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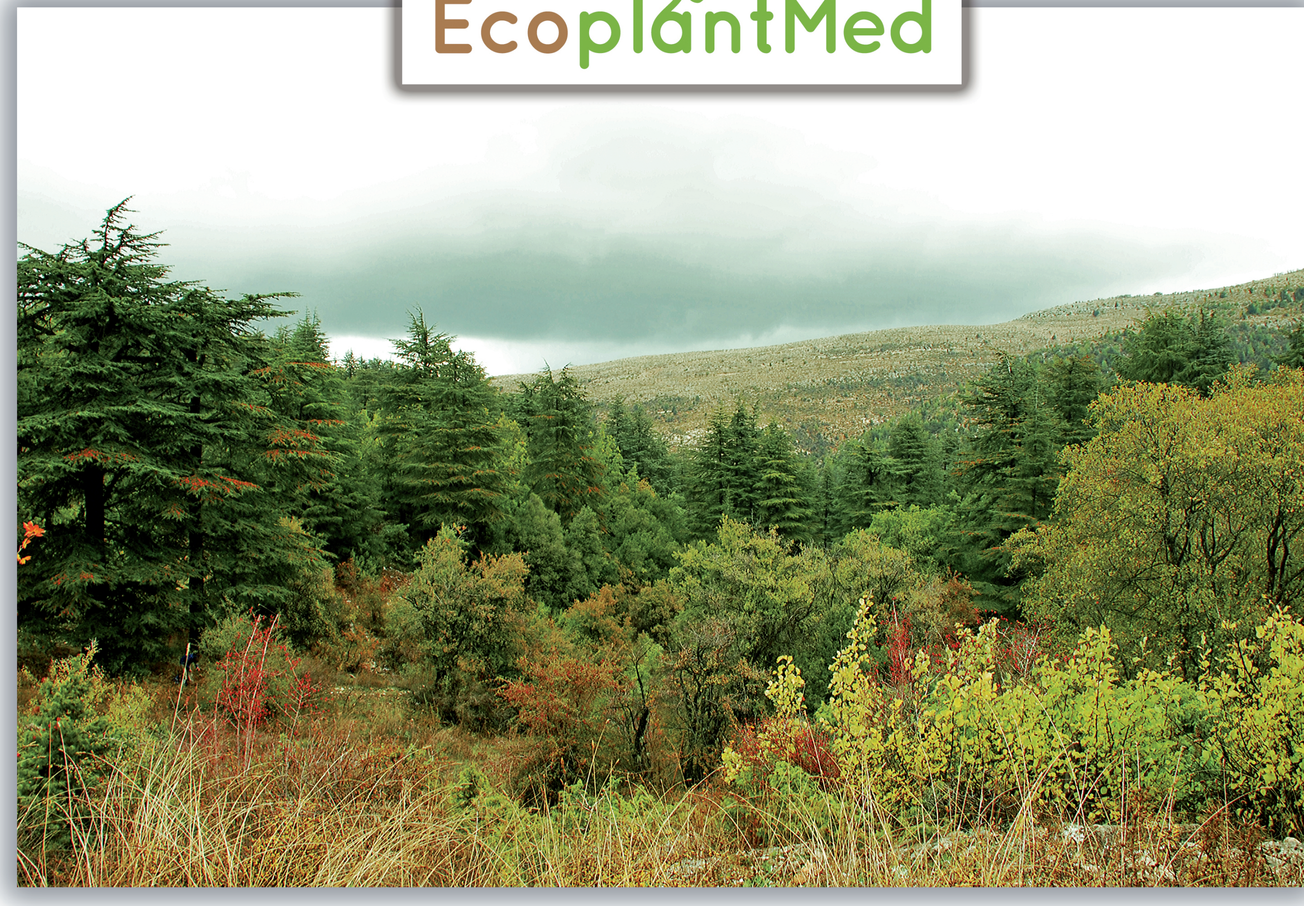

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Mimicking natural processes on urban dunes

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Abstract
Dunes are not only shelters for threatened biodiversity and beautiful landscapes, but an important part of the global sand budget of beaches. Coastal dunes thus constitute a nature-based solution to sea level risk. This is even more important in an urban context where coastal regression leads to coastal squeeze (Pontee, 2013). There is also a need to preserve the dynamic component of dune ecosystems in order to avoid biodiversity loss (Heslenfeld *et al*., 2004) and maintain sustained dune volume growth. In urban landscapes the natural processes of dune creation are impaired, and ruderal and invasive plants exercise higher pressure on the system. This paper discusses different experiences of dune construction and management on the metropolitan beaches of Barcelona, and proposes new strategies to transform the management of urban dunes into a core component of a global beach management strategy to create resilient beaches.

Key words: *Ammophila arenaria* decay, ecosystem services, nature based solution, sea level rise, urban dunes.

Introduction

The hybrid dune project

The metropolitan beaches of the Llobregat delta comprise over 14 km of shore length, and constitute the most visited landscape in the metropolitan area of Barcelona, with maximum summer densities of 500 sun-bathers on one 100 m stretch of beach. During winter, especially where there are constructed maritime promenades, the cultural use of beaches remains intense.

The "Hybrid dunes" project is a case study of the EU FP7 funded OPERAs project, with the aim of studying how the ecosystem services concept can provide new management approaches at the interface between management, economy and ecological processes. The Metropolitan Administration of Barcelona (AMB) has funded dune construction research. The Demarcación de Costas en Catalunya, Ministerio de Agricultura, Alimentación y Medio Ambiente (hereafter MAGRAMA) has also conducted different dune construction works and backshore profile restoration projects.

Beach morphodynamic context

The beaches of the metropolitan area of Barcelona on the Llobregat delta are undergoing regression processes due to the lack of sediment input from the river, and the disruption of the natural longshore sand transport processes after the construction, in 2004, of a new port breakwater which extends 1.8 km into the sea. The low topography of the delta creates a higher vulnerability due to the sea level rise linked to climatic change. This poses significant threats to the local economy and the provision of cultural ecosystem services.

The only formal strategy applied until now has been beach nourishment, consisting of the annual dredging of approximately 100,000 m^3 from the seabed (4-10 m depth) at the south-west end of the delta, and the subsequent discharge of this volume to the beach-face close to the river mouth at a similar depth. Recent studies (Instituto de Hidrologia Ambiental de la Universidad de Cantabria, 2015) show that this beach nourishment strategy is not delivering the desired results.

The "urban" factor in the dune ecosystem

Most of the beaches on the European Mediterranean coast are greatly frequented by humans extending beach use beyond summertime. The motivation of most restorations projects are thus the disappearance of dunes due to housing, deliberate flattening and trampling.

The beaches of the Llobregat delta have endured similar processes of habitat loss, but two different processes have led to a new configuration, where natural dune construction might be possible:

– Updrift accretion triggered by the groin of Port Ginesta (southwest end).

– Coastline flipping towards a new equilibrium state, thus limiting the erosion capacity of the longshore currents at the previously more protruding stretches of the deltaic front.

The analysis of photographs from cartographic flights in 1945 show that the transverse dunes of Castelldefels were formed under a wind fetch of 70 meters, a distance that is currently met at several parts of the west half of the beach. The seasonal overlap of conditions favourable to natural dune construction (dry sand and winds with the needed azimuth and strength), however, with the increasingly extended bathing season, has

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impaired the natural construction of dunes. Wind is no longer able to construct dunes through natural aeolian sand transport.

Another "urban" issue is the increasing frequentation of the beach by pets, with an estimated dog population of 6,000 dogs living less than 1 km from the beach.

The average dog delivers 0.3 kg of solid excrements and 0.75 litres of urine daily, and so the constant input of nutrients profoundly alters an ecosystem typically described as oligotrophic. This nutrient input is probably one of the factors leading to rapid dune stabilisation by vegetation, and thus leading to the loss of the biodiversity linked to mobile dunes, and the promotion of ruderal and alien-invasive species.

The dune stabilisation processes and the degeneration and disappearance of *Ammophila arenaria*, are a common fate of the greater part of dune restoration projects. The degeneration and disappearance of *Ammophila arenaria* (marram grass) when the inflow of sand deposition stops, and when vegetation cover increases, exposing their root system to soil pathogens, is classic negative soil feedback, as described by van der Putten (1998, 2013).

Previous references on dune construction and management

Most dune construction notes the relevant aim (if not the most important) as the stabilisation of the dune system (MMAMM, 2008; Ley *et al*., 2012; Hanley *et al*., 2014; Marzo *et al*., 2015).

The obvious risk of dune erosion after artificial dune construction has led systematically to the use of different strategies to fix the sand (MMAMM, 2008).

There is a striking lack of references to the disappearance of *Ammophila arenaria* and the subsequent loss of biodiversity linked to mobile and semi-mobile dunes. There are no precedents of projects with the stated aim of creating and maintaining mobile or semi-mobile dunes. There is an increasing scientific literature citing dune rejuvenation projects (Arens *et al*., 2006), mainly acting to create new blowouts, control afforestation processes, and restore dune dynamics and sand movement.

Aims and goals of urban dune construction

The aim of the project is to search for dune construction and management strategies to sustain mobile and semi-mobile dunes and accomplish the following further objectives:

– Promote and preserve the biodiversity linked to mobile dunes.

– Let the dune system act as a core component of the emerged sand management scheme in order to protect the coastal system ahead of the risks posed by climatic change (increased storm event intensity and flood risk linked to sea level rise).

Materials and methods

This paper presents the results of different blow-out excavation and dune construction projects undertaken along a 9 km stretch of metropolitan beaches, which was undertaken by the AMB and the MAGRAMA between June 2014 and December 2015.

A visual and photographic survey was also undertaken, of the different dune construction projects conducted by the metropolitan administration of Barcelona in 1992 (directed by myself) and in later projects (1998, 2009, 2015) spanning over 10 km of beach.

The Institut Cartogràfic i Geològic de Catalunya (ICGC) provided flights and orthoimages in different years and at different resolutions:

– 1:5,000: 1994, 2000, 2004, 2006, 2008, 2009.

– 1:2,500: 2009, 2010, 2011, 2012, 2013.

– 1:1,000: 2014, 2015, 2016.

The only species introduced was *Ammophila arenaria*, in containers of 200 cc. It was the only introduced species because the seed and propagule bank is quite rich in species such as *Eryngium maritimum*, *Echinophora spinosa*, *Calystegia soldanella*, and *Pancratium maritimum*.

Results

Beach width

Beach width was a strong controlling factor in dune construction for two reasons. Firstly it controls the available sediment and the extent of overwash frequency (thus affecting the long term persistence of the dunes); and secondly, it determines the comfort width strip, defined as the required width of beach to keep the maximum sun-bathers affluence with a good comfort perception (5 m^2/person), or at minimum, an acceptable perception (4 m^2/person).

As the highest measured density of sunbathers is 50 for each 10 m of beach stretch, the required backshore width would be 20 m. This is the reason one of the groups of dunes constructed in 2014 on a beach narrowed by a summer storm was occupied by sunbathers and consequently fattened by trampling.

Blowouts

The only blowouts that kept without vegetation were over 150 m^2 in surface area and 12 m minimum diameter. Smaller ones, and those where only 20 cm of topsoil was excavated, presented vegetation colonisation, mainly from invasive and ruderal species (*Ambrosia coronopifolia* Torr. et A. Gray and *Xanthium echinatum* subsp. *italicum*, *Salsola kali*).

Source of sand and its relationship to the fate of dunes

All the dunes constructed with sand from the blowout excavation were rapidly covered by vegetation, mostly by *Xantium italicum* and *Salsola kali*. Grain size was also a relevant factor in relation to aeolian sand transport. As most sand transport occurs in saltation, dunes are dependent on this mode of aeolian sand transport. Saltation occurs with grain diameters between 70 and 500 μm (Nickling & McKenna Neuman, 2009). Bigger diameters need a much faster threshold speed. This is why an attempt to construct dunes at the Besòs mouth failed, as this beach was a typical coarse-sand reflective type.

Grain size can be a control factor as a result of its ability to be transported by wind, but also as an indirect controller of beach width. Coarse sand-reflective beaches (Wright & Short, 1984) have narrower beaches than dissipative ones, characterised by finer sand and lower slopes. The same is true for intermediate forms, which is the case in the eastern half of the Llobregat delta.

Grain diameters under 200 μm are easily eroded by low velocity winds and tend to retain more nutrients, thus accelerating dune fixation, so the ideal grain size is a range between 200 and 500 μm.

Ammophila arenaria persistence

An area planted in 2009, mostly with *Ammophila arenaria* as a monoculture, has evolved to a nearly monospecific grassland of Lotus creticus (which was planted to a lesser extent). The last remaining *A. arenaria* are decaying, with their tussocks invaded by *Lotus creticus*. In areas where species like *Lotus creticus* and *Medicago marina* have been introduced, there is a trend to displace *Ammophila* and form nearly mono specific stands. Most of the dune plantations in 2009 resulted in fixed dunes with a dense cover of vegetation, and most of the *A. arenaria* and *Elymus farctus*, has disappeared or is in the last stage of decay (Fig. 1).

The only marram grass remaining in good condition were those placed on the outer limits of the plantations and receiving sand input from a cleared area by a playground with a wind fetch length over 140 metres. Wind fetch lengths twice those that generated transversal dunes in the same area as seen on the 1947 flight, can today still construct dunes, and suggest that aeolian sand transport is not completely impaired.

Constructed dune erosion and marram grass uprooting

There is compression of flow where the onshore winds encounter the dune (Parsons *et al*., 2014). Where the slope is steep, acceleration at the dune crest may duplicate the velocity of the flow, but the effect is reduced as the angle of wind becomes more oblique and the apparent slope decreases. The interaction of the angle of onshore winds and the apparent slope are the most relevant biophysical factors controlling erosion risk in constructed dunes. The role of vegetation depends on its development and coverage, and marram grass usually needs at least one growing season after plantation to start fixing sand. This is why most of the first plantations of *Ammophila arenaria* were uprooted, even though they were planted 25 cm deeper than the forest pot upper limit (Fig. 2).

The extent of the dune erosion problem clearly showed that it can be easily mapped, and that the vulnerable areas were a function of the apparent slope, determined by wind direction and topography (Fig. 3).

The azimuth was determined by assessing the orthogonal wind over 23 transverse dunes over the historic photographic 1945-47 flights and by GPS determination of 30 downwind deposition lines on poles and plants (nebkas) in fieldwork. The average azimuth was of 238º (Fig. 4).

Fig. 1 - Previous plantations of *Ammophila arenaria* have led to rapid dune fixation, loss of relief; and in a 6-10 year period, most decay and disappear. In this photograph decaying marram grass can be seen in the first term.

Fig. 2 - Three different stages of uprooting. 1: near the toe of the upwind slope wind flow is not accelerated. 2: On an upper level of the windward slope the plant has been partially uprooted. The exposure of the root system will lead rapidly to hydric stress and the death of the plant. 3: At the dune crest the erosion potential is highest and plants lay completely uprooted. In this area a layer of more than 50 cm of sand has been completely eroded.

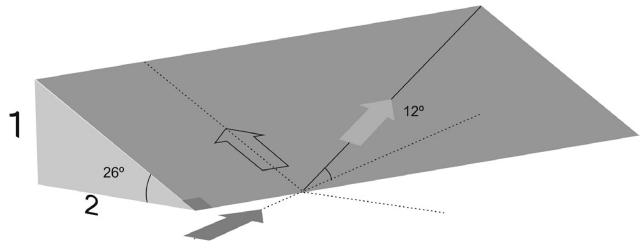

Fig. 3 - The apparent slope controls the shear stress and velocity of wind. In this example, on an upwind slope of 2H:1V or 27º, a flow at an oblique angle of 27º is only half the steep of the real slope.

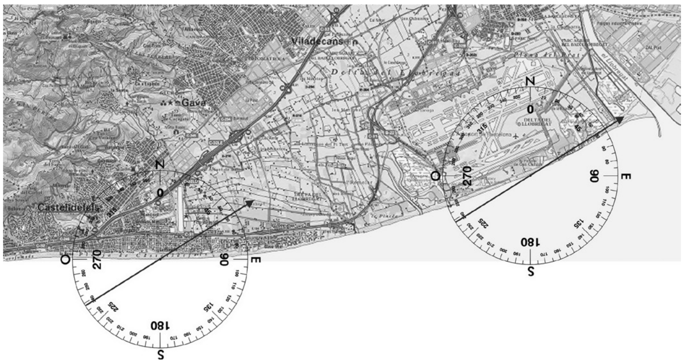

Fig. 4 - The geometry of deltaic beaches makes a big difference with the same wind direction. The biggest erosion problems were located at the west half of the area.

Winds approaching at oblique angles tend to be deflected to the foredune crest and high oblique winds tend to be deflected parallel or at much lower apparent angles. The varying geometry of the deltaic beach makes different angles in relation with the same wind, thus producing differences in the erosion potential. Where the angle is over 30º the aerial photographs of 1945 show transverse dunes, and where the beach was nearly parallel to the wind, there were only small longitudinal dunes. In relation to erosion risk, the most affected areas were those located at the western half of the delta, where the angle of the onshore wind was greater than 20º.

A successful strategy

On October 2014 marram grass was planted over the unaltered beach profile in areas corresponding to potential incipient dunes. Those plants showed a better response due to the lack of wind erosion and the access to sand humidity. Seven months after planting, an experiment of artificial sand accretion was undertaken just when the plant had achieved threshold development. This experiment consisted of the placement of sand mounts of 80 cm height windward and, to a lesser extent, also downwind. At the end of the storm winter session, the plant started to form a naturally shaped dune, 15 months after planting (Figs. 5, 8).

Other sand mounds placed windward of constructed dunes which were not eroded and maintained marram grass (15 months old) close to the top also resulted in the mimicking of healthy natural aeolian sand transport, thus creating dynamic dunes of much better visual quality.

Sand fences and wind direction

The Demarcacion de Costas en Barcelona (MAGRAMA) conducted two different experiments in dune construction with sand fences. Those experiments resulted in generalised failure where the fences were not placed perpendicularly to the most prevalent wind on sand construction and erosion (238º azimuth), thus showing that both canework and wicker sand fences are only useful when placed orthogonally to wind direction (Figs. 6, 7, 8).

Discussion

As the main goal of this project was to create mobile and semi-mobile dunes with a significative volume

Fig. 5 - Ten months between the two photographs.
1: This marram grass was planted on October 12th 2014. At the time of the photo (8-5-2015) the plant was old enough to obtain a sufficient size to fix moving sand and withstand sand burial. The photo shows just the first sand mound windward. Another mound of sand was deposited downwind just after the photo.
2: the same plant photographed 10 months later (4 3-2016) but from the opposite direction. It looks like a natural dune.

Fig. 6 - Reed sand fences create accretion zones upwind, and shadow areas of sand deposition downwind, but this rule only works when the orientation of the sand fence is properly located perpendicular to the prevailing wind. Taller sand fences are more visually intrusive and their effectiveness is restricted to the narrow upwind strip and the "shadow" area which width is no longer than 3 or 4 times the height of the fence.

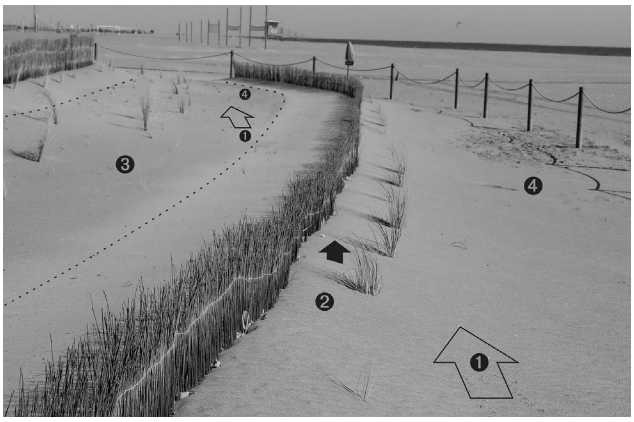

Fig. 7 - Tall sand fences are not very effective when nearly parallel to wind direction. In this image wind direction (1) marks the upwind accretion strip (2) and the narrow downwind zone. From 3 to 4 times the fence height, a new erosion area appeared (3) with uprooted plants (4) where wind had a higher velocity.

and height (around 2 metres at the upper crests), there is a need to maintain the marram grass population. To achieve this goal it is necessary to maintain a permanent sand inflow (only possible by artificial means), but also to avoid the negative plant-soil feedback linked to soil pathogens.

The pre-existing spatial distribution of dunes shows a strong dependence on the onshore prevailing wind direction and the length of the path of those winds over dry sand, but as the "hybrid dune" concept consists of imitating a natural process, there is the possibility of constructing dunes in places where there were previously only incipient foredunes, but always following a minimum set of rules.

To construct dunes in order to keep and increase the emerged sand volume in a perdurable way, it is necessary to disentangle the complex relationships between marram grass (*Ammophila arenaria*) aeolian sediment transport, and the negative feedback processes linked to dune stabilisation.

Sand fences create localised accretion on the upwind slope, and also downwind, in the place where wind velocity decreases and creates wind shadow areas, thus increasing topographic variability. It is therefore more effective to place them in specifically designed locations, and not occupying extensive areas, in order to avoid visual impact and undesired dune fixation.

Dunes constructed by the sand excavated from blowouts should be covered by a outer layer of clean sand of at least 30 cm thick.

A new method of dune construction is described, consisting of planting first and, after letting the marram grass reach a threshold development, creating mounds of sand that could function as aeolian sand providers. This method is extremely cheap: 0.45 € each plant, and 40 € for the cost of creating a 100 m length of 80 cm high sand mounds with a common backhoe loader.

The most evident research needs and questions are:

– Is it possible to prevent marram grass decay over a longer term?

– What is the upper limit of the dune construction? Can an ideal stage be achieved which should later be maintained to keep its topography?

– Until what level is needed to extract other psammophilic species to prevent marram grass decay?

– Can different dune types be designed in order to improve biodiversity?

– As this is an adaptive process, what will be the future control factors be?

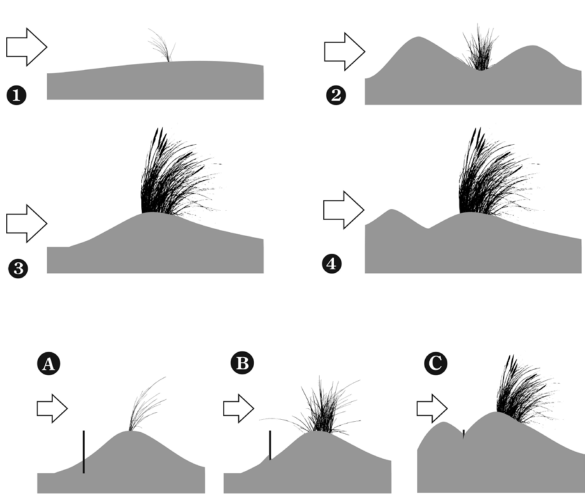

Fig. 8 - Two different methods of dune construction but with no end point. From 1 to 4 the "first marram grass plantation strategy" but followed by a yearly construction of sand mound windward of the plant. The second strategy "dune and marram grass plantation at once" also needs an artificial sand inflow on a yearly basis.

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