# Conservation approach of a front dune system through the study of its blowouts (Cala Agulla, Mallorca)

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Most of the beach-dune systems in the western Mediterranean today show an important state of fragmentation with obvious signs of erosion, largely because of blowouts on the dune front. Blowouts were studied in the dune front of the Cala Agulla beach-dune system (Mallorca, Spain) in order to better understand and quantify the backward dune movement over the last decades. A spatiotemporal analysis taking into account the boundary drawn by the vegetation along the first line of dunes was carried out. The analysis was performed using GIS software ArcView, applying DSAS extension 2.0 (*Digital Shoreline Analysis System*). Fourteen blowouts located along a front about 600 m long were studied. For each blowout, some ecological and morphometric variables were analyzed in order to establish the relationship between the different types of blowouts. To this end, it was applied an index $R_{t\text{-}v}$ to link each morphology with the patterns shown by the existing vegetation, both herbaceous and woody. Applying the iTx index represents the link between each typology and its inner topography. The results show integral recoil of the dune front over the last decades – the average recoil ranges from 10-20 m, although in some places exceed 20 m –. However, from 2008 to 2010 some advances were recorded, except at the sites that coincided with the main entrances to the beach, which suggests a direct relationship between maximum erosion and the places with highest attendance. Blowouts were divided into 5 categories, trough blowouts being the most prevalent (50% of samples). Each type showed distinct morphometric features and had a different relationship with the vegetal species.

***Key words:*** *Blowout; Sandy coast; Beach-dune system; Erosion; Fragmentation; Mallorca.*

APROXIMACIÓ A LA CONSERVACIÓ D'UN SISTEMA DUNAR A TRAVÉS DELS SEUS BLOWOUTS (CALA AGULLA, MALLORCA). Gran part dels sistemes platja-duna a la mediterrània occidental mostren avui dia un important estat de fragmentació amb signes palpables d'erosió, principalment a causa de l'existència de blowouts al llarg dels fronts dunars. S'estudien els blowouts existents al front de dunes del sistema de Cala Agulla (Mallorca, Espanya) amb l'objectiu de conèixer i quantificar el retrocés del sistema al llarg de les darreres dècades. Per això s'ha realitzat una anàlisi espacio-temporal prenent com a línia de referència la marcada per la presència de vegetació herbàcia. L'anàlisi s'ha dut a terme a partir de la utilització del sistema d'informació geogràfica ArcView, i amb l'aplicació de l'eina DSAS *(Digital Shoreline Analysis System).* Un total de 14 blowouts localitzats al llarg d'un front dunar de 600 m han estat estudiats. Per a cada un dels blowouts algunes variables geomorfològiques i ecològiques han estat analitzades en tant a poder establir una relació entre els distints tipus de blowouts. Amb aquest fi, s'aplica l'índex Rt-v per tal de relacionar cada morfologia amb els patrons mostrats per la vegetació existent, tant herbàcia com arbustiva. D'altra banda, l'aplicació de l'índex iTx representa la relació existent entre cada tipologia i els seus perfils topogràfics interns. Els resultats obtinguts mostren un retrocés integral del front de dunes al llarg de les darreres dècades – el retrocés mitjà oscil·la entre els 10-20 m, tot i que en alguns llocs aquest excedeix els 20 m –. No obstant, de 2008 a 2010 es perceben alguns punts d'avançament, sempre excepte els indrets que coincideixen amb les entrades principals a la platja, la qual cosa suggereix una relació directe entre els màxims d'erosió i els llocs amb major influència d'usuaris. Els blowouts han estat dividits en 5 categories, sent els trough blowouts els que més importància tenen (50% de la mostra). Cada una de les tipologies mostra característiques morfomètriques diferents, i distinta relació amb les espècies vegetals inventariades.

***Paraules clau***: *Blowout; costa arenosa; sistema platja-duna; erosió; fragmentació; Mallorca.*

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## Introduction

Sandy coastal systems are characterized by their high dynamism and fragility. Any change to it can have potential adverse effects on their stability. Over the last decades, in places such as Balearic Islands (Spain), these environments have been heavily exploited for recreation with management practices that do no have enough consideration of protective and aesthetic values. As a result, erosion has increased – mainly in the foredunes – and upset the sedimentary balance of the beach-dune system (Roig-Munar *et al.*, 2012). Current literature often links erosion processes with the human pressure and poor management policies. Roig-Munar (2004) showed erosion rates could derive from the beach mechanical cleaning, while Roig-Munar *et al.* (2006) accounted the sedimentary losses through users attendance in some beaches of Menorca (Balearic Islands). Other authors such as Martín-Prieto *et al.* (2010) and Roig-Munar *et al.* (2012) concluded that the coastline recoil in some beach-dune systems of Balearic Islands is also related to anthropogenic pressure. Nevertheless, more recently Hesp and Walker (2012) and Smyth *et al.* (2012) suggest that erosion processes can be also related to natural and physical issues. This means, for example, the interaction between wind incidence and the presence of blowouts morphologies along the dune front, which enhances sand erosion from the emerged beach to landward. This is why Mir-Gual (2014) concludes that the presence of blowouts can increase the erosion patterns existing on the beach.

The theoretical knowledge of blowouts is scant (Cooper, 1958; Hesp, 1996, 2002; Hesp and Hyde, 1996; Bate and Ferguson, 1996; Davis and Fitzerald, 2004; Hugenholtz and Wolfe, 2009; Mir-Gual and Pons, 2011; Smyth *et al.*, 2011; González-Villanueva *et al.*, 2011) compared with that of other topics concerning the beach-dune systems.A blowout is a saucer or trough shaped depression or hollow formed by wind erosion on a preexisting sand deposit (Cooper, 1958; Hesp, 2002). However, some authors contend that the adjoining accumulation of sand, the depositional lobe, should be normally considered part of the blowout (Glenn, 1979; Carter *et al.,* 1990; Hesp, 2002). The formation of blowouts can be due to a variety of factors, with a genesis that is either natural or anthropogenic. Once initiated, the morphology will depend on its original size (Borichansky and Mikhailov, 1966), the height, length, type and location of the dune, on whether it is coastal or continental (Gutiérrez-Elorza *et al.,* 2005), the cover rate and the vegetation type (Esler, 1970), the magnitude, direction and strength of local winds, the degree and angle of exposure of the dune front to the main wind (Jennings, 1957), the strength and recurrence of the wave storms above the emerged beach and foredune strip, the local topography conditions, or the erosion caused by surface runoff (Hesp, 2002). Finally, Mir-Gual (2014) conclude that the conservation state of the foredune strip can affect to the blowout formation along the dune front. Nevertheless, in addition to natural factors, the creation and intensification of these erosive forms are often attributed to high attendance by users (Bate and Ferguson, 1996; Hesp, 2002).

Given the large number of factors that support the formation and intensification of blowouts, their shape can be highly variable over time. Thus, in the literature some classifications have been made in terms of the form adopted. Although some authors such as Smith (1960) or Ritchie (1972) define four different types of blowouts, it seems that simpler classifications such as the one by Cooper (1958), and supported by Hesp (1996; 2002), have had more success, differentiating only between trough blowout and saucer blowout. Saucer blowouts adopt a semicircular shape and commonly occur in flat areas without adjacent steep topography, whilst trough blowouts usually adopt elongated shapes, forming deep deflation corridors, intensifying the erosion on its side walls and sediment accumulation landward, forming at the same time depositional lobes of sand.

The formation and evolution of the blowout takes place in an environmental regime characterized by an erosive tendency on the dune front, where the impact of wind is higher, forming depositional lobes which can sometimes simulate the formation of a new dune.The deflation of sediment within the blowout can act as a fresh of sand to inland dunes (van Boxel *et al.,* 1997). This can often enhance sedimentary dynamism of the whole dune complex, supposing changes in its morphological and ecological features.

The presence of blowouts, due to their topographical shape, has a direct relationship with the patterns of airflow incidence on the dune field, as well as with patterns of sand transport from the upper beach to inland. In this way Mir-Gual (2014) concludes that the topographic conditions and evolution of blowouts, normally perpendicular to the dune front orientation, aids the presence of corridors that help to increase the sediment transport from the emerged beach to the innermost of the dune complex. These corridors suppose the wind flow channeling along the deflation basin increasing its speed and its power of sand transport. In addition to the aeolian trend, other key factors also play a part in these places. One of the most important is vegetation, which has a very important role in fixing and stabilizing the sand through the growth and development of roots (Pethick, 2001). The removal of vegetation cover will increase the vulnerability of the sedimentary mass as a result of sustained wind pressure, increasing exponentially their vulnerability to erosion and fragmentation of the dune front. Additionally, the herbaceous vegetation along the first line of the dunes is closely related to its state of conservation (Mir-Gual *et al.*, 2011). This type of vegetation is essential for sediment retention and capture. Some species such as *Ammophila arenaria* are remarkably efficient and optimal, and owing to their internal structure are able to interfere with the dynamics of sediment transport between the emerged beach and dune system, causing a deposition of sand and the formation of sandy embryonic structures, shadow dunes or echo dunes (Pethick, 2001; Hilton and Konlechner, 2011).

The fragmentation state of the coastal dune fields in Balearic Islands is highly related with the presence of blowouts along the first line. Otherwise, their conservation depends of the existence of a well developed foredune (Mir-Gual, 2014). The high rate of blowouts recurrence increase the fragmentation of this environ-ments, as well as enhances the sand erosion from the emerged beach to inland. In this context, a number of issues must be considered: (1) the density of erosional forms along the dune front, (2) the characterization of blowouts, and (3) the influence of blowouts in sediment erosion.

Works such as Roig-Munar *et al.* (2012) involve beach-dune erosion with a lack of management policies, as well as with users attendance. However, some space-time analysis carried out by Mir-Gual (2014) over some coastal dune fields induce to consider that the lack of foredune strip and

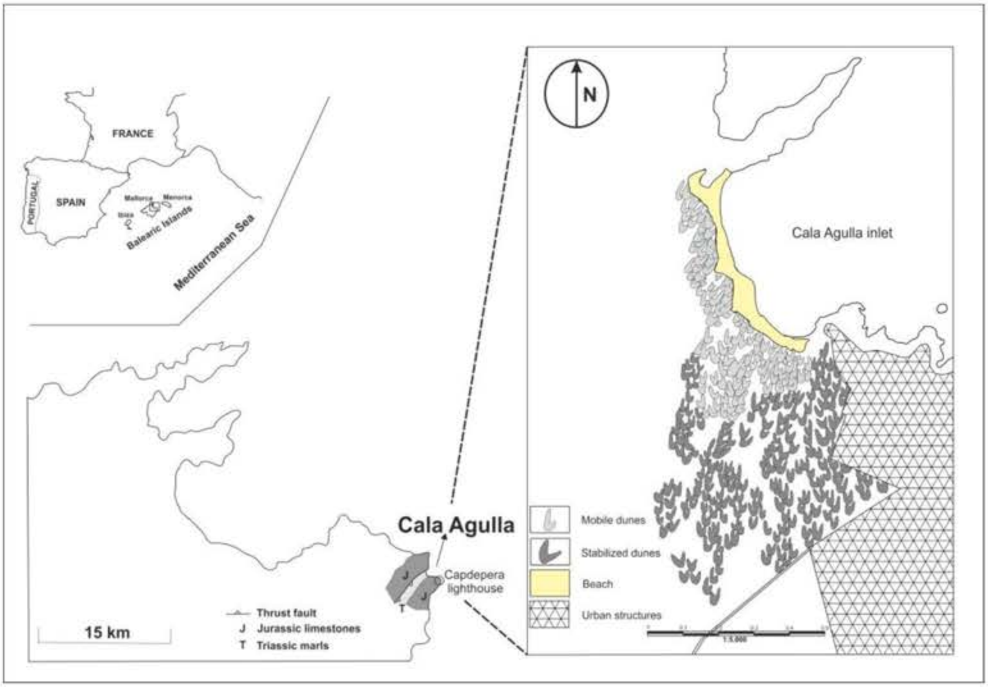

**Fig. 1.** Location and geomorphological sketch map of the Cala Agulla beach-dune system (Majorca).
***Fig. 1.*** *Localització i esquema geomorfològic del sistema platja-duna de Cala Agulla (Mallorca).*

the presence of blowouts can play an important role for explaining the erosion processes in these environments. This paper seeks to show how an optimum conservation of the dune front has an important role among the equilibrium of the whole system. With this, it aims to establish the physical characterization of the blowouts existing on the dune front of Cala Agulla dune system (Mallorca, Balearic Islands) (Fig. 1), and try to show how the dune front degradation enhances the beach erosion and the dune field recoil over the time.

## Study area characterization

### *Geological settings and dune system features.*

The Cala Agulla beach-dune system is located on the eastern coast of the island of Mallorca (Balearic Islands, Spain) (location in Fig. 1). The area presents a semi-arid climate, with a mean annual precipitation of 600mm. The tidal regime is microtidal with a spring range of < 0.25. Wave period ranges from 4-7 s. Wave exceeding 3 m in height and lasting longer than 10 s only occur for 3% of the year, with considerable differences between summer and winter (Basterretxea *et al.,* 2007; Servera *et al.,* 2009). According to the Capdepera's lighthouse (Fig. 1) the northern winds prevail (41% of the days), whilst the northeast winds also play a role in the behaviour of the dune complex because the inlet opens to NE.

The system has a surface of 1.7 km$^2$, of which 0.53 km$^2$ corresponds to Holocene dune formations (Servera, 1997; 2002). The system is made up of a beach stretch of 600 m in length and a fixed dune system landward (Fig. 1). The dune cordons are parallel to the coastline that feeds them. Structurally, the Cala Agulla system is on the thrust and fold structures of the Llevant Ranges. The small bay develops on Triassic marls, surrounded by coastal headlands consisting of Jurassic limestones. Thus, the development of dune morphologies is primarily controlled by the structural arrangement of the adjacent terrain.

The beach occupies a land area of approximately 0.024 km$^2$, with a width between 25 and 40 m (Servera, 1997). The beach surface in the northern part is higher because it coincides with the mouth of the torrent. Nowadays it is not possible to describe the strip of foredunes because it has disappeared as a result of human activity over the last decades. However, it is possible to find some embryonic sandy formations that are normally associated with the presence of psammophyte vegetation at the front of the blowouts. Mobile dunes occupy an area between 100-300 m wide, covering a surface of 0.11 km$^2$ arranged parallel to the coastline. The strip of the mobile dunes is also subjected to the influence of blowouts which grow from the first line landward, generating erosion effects on the semi stabilized dune sector. Most of the stabilized dune sector has been destroyed because of urbanization and the growth of adjacent agricultural fields. Currently the dunes are fully stabilized by a forest of *Pinus halepensis* and are not actively engaged in the sedimentary regime of the beach-dune system.

## Material and methods

Blowouts were identified and analysed through fieldwork and lab analysis. Aerial photographs were also used to find the orientations of each of the morphologies identified. For this purpose, each orienttation was traced using an angle protractor to obtain its directionality. Finally orienttations were obtained using the software OpenRose 0.01.

The morphological classification of blowouts was made through the analysis of aerial photographs using stereoscope along 52 years, from 1956 to 2008 (scale 1:18,000 approximately), and through field work, considering as a reference the definitions established by Cooper (1958) and Hesp (1996). Each blowout was located and referenced by GPS HD. The classi-fication of different typologies was made taking into account the current form and structure adopted by each blowout using the aerial photographs of 2010.

The internal topographic profiles of the blowouts were made by a beach profiler (pantometer) of 1.5 m x 1.5 m and 0.5 m x 0.5 m, respectively (Fig. 2) in order to draw two-dimensional profiles with axis of length (x) and height (y), in accordance with the method of Emery (1961), Delgado and Loid (2004), Puleo *et al.* (2008) and Mir-Gual (2013).

For each of the sampling points, a longitudinal profile and three cross-sectional topographic surveys were made at the mouth of the blowout (T1), in the middle (T2), and in the innermost part of the blowout (T3) (Fig. 2).

In order to verify the first morphometric classification made by analysing the aerial photographs, each type of blowout was matched with the profiles to ascertain whether the topographic patterns obtained corresponded to the forms initially identified. An 0-1 index was employed accordingly

$$iT_x = Tx / L$$

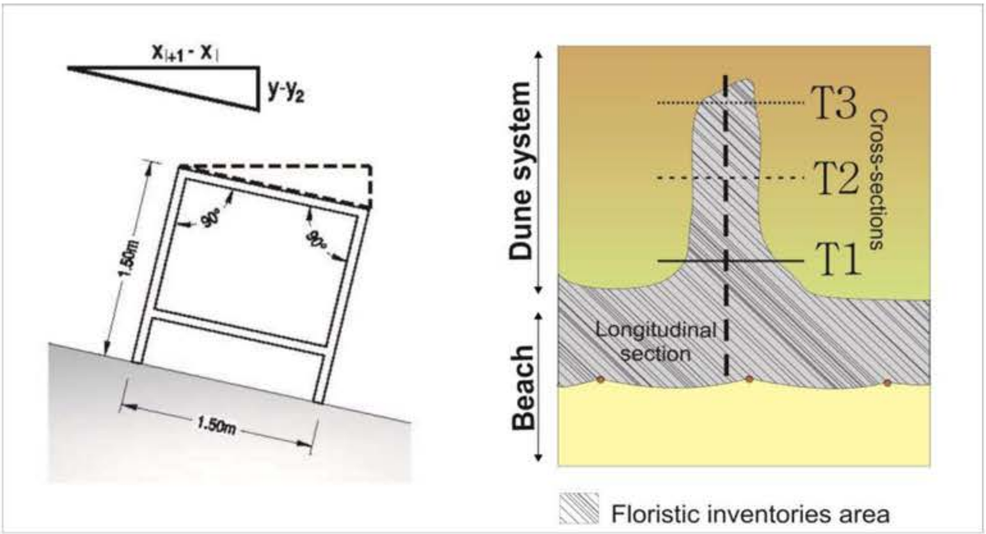

**Fig. 2.** Scheme of the method used for the construction of topographical profiles. Graphical reproduction of the beach profiler (pantometer) used. The figure also shows the area where floristic inventories have been carried out.

***Fig. 2.*** *Esquema de la metodologia utilitzada per a la construcció dels perfils topogràfics. Reproducció gràfica del pantòmetre utilitzat. La figura també mostra l'àrea a on s'han realitzat els inventaris florístics.*

where $iT_X$ is the relation between the length of the blowout and each longitudinal transect, $T_x$ is the length of each cross section, and L is the length of the blowout. Next, the synthetic value reflecting the area represented by each typology is expressed as,

$$iA = \Sigma\, iT_x / 3$$

where iA is the area of the blowouts for one typology, whereas $\Sigma\, iT_x$ is the sum of the mean values of each of the cross sections for each type of blowout.

To improve the interpretation, the results were schematically represented using the mean values obtained for each type of blowout. Each value was converted to cm assuming that L=10cm, thus achieving the standardization of the representation of each type described.

For floristic inventories the herbaceous and woody species were differentiated. Inventories were made taking into account the presence / absence of species at each sampling point, and were conducted within the area of influence of each blowout (Fig. 2), considering as reference points the side walls and protective cordon between the beach and dune system.

Finally, in order to relate the presence of vegetation to each typology of blowout, an index was applied

$$R_{t\text{-}v} = \frac{\Sigma p}{\Sigma BOc}$$

where $R_{t\text{-}v}$ shows the relation between the blowout typologies and the species identified, $\Sigma_p$ is the number of times that one species appears in a blowout of the same typology, and $\Sigma_{BOc}$ is the overall blowout of the same typology.

After the physical characterization of the dune front some signs show how the blowout morphologies could be responsible of the dune complex recoil over the time. In order to better understand and quantify the backward dune movement over the last decades a spatiotemporal analysis was performed taking into account the boundary drawn by the vegetation along the first line of dunes, between the upper limit of the aerial beach and dune system. The analysis was carried out using GIS software ArcView. The first step was to digitize the lines of existing vegetation for 1956, 2002, 2008 and 2010 and obtain the spatial patterns of the first line of dunes over a 54 year period. For each of the lines drawn, a 5 m buffer was employed for the final analysis using the DSAS 2.0 (*Digital Shoreline Analysis System*) (Thieler *et al.*, 2003).

## Results

There are 14 blowouts (BO) that are not evenly distributed along the dune front on the beach of Cala Agulla (Fig. 3). The highest densities are found in the southernmost part of the beach, whereas the lowest densities of blowouts are in the northern part.

### *Morphological classification*

Five categories of blowout have been distinguished according its shape (Fig. 5): trough blowout (50%), which is the predominant form, saucer blowout (7.14%), mixed shape (14.29%), conical blowout (14.29%) and bitten blowout (14.29%). The classification based on its structure is simpler because only 2 categories have been distinguished (Fig. 5): the simple blowout, accounting for 78.57% of the total, at the expense of branched blowout, representing 21.43% of the sampling points.

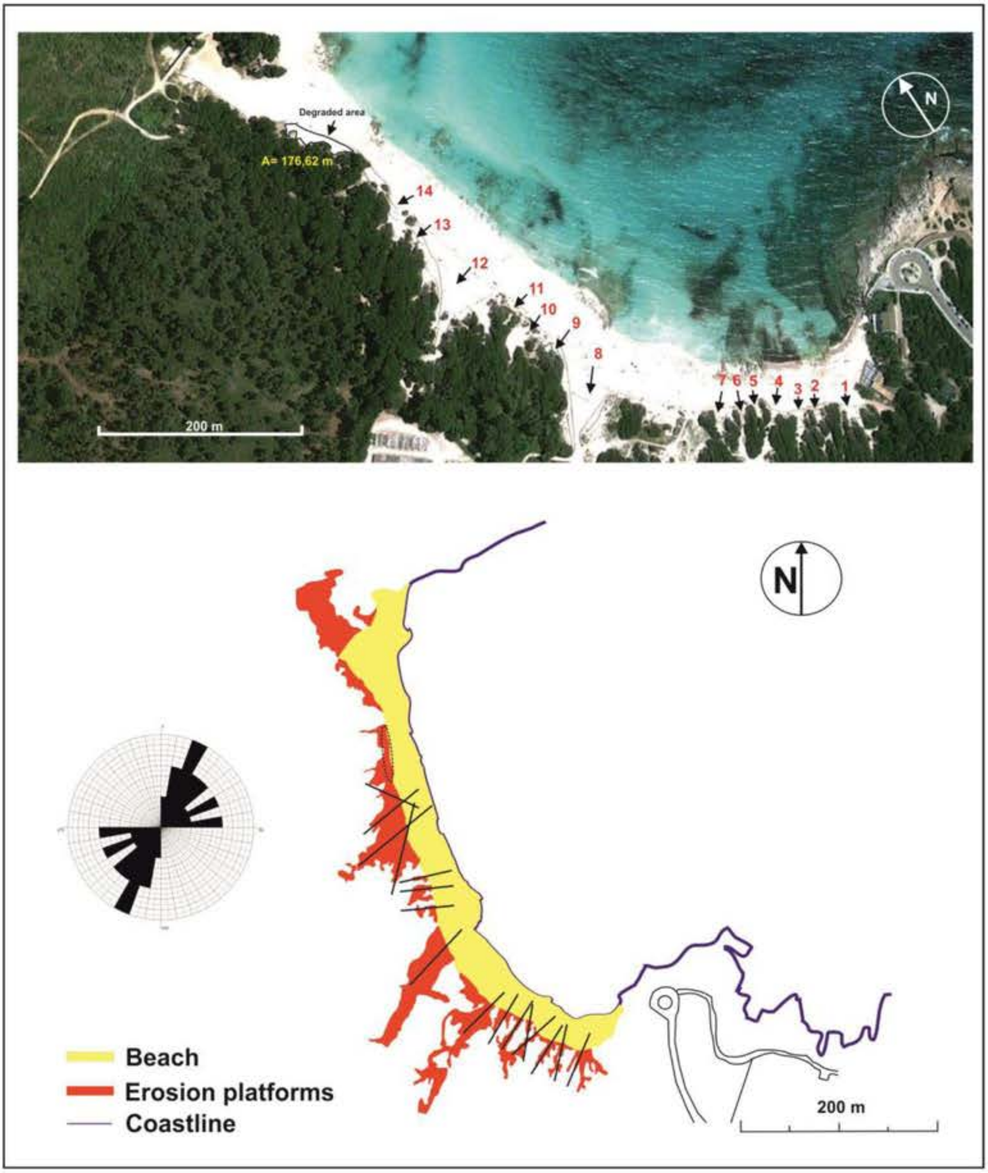

**Fig. 3.** Location and orientation of the blowouts identified along the dune front at Cala Agulla (Mallorca).

***Fig. 3***. *Localització i orientació dels blowouts identificats al llarg del front de dunes de Cala Agulla (Mallorca).*

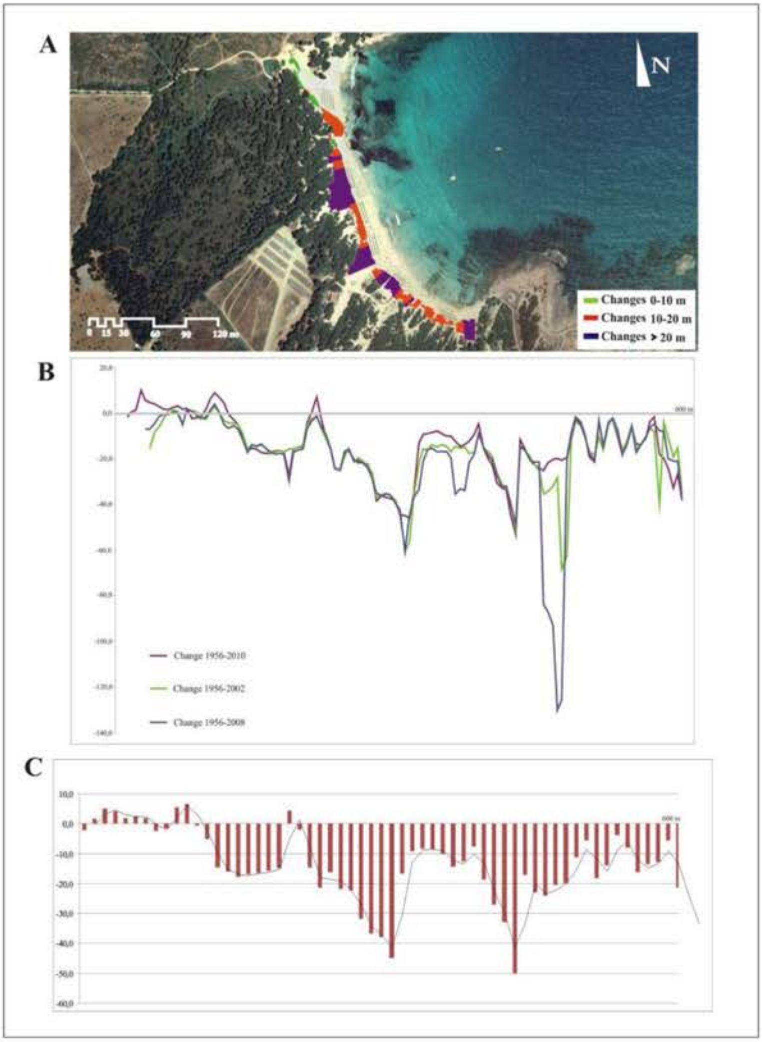

**Fig. 4.** Spatio-temporal analysis (1956-2008) of the dune front of Cala Agulla considering the line drawn by the vegetation, where a) shows the different recoil intensities suffered along the front of dunes analyzed, b) represents the evolution of the front in the periods 1956-2002, 1956-2008 and 1956-2010, and c) shows the trend of the overall backward movement in the period of analysis.
***Fig. 4.*** *Anàlisi espai-temps (1956-2008) del front de dunes de Cala Agulla considerant la línia marcada per la presència de vegetació, a on a) mostra les diferents intensitats de retrocés sofertes al llarg del front de dunes analitzat, b) representa l'evolució del front the dunes en els períodes 1956-2002, 1956-2008, i 1956-2010, I c) mostra la tendència general del retrocés del front de dunes en el període analitzat.*

Trough blowouts are generally more elongated than the others, with deeper deflation floors and basins, and with steeper and longer erosion lateral walls whereas saucer blowouts are semi-circular or saucer shaped and often appear as shallow dishes.

The mixed shape is a combination of the two forms described above. This consists of a trough blowout form at the mouth, and a semicircular structure in the interior, often linked to forms of deposition. Conical blowouts (see BOA8 and BOA12 in Fig. 5)

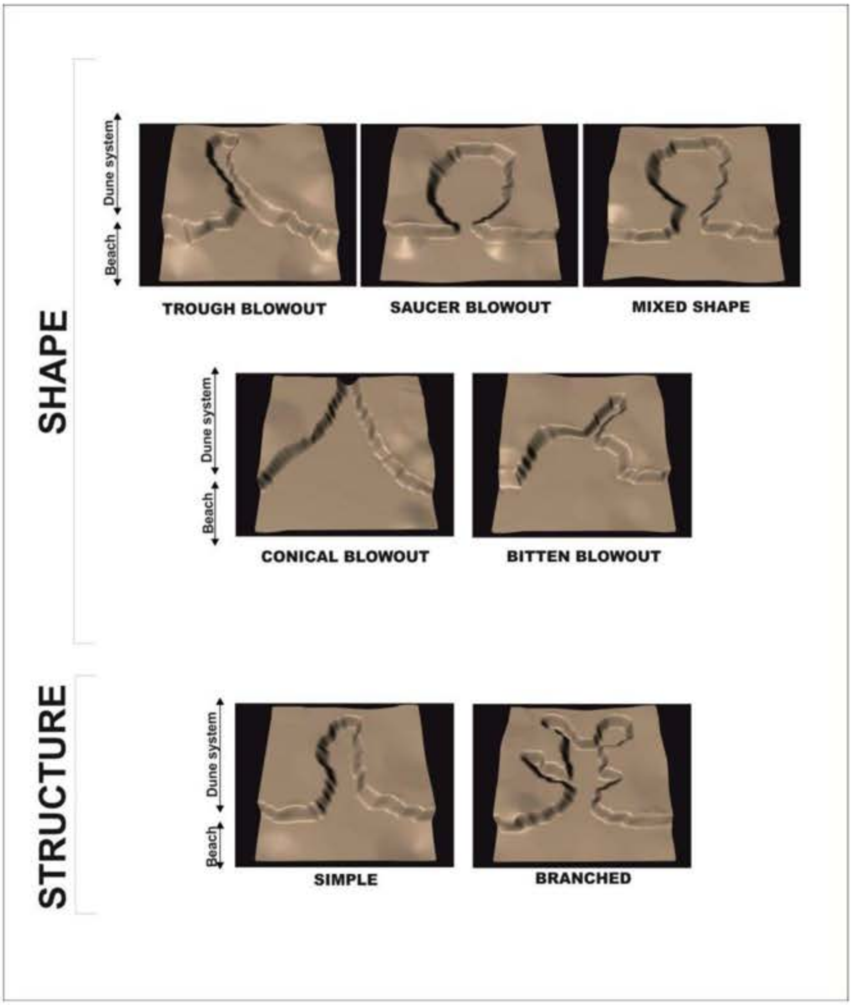

**Fig. 5.** 3D blowouts classification in the dune system of Cala Agulla (Majorca), considering both its shape and structure.

***Fig. 5.*** *Classificació en 3D dels blowouts al sistema dunar de Cala Agulla (Mallorca), considerant la seva forma i la seva estructura.*

have a conical shape with a very wide mouth that gradually decreases landward (Fig. 5 and 8). These forms are associated with the main entrances to the beach that are heavily used by holidaymakers. The dimensions of the mouth characterize bitten blowouts. In this case, blowouts develop from an erosive bite existing on the front dune that determines their status and evolution. Finally, with respect to the structure, a single channel of deflation characterizes simple forms, while branched blowouts draw several channels of deflation, each taking a different direction and increasing the risk of merging with the adjacent blowouts.

### *Blowout orientation*

In quantitative terms, 4 of the 14 orientations studied correspond to NE-SW (25%), 4 to NNE-SSW (25%), and 3 to E-W (18.7%). The existence of other orientations that are less representative such as ENE-WSW, with 2 blowouts (12.5%) or N-S, only with 1 blowout (6.25%) was also considered. The first two orientations account for 50% of blowouts. However in the southern part of the beach, which is more exposed to the northern winds, the direction of blowouts is clearly NNE-SSW, whereas in the central and northern parts, the most exposed directions are ENE-WSW. Thus, because of the structural characteristics displayed by the cove, which faces the NE, the main orientations of the blowouts analyzed in the system of Cala Agulla are NNE-SSW and NE-SW (Fig. 3). Thereby, the mean orientation of sampling points is 46.7°, which is closely related to the NE cove aperture and direction.

As for the typologies, the main direction of trough blowouts is NNE-SSW (mean of 24°). Bitten, conical and saucer blowouts have an ENE-WSW orientation (mean of 58°), whereas the mixed shape are oriented to E-W (mean of 88°) (Table 1).

| | nº BO | Degrees | Orientation |
|---|---|---|---|
| Trough blowout | 1 | 20 | NNE-SSW |
| | 2 | 14 | NNE-SSW |
| | 3 | 29 | NNE-SSW |
| | 4 | 52 | NE-SW |
| | 5 | 4 | N-S |
| | 6 | 25 | NNE-SSW |
| | Mean | 24 | NNE-SSW |
| Bitten blowout | 7 | 37 | NE-SW |
| | 11 | 80 | E-W |
| | Mean | 59 | ENE-WSW |
| Conical blowout | 8 | 47 | NE-SW |
| | 12 | 62 | ENE-WSW |
| | Mean | 55 | ENE-WSW |
| Mixed shape | 10 | 86 | E-W |
| | 14 | 90 | E-W |
| | Mean | 88 | E-W |
| Saucer blowout | 9 | 62 | EBE-WSW |

**Table 1.** Orientations followed by blowouts of each of the types described are shown.
***Taula 1.*** *Orientacions seguides pels blowouts en cada una de les tipologies descrites.*

### *Dimensions and inner morphometry of blowouts*

The mean length of the blowouts studied is 35.2 m. BOA8, which coincides with one of the main entrances to the beach, attains a maximum length of 64.37m. The minimum length (16.19m) is found in BOA5. This blowout is located between blowouts BOA4 and BOA6, which are both connected in the interior.

The mean height of the sampling points is 5.35m. The maximum height (9.11m) is located in BOA3, whereas the lowest height (2.42m) is in BOA5. In this case there is no correlation between the longest blowout and the maximum height. In the case of BOA5, however, the minimum length and height coincide.

Considering the variables of length and height, the mean slope of blowouts on the beach of Cala Agulla is 16.33%. The maximum occurs in BOA7 with a slope of 22.19%. However, other sampling points are significantly close to this number, as in the case of BOA3, BOA11 and BOA12, each with an approximate slope of 20%. The minimum occurs in BOA8 with a slope of 5.2%.

The Pearson correlation index shows a positive relationship between the variables of length and height and is $r= 0.29$. Nevertheless, this correlation is close to $r=0$, indicating that its linear relation is not very strong. However, the situation changes when comparing the length and slope with a negative relationship expressed as $r= -0.58$. Thus, the trend of the blowouts analyzed shows that when one of the variables increases (e.g. length) the other one decreases (e.g. slope).

Topographic profiles were made of 14 blowouts (Fig. 6 and 7). There are marked differences between the cross sections. Normally the width of the blowouts decreases from the front towards the interior. This trend is represented by the mean width of T1 = 17.76 m, T2= 12.53 m, and T3 = 07.03 m, the erosive structures being wider at the front than in the interior. Nevertheless, there are some exceptions where the width of the T3 is larger than T1 and T2. According to Glenn (1979) and Carter *et al.* (1990), the inner parts of the blowouts sometimes assume greater widths, often in line with the existence of associated sedimentary deposition platforms. One good example is BOA3 where the width of T3 (10.79 m) is greater than T1 (3.40 m) and T2 (3.36 m).

In the case of T1 the maximum width (63.47m) is located in BOA12, whereas the lowest (3.4m) is in BOA3. As for T2 the highest value (35.07m) is in BOA9, whereas the minimum (3.36m) is again found in BOA3. Finally, the broadest (13.25m) of T3 is located in BOA11, whereas the minimum (3.41m) is located in BOA7.

The morphology of the interior sections varies in accordance with their location. In the case of T1 these usually have a uniform shape, flat especially in the central part and with a small slope on the side walls, as shown in BOA4, or BOA14 BOA8 (Fig. 6 and 7). However, a characteristic feature of this first section is the presence of deflation furrows in some profiles, as observed in BOA12, but also in others such as BOA1, BOA7 and BOA11 (Fig. 6 and 7). There is a fairly direct relationship between the existence of these furrows and a higher slope on the sidewalls. This occurs for example in BOA1, with very marked furrows and steep sidewalls, unlike in BOA10, where the situation is reversed (Fig. 7).

Sometimes these deflation furrows are prolonged into the blowout, as in BOA2, BOA11 and BOA12, where they are located in T2 as well. The T3 sections show

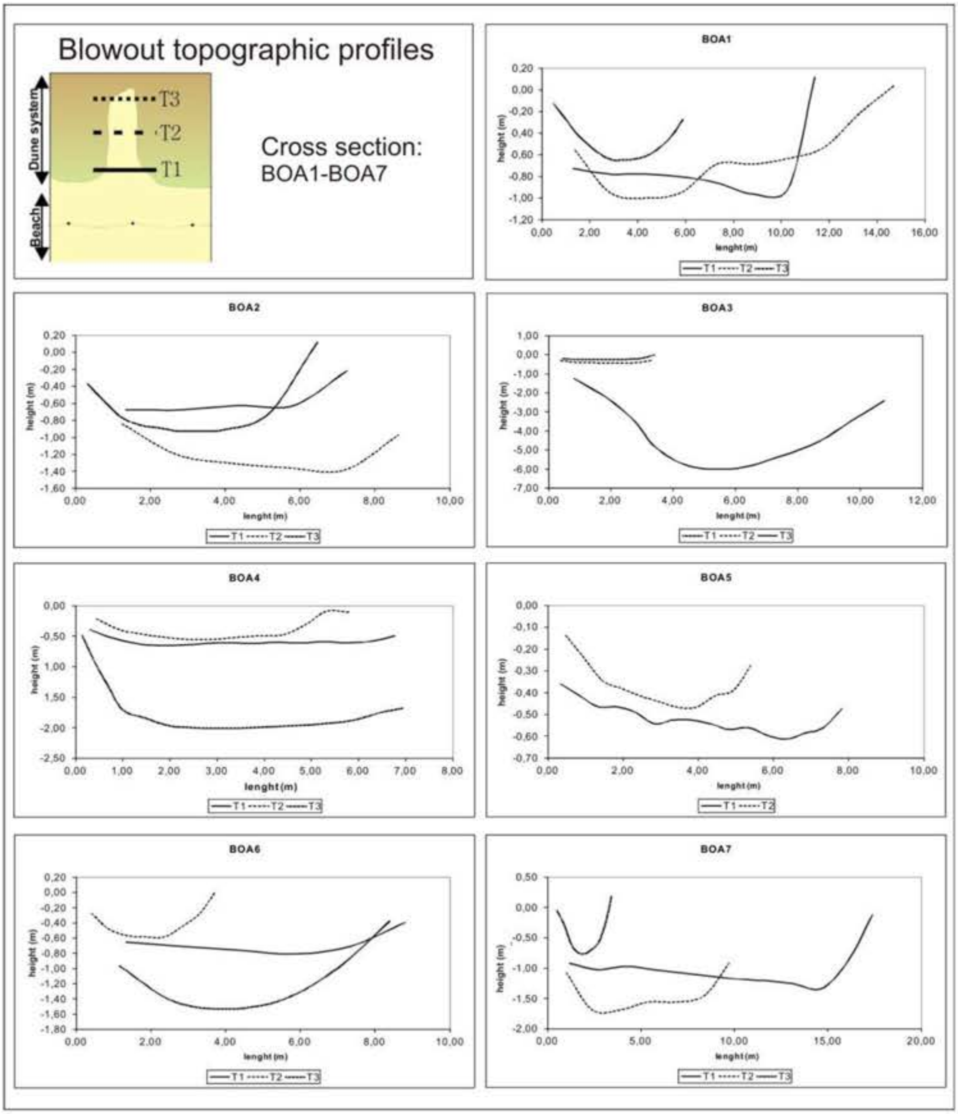

**Fig. 6.** Topographic profiles of BOA1-BOA7. The trend of the cross sections T1, T2 and T3 are shown.

***Fig. 6.*** *Perfils topogràfics dels BOA1-BOA7. Es mostra la tendència del perfils transversals T1, T2, i T3.*

concave and narrow profiles, especially in BOA12 and BOA7. Conical blowouts cover the largest areas (iA = 0.52). However, saucer blowouts yield values of iA = 0.45. The minimum dimensions are in trough blowouts, particularly in subtype B, with values of iA = 0.21. With intermediate values that are close to each other, there are trough blowouts A (iA = 0.34), the bitten blowouts (iA = 0.38), and mixed shape (iA = 0.39). The relationship between the longitudinal and transverse profiles shows

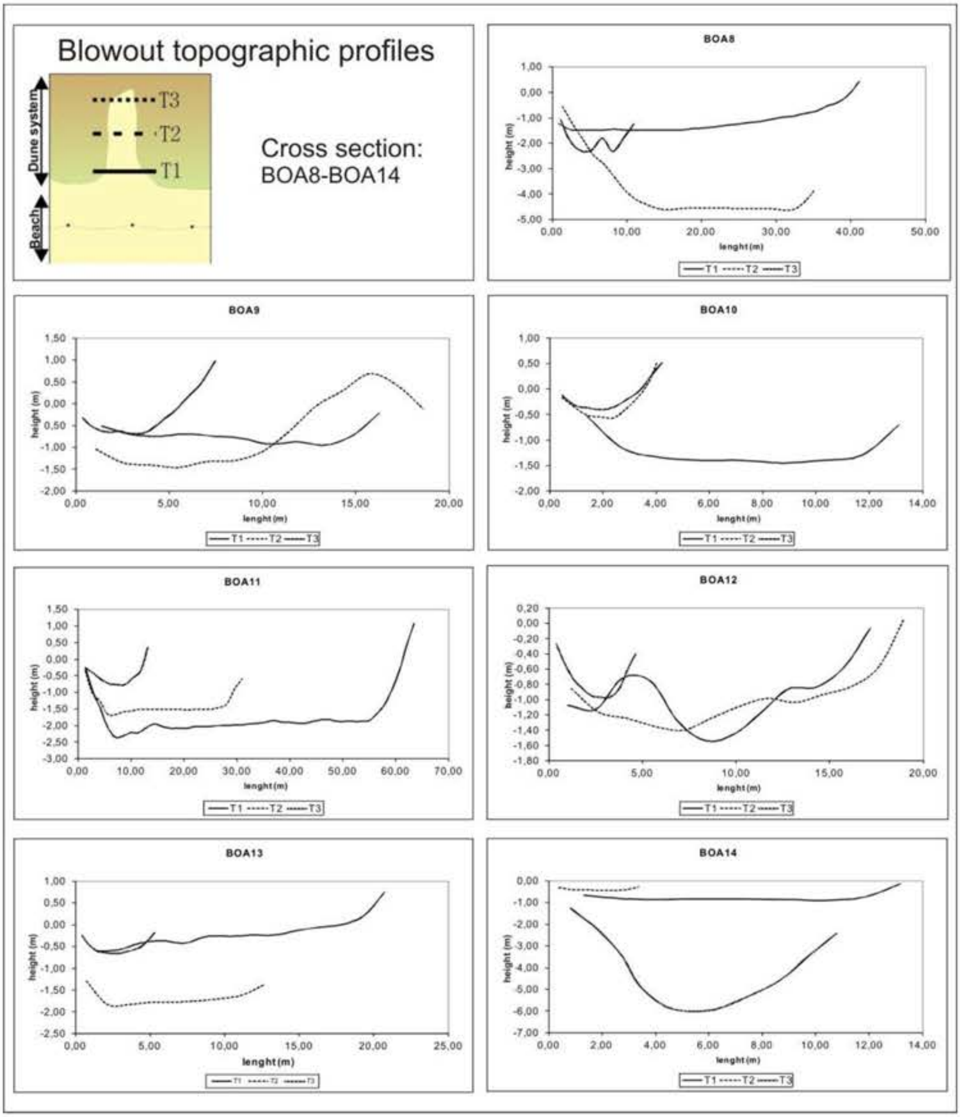

**Fig. 7.** Topographic profiles of BOA8-BOA14. The trend of the cross sections T1, T2 and T3 are shown.

***Fig. 7.** Perfils topogràfics dels BOA8-BOA14. Es mostra la tendència del perfils transversals T1, T2, i T3.*

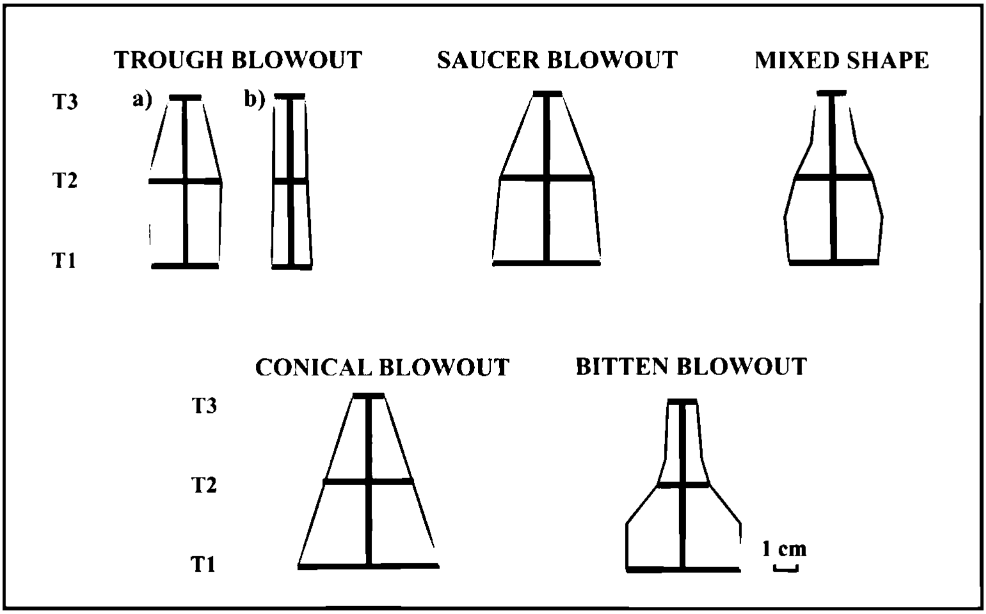

**Fig. 8.** Outline of blowout typologies according to the Rt-v index.
***Fig. 8.*** *Tipologies de blowout d'acord a l'index Rt-v*

morphologies adopted by each type (Table 2 and Fig. 8). Considering the application of $iT_X$, within trough blowouts, there are two subcategories, A, with wider forms mainly in the T1 and T2 profiles, and B, with even more elongated and narrow forms. Saucer blowouts have significant widths in their T1 ($iT_1$= 0.64) and T2 ($iT_2$= 0.54) profiles, whereas the width diminishes toward the interior ($iT_3$= 0.17). Mixed shape and bitten blowouts have a similar morphometric pattern, but with some differences. Bitten blowouts are characterized by a greater width at the mouth ($iT_1$ = 0.67) and smaller dimensions in the interior ($iT_2$= 0.29 and $iT_3$= 0.17). However, mixed shape blowouts present a more homogeneous width at the mouth ($iT_1$= 0.53) and center ($iT_2$= 0.45), while it decreases significantly in the interior part ($iT_3$= 0.18), resulting in a saucer shape in the lower part of the blowout followed by a trough shape in the upper part. Finally, conical blowouts are characterized a greater width at the mouth ($iT_1$= 0.84), which decreases toward the interior, plotting at the same time a conical structure from the first line landward.

### *Floristic inventories*

Vegetation is one of the most important variables that should be taken into account when characterizing a dune front. The present study differentiates between the role of herbaceous and that of woody vegetation. At the dune front of Cala Agulla there are 15 major herbaceous species, each one with a different index of presence / absence. One group of species, which includes *Lotus cytisoides* (93.33%), *Pancratium maritimum* and *Cutandia maritima* (86.67%), *Matthiola incana* (80%), *Ammophila arenaria* (73.33%) or *Cakile maritima* (66.67%), has a large recu-

| | | **Lenght (m)** | **iT1** | **iT2** | **iT3** | **iA** |
|---|---|---|---|---|---|---|
| Trough BO | BOA1 | 28.18 | 0.40 | 0.52 | 0.21 | A |
| | BOA2 | 20.11 | 0.36 | 0.43 | 0.32 | |
| | BOA5 | 16.19 | 0.46 | 0.34 | 0.00 | |
| | Mean | 21.49 | 0.41 | 0.43 | 0.18 | 0.34 |
| | BOA3 | 45.52 | 0.07 | 0.07 | 0.24 | B |
| | BOA4 | 39.37 | 0.17 | 0.15 | 0.18 | |
| | BOA6 | 47.71 | 0.18 | 0.08 | 0.18 | |
| | BOA13 | 35.49 | 0.48 | 0.54 | 0.13 | |
| | Mean | 42.02 | 0.23 | 0.21 | 0.18 | 0.21 |
| Saucer BO | BOA9 | 64.37 | 0.64 | 0.54 | 0.17 | |
| Mixed shape BO | BOA10 | 33.86 | 0.48 | 0.55 | 0.22 | |
| | BOA14 | 35.61 | 0.58 | 0.35 | 0.15 | |
| | Mean | 34.74 | 0.53 | 0.45 | 0.18 | 0.39 |
| Conicap BO | BOA8 | 64.37 | 0.64 | 0.54 | 0.17 | |
| | BOA12 | 61.35 | 1.03 | 0.51 | 0.22 | |
| | Mean | 62.86 | 0.84 | 0.53 | 0.19 | 0.52 |
| Bitten BO | BOA7 | 26.14 | 0.67 | 0.37 | 0.13 | |
| | BOA11 | 19.28 | 0.68 | 0.21 | 0.22 | |
| | Mean | 22.71 | 0.67 | 0.29 | 0.17 | 0.38 |

**Table 2.** The relation between the inner topographic surveys and the typologies described according to the application of the iTx index is shown. The mean values of each typology are depicted in bold.
***Taula 2.*** *Es mostra la relació entre els perfils topogràfics interns i les tipologies descrites d'acord a l'aplicació de l'índex iTx. Els valors mitjans de cada tipologia són resaltats en negreta.*

rrence at more than 10 sampling points. A second group consists of species with a small recurrence (10 < n < 5), such as *Eryngium maritimum* (46.67%), *Aetheorhiza bulbosa* subs. *bulbosa* (33.33%), *Euphorbia paralias* (46.67%) or *Crucianella maritima*, *Helichrysum stoechas* and *Crithmum maritimum* (40%). Finally, there are species with a low degree of recurrence (n < 5), *Teucrium dunense* (26.67%) and *Beta maritima* subs. *maritima* (13.33%).

A level of partnership when considering the presence/absence of the species identified is distinguished between some groups of species, each with different patterns of similarity (Fig. 9).

The first group (A) formed by *Cakile maritima*, *Ammophila arenaria*, *Cutandia maritima*, *Pancratium maritimum*, *Lotus cytisoides and Matthiola incana* has a degree of association between 80-90%.

The second group (B) consists of *Helichrysum stoechas*, *Eryngium maritimum* and *Euphorbia paralias*, which show a degree of similarity between 60-70%. Moreover, this group is associated with the species of group (A) with values close to 60%.

In addition, there are two independent groups, each consisting of two species, and characterized by a low degree of association.

The third group (C) is formed by *Aetheorhiza bulbosa* subs. *bulbosa* and *Crithmum maritimum*, both with an association of 60%.

The fourth group (D) is formed by *Beta maritima* subs. *maritima* and *Crucianella maritima*, both with an association of 40%.

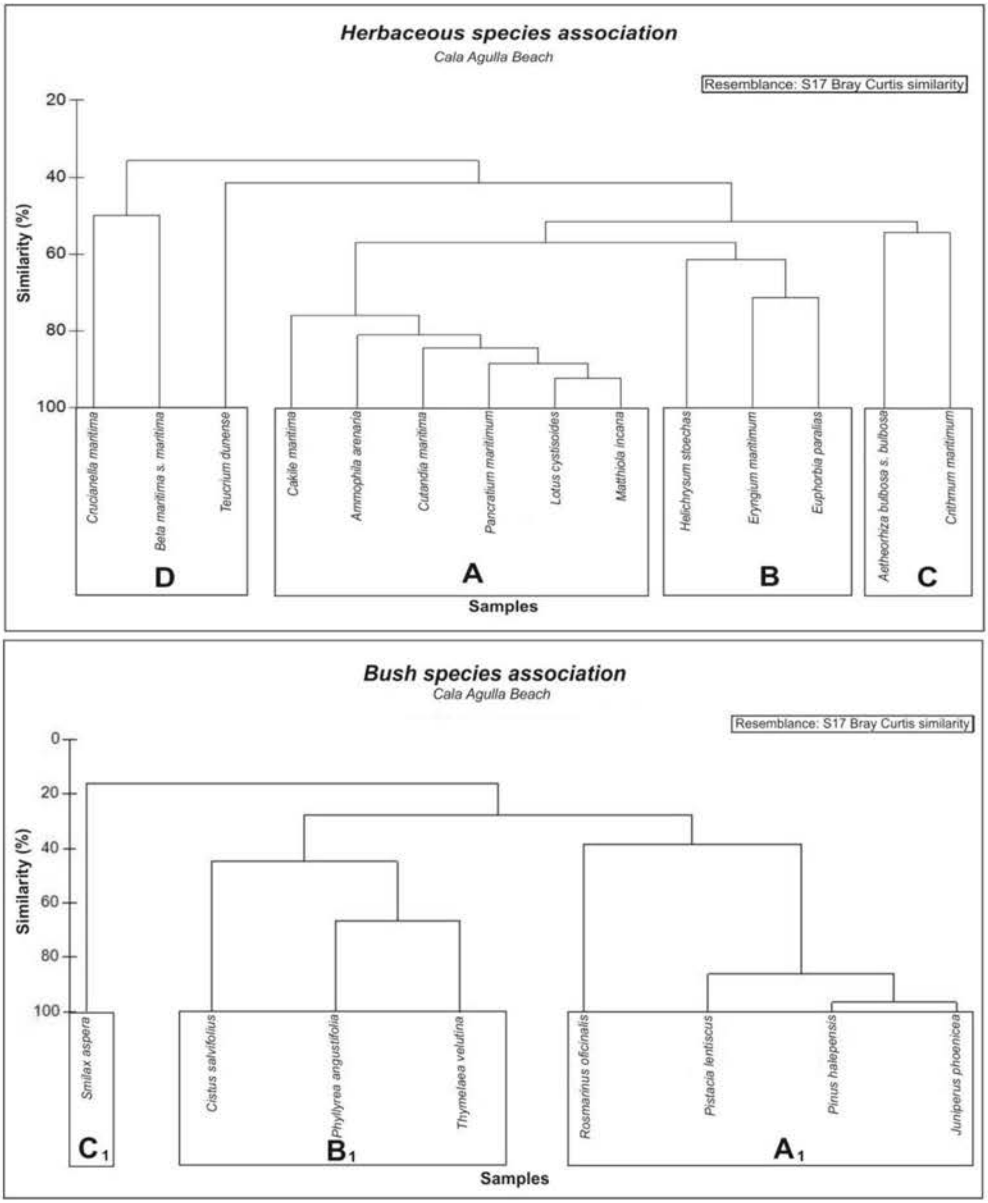

**Fig. 9.** Cluster analysis resulting from the association between both herbaceous and woody species identified in each of the blowouts analyzed.

***Fig. 9.*** *Anàlisi cluster (dendograma) resultat de les associacions entre la vegetació herbàcia i llenyosa identificada en cada un dels blowouts analitzats.*

are related to major groups (A and B) with values below 40%. The situation presented by woody vegetation is simpler than in the case of herbaceous vegetation, not only because of the number of the species identified but also because of the patterns of association.

A total of 8 different wood species were identified and were classified into 2 groups. The first group includes high recurrences of *Juniperus phoenicea* (100%), *Pinus halepensis* (93%) and *Pistacia lentiscus* (73.33%) with a high recurrence, present at more than 10 sampling points. The second group of the species has much lower rates of recurrence (n < 5) and is formed by *Rosmarinus officinalis* (26.67%), *Cistus salvifolius* (20%), *Smilax aspera* and *Thymelaea velutina* (13.33%), and *Phyllirea angustifolia* (6.67%).

At a level of partnership 2 main groups are distinguished (Fig. 9). The first group ($A_1$) includes *Juniperus phoenicea*, *Pinus halepensis* and *Pistacia lentiscus*,

| | **Trough BO** | **Saucer BO** | **Mixed shape** | **Conical BO** | **Bitten BO** |
|---|---|---|---|---|---|
| % among total | 50% | 7.14% | 14.29% | 14.29% | 14.29% |
| *Ammophila arenaria* | 1 | 0 | 0.5 | 0.5 | 0.5 |
| *Eryngium maritimum* | 0.43 | 0 | 1 | 0 | 0.5 |
| *Pancratium maritimum* | 0.75 | 1 | 1 | 1 | 1 |
| *Aetheorhiza bulbosa s. bulbosa* | 0.3 | 0 | 0 | 0.5 | 0.5 |
| *Lotus cytisoides* | 1 | 1 | 1 | 0.5 | 1 |
| *Matthiola incana* | 0.75 | 1 | 0.5 | 0.5 | 1 |
| *Euphorbia paralias* | 0.43 | 0 | 1 | 0.5 | 0.5 |
| *Cutandia maritima* | 0.85 | 1 | 0.5 | 1 | 0.5 |
| *Crucianella maritima* | 0.43 | 0 | 1 | 0 | 0.5 |
| *Helichrysum stoechas* | 0.14 | 1 | 1 | 0.5 | 0.5 |
| *Crithmum maritimum* | 0.43 | 0 | 0 | 0 | 1 |
| *Cakile maritima* | 0.43 | 1 | 1 | 1 | 1 |
| *Beta maritima s. maritima* | 0.14 | 0 | 0 | 0 | 0 |
| *Teucrium dunense* | 0 | 0 | 1 | 1 | 0 |
| **Herbaceous - tipologies** | **0.506** | **0.429** | **0.679** | **0.500** | **0.607** |
| *Cistus salvifolius* | 0.3 | 0 | 0 | 0 | 0 |
| *Phyllirea angustifolia* | 0 | 0 | 0 | 0 | 0 |
| *Pinus halepensis* | 1 | 1 | 1 | 1 | 0.5 |
| *Juniperus phoenicea* | 1 | 1 | 1 | 1 | 1 |
| *Pistacia lentiscus* | 0.85 | 1 | 0.5 | 0.5 | 0.5 |
| *Smilax aspera* | 0 | 0 | 0.5 | 0 | 0 |
| *Rosmarinus officinalis* | 0.14 | 0 | 0.5 | 0 | 0.5 |
| *Thymelaea velutina* | 0 | 0 | 0 | 0.5 | 0 |
| **Woody - tipologies** | **0.411** | **0.375** | **0.438** | **0.375** | **0.313** |

**Table 3.** The relation between the inner topographic surveys and the vegetal species identified, both herbaceous and woody, according to the application of the Rt-v index is shown. The mean values by each typology are depicted in bold.

***Taula 3.*** *Relació entre els perfils topogràfics interns i les espècies vegetals identificades, tant herbàcies com llenyoses, d'acord a l'aplicació de l'índex Rt-v. Els valors mitjans de cada tipologia són resaltats en negreta.*

These two last groups which are noted for their high degree of association with values ranging from 80-100%.

The second group ($B_1$) consists of *Cistus salvifolius*, *Thymelaea velutina* and *Phyllirea angustifolia* with a degree of association between 40-60%, and is related to group ($A_1$) with approximate values of 20%. Finally, there are species such as *Smilax aspera*, which have little association with other species because of their insignificant presence along the dune front (below 20%).

The relationship that identifies each species at the sampling points with the different types of blowouts defined above is not homogeneous. The application of $R_{t\text{-}v}$ shows the difference in weight of the species according to each type of blowout, and the existence of different patterns of relationship between the role played by both herbaceous and woody vegetation (Table 3). Mixed shape blowouts with $R_{t\text{-}v}$= 0.679 is the typology with the strongest relationship with herbaceous vegetation, while the lowest one is shown by the link with saucer blowouts, expressed as $R_{t\text{-}v}$= 0.429. The link between herbaceous species and bitten blowouts also constitutes an important weight expressed as $R_{t\text{-}v}$= 0.607, while the values of trough blowouts ($R_{t\text{-}v}$= 0.506) and conical blowouts ($R_{t\text{-}v}$= 0.5) have a lower weight.

The relation patterns between woody vegetation and blowout typologies differ slightly from the above case. While mixed shape blowouts are still the type that is most associated with this kind of vegetation, with $R_{t\text{-}v}$= 0.438, in this scenario the lowest relation pattern is with bitten blowouts, only with $R_{t\text{-}v}$= 0.38. The relation between woody vegetation and trough blowouts is also important. Overall, as shown in Table 1, the relationship between blowouts and herbaceous vegetation, with $R_{t\text{-}v}$= 0.51, is higher than that with woody vegetation with $R_{t\text{-}v}$= 0.38.

### *Space-temporal analysis of dune front (1956-2010)*

The dune system of Cala Agulla has undergone an important retreat over the last decades. The spatio-temporal analysis performed over the last 54 years (Fig. 4) shows how the backward movement has been comprehensive, albeit with different intensities along the beachfront. As shown in Fig. 4A, the areas with minor erosion, with patterns of retreat ranging from 0-10 m, are located in the northern part of the beach. The average recoil ranges from 10-20 m, although in some places they exceed 20 m, as at the points that coincide with the main entrances to the beach (currently identified by the BOA8 and BOA12).

However, as shown in Fig. 4B, the patterns of backward motion have been progressive over time. Thus, with respect to the situation in 1956, the regression suffered in 2002 and 2008 is integral and comprehensive, showing an almost homogeneous behaviour. However, the areas that experienced most retreat in the period 1956-2002 and 1956-2008 are again the main accesses to the beach. But in 2010 the situation changes since despite the continuation of the regression patterns, these diminish and at some points the front dune undergoes a recovery. These changes are however not perceived at the points of maximum regression, which suggests thus a direct relationship between the points of maximum erosion and maximum attendance zones. Despite signs of recovery in recent years, Fig. 4C demonstrates that the overall trend in the front dune of Cala Agulla over the last few decades has clearly been negative. This is evidenced by the patterns of erosion and the retreat of the system.

## Discussion

The fragmentation of the beach-dune system of Cala Agulla is closely related to the existence of blowouts on the first line. The presence of these deflation corridors has constituted an important setback for the system in recent decades. A number of theories have attempted to explain the erosive effects suffered by the sandy coastal systems. The first of these attributes erosion to rise in sea level, affecting unequally sandy coastal systems and their associated ecosystems (Church *et al.,* 2004; Fahrig, 2003; Nicholls *et al.,* 2007). Another theory links the erosion of beach-dune systems to the readjustment of sedimentary deposits in the Holocene period (Emery *et al.,* 1988; Tastet and Pontee, 1998). Finally, erosive effects have been ascribed to the lack of planning and management in coastal sandy systems and to the absence of rules and regulations governing public areas (Barros, 2001; Jaramillo *et al.,* 2002; Roig-Munar *et al.,* 2009). Finally, some authors have related the erosion processes to physical issues. In this sense Mir-Gual *et al.* (2013) concluded that the erosion processes on the beach and foredune strip are closely related with the presence of blowouts, which act as a deflation corridors. Within this thesis Smyth *et al.* (2012) showed how a blowout, according to its topography, act as a corridor which channels the airflow and increases the sediment transport landward. Thus, the results of this work suggest as well that the presence of the 14 blowouts inventoried have had an important role at the time to explain the dune front recoil over the last decades. In this regard, the spatial-temporal analysis performed shows an erosive trend along the first line of dunes, suggesting a direct relationship between the areas of maximum erosion and those with the highest attendance.

The dune front of Cala Agulla has undergone a considerable retreat over recent decades (1956-2010). Although this decline has been comprehensive, it has produced up with different intensities. The areas of maximum erosion have suffered regression in excess of 20 m, although the average retreat in the dune front is 10-20 m. Despite the general erosive trend, over recent years (2008-2010) in some parts of the beach there has been a slight recovery along the first line of dunes, mainly in the northern part.

Today the dunes on the first line of the Cala Agulla system show a significant state of fragmentation evidenced mainly by the presence of 14 blowouts along a 600 m long front. The blowouts identified were classified into different forms that are apparently heterogeneous. However, according to Hesp (2002), despite the wide variety of blowouts shapes in sandy coastal systems, most of them may be identified using the two morphologies described by Cooper (1958), i.e. trough and saucer blowouts. The present study subscribes to this theory, except in the case of conical blowouts, which have a particular shape and coincide with the two main entrances to the beach. Given that the conical blowout has the largest areas and the poorest vegetation, the adverse consequences of high attendance are aggravated. According to their current form 5 categories were differentiated: trough blowout (50%), saucer blowout (7.14%), mixed shape (14.29%), conical blowout (14.29%) and bitten blowout (14.29%). Two types of structure were distinguished: simple structures (78.57%) and branched structures (21.43%). The main orientations of the blowout analyzed are NE-SW (25%) and NNE-SSW (25%). However, in the southern part of the beach, which is more exposed to the prevailing wind direction, the most important orientation is NNE-SSW, while in the central part it is ENE-WSW. The arrangement of blowouts shows a direct relationship between their orientation and the structural opening of the cove. Although data on existing wind dynamics on the front dune are not presented, this relationship suggests that the structural arrangement of the surrounding area can play an important role in both the formation and development of blowouts. The mean trend followed by blowout forms, with larger dimensions at the mouth, suggests that most erosion occurs at the bottom, bordering the emerged beach, whereas the inner parts, which are more protected by woody vegetation cover, are more resistant to erosion.

As for the dimensions, the average length of the blowout is 35.2 m (peaking at 64.37 m), with an average width of 3.35 m and a slope of 16.33%. Normally the width of the blowouts decreases from the front towards the interior. This trend is represented by the mean width of T1= 17.26 m, T2= 12.53 m and T3= 07.03 m. The conical blowouts present the largest areas (iA= 0.52), whilst the area of saucer blowouts, with values of iA= 0.45, should also be noted. The minimum dimensions are in trough blowouts, especially in subtype B, with values of iA= 0.21.

The formation, evolution and intensification of blowouts are linked to the presence of vegetation. Some authors such as Pethick (2001), Hilton and Konlechner (2011) and Mir-Gual and Pons (2011) emphasize the role of vegetation in both conservation and the recovery of sandy coastal systems. This therefore is an important variable that should be taken into account in both the conservation of the dune front and in the evolution of blowouts. Herbaceous vegetation is characterized by its capacity to retain sediment on the front line. Group (A) consists of 6 species - *Ammophila arenaria, Lotus cytisoides, Cutandia maritima, Cakile maritima,* and *Matthiola incana Pancratium maritimum.* These species have a high presence at the sampling points and constitute the largest plant community at the dune front of Cala Agulla. As for woody species, with a high capacity for fixing mobile dunes, the A1 group is composed of 4 species -*Pinus halepensis, Juniperus phoenicea, Rosmarinus officinalis* and *Pistacia lentiscus*- which also constitute the most important woody plant association along the first line dunes.

The relationship showing each species identified, at the sampling points, with the different types of blowouts defined above is not homogeneous. Mixed shape blowouts with Rt-v= 0.679 is the typology that shows the strongest relationship with herbaceous vegetation, whereas the lowest relationship is shown by saucer blowouts, expressed as Rt-v = 0.429. The relation between woody vegetation and blowout typologies differs slightly from that of herbaceous vegetation. Although the mixed shape is still the type most associated with this kind of vegetation, with Rt-v= 0.438, the lowest relation is with the bitten blowout, with only Rt-v= 0.38.

After the results obtained in this work, as well as by others such as Smyth *et al.* (2012) or Mir-Gual *et al.* (2013), the presence of blowouts along the front dune can increase the potential erosion in these environments. In places such as Balearic Islands, with an important economical activity linked to the sun and beach tourism, the management efforts on beach-dune system conservation should have an important relevance. Unfortunately, in many cases the management policies have focused their efforts on economical features but never on environmental ones (Roig-

Munar *et al.*, 2009). The intervention along ther first line of dunes is postulated as an important act to decrease the erosion of the emerged beach. Mir-Gual (2014) concludes that the existence of well-developed foredune is highly important by the proper equilibrium of the whole dune system. A proper first strip of dunes helps to decrease the speed of the wind incidence and increase the sedimentation processes by gravity. That avoids the deflation of sand located on the emerged beach through the blowouts. In this sense, and thinking with an optimum management for the conservation of these environments, getting a good foredune should be postulated as an essential action at the time to avoid the sand erosion from the beach to landward through the blowout morphologies, as well as to obtain a sediment reservoir available on the upper part of the emerged beach which help to rebuild the beach profile after erosion episodes.

## Conclusions

The beach-dune system of Cala Agulla today shows significant signs of fragmentation and degradation, mainly on the emerged beach and its dune front. The blowout forms on the front dune were characterized and quantified to assess the present situation of the system.

Fifteen blowouts were distinguished along circa 600m long beach front. The blowouts are distributed evenly along the first line of dunes, presenting the highest density in the southern and central part of the beach. On the basis of the geomorphological characteristics 5 categories were differentiated: a) trough blowout, b) saucer blowout, c) mixed shape, d) conical blowout, and e) bitten blowout, which adopts 2 types of structures: a) simple and b) branched. Blowouts have a direct relationship with the erosion and the recoil of the whole dune complex. This is shown by the space-time analysis from 1956 to 2010, with average recoil of 10-20 m, although in some places exceed 20 m, as at points that coincide with the main entrances.

This case study highlights the role of vegetation in both conservation and the recovery of sandy coastal systems. However some species play a more important part than others because of their presence and degree of similarity. Thus some species such as *Ammophila arenaria* play an essential role in the conservation of dune fronts. There is no clear relationship between different types of blowout and inventoried plant species. However, it should be noted that conical blowouts, which coincide with the main entrances to the beach, have the lowest relationship with vegetation, which suggests a direct correlation between high attendance and decreased vegetation cover.

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## References

Barros, F. 2001. Ghost crabs as a tool for rapid assessment of human impacts on exposed sandy beaches *Biological Conservation*, 97: 399-404

Basterretxea, G., Orfila, A., Jordi, A., Fornós, J.J. and Tintoré, J. 2007. Evaluation of a small volume renourishment strategy on a narrow Mediterranean beach. *Geomorphology*, 88: 139-151.

Bate, G. and Ferguson, M. 1996. Blowouts in coastal foredunes. *Landscape and Urban Planning*, 34: 215-224.

Borichansky, L.S. and Mickhailov, V.N. 1996. Interaction of river and sea water inthe absence of tides. Scientific problems of the humit Tropical deltas and their implications. UNESCO, pp. 175-180.

Carter, R.W., Hesp, P. and Nordstrom, K.F. 1990. Erosional landforms i coastal dunes. *In:* Nordstrom, K.F., Psuty, N.P., Carter, R.W. (Eds.), Coastal dunes: form and processes. John Wiley, London, pp. 217-249.

Church, J.A., White, N.J., Coleman, R., Lambeck, K. and Mitrovica, J.X. 2004. Estimates of the regional distribution of sea-level rise over the 1950-2000 period. *Journal of Climate*, 17: 2609-2625.

Cooper, W.S. 1958. *Coastal sand dunes of Oregon and Washington*. Geological Society of America 72, 169.

Davis, J.R. and Fitzerald, D.M. 2004. *Beaches and Coasts*. Blackwell Publishing, Carlton (Australia).

Delgado, I. and Lloyd, G. 2004. A simple low cost method for one person beach profiling. *Journal of Coastal Research*, 20: 1246-1252.

Emery, K.O., 1961. A simple method of measuring beach profiles. *Limnology and Oceanography*, 6: 90-93.

Emery, K.O., Aubrey, D.G., Goldsmith, V., 1988. Coastal Neo-tectonics of the Mediterranean from Tide-gauge Records. *Marine Geology*, 81: 41-52.

Esler, A.E. 1970. Manawatu sand dune vegetation. *Proc. N. Z. Ecological Society*, 17: 41-46.

Fahrig, L. 2003. Effects of habitat fragmentation of biodiversity. *Annual Review of Ecology, Evolution and Systematics*, 34: 487-515.

Glenn, M. 1979. Glossary. A study of global sand seas. *In:* McKee, E.D. (Ed.), US Geological Surveys Professional Paper, 1052. Washigton, pp. 399-407.

González-Villanueva, R., Costas, S., Duarte, H., Pérez-Arlucea, M. and Alejo, I. 2011. Blowout evolution in a coastal dune: using GPR, aerial imagery and core records. *Journal of Coastal Research*, SI64: 278-282.

Gutiérrez-Elorza, M., Desir, G., Gutiérrez-Santolalla, F. and Marín, C. 2005. Origin and evolution of playas and blowouts in the semiarid zone of Tierra de Pinares (Duero Basin, Spain). *Geomorphology*, 72: 177-192.

Hesp, P. 1996. Flow dynamics in trough blowout. *Journal of Boundary-Layer Meteorology*, **77**: 305-330.

Hesp, P. 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. *Geomorphology*, 48: 245-268.

Hesp, P. and Hyde, R. 1996. Flow dynamics and geomorphology of trough blowouts. *Sedimentology*, 43 (3): 505-525.

Hesp, P. and Walker, I.J. 2012. Three-dimensional Aeolian dynamics within a bowl blowout during offshore winds: Greenwich Dunes, Prince Edward Island, Canada. *Aeolian Research*, 3: 389-399.

Hilton, M. and Konlechner, T. 2011. Incipient Foredunes Developed from Marine-dispersed Rhizome of *Ammophilia arenaria*. *Journal of Coastal Research*, SI64 (I): 288-292.

Hugenholtz, C. H. and Wolf , S.A. 2009. Form-flow interactions of an aeolian saucer blowout. *Earth Surface Processes and Landforms*, 34: 919-928.

Jaramillo, E., Contreras, H. and Bollinger, A. 2003. Beach and faunal response to the construction of a seawall in a sandy beach of south central Chile. *Journal of Coastal Research*, 18: 523-529.

Jennings, J.N. 1957. On the orientation of parabolic U-dune. *The Geographical Journal*, 124 (4): 474-480.

Martín-Prieto, J.A., Roig-Munar, F.X., Rodríguez-Perea, A. and Pons, G.X. 2006.

Evolució de la línia de costa de la platja des Trenc. *In:* Mayol, J., Muntaner, Ll., Rullan, O. (Eds.), Homenatge a Bartomeu Barceló i Pons, geògraf, Lleonard Muntaner Editor, Palma, pp. 423-440.

Mir-Gual, M. 2014. *Analysis, characterization and dynamics of blowout erosive morphologies in dune systems of Mallorca and Menorca (Balearic Islands).* PhD, University of the Balearic Islands, Spain, 423 pp.

Mir-Gual, M. and Pons, G.X. 2011. Coast sandy strip fragmentation of a protected zone in the N of Mallorca (Western Mediterranean). *Journal of Coastal Research,* SI64 (1): 1367-1371.

Mir-Gual, M., Pons, G.X., Martín-Prieto, J.A., Roig-Munar, F.X. and Rodríguez-Perea, A. 2011. Estudio ecológico de un frente dunar como indicador cualitativo de su estado de conservación. Playa de es Comú de Muro (Mallorca, Islas Baleares). *In:* Montoya Montes, I., Rodríguez Santalla, I. and Sánchez García, M.J. (Eds.), Actas de las VI Jornadas de Geomorfología Litoral. Tarragona, Spain, pp. 111-114.

Mir-Gual, M., Pons, G.X., Martín-Prieto, J.A., Roig-Munar, F.X. and Rodríguez-Perea, A. 2013. Geomorphological and ecological features of blowouts in a western Mediterranean coastal dune complex: a case study of the Es Comú de Muro beach-dune system on the island of Mallorca, Spain. *Geo Marine Letters,* 33: 129-141.

Nicholls, R.J., Wong, P.P., Burkett, V., Codignotto, J.O., Hay, J., McLean, R., Ragoonaden, S. and Woodrofe, C. 2007. Coastal System and Low-lying Areas. *In:* Climate change: Impacts, adaptation and vulnerability. IPCC, Cambridge Press, pp. 315-356.

Pethick, J. 2001. *An introduction to Coastal Geomorphology.* Edward Arnold Publishers, United States.

Puleo, J.A., Pearre, N.S., He, L., Lauren, S., O'Neal, M., Pietro, L.S. and Fowler, M. 2008. A single-user subaerial beach profiler. *Journal of Coastal Research,* 24: 1080-1086.

Ritchie, W. 1972. The evolution of coastal sand dunes. *Scottish Geographical Magazine,* 88: 19-35.

Roig-Munar, F.X. 2004. Análisis y consecuencias de la modificación artificial del perfil de playa-duna provocado por el efecto mecánico de su limpieza. *Investigaciones Geográficas,* 33: 87-103.

Roig-Munar, F.X. 2006. Quantificació de les pèrdues de sediment produïdes pels usuaris de les platges de Menorca (Illes Balears) com a factor erosiu significatiu. *Boll. Soc. Hist. Nat. Balears,* 49: 115-122.

Roig-Munar, F.X., Rodríguez-Perea, A., Martín-Prieto, J.A. and Pons, G.X. 2009. Soft management of beach-dune systems as a tool for their sustainability. *Journal of Coastal Research,* SI56 (II): 1284-1288.

Roig-Munar, F.X., Martín-Prieto, J.A., Rodríguez-Perea, A., Pons, G.X. and Mir-Gual, M. 2012. Risk assessment of beach-dune system erosion: beach management impacts on the Balearic Islands. *Journal of Coastal Research,* 28 (6): 1488-1499.

Servera, J. 1997. *Els sistemes dunars litorals de les Illes Balears.* Ph.D. Thesis, University of Balearic Islands, Mallorca, Spain.

Servera, J. 2002. Eurosion Case Study. Can Picafort, Isle of Mallorca (Spain). In: http://copranet.projects.euccd.de/files/000153_EUROSION_Can_Picafort_fin.pdf

Servera, J., Gelabert, B. and Rodríguez-Perea, A. 2009. Development and setting of the Alcudia Bay beach-dune system (Mallorca, Spain). *Geomorphology,* 110: 172-181.

Smith, H.T. 1960. Physiography and photo interpretation of coastal sand dunes. Final report NONR – 2242 (00), Office of Naval Research, Geographical Branch, 60 pp.

Smyth, T.A.G., Jackson, D.W.T. and Cooper, J.A.G. 2011. Computational fluid dynamic modelling of three-dimensional airflow over dune blowouts. *Journal of Coastal Research* SI64 (1): 314-318.

Smyth, T.A.G., Jackson, D.W.T. and Cooper, J.A.G. 2012. High resolution measured and modelled three-dimensional airflow over coastal bowl blowout. *Geomorphology,* 177-178: 62-73.

Tastet, J.P. and Pontee, N. 1998. Morpho-chronology of coastal dunes in Medoc. A new interpretation of Holocene dunes in Southwestern France. *Geomorphology,* 25: 93-109.

Thieler, E.R., Martin, D. and Ergul, A. 2003. The digital shoreline analysis system, version 2.0.: shoreline change measurement software extension for ArcView: USGS N.S. Geological survey open-file report, 03-078.

Van Boxel, J.H., Jungerius, P.D., Kieffer, N. and Hample, N. 1997. Ecological effects of reactivation of artificially stabilized dunes. *Journal of Coastal Research,* 3: 57-62.60: 1-34.