrubs and, rarely, 100 to 200 m year^{-1} when migration occurs over short grasses and herbs.

A good example of this phenomenon occurs in the Doñana National Park, southwest Spain, where the large dunes migrate 5 to 6 m year^{-1} over a stable forested area, killing all but the largest trees. The dead tree trunks eventually emerge from the lee side of the migrating dunes, after 40 to 50 years of burial.

The formation of barrier islands is rather different. All barrier islands are formed in response to several factors: a rising sea level (not necessary), a large sand supply, a gently sloping coastal plain, sufficient energy to move the sand and a low tidal range (preferentially).

Many theories have been proposed to explain the formation of barrier islands. One theory suggests that barrier islands are formed by the upward building of offshore bars. According to this theory, the bars gradually grow, until eventually dunes develop on top of them. These dunes are stabilized by the vegetation, and then an island is formed (Figure 3).

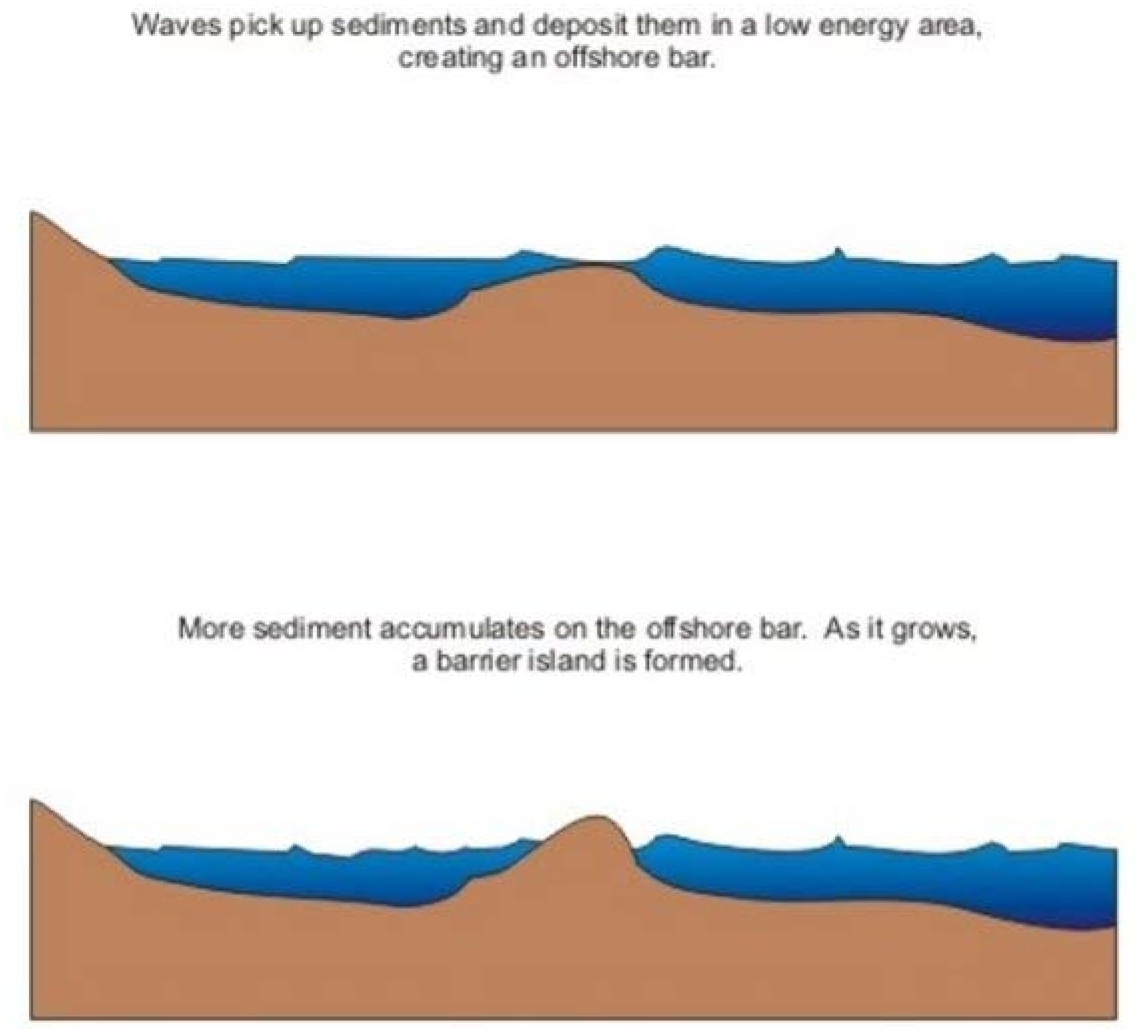

Figure 3. The formation of a barrier island

In barrier islands, wave overwash is mostly responsible for substrate mobility. When overwash occurs, sea water and suspended sediments are transported from the seaward face of the barrier island to the landward side, where salt marsh or mangrove swamps are usually found. Washover events after storms and hurricanes can move large volumes of sediments across the islands and can even transport whole barrier islands onto the marshes or mangroves. Thus, this process is very important as it maintains island morphology and moves barrier islands towards the main land through flooding and shoreline erosion. Barrier islands move landward (migrate) in response to the rising sea level. By migrating they avoid being drowned by the sea. In general, four events must occur in order for an island to migrate: 1) the front side (ocean) must move landward via shoreline retreat; 2) the back (sound) side must move landward and grow (island widening); 3) the island must continually build up in order to maintain its elevation above a rising sea level; 4) the mainland shore must retreat to keep pace with the island's migration. Each island changes in different ways and moves at different rates. For instance, in the lower coastal plain of North Carolina it has been calculated that for every 30 cm of sea level rise, the shoreline will have to retreat, theoretically, more than 50 m. This is a much faster rate of shoreline retreat than has been observed to date inland of barrier islands on this coast.

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Biographical Sketches

M. Luisa Martínez was born in Mexico city in 1963. She obtained her PhD degree in 1994 at the Universidad Nacional Autónoma de México (National Autonomous University of Mexico). Since 1995 she has been working as an associate researcher at the Instituto de Ecología, A.C., located in the city of Xalapa, the capital city of the state of Veracruz, Mexico. She has been studying the ecology of tropical coastal sand dunes in the central part of the Gulf of Mexico since 1986, when she was in her B.Sc. level studies in Biology. She has eighteen published studies on the germination of coastal sand dunes species, growth under limiting conditions, population and community dynamics during the early stages of primary succession in mobile dunes. Currently, she is working on the role of positive plant-plant interactions as a key process in the dynamics of communities developing on mobile dunes. She is also studying the genetic variability of the specific tolerance of plants to burial by sand. She participates in a restoration project in the dunes located in the Port of Veracruz, Mexico.

M. Luisa has national and international collaboration with researchers performing studies in different coasts, such as Baja California (Mexico), the Gulf of Mexico, USA, Canada, Spain, The Netherlands, and New Zealand. To different degrees of interaction, she has joint projects with national and international colleagues. This wide interaction has allowed her to become the senior editor of an international collaboration which will result in the publication of the first book where tropical and temperate sand dunes will be covered.

M. Luisa has been continuously teaching different courses in Ecology since 1989 (undergraduate level) and since 1995 at a graduate level.

Gabriela Vázquez was born in Mexico city in 1958. She obtained her PhD degree in 1994 at the Instituto Politécnico Nacional (National Polytechnic Institute). Since 1990 she works as an associate researcher at the Instituto de Ecología, A.C., located in the city of Xalapa, the capital city of the state of Veracruz, Mexico. She has been studying the ecology of freshwater aquatic ecosystems in the tropics. Among them, slacks have been her main interest since 1990. Some of the research areas in slack communities include the role of algae in the germination and establishment of phanerogams during the early stages of succession. She has also studied vegetation dynamics in response to different disturbance regimes caused by water table fluctuations in the interdune slacks. She is also studying the algae community in inundated slacks. She has participated in several projects where the conservation status of freshwater systems has been evaluated.

Gabriela also has national and international collaboration with researchers performing studies in different freshwater aquatic systems, such as Queretaro (México), Argentina, Spain and France. To different degrees of interaction, she has joint projects with national and international colleagues.

Gabriela has been continuously teaching different courses in Ecology since 1981 (undergraduate level) and since 1985 at a graduate level.