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1 **Geomorphologic characteristics and evolution of managed dunes** 2 **on the South West Coast of France**

3

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8

9 **Highlights:**

10 - A geomorphologic classification of calibrated foredunes along the 230 km of the Aquitaine coast

11 - Relation between dune management actions, marine and aeolian driven process

12 - 55.5% of the calibrated foredunes meet the “ideal profile”, 21.5% need specific attention

13 - Soft management strategies require 4 to 5 years to stabilize dunes

14 - Maintaining the foredunes over the next decades requires extensive new management strategies

15

16 **Abstract**

17 The calibrated foredunes of the Aquitaine coast (SW France) constitute an example of secular extensive
18 application of nature-based solution. Being one of the longest and largest dune systems in Europe, this
19 iconic landscape offers considerable services to coastal societies. Since the mid-half of the 18th century,
20 human work on sediment flows has resulted in the emergence of large sets of foredunes, currently
21 constituting an almost 230 km-long managed barrier against inland sand invasion, coastline erosion,
22 coastal flooding and also a major reserve of biodiversity. Last massive mechanic shaping of the
23 foredunes following a so-called “ideal profile” date back to the 1970s-80s and aimed to limit erosion
24 dynamics and sediment mobility. Since, they have been facing multiples disruptions over the years
25 which have considerably modified their morphology, especially during the last decades. Calibrated
26 foredunes are currently exhibiting impressive dimensions with a mean dune height of about 16.6 m
27 (peaking at more than 30 m in some locations) and a dune width mean along the coast of 187 m. Today,

1 55.5% of them meet the “ideal profile” shape standards or surpass the in terms of dimensions whereas
2 21,5% of the calibrated foredunes are considered “narrowed” and need specific attention. This regional
3 analysis, based on extensive airborne LiDAR datasets from 2011 to 2018, includes (i) a dune
4 morphology classification based on several basic geomorphological indicators (dune width, height, crest
5 position, back dune elevation) compared to a calibrated “idealised” shaped profile, (ii) a quantification
6 of marine beach-dune and aeolian sediments flows (in m/year and m/m²/year) and forms on dunes
7 (scarps, blowouts, depositional lobes), as an indicator of the recent dynamics affecting dune morphology
8 and (iii) a study of management control of calibrated foredunes (4 613 interventions) including actions
9 taken after the outstanding winter of 2013-2014. As expected, intensive dune management are mainly
10 focused where assets are directly threatened. The study highlights the importance and the efficiency of
11 human management on dune evolutions (long term dune form stability, control of gullies and incipient
12 frontal blowout after marine erosion, protection of human issues). However, today management actions
13 (wind fence, branch cover, planting and reshaping) are not conditioned by foredune morphology or last
14 decade’s beach-dune dynamic (sediment availability, chronic coastline erosion). Considering long-term
15 erosion projections and expected impact of climate change, the analysis shows the need of more global
16 and extensive strategies in order to preserve the protection role of foredunes in the coming decades.

17

18 **Keywords:** *coastal geomorphology, LiDAR, Calibrated foredunes, dune management, Nature based*
19 *solution, Aquitaine coast*

20

21

22

1. Introduction

Dunes constitute a major subject of interest for coastal management, underlying an extensive appropriation of coastal areas. These particular environments provide several services to coastal societies (*Barbier et al., 2011; Barbier, 2017; Van der Biest, 2017; Drius et al., 2019*). They form rich and diverse ecosystems where plants and animals have adapted to their specific climate and resources (*Grootjans et al., 2004; Acosta et al., 2008; Everard et al., 2010*). As coastal dunes form an interface between marine and land areas, they also play an important role in human protection against natural hazards (*Hanley, 2014; Silva et al., 2016; Feagin et al., 2015; Maximiliano-Cordova et al., 2019*).

In the past decades, coastal dunes have been facing increasing external pressures (*Defeo et al., 2009*). Being structurally mobile features, they are very sensitive to sediment availability (*Davidson-Arnott and Law, 1996; Bauer and Davidson-Arnott., 2003; Aagaard et al., 2004*) as well as human activity, primarily urbanization processes (*Martinez et al., 2019*), and leisure activities (*Lemauiel and Rozé, 2003*). They are influenced by climate change processes such as changes in storm intensity and patterns and sea level rise, which both have an impact on their morphology (*Winter and Ruessink, 2017*), vegetation cover (*Keijsers et al., 2016; Ruggiero et al., 2018*) and mobility (*Carter 1991, Pusty and Silveira 2010*).

Recently, coastal researchers provided numerous studies to better understand foredunes' diversity and evolution paths. They include sand transport activation (*Nordstrom et al., 2007; Meerkerk et al., 2007; Schupp et al., 2013; Pye and Blott, 2017; Ruessink et al., 2018; Castelle et al., 2019*), vegetation interaction with sediment transportation (*Ruggiero et al., 2018; Keijsers et al., 2016; Figlus et al., 2017; Feagin et al., 2015*) and beach/dune sediment transfer processes (*Bauer and Davidson-Arnott, 2003; Houser et al., 2015; Ruessink et al., 2016; O'Keefe et al., 2018; Laporte-Fauret et al., 2019*).

At regional scale, studies of classification of foredunes and dunes (morphology and dynamics) can be found in Australia (*Hesp, 1988; Doyle et al., 2019*); North America (*Houser et al., 2015; Brodie and Spore, 2015, Davidson-Arnott et al., 2018*) or in Europe in the Netherlands (*Arens and Wiersma, 1994*) and Italy (*Carbau et al., 2015, Bezzi et a., 2018*). While the Aquitaine coast presents one of the longest and largest dune system in Europe (*Froidefond and Prud'homme, 1991*), existing classifications at the

1 regional scale are mainly qualitative (*Favennec 2002, Bernon et al. 2018*) and disregard the relationship
2 between dune morphology and management strategy. *Hesp (2002)* defines foredunes as “*shore-parallel*
3 *dune ridges formed on the top of the backshore by aeolian sand deposition within vegetation*”. In the
4 South West of France, the history, size and morphology of foredunes differ from classical definitions
5 and classically described beach-dune relationship (*Short and Hesp 1982*). Measures taken since the
6 beginning of the 19th century to limit inland sand invasion led progressively to the development of
7 massive foredunes along the coast (*Barrère, 1992*). Thus, we name calibrated foredunes this first line of
8 dunes whose former development is the results of human work and massive reshaping actions. Though
9 their maintenance was variable during the 19th and 20th century, they have been continuously managed
10 (wind-fences, marram grass planting, reshaping...) since the 1980s to limit erosion processes. This
11 shaped and managed coastal dunes system constitutes a fence all along the coast, whereas areas of free
12 evolution dune are very limited (*Castelle et al., 2019*). Current characteristics of calibrated foredunes
13 are the result of different evolution paths closely linked to sediment availability and their resilience after
14 storm events (*Castelle et al., 2018, Nicolae Lerma et al., 2019*).

15 In this study, we aim to provide a geomorphological analysis and classification of calibrated foredune
16 along the Aquitaine coast. We identify the specificities of foredune systems and confront them with
17 current management strategies. Our methodology relies on a quantitative analysis that uses extensive
18 coverage LiDAR (Light Detection And Ranging) and inventories of management actions. This analysis
19 is conducted at regional (along 230 km of continuous coast) and local scale (few hundred meters) for
20 complementarity, focusing on two contrasted examples uniformly exposed to coastal hazards.

21 Through the evaluation of foredune characteristics and evolutionary paths, we aim to identify areas
22 vulnerable to chronic erosion (long-term) or storm induced perturbations (short-term). By doing so, we
23 seek to shed light on some highly vulnerable areas and provide a global diagnostic in order to preserve
24 foredune protection services in the long run. As this work aims to connect foredune evolution to
25 management practices, we then offer integrated management scenarios and orientations of foredunes in
26 a context of a receding coastline.

27

28

2. Study area

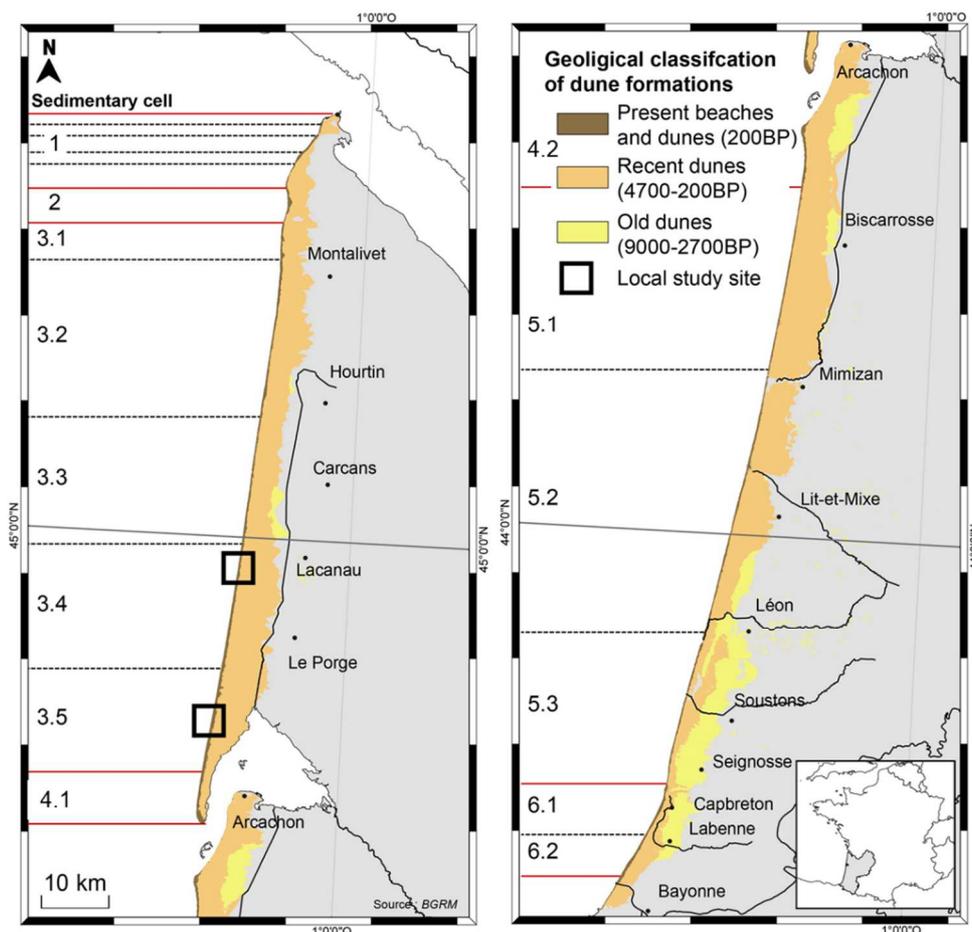
2.1. The Aquitaine dune system

The South West of France presents a 350 km-long coastline that includes a 230 km long sandy coast, from the Gironde Estuary to the rocky headland of Cap Saint-Martin (*BRGM and ONF, 2018*). The coast shows significant different alongshore characteristics (e.g. dominant longshore drift, nearshore sandbars configuration, beach width or sediment grain size) leading to a division of the coast into relatively homogeneous sedimentary cells or subcells (cf. Fig. 1). A full description of the segmentation of the coast is detailed in *BRGM and ONF (2018)* and summarized in *Nicolae Lerma et al., 2019*.

The Aquitaine coast is meso- to macrotidal, with an annual mean spring tidal range of approximately 3.7 m and a maximum tidal range reaching up to 5 m during spring tides. It exhibits large sandy beaches with a width at low tide between 100 to 300 m from north to south (cell 3 to 5) and a median grain size about 0.03 mm. Compared to rest of Aquitaine coast, beaches located at the extreme north of the region (cell 1 and 2, Fig. 1) are almost flat (slope = 2 to 4%) and less than 50 m wide. Coarser sediment (cell 2) and paleosol outcrop are often observed due to a specific geological history (*Stéphan et al., 2019*). At the extreme south (cell 6), beaches are also characterized by coarse sand to gravel sediment and dry beaches at low tide are around 100 meter wide (*Nicolae Lerma et al., 2019*). Beach slope are steeper, reaching more than 10% and the upper part of the beach generally exhibit successive generations of wave built berms.

Since the last glaciation, the combination of high sediment supply, sea level-variation, and sustained wind dynamics has led to the development of several dune forms (*Tastet and Pontee, 1998*). Three different dune generations spreading out around 10 kilometres inland (Fig. 1) have been identified (*Froidefond and Prud'homme, 1991*). The older and more remote inland dunes are parabolic dunes. They naturally developed and migrated from 1200 to 500AD (*Tastet, 2004*). A second generation is composed of barkanoid dunes. They developed from 1500 to the beginning of the 19th century. Both generations represent respectively 25 000 and 85 000 ha of dunes (*BRGM and ONF, 2018*). The last generation is composed of large calibrated foredunes mostly shaped by massive human management actions.

1 Today, facing the ocean, the calibrated foredunes of the Aquitaine coast are part of the highest and
 2 largest coastal dunes in Europe, peaking at more than 30 m above Mean Sea Level (MSL) and easily
 3 extending 150-200 m landward (cf. Fig. 2).
 4 Having a global look at those dunes, they regularly appear as linear and vegetated entities (Fig. 2). Their
 5 development is the result of important human intervention and accompaniment of natural processes
 6 since the mid of the 19th century.



7
 8 *Fig. 1: Geological classification of the coastal dune systems and sedimentary cells (with their*
 9 *subdivisions) along the Aquitaine region (SW France). Black squares represent areas where recent*
 10 *dune evolution and management practices are closely analysed and detailed.*

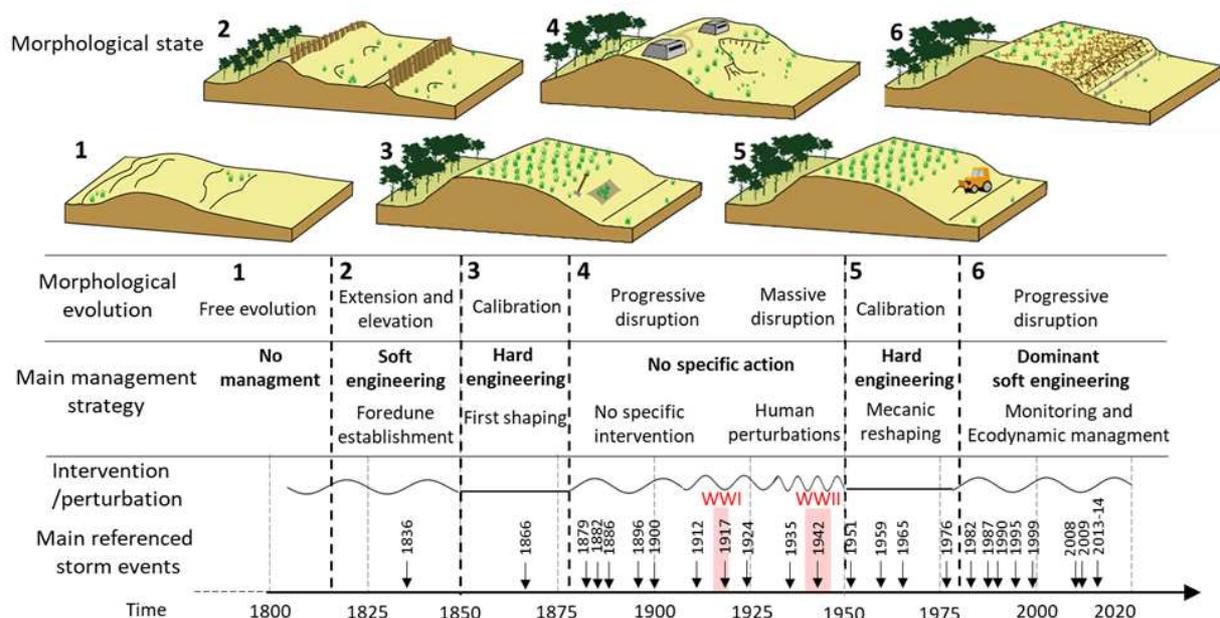
11



1
 2 *Fig. 2: Oblique photographs at low tide of beach-dune systems along the Aquitaine coast in July 2018.*
 3 *From North to South : a) Cell 3.1 (Grayan et l'Hopital) ; b) Cell 3.2 (Hourtin) ; c) Cell 3.5 le Porge ;*
 4 *d) Cell 4 (la Teste-de-Buch) ; e) Cell 5.2 (Lit et mixe) ; f) Cell 6.2 (Tarnos). Source: Observatoire de la*
 5 *Côte Aquitaine*

6
 7 Figure 3 illustrates the key management initiatives conducted along the Aquitaine coast during the last
 8 two centuries. First actions were taken in order to limit sand invasion and preserve the incipient planted
 9 pine forests. The French State decided to establish and maintain a stable first line of dunes. Thus, all
 10 along the coast, state agents put successive rows of wooden fences up on the beach (see Fig.3, state 2).
 11 Interactions with sediment flows resulted in their deposition and accumulation in the form of dunes
 12 (*Barrère, 1992*). Stabilized through the planting of marram grass, these foredunes progressively elevated
 13 and widened to form the existing barrier against coastal hazards. Major calibration works took place
 14 during the 19th and 20th centuries along most of the Aquitaine coastline (see Fig3, state 3). However,
 15 during the first half of the 20th century and especially during the World Wars periods, foredunes suffered
 16 important destructuration due to successive storms and lack of maintenance (see Fig.3, state 4). From

1 1945 to the beginning of the 1980s, the spread of motorized tools allowed massive reshaping works (see
 2 Fig. 3, state 5). The specific morphology and dimensions used for shaping works was designed by the
 3 engineer J. J. Goury and known as the “ideal profile” (*Paskoff 2001*), seek to limit sediment
 4 transportation and provide protection against hazards (*Barrère, 1992*). Until the 1980s, managers have
 5 mostly taken soft management action to maintain a particular dune shape following an eco-dynamic
 6 approach (*Barrère 1992*). Nowadays, the French National Forestry Office (ONF) is the main
 7 administrator of state dune management on the Aquitaine coast. Following State directives, it acts to
 8 preserve calibrated foredunes stability and limit erosion processes on the long term (*Favennec, 2002 ;*
 9 *Gouguet, 2018*). For more than 30 years, environment-based engineering has been commonly used to
 10 manage dune dynamics in areas where human stakes are limited (*Favennec, 2002 ; Gouguet, 2018*). It
 11 includes branches cover laying to limit sand transportation, wind-fences setting-up to enhance sediment
 12 accumulation and marram grass planting to stabilize sediment accumulation (Fig. 3, state 6).



13

14 *Fig. 3 : Synthesis of foredune morphological evolution and management strategies during the last two*
 15 *centuries. The listing of the main storm events (non-exhaustive) is extracted from the storm database of*
 16 *the Observatoire de la Côte Aquitaine ([http://www.observatoire-cote-aquitaine.fr/-Historique-des-](http://www.observatoire-cote-aquitaine.fr/-Historique-des-tempestes-)*
 17 *tempestes-)*

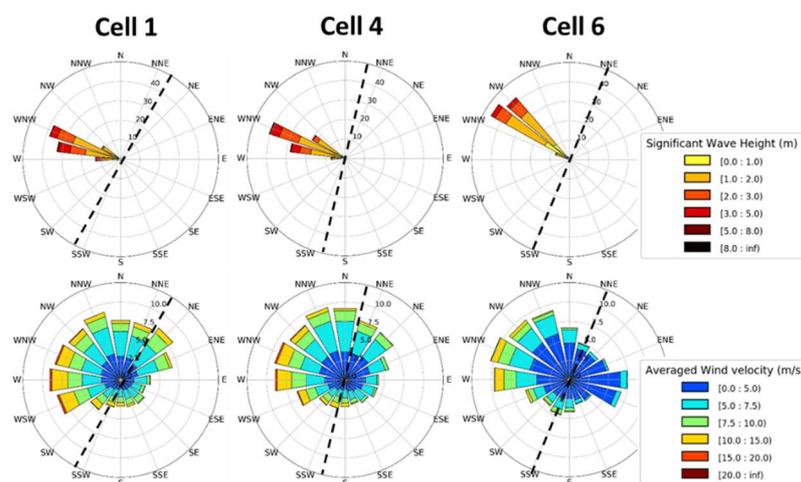
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19

1 2.2 Forcing conditions and actual evolution of the coast

2 2.2.1 Forcing conditions

3 The coast is exposed to Atlantic swell for both annual means and storm conditions. The wave climate is
 4 energetic and strongly seasonally modulated with a monthly-averaged significant wave height H_s (peak
 5 wave period T_p) ranging from 1.1 m (8.5 s) in July with a dominant W-NW direction to 2.4 m (13 s) in
 6 January with a dominant W direction (*Castelle et al., 2017*). Mean wave directions explain, relatively
 7 to the orientation of the coast, the general characteristics of the residual longshore drift (*Idier et al.,*
 8 *2013*), almost North-South oriented (except in Cell 1, cf. Fig. 4). Extreme offshore H_s conditions defined
 9 here as 100-year return values are quite similar with a slight increase from north ($H_s = 11$ m) to south
 10 ($H_s = 11.6$ m) (*Nicolae Lerma et al., 2015*).



11
 12 *Fig. 4: Directions and values of significant wave heights (m) and averaged wind velocities (m/s)*
 13 *recorded between 2008 and 2018 along three of the six sedimentary cells of the Aquitaine coast*
 14 *(hourly hindcast data, www.umr-lops.org/marc). Dashed black lines represent the coastline*
 15 *orientation at each sedimentary cell.*

16
 17 Winds orientations on the Aquitaine Coast are equal along the coast except at the extreme south, where
 18 offshore winds are overrepresented in comparison with the rest of the coast (see Fig. 4). Winter winds
 19 mainly come from the west whereas dominant spring and summer winds (from April to September)
 20 come from the northwest and north. Main constructive winds, which are prone to sand accumulation on
 21 the dune foot, mostly come from the north or south with a velocity > 5 m/s (*Nicolae Lerma et al., 2019*)

1 respectively to the typical median grain size, between 0.02 and 0.04 mm (*Pedrerros et al., 1996*). Relative
2 to the main orientation of the coast, these directions allow longer fetches and thus a larger transport
3 capacity. Westerly winds can also contribute to foredune growth, but only where the beach systems are
4 the widest in the southern Gironde (Cells 3.5, 4) and Landes coasts (Cell 5.1 to 5.3). Sediment mobility
5 associated with aeolian flux along the coast was estimated at 15 to 30 m³/m/yr before the fixation of the
6 dune (*Froidefond and Prud'homme, 1991*). Because of historical massive reshaping and current
7 management actions, aeolian sand loss moving landward is today almost negligible (*Aubié and Tastet*
8 *2000*). However, accumulation and development of incipient foredunes at the beach-dune interface after
9 an erosion sequence can occur after a few seasons (*Nicolae Lerma et al., 2019*)

10

11 ***Recent coastline evolution***

12 Nowadays, the Aquitaine coast is largely eroding (*Bernon et al., 2016*). Since the mid of the 20 century,
13 available aerial photography processing has showed contrasted situations along the coast, from almost
14 stable areas to 300 m and 600 m retreating areas since 1950, respectively near to the Gironde estuary
15 and the Cap Ferret spit (*Castelle et al., 2017*). Some areas even have experienced loss of hundred meters
16 during the same period mostly near to the Gironde estuary mouth (cell 1) or near to the Arcachon lagoon
17 pass (cell 4). *Bernon et al. (2016)* show an average coastline retreat (period 1985-2014) of 2.5 m/year
18 in Gironde and of 1.7 m/year in Landes. Nevertheless local coastline evolution trends are highly variable
19 with a rate of -3.3 m/year in Nord Medoc (Cell 1) and -0.8 m/year in central Landes (sub-Cell 5.2 or
20 5.3). If the long-term tendency is quite well estimated, extreme winter energetic conditions and cluster
21 effect in term of erosion are still a theme of research. Short-term storm events such the ones that occurred
22 in 2013-2014 had a massive impact on beach-dune systems (*Bulteau et al., 2014 ; Castelle et al., 2015,*
23 *Masselink et al., 2016*). Some part of the coast have experienced coastline retreats higher than 20 m
24 (*Bulteau et al., 2014 ; Castelle et al., 2015*) and sediment losses were massive at the beach-dune interface
25 leading to major dune destabilisations. However, during the 2014 – 2018 period, sediments have
26 massively move back to the beach dune-interface (*Nicolae Lerma et al. 2019; Robin et al., 2020*). The
27 accumulation of 4 years of relative moderately energetic winters and over representation of most
28 constructive winds (NNW to N > 5 m.s⁻¹) during springs and summers lead to the accumulation and

1 development of an incipient foredunes against the dune foot. Incipient foredunes are generally
 2 observable along the coast of Gironde and Landes (Cells 3.3 to 5.3).

3

4 **3. Data and methods**

5 **3.1 LiDAR and orthophotographs**

6 As part of the OCA, the French National Geographic Institute (IGN) regularly sets up airborne LiDAR
 7 campaigns covering the whole Aquitaine coastline. Generated DTMs are 1m horizontally gridded. They
 8 use the French official topographic reference NGF/IGN69. Datasets used in the present study cover
 9 years 2011, 2014, 2016, 2017 and 2018, the latter being only used in the local analysis (Table 1). Apart
 10 from the 2011 campaign that took place after winter, all campaigns were conducted in autumn. It allows
 11 interannual comparisons and limit seasonal bias. All data sets were controlled using 1 550 D-GPS point
 12 measured in unobstructed and flat surfaces on hard ground, such as parking, sports grounds, and roads
 13 all along the coast (*Ulvoas and Ayache 2019*). Comparisons emphasises an error inferior to 20 cm and
 14 generally near to 10 cm (Table 1), meeting typical LiDAR accuracy. To complete LiDAR data
 15 acquisition, synchronic orthophotographs were acquired and are used in the present study on the same
 16 periods.

17

18 Table 1: Main characteristics of the airborne LiDAR campaigns used in the study.

Campaign	Date of the survey	Altimetric estimated error Z (m)
LiDAR 2011	5 March to 21 May 2011	0.196
LiDAR 2014	23 - 24 October 2014	0.144
LiDAR 2016	29 - 30 October 2016	0.106
LiDAR 2017	4 - 6 and 7 October 2017	0.102
LiDAR 2018	23 - 24 October 2018	0.096

19

20 LiDAR is a commonly used method to survey coastal environments (*Doyle et Woodroffe, 2018 ; Saye*
 21 *et al., 2005; Brodie and Spore, 2015*). It can provide precise data on dunes topographic characteristics

1 and their evolution. Several indicators can be defined (*Brodie and Spore, 2015 ; Hardin et al., 2012*)
2 and monitored at different time scales: event-scale (*Pye and Blott, 2016*) and pluriannual-scale (e.g. *Le*
3 *Mauff et al., 2018, Nicolae Lerma et al., 2019*). The following analysis relies on various data processing
4 that use GIS tools that will be explain in the following sections. Morphological parameters and
5 geomorphological dynamics will be analysed at regional scale and regarded relatively to management
6 actions.

7
8 Because soft dune management is always locally scaled, we will focus on two specific sites where dunes
9 present contrasted characteristics and management strategies. Both sites, site of Dune Rambaud at the
10 south of Lacanau town and site of la Torchère at the root of the Cap Ferret Spit (Fig. 1), were subject to
11 important shoreline retreat and sediment mobility after 2013-2014 winter, leading to ONF's intervention
12 the following years.

13

14 **3.2 Calibrated foredunes delimitation**

15 *Identifying dunes as a geomorphological feature*

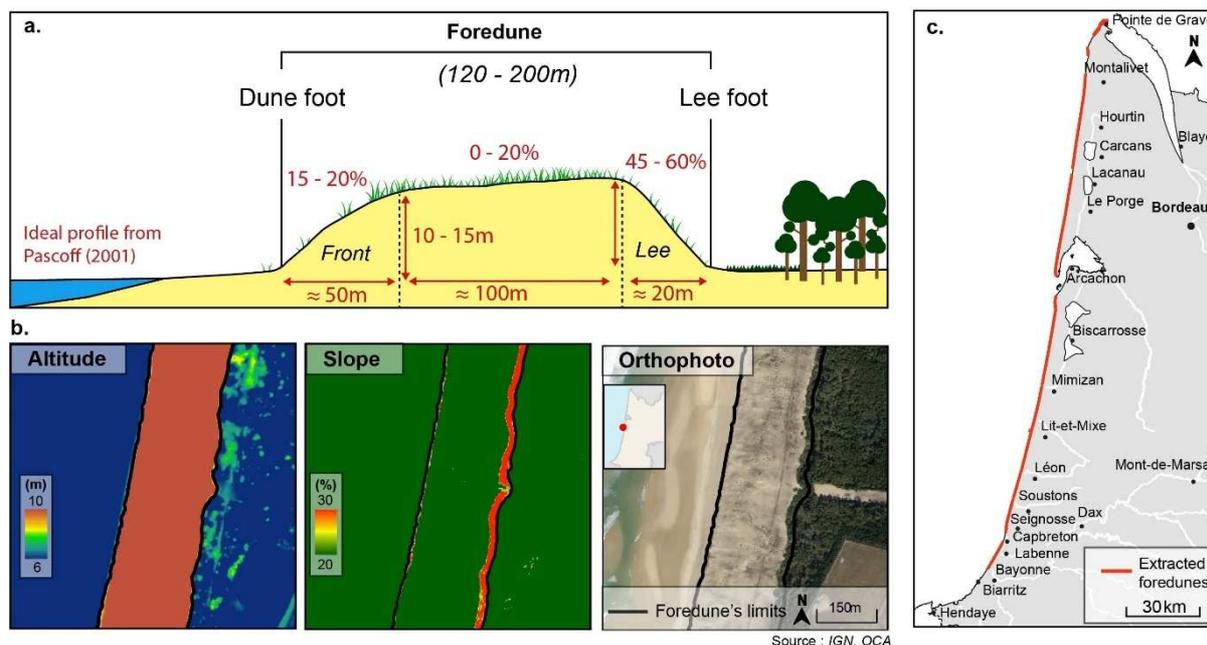
16 As most of Aquitanian calibrated foredunes were originally shaped following specific dimensions and
17 profiles, called the “ideal profile”, (*Duparc, 1983; Barrère 1992; Favennec, 2002*), the current dune
18 profile is compared to this reference state (Fig. 5a). Through this process, we aim to offer a regionally
19 scaled and homogenous method to grasp global dune morphodynamics and evaluate human hold on
20 these particular geomorphologic features. Given their geometrical shape, calibrated foredunes of the
21 Aquitaine can be identified as individual features. Their limits are marked out by two slope breaks. The
22 seaward transition from the dune to the beach is defined as the dune foot. Among the numerous existing
23 indicators to define shoreline position (*Boak and Turner, 2005*), the slope break representing the dune
24 foot is a common feature used for shoreline extraction (*Castelle et al., 2015, Nicolae Lerma et al., 2019*).
25 Consistent with the more recent LiDAR dataset analyzed at regional scale, the shoreline position in 2017
26 is used to represent the dune foot line. On its landward side, transition from the dune to the backdune
27 area is defined as the “lee foot”. Backdunes along the Aquitaine coast are generally composed by large
28 flat areas covered with moss and grass or by a first line pine forest. This specific area at the back of

1 foredunes is locally named “lette”. As shown in Fig. 5 (b), the lee foot line is manually digitalized based
2 on the combination of altimetric criteria (step 1), slope maps (step 2) and orthophoto interpretation (step
3 3) following an iterative process leading to a semi-automatic detection (Fig. 5, b). In case of no clear
4 landward transition between dunes and the lee, cross-shore altimetric profiles are extracted to determine
5 the most appropriate location of the lee foot position in 2017.

6 Parts of the coast composed of free evolving dune sites or urbanised sea front are not considered in this
7 study as (i) we aim to focus on the evolutionary path of calibrated and softly managed foredunes, (ii)
8 the way non-managed dunes evolves is very different compared to managed or vegetated foredunes and
9 (iii) our foredune classification is based on the calibrated dune “ideal profile”. Furthermore, the dune
10 extraction process relies on a clear identification of the foredune dune foot and lee foot. Consequently,
11 several locations where former calibrated foredunes do not present clear boundaries (such as the North
12 of Gironde) had to be set aside (see Fig. 5, c.).

13
14 Using this methodology, 87% of the Aquitaine sandy coast presents clearly delimited calibrated
15 foredunes. Potential error in limit detection, taking into account both LiDAR and orthophotography
16 error and work subjectivity’s degree (both dune foot and lee foot location), is estimated in the worst case
17 about 10 to 20 m. These values correspond to about 5% of mean dune width along the coast, limiting its
18 influence on results.

1



2

3 *Fig. 5: Calibrated foredunes extraction methodology: (a) Managed dune average shape and*
 4 *dimensions on the Aquitaine in relation to the “ideal dune profile” that served as a reference in dune*
 5 *management practices. (b) Calibrated foredune dune extraction process using GIS tools : LiDAR data*
 6 *is used to differentiate important altitude change and slope breaks (1,2) while orthophotographs help*
 7 *identifying changes in vegetation cover and potential bias (3).(c) Locations on the coastline where*
 8 *calibrated foredunes have been extracted into a GIS using our methodology.*

9

10 In order to study morphologic dune variability, polygons of dunes are cut-up using cross-sections
 11 defined with a spacing of 100 m. Successfully used in several studies (*Debaine et Robin, 2012 ; Juigner*
 12 *et al., 2017 ; Wang et al., 2018*), this process allows creating 100 m-large polygons representing a
 13 specific section of the coast. Cross-shore transects are then relocalised at the centre of each boxes. Both
 14 cross-shore transects and boxes are used to extract multidimensional data on specific locations, allowing
 15 alongshore comparisons.

16

17

18

1 3.3. Morphometric parameters

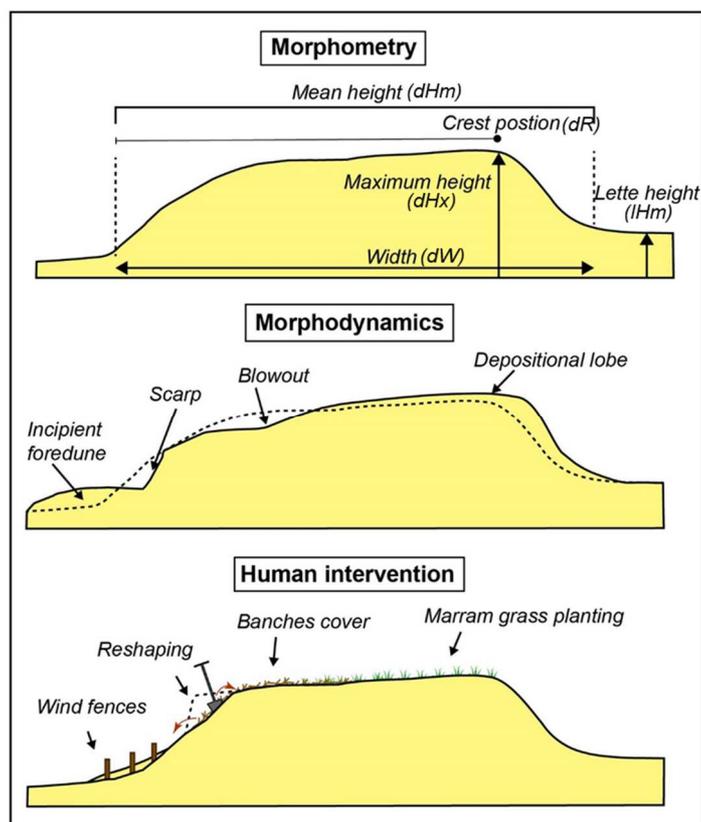
2 LiDAR data are used to evaluate morphometric characteristics of dunes. Fig. 6 explains the different
3 parameters that are extracted to figure global dune morphology. They include:

- 4 • Width (dW): for each transect, distance between the dune foot and the lee foot (in meters)
- 5 • Mean height (dHm): for each box, mean dune height (in meters/NGF)
- 6 • Max height (dHx): for each box maximum reached height (in meters/NGF)
- 7 • Dune crest position (dR): for each transect, distance of the highest point from the dune foot (% of
8 the dune width)
- 9 • Lette mean height (lHm): for each box, a buffer-zone is created hundred meters landward from
10 dune's lee foot position. Mean height values are extracted from the buffer using LiDAR data (in
11 meters/NGF).

12

13 Calibrated foredune dimensions (width and height) give a general overview of the dune shape.

14 Comparisons with managed “ideal profile” reference emphasise on their long-term evolution. Dune crest
15 position reinforce the measurement of dune morphology and informs on current sediment dynamics (e.g.
16 sand deposition at the crest front or at the back of the dune). Compared to the “ideal dune profile” where
17 the highest point is usually located on the landward section of the dune, this parameter highlights recent
18 morphological evolutions in addition to giving elements on the global dune form. These parameters, as
19 well as the lette mean height, are also valuable information to evaluate calibrated foredunes protection
20 role against natural hazards.



1
2 Fig. 6: Parameters extracted using transects and boxes segmentation of dunes on LiDAR and ONF's
3 management data sets. This process helps analysing dune dimensions (morphometric parameters),
4 shape (morphodynamic parameters) and management (human intervention) at different scales.

5

6 3.4. Geomorphologic parameters and pluriannual dune evolution

7 3.4.1 Shoreline mobility rate

8 The coastline evolution trends are geographically highly variable along the Aquitaine coast. Since 1985,
9 (Bernon *et al.*, 2016) the coastline has retreated at 2.5 m/year on average in Gironde and at 1.7 m/year
10 on average in Landes. However, along the Aquitaine coast, the erosion rate at the pluri-decadal scale
11 (Castelle *et al.*, 2018) and at the seasonal scale (Bulteau *et al.*, 2014) can have high geographic
12 variability. Local pluridecadal trends based on historical photography analysis since 1985 and DSAS
13 treatment (Bernon *et al.*, 2016) are considered. Shoreline evolution rate using the dune foot location is
14 measured using linear regression on shoreline position between 1985 and 2014 (including the effect of
15 the 2013-2014 winter). Values in m/years, have been attributed for each box (100 m alongshore). They

1 inform on dune front evolution and potential erosion perspectives when compared to dune dimensions
2 (see Fig. 17).

3

4 **3.4.2 Recent beach/dune interface evolution and Potential Pluriannual Resilience (PPR)**

5 On energetic open coasts, the beach-dune interface (defined here as an area extending 100 m seaward
6 on the beach (near the Mean Sea Level) and 50 m landward on the dune starting from the dune foot),
7 can massively evolve under storm conditions (*Castelle et al., 2015, Biauxque et al., 2019*). Between two
8 LiDAR campaigns, automatic detection of massive beach scarps (defined as an altitude loss exceeding
9 3 m, directly in contact with the dune foot) and incipient foredunes (altitude gains exceeding 1 m in
10 direct contact with the dune foot) realized in *Nicolae Lerma et al. (2019)* are exploited.

11 The beach-dune interface geomorphology is analysed through the identification of dune scarps and
12 incipient foredunes along the coast at two different time periods. Through this process, we aim to
13 illustrate the recent behaviour of the beach-dune interface. Relying on differential LiDAR data between
14 2014 and 2017, a beach-dune interface *potential pluriannual resilience (PPR)* indicator is proposed.
15 This qualitative indicator uses differential LiDAR data for 2011-2014 (after massive 2013-2014 storms
16 erosive sequence) and 2014-2017 (where the coast was globally subject to substantial recovery). Results
17 are classified using a graduation of identified features and the way they follow between the two periods:

- 18 - *Very high PPR: Only incipient foredune are observed*
- 19 - *High PPR: No scarp are observed*
- 20 - *Medium PPR: Scarp followed by incipient foredune*
- 21 - *Low PPR: Scarp and no incipient foredune*
- 22 - *Very low PPR: succession of dune scarps*

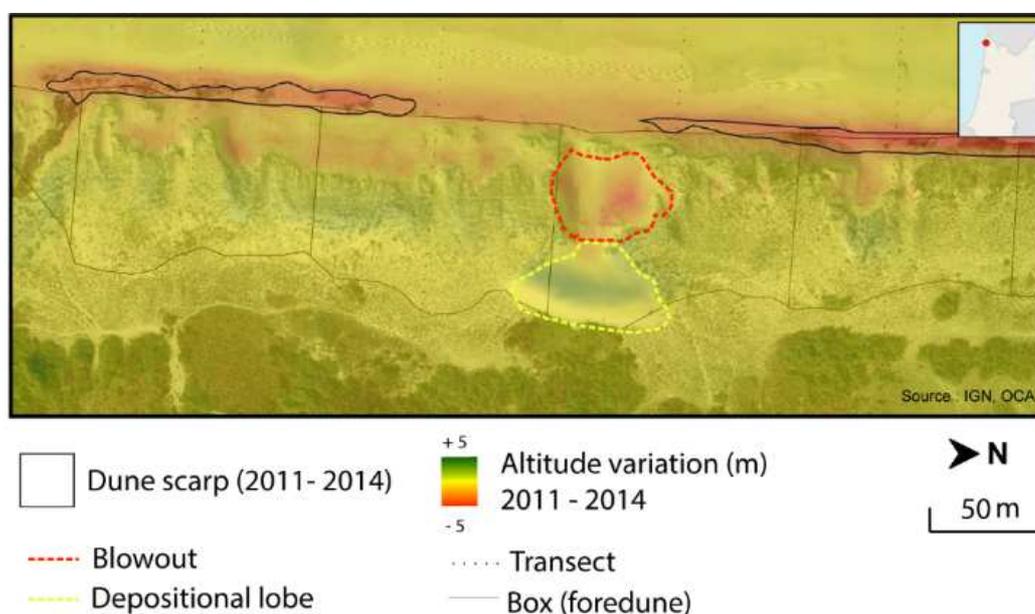
23

24 **3.4.3 Calibrated foredunes evolution mark and Aeolian effective sediment mobility**

25 Vegetated dunes are generally characterised by limited sand movements, making them relatively stable
26 on the long term (*Hesp 2002*). Sediment transport is often located on small-extended areas called
27 blowouts. These depressions cutting the dune front (frontal blowout) or located on the dune ridge evolve
28 at different timescales depending on wind forcing, location and form of the deflation basin, potential

1 vegetation recolonization and management actions. An inventory of geomorphologic features reflecting
 2 sediment mobility by wind driven processes is realised using orthophotos and LiDAR data from 2017
 3 (Fig. 7).

4 It includes detection of (1) *blowouts* on the dune front and (2) *depositional lobe* on the lee. Features
 5 maximum width are measured and added into a database. In Fig. 7, a differential elevation map (2011-
 6 2014) overlays an orthophotograph (2017). Important altimetric changes (± 5 m) matches bare sand
 7 areas (red and yellow dashed lines) with specific shapes. As the presence of blowouts is a sign of high
 8 sediment dynamics, depositional lobes highlight dune destabilisation processes and landward sediment
 9 migration (*Carter et al., 1990, Hesp and Hyde 1996*).



16 *Fig. 7: Example of dune geomorphologic features extracted using orthophotographs and LiDAR GIS*
 17 *treatment. Black lines show dunes scarps identified through semi-automatic detection on 2011-2014*
 18 *LiDAR differential elevation maps. Red and yellow dashed lines show geomorphologic features*
 19 *indicating aeolian sediment activity, inventoried through the analysis of 2017 orthophotographs.*

16 In addition, an evaluation of aeolian effective sediment mobility rate ($m/m^2/year$) is proposed. For each
 17 box, difference in altitude between 2017 and 2011 LiDAR data sets are computed. Results are given in
 18 absolute value, regardless of value's sign (increase or decrease). The resulting average rate (*per m²*)
 19 gives information on dune response to wind driven dynamics.

1 **3.5. Recent foredune management actions**

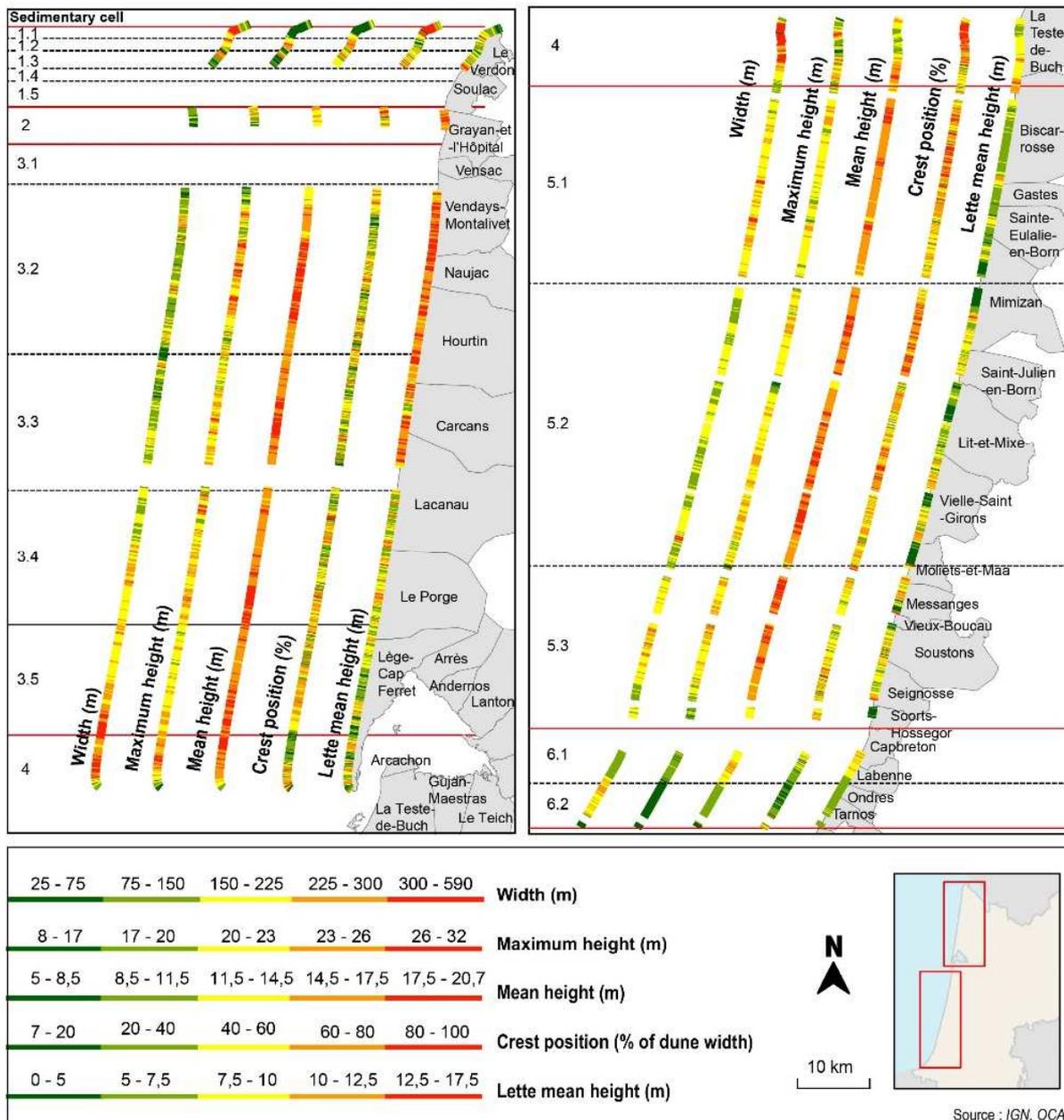
2 As part of its management strategy, the ONF gathers data on its actions to limit dunes erosion and
 3 migration processes. Information related to interventions are collected and integrated into a GIS
 4 database. It uses spatialised polygons, polylines or points depending on their characteristics. Datasets
 5 are organised on a year-to-year basis and according to intervention type. Management data used in this
 6 study relates to years 2011 to 2017 in order to meet available LiDAR datasets. Information related to
 7 ONF intervention on dunes during this period are extracted using boxes division. For each box, the
 8 number of interventions listed is computed using “select by location” tools. Only interventions related
 9 to sediment flow management are considered. They correspond to marram grass planting, wind fence
 10 set up, branches cover and dune front cut off. Pathways maintenance and waste collection are not
 11 considered in the present analysis.

12

13 **4. Results**

14 **4.1 Regional analysis**

15 A total of 1925 boxes and transects are used to extract data as described above. Results are organised
 16 using basic statistic parameters such as standard deviation and equal distribution. They show a large
 17 range of values for every considered parameter but several clusters are observable and geographic
 18 distribution of calibrated foredunes morphometric characteristics are close to the sedimentary cell
 19 division (Fig. 8). At the regional scale, except for some local areas described further on (e.g. North and
 20 South extrem end or Arcachon lagoon pass), the mean dune height is similar along the coast ($\overline{dHm} =$
 21 16.6 between 10 to 21 m). Considering all transects, $\overline{dHx} = 21.5$ m, between 8 to 31 m. On the other
 22 hand, dune width is much more variable with values extending from tens to several hundred meters (\overline{dW}
 23 = 187 m). This large dune width amplitude is closely related to current local sediment availability in the
 24 nearshore area. Lette mean height along the sandy coast is 8.6 meters. The lHm high values (>10m) are
 25 manly found in northern Gironde within cells 2 to 3.3. In contrast, lower values (around 7 m) are found
 26 in areas close to rivers mouth mostly in the Landes coast (Cell 5) underlying the role of calibrated
 27 foredunes as barrier against coastal flooding in this sector.



1
 2 *Fig. 8: Morphometric characteristics of the calibrated foredunes extracted using LiDAR data. They*
 3 *include dune width (distance between dune foot and lee foot in meters), Maximum height (highest*
 4 *point on each transect, in meters), Mean height (mean height within each box, in meters), crest*
 5 *position (highest point on each transect, % of the dune width from the dune foot) and Lette mean*
 6 *height (mean height on a buffer-zone generated hundred meters landward from dune's lee foot for*
 7 *each box, in meters). Transects are 100 meters apart from each other.*
 8

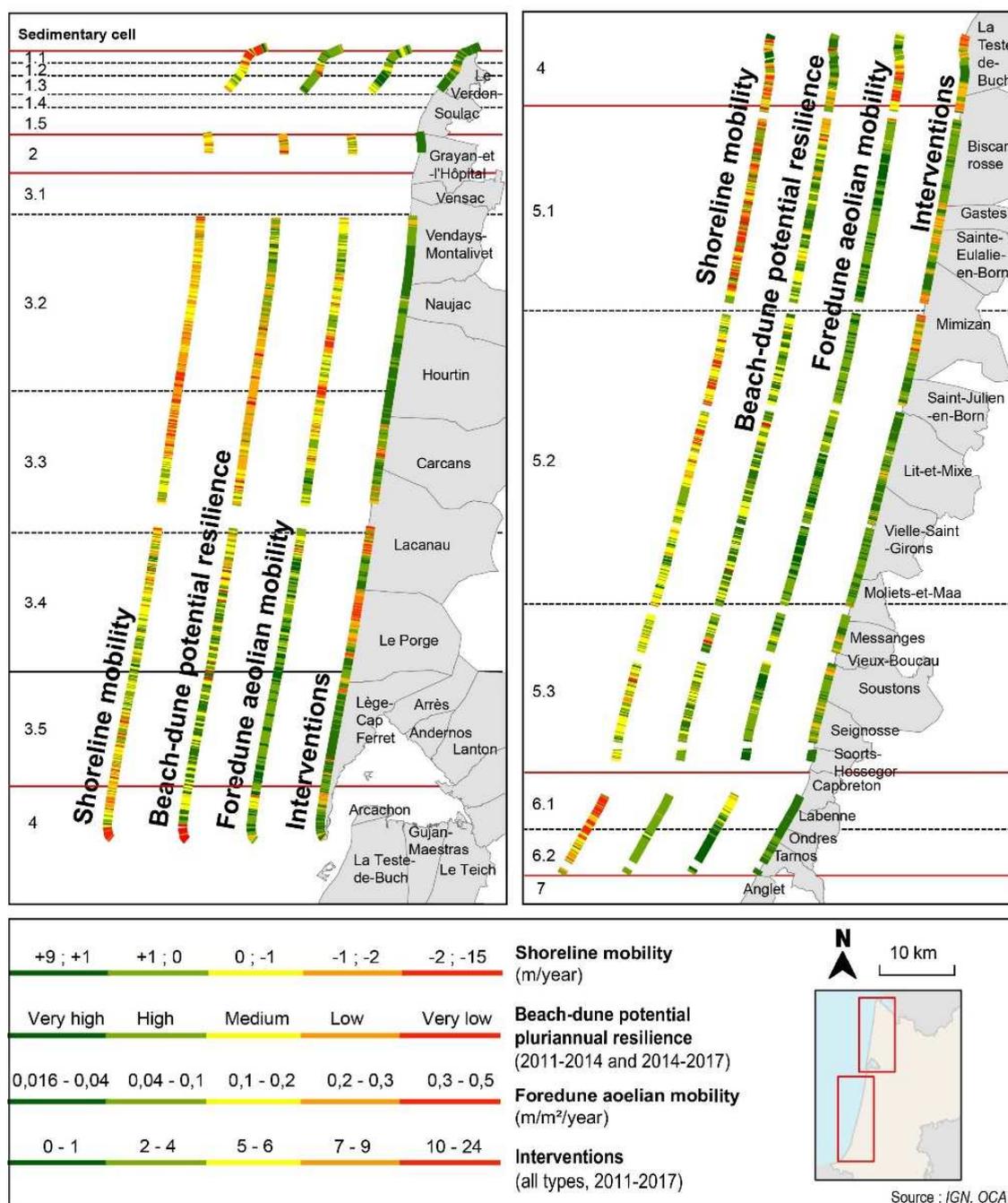
1 The dune crest position (dR) is analysed to complete this morphological investigation (Table 2). It is
2 often located close to the dune front in Gironde (usually within the first quarter of dune width starting
3 from the dune foot) whereas its position is closer to the back of the dune in the Landes, meeting the ideal
4 profile's characteristics. Compared to this reference state, results highlight potential sand deposal on the
5 dune front. Sand migration from the beach to the dune is highly dependent on dune front shape and
6 vegetation state. In presence of a steep slope front, sediments tend to accumulate at the back of the ridge.
7 Sand accretion progressively changes the dune morphology to the point where the highest point is
8 located close to the front (Fig. 2, c). Dune fronts with a softer slope have different dynamics as they
9 allow a more homogenous sand deposit on the dune. In this case, dunes highest point tends to remain on
10 its landward side (Fig. 2, f).

11 Fig. 9 focuses calibrated foredunes geomorphologic evolution related to sediment dynamics. They
12 include marine and aeolian induced processes observable on the dune. At the beach-dune interface, the
13 so-called shoreline mobility, beach-dune potential pluriannual resilience or PPR, are considered. Within
14 the dune boundaries, effective aeolian activity is considered. Effective Aeolian activity is completed by
15 a blowout and back dune depositional lobe cartography (Fig. 10). Results show large value ranges and
16 a substantial spatial variability along the coast. Shoreline position is globally retreating but the computed
17 resilience index shows that dune front with low short-term potential resilience to massive erosion
18 represents only 21% of the coast (Low to very low PPR). This confirms the relative high potential of
19 resilience of the coast to massive erosion under moderately energetic winters (*Nicolae Lerma et al.,*
20 *2019*).

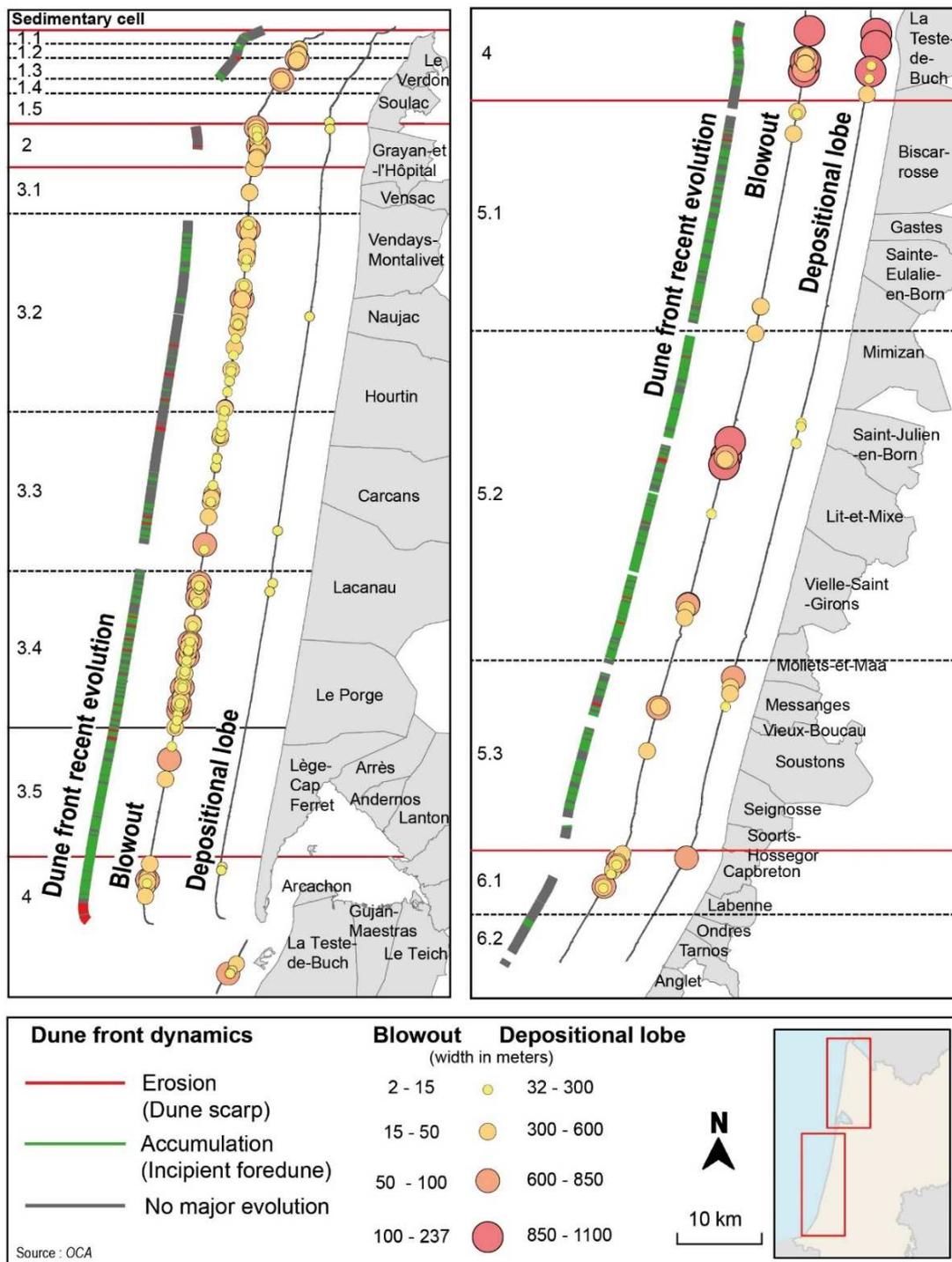
21 Average sediment movement due to aeolian driven processes between 2011 and 2017 is on average 0.08
22 m/m²/year, highlighting a great stability of the dune in comparison with beach-dune interface. However,
23 this value can notably vary locally. Maximum observed effective aeolian mobility by box is higher than
24 0.3 m/m²/year in almost all sedimentary cells and can reach more than 0.5 m/m²/year in North Gironde
25 or near to the Arcachon lagoon pass. Representative of this mobility, a total of 228 blowouts and 30
26 back dune depositional lobe are inventoried along the coast (width superior to 5 meters, Fig. 10).

27 The comparison of shoreline and aeolian mobility shows no significant correlations ($r^2 = -0,19$).
28 However, the superposition of both geographic distributions exposes similar pattern along the coast,

1 especially for Gironde coast. They show that chronic shoreline retreat (particularly in North Gironde) is
2 responsible for a progressive destabilisation of the dune morphology, promoting frontal blowout
3 generation and digging. In the centre and south Gironde, an area where chronic coastline erosion is less
4 marked, massive erosion sequences like the one that took place during winter 2013-2014, have also
5 deeply destabilised the dune front. In both cases (covering almost all the Gironde coast), steep and high
6 dune scarps have promoted dune front blow out development leading to higher effective sand mobility
7 in comparison to the rest of the coast. Even if the centre and the south Gironde present a relatively high
8 PPR and incipient foredune are currently observable, blowout development dynamics triggered in
9 response to the massive erosion are still active. Along the Landes coast, the coastline position is globally
10 more stable. Marine retreats of winter 2013-2014 were lower and beach-dune interface shows a greater
11 resilience potential. Consequently, observed aeolian activity is less significant than in Gironde and
12 massive blowouts and back dune depositional lobes are only observed in few locations. They are
13 significant in the northern part of locally free evolving dune (as commented further). In few local places,
14 the absence of recent dune management also results in dune destabilisation and sand mobility
15 reactivation. Along the rest of the coast of the Landes and unlike the Gironde coast, smooth slope of the
16 incipient or established foredunes tend to dissipate wind energy more efficiently whereas incipient dune
17 vegetation contributes to reduce sand transfer to the dune. In this part of the coast, sediment aeolian
18 mobility is lower and interventions are less frequent, illustrating the efficiency of shaped dune profile
19 properties to reduce sand mobility in context of long term stable or almost stable coast. On the opposite,
20 in the centre part of Gironde, more intensive management is required and is still dedicated to control
21 post 2013-2014 winter frontal blow out activation responding to beach-dune marine erosion.



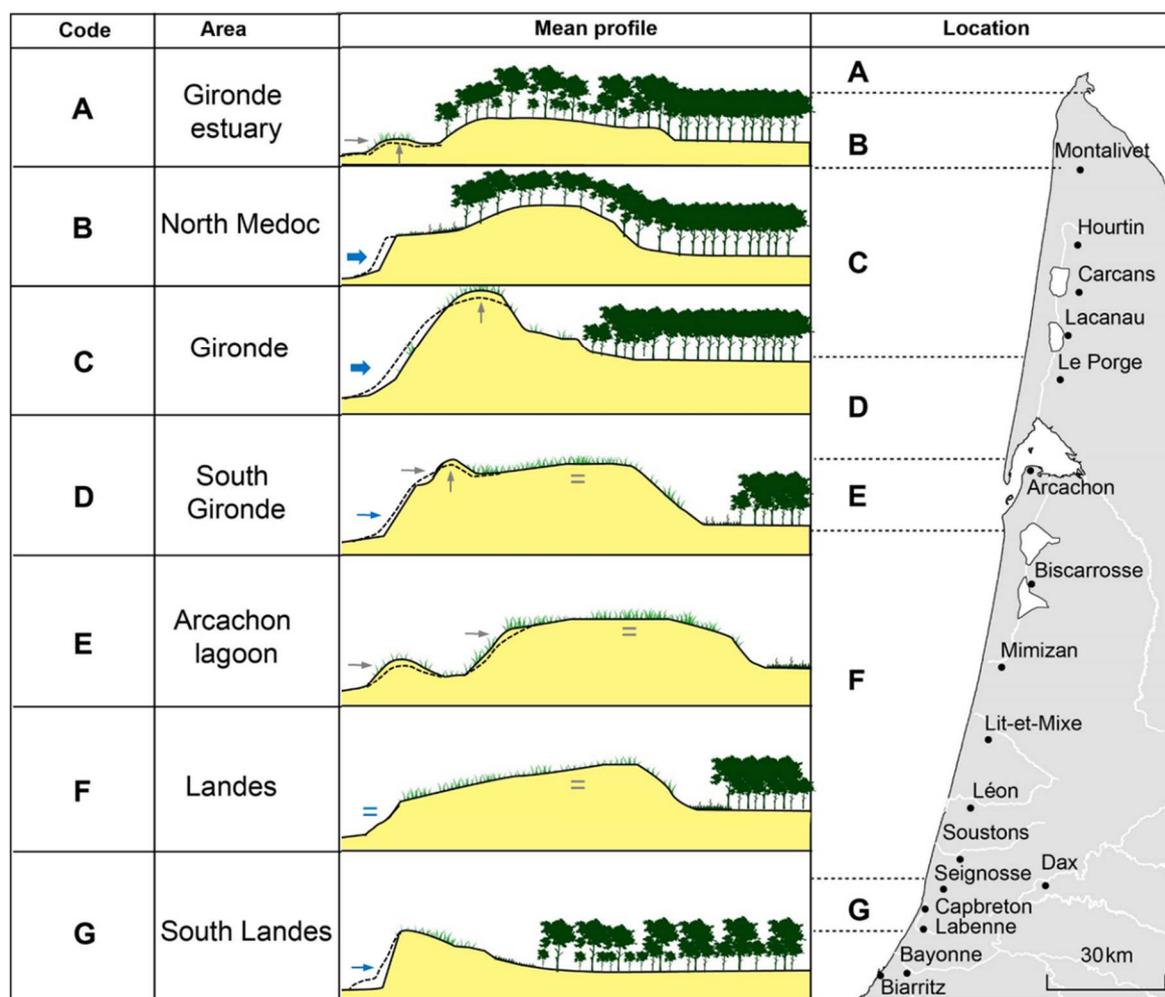
1
2 Fig. 9 : . Morphodynamic characteristics of the beach-dune system extracted using LiDAR data and
3 cross-shore transects and polygons. Transects are 100 meters apart from each other. Marine
4 dynamics are evaluated using shoreline mobility rates between 1985 and 2014. Aeolian dynamics are
5 evaluated within dunes' boundaries (box division) between 2011 and 2014 using elevation
6 differentials. Beach-dune potential resilience (PPR) is evaluated using dune scarps identification for
7 2011-2014 and 2014-2017 periods. PPR's degree depends on scarps' layout between the two periods.
8 The sum of ONF's management interventions is extracted using box division between 2011 and 2017.



1
 2 *Fig. 10: Morphologic features observed and measured on calibrated foredunes in 2017. Dunes front*
 3 *dynamics are evaluated by identifying dune scarps and incipient development between 2014 and 2017.*
 4 *Circles represent signs of important aeolian activity (blowout and depositional lobes). They are*
 5 *manually inventoried using orthophotographs and differential elevation maps.*
 6
 7

1 4.2 Calibrated foredunes morphology and dynamics at the sedimentary cell scale

2 The confrontation of foredune systems characteristics, morphological variability and spatial distribution
 3 highlights several clusters along the coast. Results are organised into a classification of calibrated
 4 foredunes of the Aquitaine coast (Fig. 11). In addition, dominant current wind (symbol in grey) and
 5 marine (symbol in blue) dynamics are schemed. Comparison between dashed and solid lines summarise
 6 the current morphological evolutions under marine (storm) and aeolian processes (which intensity is
 7 represented by symbols). In the following sections, main characteristics of each cluster are described.



8
 9 *Fig. 11: Conceptual classification of calibrated foredunes along the Aquitaine coast. The division is*
 10 *based on observed clusters, showing the variability of dune's morphologies along the coast. Symbols*
 11 *and dashed lines are indicating current dominant tendency of morphological evolutions, due*
 12 *respectively to marine storm driven processes (in blue) and wind driven processes (in grey).*

13

1 **4.2.1 Extreme North Gironde (type A : Cell 1.1)**

2 Foredunes located at the extreme north end of Cell 1 are some of the largest observed along the coast.
3 These characteristics that contrast with the rest of the cell are due to the local dominant longshore drift
4 (South-North oriented). The presence of massive sand banks throughout the last decades have promoted
5 the development of successive large foredunes. Today's wind driven dynamics are still influencing the
6 development of incipient foredunes. In consequence, the coastal dune is extended but with low a dHm
7 (< 8.5 m) that sets it apart from the standard calibrated dune.

8

9 **North Gironde (Type B : Cell 1.2 to Cell 3.1)**

10 Foredunes located in the rest of the Cell 1, Cell 2 and Cell 3.1 generally exhibit subtle morphologic
11 characteristics in comparison with the rest of the coast. This part of the coast is globally facing strong
12 and chronic marine erosion processes that limit dune development and progressively reduce their global
13 volume. In several locations, the dune is non-existent as evident by the presence of a forest at the direct
14 top of the dune cliff (Fig. 11 code B). The calibrated foredune system presents active cliffs and is perched
15 above paleosoil. The latter is constituted by several geologic layers (clay, truff or fluviatile sand)
16 outcropping at the dune foot.

17 Within this part of the coast, the Cell 2 presents particular characteristics as the sector has not undergone
18 any mechanic remodelling. It therefore constitutes a certain originality along the coast. Many blowouts
19 and mobile parabolic dunes are observable. Due to steep cliff at the beach-dune interface and limited
20 sand available on the beaches, dunes are not supplied by the sand from the beach and their dynamics are
21 linked to the remobilisation of the pre-existing sand (*BRGM and ONF 2018*). In the continuity, the dune
22 is almost inexistent and the topography globally flat in Cell 3.1, without clear delimitation between a
23 coastal dune and the lee (cf Fig. 2 a)).

24

25 **Center Gironde (type C : cell 3.2, 3.3)**

26 From Cell 3.2 to the south of cell 3.3, the foredunes have been mechanically remodelled during the
27 1970s and 1980s (*Barrère, 1992, Paskoff 2001*). As Cell 3.2 and cell 3.3 are the upstream part of the
28 sediment cell with respect to the dominant longshore drift (North-South oriented), the beach-dune

1 interface is characterised by higher coastline retreat rates than further south. This part of the coast
2 exhibits a narrow foredune (thin but high) compared to calibrated dune standards (code C on Fig. 11)
3 and dunes are globally tending to thicken from north to south. Dune width and altitude are equally
4 variable alongshore and are presenting a destructured aspect in several location. dHx is often superior
5 to 20 meters and reaches 31 meters within sedimentary cell 3.2 (cf. Table 2). On the opposite, dune
6 width values dW are in average inferior to 150 meters, and the lowest value observed along the coast is
7 equal to 26 m in cell 3.3. This dune shape (Fig. 2 b)) is explained by the chronic erosion process that
8 results in a long-term shoreline retreat <1 m/year. Incipient foredunes are rarely observable in the area.
9 Compared to the dominant incipient foredune dynamic along the coast that characterises the 2014-2017
10 period, the northern part of the Gironde coast does not show significant recovery at the beach-dune
11 interface, neither signs of dune development (*Nicolae Lerma et al 2019*). This area also presents most
12 of inventoried blowouts and recent aeolian activity is about the highest along the coast (>0.1 m/m²/year).
13 These observations underline the link between marine erosion and blowout activation and dynamism.
14 Due to steep active cliffs at the dune front (slope of 40-50%) and high wind driven sediment mobility,
15 frontal blowouts are often observable and sediments easily accumulate on the dune crest. Thus, the dune
16 crest is progressively elevating (several meters, reaching almost 5 m locally and corresponding to an
17 elevation greater than 0.8 m/year between 2011 and 2017) and leading to a pyramidal shape profile.
18 Some areas are given a certain freedom in terms of dune evolution (Hourtin in cell 3.2). Last calibration
19 works on these areas are sometimes way older than average and mainly because no stakes are directly
20 exposed.

21

22 **South Gironde (Type D cell 3.4 and 3.5)**

23 Apart from limited local areas, foredunes of south Gironde (cells 3.4 and 3.5) exhibit larger dW than
24 average values and tend to become larger from north to south, going up to 200 meters. Parameters dHm
25 and dHx are very close to average values along the coast, respectively 17 m and 22 m. These massive
26 calibrated dunes are almost continuously supported by incipient foredune that have been accreting since
27 2014. After 2013-2014 massive mega cusp erosion, dune front crests were quickly notched by local
28 blowouts (*Castelle et al., 2015*). Several years after, this part of the coast shows numerous active frontal

1 blowouts. They sometimes are of no-significant width, greater than 50 m or even 100 m. Furthermore,
 2 wind driven sediments are accumulating directly beyond the seaward dune crest because of a steep slope
 3 front. Consequently, in many locations the higher point of the dune is located near to sea front contrary
 4 to what is expected for an idealized profile (Fig. 2 c) and Fig. 11).

5
 6 *Table 2 : Morphometric characteristics of calibrated foredunes along the Aquitaine coast. Values are*
 7 *calculated in meters for every sedimentary sub-cell located in the study area. dR is expressed in % of*
 8 *dW*

Cell	dW			dHm			dHx			lHm			dR		
	Moy	Max	Min	Moy	Max	Min	Moy	Max	Min	Moy	Max	Min	Moy	Max	Min
Cell 1.1	261.8	590.9	70.3	7.9	12.9	5.3	14.3	20.4	10.8	7.1	13.6	1.8	68	95	25
Cell 1.2 to Cell 1.5	166.2	362.6	52.7	13.7	18.8	9.1	19.7	27.4	12.3	8.6	13.4	3.8	50	96	12
Cell 2	90.9	159.1	31.0	14.2	16.1	12.0	20.8	24.8	16.4	12.0	15.1	9.7	56	86	17
Cell 3.2	146.9	358.7	50.8	16.6	20.7	11.5	22.6	31.4	15.2	12.3	17.0	9.0	49	90	11
Cell 3.3	143.3	258.2	26.0	17.1	20.1	12.4	22.4	27.4	17.6	11.2	17.4	5.5	46	85	12
Cell 3.4	191.2	373.2	98.8	16.9	20.3	13.5	22.6	29.6	17.4	8.6	13.7	5.1	49	89	12
Cell 3.5	245.4	435.6	157.7	17.0	19.2	13.4	22.0	25.6	18.8	7.6	12.3	3.1	55	95	10
Cell 4.1	267.7	411.1	41.5	16.5	20.0	9.8	23.1	29.0	12.3	8.0	13.5	3.6	40	84	14
Cell 4.2	293.3	572.4	43.3	13.6	18.7	9.4	20.9	26.5	13.8	8.8	13.4	6.5	52	89	16
Cell 5.1	209.2	438.5	117.1	16.4	18.6	13.4	21.6	25.6	16.6	6.9	12.0	3.9	64	92	16
Cell 5.2	158.0	406.5	96.7	16.9	19.6	11.6	22.0	25.5	15.2	7.1	14.4	2.7	62	99	22
Cell 5.3	186.1	316.7	71.5	16.5	18.8	10.2	21.5	26.5	12.2	8.2	14.3	0.1	55	98	17
Cell 6.1	129.7	232.6	79.7	13.8	15.3	11.8	18.1	20.4	16.2	8.8	10.8	6.1	35	62	11
Cell 6.2	189.6	256.7	26.0	10.3	12.2	6.6	13.2	16.6	8.4	6.6	8.0	5.7	25	88	7
All	187.1	590.9	26.0	16.1	20.7	5.3	21.5	31.4	8.4	8.6	17.4	0.1	53	99	7

9
 10 **Arcachon lagoon pass (Type E : cell 4)**
 11 The dunes located in cell 4 show very variable morphologies, alike the systems close to the pass of the
 12 Arcachon Lagoon. These characteristics are partly related to the great spatio-temporal variability of
 13 available sediments on the beach. In this area, very thin dunes are observable (around 10 to 15 m wide
 14 and 20 m high at the spit of Cap Ferret 4.1) as well as monumental forms such as the Dune du Pilat
 15 (Around 600 m wide and 110 m high, Cell 4.2). Note that the Dune du Pilat is not integrated in our study
 16 as it is currently not managed and its characteristics are nothing comparable with calibrated foredune
 17 standards.

1 Foredunes located in Cell 4.1 show characteristics similar to the dunes of the cell 3.5 Some exceptions
2 are found at the extreme south end where the coast orientation is rotating at the end of Cap Ferret spit
3 and where the coastline has been continuously retreating for almost 50 years (*Nahon et al., 2019*).
4 Locally, the dune is progressively weakening and its protection capacities are exposed to the risk of
5 breaching.

6 South of the Arcachon lagoon (Cell 4.2), the beach dune interface alternates between beach scarps and
7 established foredune. However, the dune is generally well developed and established. It takes advantage
8 from substantial local sediment supply related to the dynamic of the bank coming from the pass of the
9 Arcachon Lagoon (Fig. 11). The largest foredunes along the coast are observed in the area and are up to
10 590 m wide. Widest blowouts as well as back dune depositional lobes are also found in this cell (see
11 Fig. 10). These dynamics may be linked to high sediment availability and shall be considered regarding
12 their management. In fact, this area is locally subject to limited interventions due to the presence of an
13 old military camp (le Trencat). In this location, dunes are following an almost free evolution process
14 (see *Castelle et al., 2019*). As described before, the aeolian activity in Cell 4.2 appears as an exception
15 due in some part to limited interventions and controlled free evolution dune management.

16

17 **Landes Coast (type F : cell 5.1 to 5.3)**

18

19 The beach-dune interface shows locally eroded dunes within a globally stable area. Long term shoreline
20 retreat is pronounced in Northern part of the Landes coast (Cell 5.1). However recent dynamics at the
21 beach-dune interface show a relatively medium to high PPR (except in urbanized sea front like the
22 Biscarrosse beach, which is currently suffering sever erosion, *Biausque et al, 2019*). Effective aeolian
23 activity is generally low apart from some few local spots where both blowouts and back dune
24 depositional lobes are located (Fig. 10). Calibrated foredunes located in the Landes (cell 5) are mostly
25 homogenous with dW , dHm and dHx close to longshore average values with a slight decrease of theirs
26 dimensions southward. They are massively exhibiting so-called stable dunes that represent idealised
27 shaped dunes. In some location, limited dimensions must be considered looking at urbanisation or small
28 estuary dynamics. The main characteristics of foredunes dunes located in the Cell 5 highlight

1 management influences in maintaining a stable morphology on a relatively long-term. Thus, they
2 emphasise on both soft management practices and ideal profile dune shape efficiency to maintain a
3 stable dune morphology in areas characterised by a stable sediment balance.

4

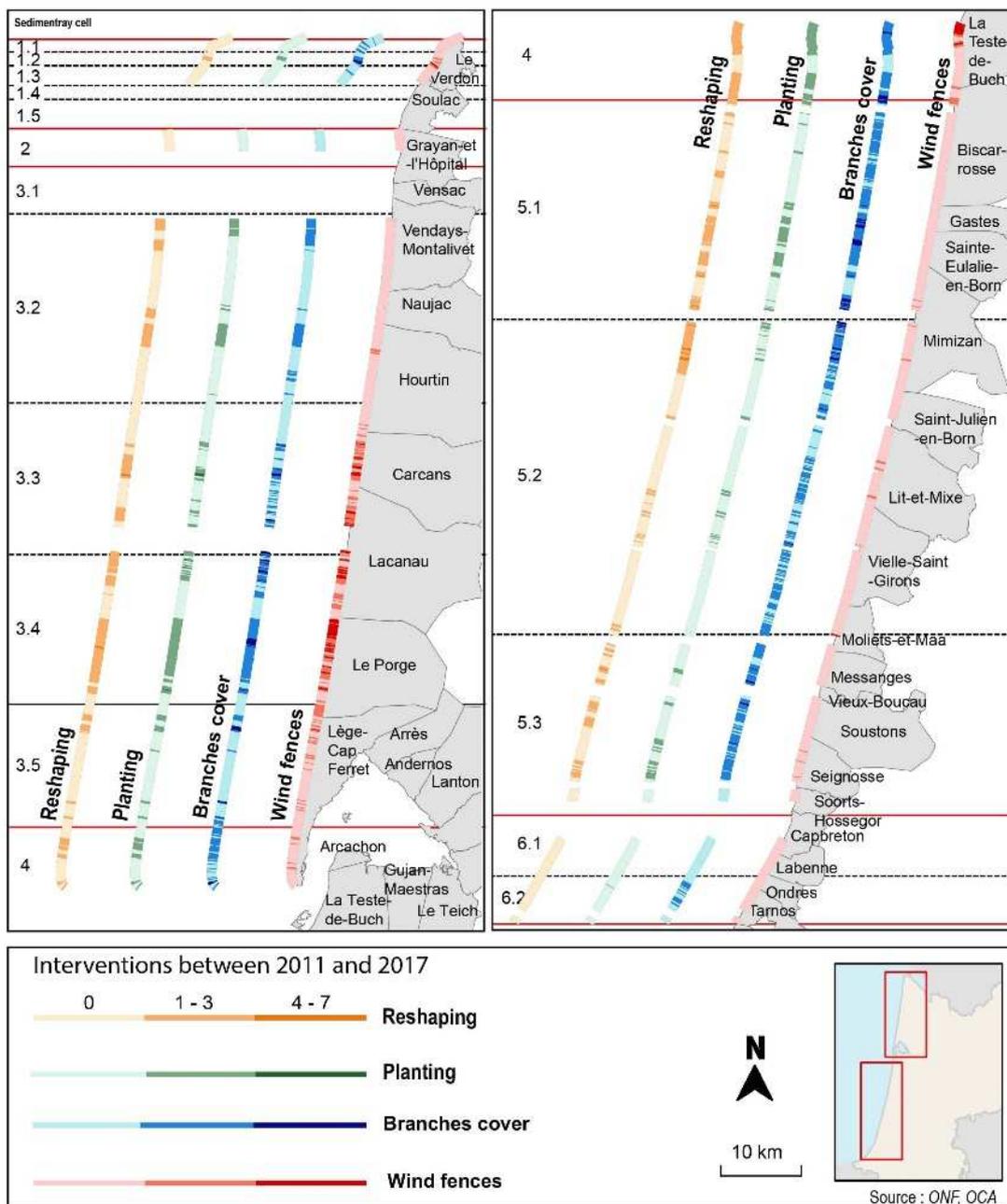
5 **South Landes (Type G : cell 6.1 and 6.2)**

6 In the South end of the Aquitaine sandy coast (Cell 6), the beach-dune interface is characterised by an
7 alternance of beach scarps and incipient foredunes. Calibrated foredunes are small shaped in comparison
8 to the rest of the coast. Foredunes located in this cell have not been shaped following the “ideal profile”
9 as the rest of the coast. They are the result of limited sediment availability and the prominence of coarser
10 sediment (coarse sand to gravel) associated with a shift in the geological nature and coastline orientation
11 (East-West component) at the South of Capbreton. There is a difference between dunes located in the
12 cell 6.1 and 6.2. In the 6.1, dunes are mainly presenting scarps and their dune front crest are massively
13 notched by blowouts without active management. In contrast, foredunes located further south (cell 6.2)
14 are generally showing incipient foredunes. They are in average large (around 190 m) but small (mean
15 $dHx = 13.2$ m). Thus, they are classified as extended dunes due to the limited dune elevation relatively
16 to their width (Fig. 11). Few aeolian activity marks are observable illustrating their high stability.

17

18 ***4.3.2 Management strategies***

19 At regional scale, Fig. 12 shows ONF’s interventions on calibrated foredunes between 2011 and 2017.
20 Results are sorted by type and number and a total 4 613 interventions are inventoried along the coast
21 during this period.



1
 2 *Fig. 12: Type and number of interventions made by the ONF (French National Forestry Office) on*
 3 *foredune boundaries between 2011 and 2017. The type of intervention is indicated using different*
 4 *colours which opacity reveals their quantity over the time period.*

5
 6 Considering the sum of all interventions between 2011 and 2017, highly managed foredunes are mostly
 7 found in sedimentary cells 3.3 and 3.4, in the north side of the Aquitaine Coast, and in cells 4 and 5.1
 8 for its south side. The sum of interventions in certain areas is up to 24 between 2011 and 2017, being on
 9 average superior 3 per year. The geographic distribution of interventions shows that intervention types

1 are usually associate with one another. Similar geographic patterns are observed for all types. Only
2 branches covers are regularly used individually. They also are interventions' most used technique,
3 representing 40% of all individual actions, mainly because it is an easier and less expensive way to
4 maintain a stable dune profile. They are regularly use as a maintenance tool compared to other types of
5 interventions which are rather used in more specific conditions (to prevent or limit storm impacts).
6 No significant link is observed with previously analysed dynamics. The correlation coefficient between
7 interventions and shoreline position change is close to zero, as well as with aeolian sediment movements
8 ($r^2=0$ and $r^2= 0.1$). Mobile or chronically eroded dune areas do not present more interventions on the
9 2011-2017 period. Additionally, management actions are not conditioned by dune morphology. Actions
10 rather take place in frequented areas, usually close to urban areas and near to local human stakes or
11 beaches entrance. Actions also focus on areas that include both human stakes behind foredunes and
12 important erosion processes following winter 2013-2014. This trend may be explained looking at
13 management organization, dedicated resources and strategy at the regional scale and will be discussed
14 further on.

15

16 **4.4. Erosion management: local case study**

17 The following analysis focuses on two specific dune areas. Soft actions are necessarily conditioned by
18 local morphology and dynamics. They are time consuming, demanding of work force and need regular
19 survey. Thus, analysis of relations between soft management and morphologic evolution is meaningful
20 at the local scale. *La Torchère* and *la Dune Rambaud* are located in sedimentary cells 3.4 and 3.5, within
21 the city boundaries of Lacanau and Lège-Cap Ferret (Fig. 1). Originally human-built dunes, they were
22 severely impacted by winter 2013-2014 storm clusters, with shoreline retreat rates up to 20 m (*Bulteau*
23 *et al., 2014 ; Nicolae Lerma et al., 2019*). Following these events, sediment mobility on the dunes
24 increased due to aeolian driven processes and the morphologic evolution of dunes became problematic
25 for managers whose goal is to limit their erosion and migration.

26 Lacanau's *Dune Rambaud* is a 100 meters long and 21 meters high dune ahead of an exploited pine
27 forest. Marine erosion caused by winter 2013-2014 created high dune scarps and directly exposed
28 previously existing blowouts to sea winds, resulting in an enlargement of the blowout's shape (Fig. 13

1 and 15). Aeolian dynamics considerably increased sand transport on the dune front. Sediment transfers
2 inland created a large depositional lobe on the lee side of the dune and digged the existing blowout.

3 Cap Ferret's *La Torchère* is located North of Cap Ferret downtown, transitioning between sedimentary
4 cells 3.4 and 3.5.

5 The specific dune section is 200 meters long and around 23 meters high at its most elevated point. Its
6 dimensions, along its geometrical aspect, make it a still calibrated dune. The dune is globally protecting
7 an oil exploitation site well behind the dune. Although its front part has suffered from strong erosion
8 dynamics during the winter 2013-2014 storms (locally 25 m), the dune shape and position are globally
9 stable on the long-term. Marine erosion indirectly stimulated aeolian sediment transport by removing
10 vegetation cover. Following the events, two wide blowouts developed, enhancing transversal sediment
11 transport (Fig. 13 and 15).

12 Differences in terms of dune morphology largely influence the way managers deal with erosion and
13 migration process. Fig. 15 illustrates the differences of dune evolution and management between 2011
14 and 2018 on both sites. In Lacanau (*Dune Rambaud*), dune's risk of breaching constrained managers to
15 act right after the storm events (Fig. 15). Several wind-fences rows were set up from the dune crest to
16 the beach to facilitate sediment accumulation (Fig. 14 and 15). Installations were annually maintained
17 and updated to keep on sediment accumulation. Associated with marram grass planting, these
18 interventions progressively filled the deflation hollow digged by wind-induced erosion. In Fig. 15, sand
19 deposition between 2016 and 2018 is observable as it completely covers wind fences. Nonetheless, due
20 to the lack of a dense vegetation cover, sediments keep on moving to the lee, increasing the height of
21 the dune by 5 meters between 2011 and 2016 (see the difference between the yellow and the blue line
22 on Fig. 13, b.). Consequently, blowout erosional walls extended sideways. In 2018, after several years
23 of work, the blowout shape seems stable and sediment flows are mainly located on the dune lee (Fig. 14
24 b). The dune keeps on moving inland but interestingly its volume has been slightly increasing of about
25 0.4% per year since 2016 (about 3 720 m³) suggesting sand catching from the beach. Eventually, the
26 risk of dune breaching that emerged after 2014 has been minimised.

27

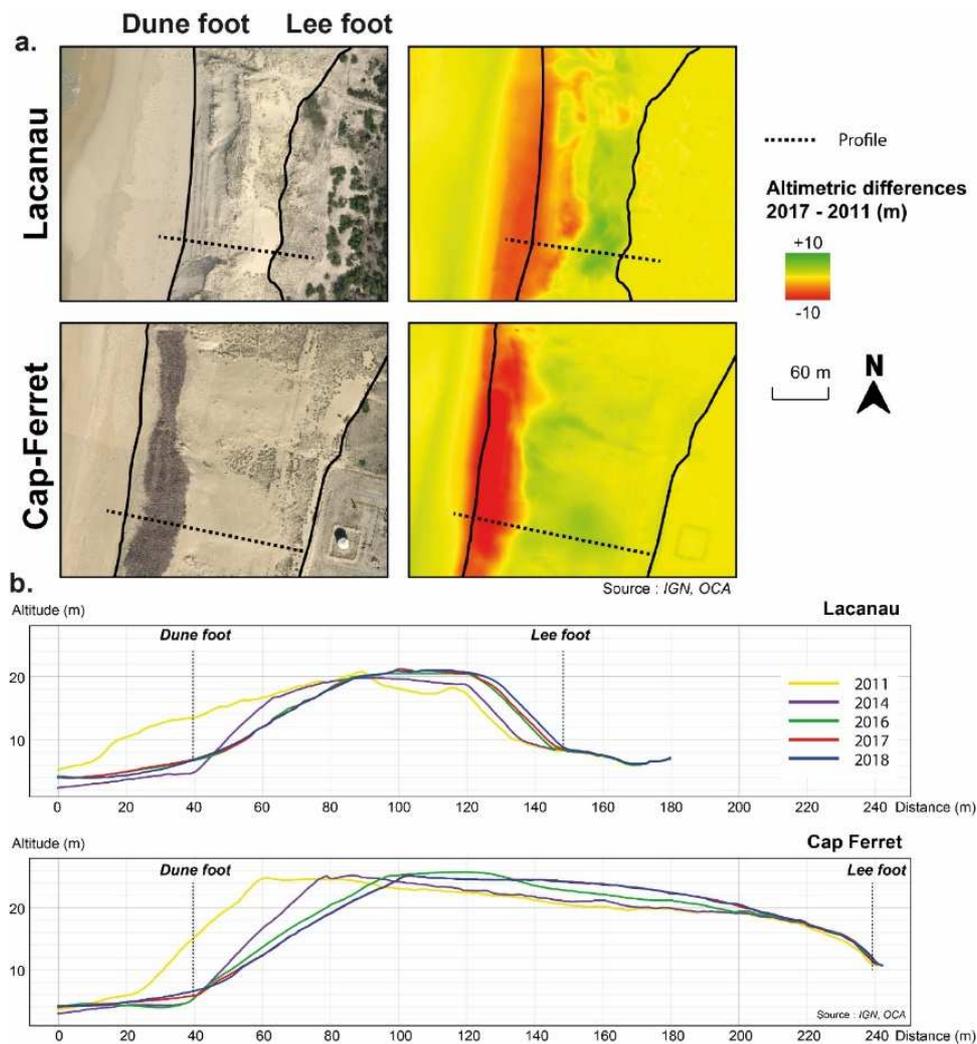


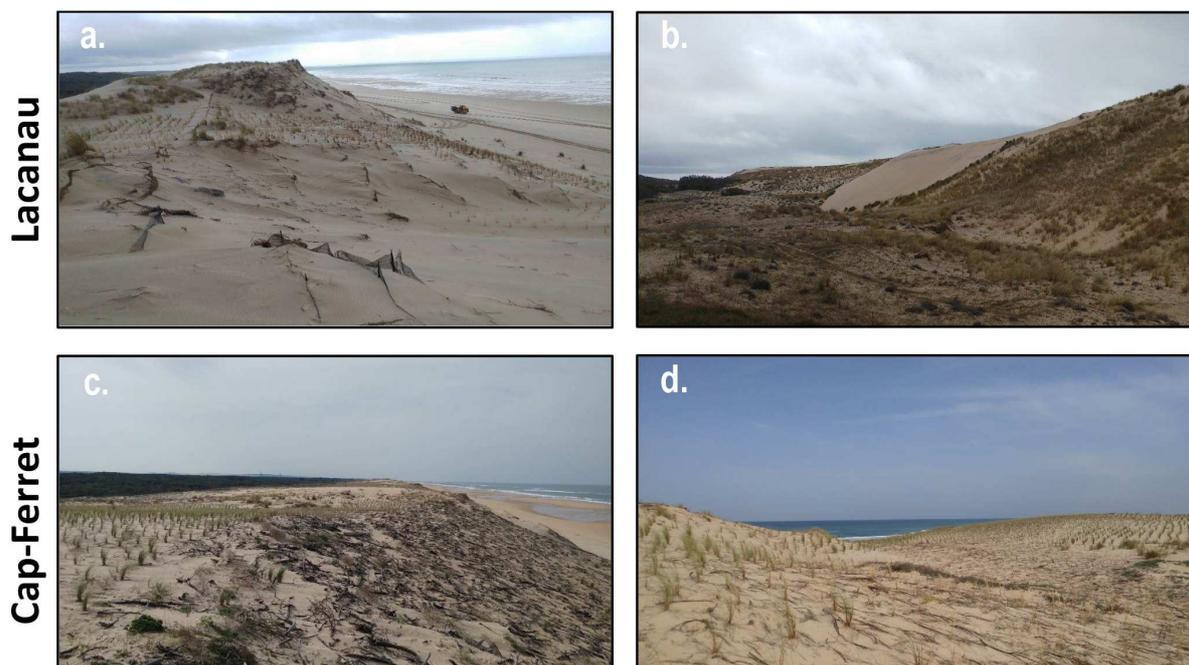
Fig. 13: Representation of the foredune evolution between 2011 and 2018 using airborne LiDAR data.

Differential elevation maps are used to highlight the importance of sediment mobility in areas made of blowouts. Cross-shore altimetric profiles located at the centre of two blowouts are extracted and compared to one another to highlight dune landward migration.

Interventions realised on the Cap Ferret's dune pursued a different objective and methodology compared to the *Rambaud Dune*. Considering its dimensions (about 200 m), actions rather focused on fixing the dune shape to limit its retreat. However, in the first few months, managers choose to limit intervention mostly because of the dune front steep slope that unable any soft intervention (Fig. 15). They let aeolian processes naturally softened its profile, resulting in significant transfer to the dune plateau, damaging the vegetation cover and progressively elevating this part of the dune (about 2 to 3,5 meters between 2014 to 2017). After a natural softening of the dune front, ONF's managers actively worked on limiting

1 sediment mobility. In 2017, massive cover branches spread out on the dune front drastically reduced
 2 wind driven sediment mobility (Fig. 14 and 15) and different types of interventions including marram
 3 planting and wind-fences have completed the system. Altimetric profile comparison shows that between
 4 2017 and 2018 (red and blue lines), the dune profile barely changed. Limited sediment transport allowed
 5 previously planted marram grass to grow and spread on the dune, fixing accumulated sediments. Only
 6 limited maintenance interventions are now considered.

7

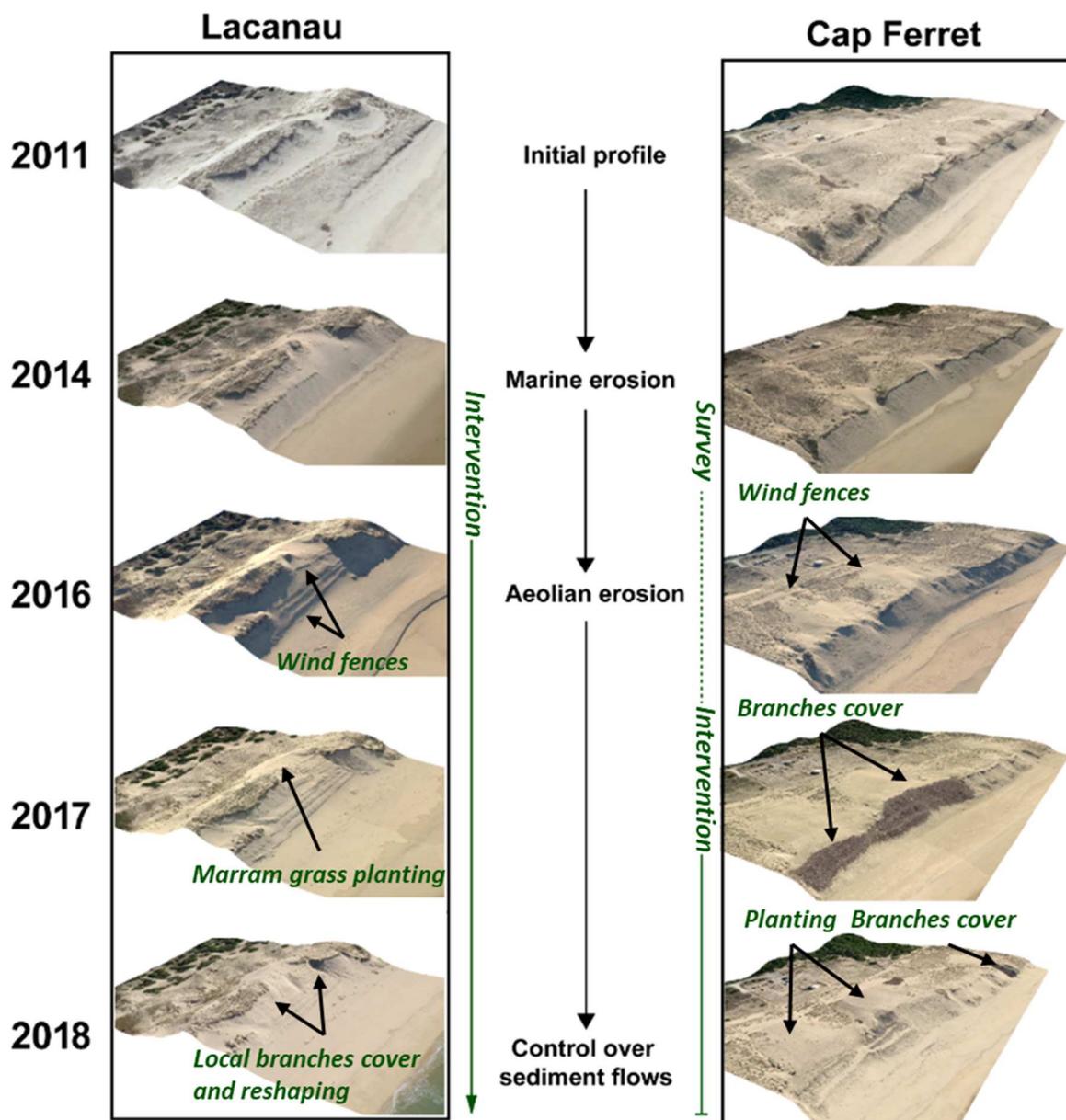


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8

9 *Fig. 14: Calibrated foredunes located in Lacanau (a,b) and Cap Ferret (c,d) in April 2019, a) wind*
 10 *fence in the blow out deflation basin, b) back dune depositional lobe, c) and d) branch coverage*
 11 *respectively on the front and the plateau of the dune*

12



1
2 Fig. 15: Foredunes evolution at Lacanau and Cap Ferret places following 2013-2014 winter storms.
3 3D representations illustrate the recovery process following the perturbations. ONF's management
4 policy towards dunes evolution is shown in relation to sediment dynamics and the time and types of
5 interventions conducted to stabilise the dune shape is represented.
6
7
8
9
10

1 5. Discussions

2 5.1. Regional variability of foredunes morphology and dynamics

3 Descriptive morphometric studies foredunes are generally a first diagnostic element for the elaboration
4 of a regional coastal management plan (e.g. *Barrère 1992; Arens and Wiersma, 1994, Houser et al.,*
5 *2015, Bezzi et al., 2018*). In the case of the Aquitaine coast, the current morphology of foredunes is the
6 result of two centuries of history of ambitious and massive interventions mixed with periods of lack of
7 management (cf. Fig. 3). The methodology proposed for the detection and analysis of calibrated
8 foredunes (homogeneous over the 230 km of the coast) provides relevant measurements to represent the
9 state and coastal variability of calibrated foredunes at regional scale.

10 Using extracted morphometric data, a height/width ratio (relation between dHx and dW) is analysed
11 along the “ideal profile” dimensions to offer the following spatial dune classification, represented in Fig.
12 16: (i) A mean ratio (6 to 12) matches stable dunes (red). It is the reference foredune aspect also called
13 “ideal profile”; (ii) a high ratio (>12) matches larger dunes (yellow). It focuses on dunes that include
14 developed incipient foredunes. Compared to a calibrated state, they are considered as extended dunes;
15 (iii) a low ratio (<6) matches thinner dunes (blue). It focuses on dunes where cross-shore sediment flows
16 narrow the dune and increases its height. Compared to a calibrated state they can be considerate as
17 narrowed dunes.

18 Analysis and comparison of indicators using boxes delimitation highlight dune variability along the
19 Aquitaine coast. Although foredunes are constantly changing locally, results emphasise on their global
20 stability. Fig. 16 shows that Stable dunes stand out as the dominant type of foredunes. They represent
21 55.5% of all studied dunes. Narrowed foredunes represent 21.5% and Expanded (including the small-
22 uncalibrated dune along the cell 6) represent 23 %. Even though their profile does not precisely fit the
23 ideal (calibrated) profile morphology, the dimensions and global shape of the majority of foredunes
24 often meets or surpass the “ideal profile” standards (Fig. 5). As last great calibration works were done
25 almost 40 years ago, it is a sign of relative stability.

26

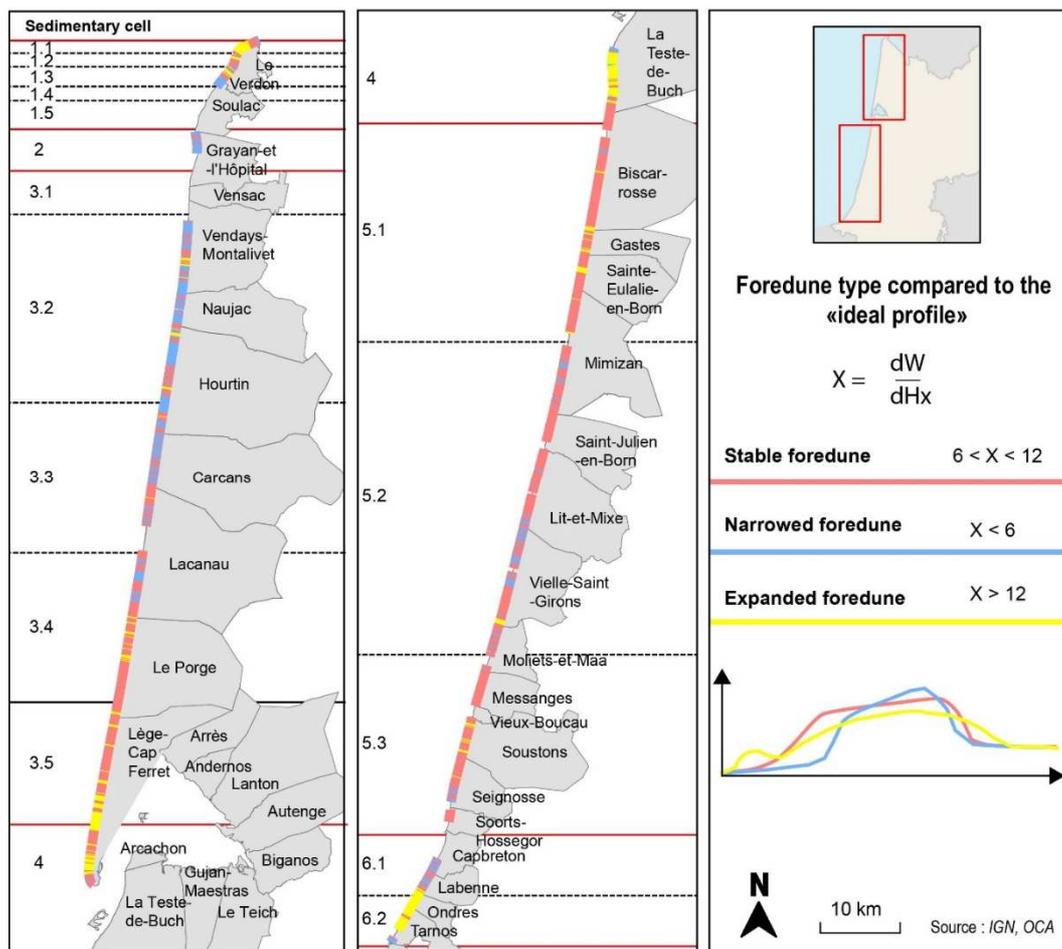


Fig. 16: Classification of calibrated foredunes along the Aquitaine coast based on the “ideal dune profile” that was used during former dune calibration. A ratio (X) between dune width (dW) and dune maximum height (dHx) is used to differentiate foredunes global shape.

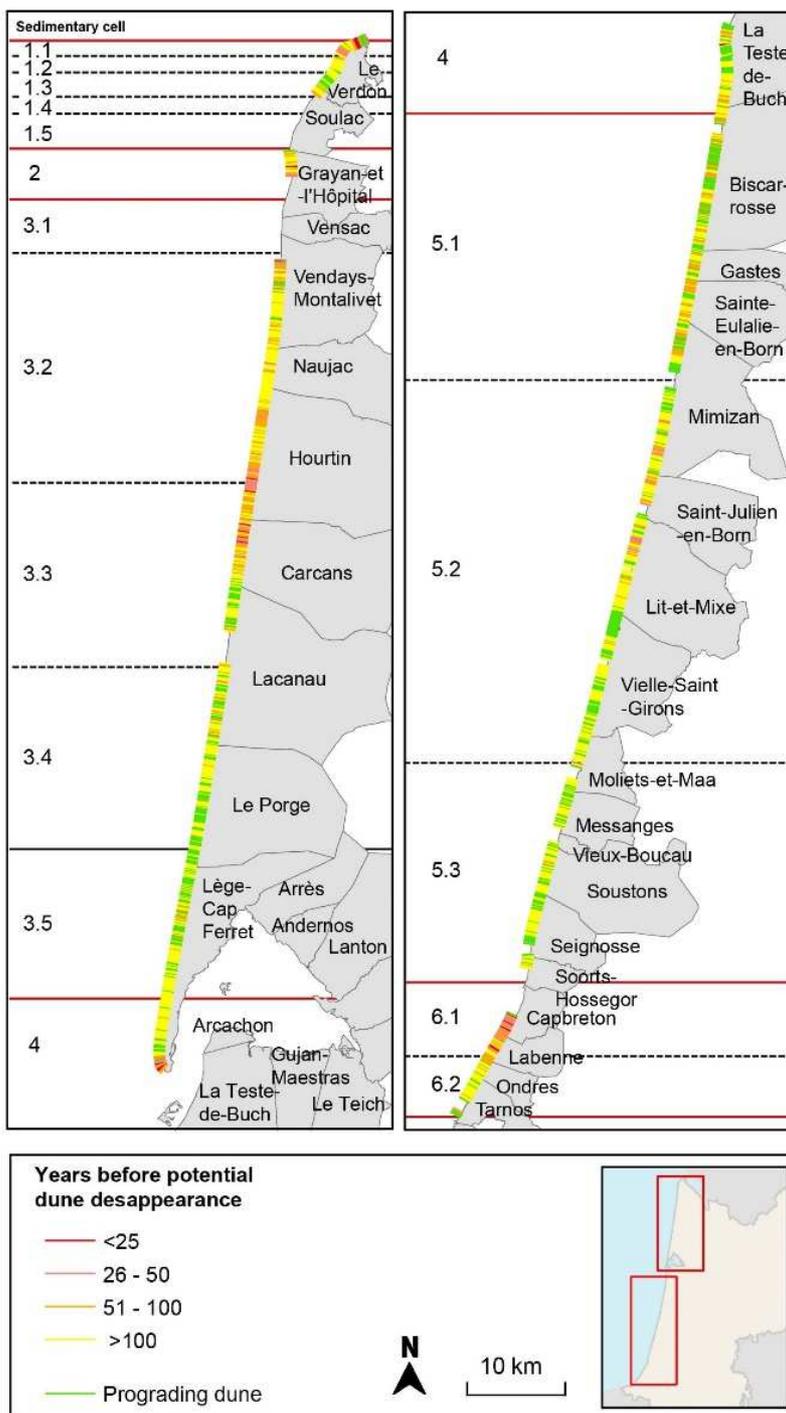
Considering the variability of dunes’ morphology, extracted features only reflect a small part of the possibilities offered by available data and tools. For instance, slope variation across the dunes, or vegetation cover are not specifically considered in the present work, although they are interesting tools to qualify dunes morphology or dynamics (Brodie and Spore, 2015). Providing a foredune typology based on the relation between two parameters (width and maximum height) may seem too simplistic to grasp dunes complex morphology. Considering that the calibrated shape was historically applied on most dunes along the coast, computed typology appeared close enough to reality to be relevant and generalizing enough to reflect general and noticeable dunes aspects. Geographic distribution of foredunes characteristics along the coast is globally consistent with existing descriptive works (Favenec 2002, BRGM and ONF, 2018).

1 **5.2. Management perspectives towards continuous erosion processes**

2 Current management strategies focus on limiting foredunes erosion and migration. Though results are
3 satisfying, long-term perspectives are questionable. If wind-induced erosion can be tackled using soft
4 engineering tools, dune retreat input to chronic marine erosion is hardly manageable. Dune development
5 can be assisted but the process is long and can take decades depending on sediment availability (*Houser*
6 *et al., 2015*) and specific conditions during energetic events. Eventually, the dune system progressively
7 narrows, though this situation generally does not constitute an immediate problem considering its width.
8 However, winter 2013-2014 exposed their vulnerability to coastal hazards, with local shoreline retreats
9 up to 40 meters (*Bulteau et al., 2014*). These dynamics were particularly strong on the central part of
10 Gironde (area between Hourtin and Carcans, cells 3.2 and 3.3) where foredunes are locally 25 to 40 m
11 large. Perspective of coastline retreat up to 50 m by 2050 along the Aquitaine sandy coast are clearly
12 questioning the possibility of maintaining calibrated foredunes and their coastal defence role. Fig. 17
13 uses a combination of foredunes width and local shoreline mobility rate from (*Bernon et al., 2016*) to
14 highlight potential risks of dune disappearance in the future.

15 In Aquitaine as well as in many coastal areas bordered by dune systems, climate change perspectives
16 and anticipated reinforcement of coastal hazards, the future of calibrated foredunes as stable
17 morphological entities is very uncertain (*Carter 1991, Pusty and Silveira 2010, Anderson et al., 2015*).
18 It may be necessary to move towards different strategies to maintain the protection service provided by
19 calibrated foredunes and at the same time limit as possible sediment loss on the dune front during storms.
20 Therefore, a specific attention shall be paid to foredunes, locally in Landes but mostly in Gironde
21 (sedimentary cell 3.2 and 3.3) where the combination of narrow dunes and low beach-dune potential
22 resilience due to a limited sediment availability could be damageable in a near future.

23



1
 2 *Fig. 17: Estimated time before potential total dune width erosion. Projected time periods are*
 3 *calculated for each transect using foredunes width and the corresponding shoreline mobility rate*
 4 *(1985-2014) in the hypothesis of sustained pace (Bernon et al., 2016). Receding and prograding areas*
 5 *are differentiated.*

6
 7

1 **5.3. Effects, condition and limits of management strategies**

2 As this study aims to connect management practices with dune morphodynamics, the analysis of ONF's
3 management database underlines the interest of having information on human actions in dune evolution
4 studies. In fact, few studies integrate such parameters in their work on dune systems (*Arens and*
5 *Wiersma, 1994*) and comparison between morphological features (*Hesp 2002, Doyle et al., 2019*) and
6 management actions is not straightforward.

7 Morphological evolutions of initiated gullies and blowouts are highly complex and uncertain over time
8 (*Carter et al., 1990; Hesp and Hyde 1996; Hesp 2002*). They depend on many intrinsic factors (outer-
9 inner bar/beach/dune morphologies and sediment availability, vegetation cover and dynamism, water
10 table level ...) and extrinsic factors (sediment supply, wave and wind forcing, fauna and human activity
11 ...). Consequently, blowouts may evolve in various ways. They may become larger and potentially lead
12 to free parabolic dunes (*Carter et al., 1990; Hesp 2002*) or observe a progressive decay of wind driven
13 sediment transport, leading to a progressive stabilization and revegetation (*Gares and Nordstrom, 1995,*
14 *Hesp 2002*). Human soft interventions to control erosional notches and incipient blowout are spread
15 over the world and their efficiency at local scale have been largely demonstrated (e.g. *Nordstrom and*
16 *McCluskey, 1984; Mendelssohn et al 1991 ; De Jong et al., 2014, Muñoz Vallés and Cambrollé 2014;*
17 *Itzkin et al., 2020*)

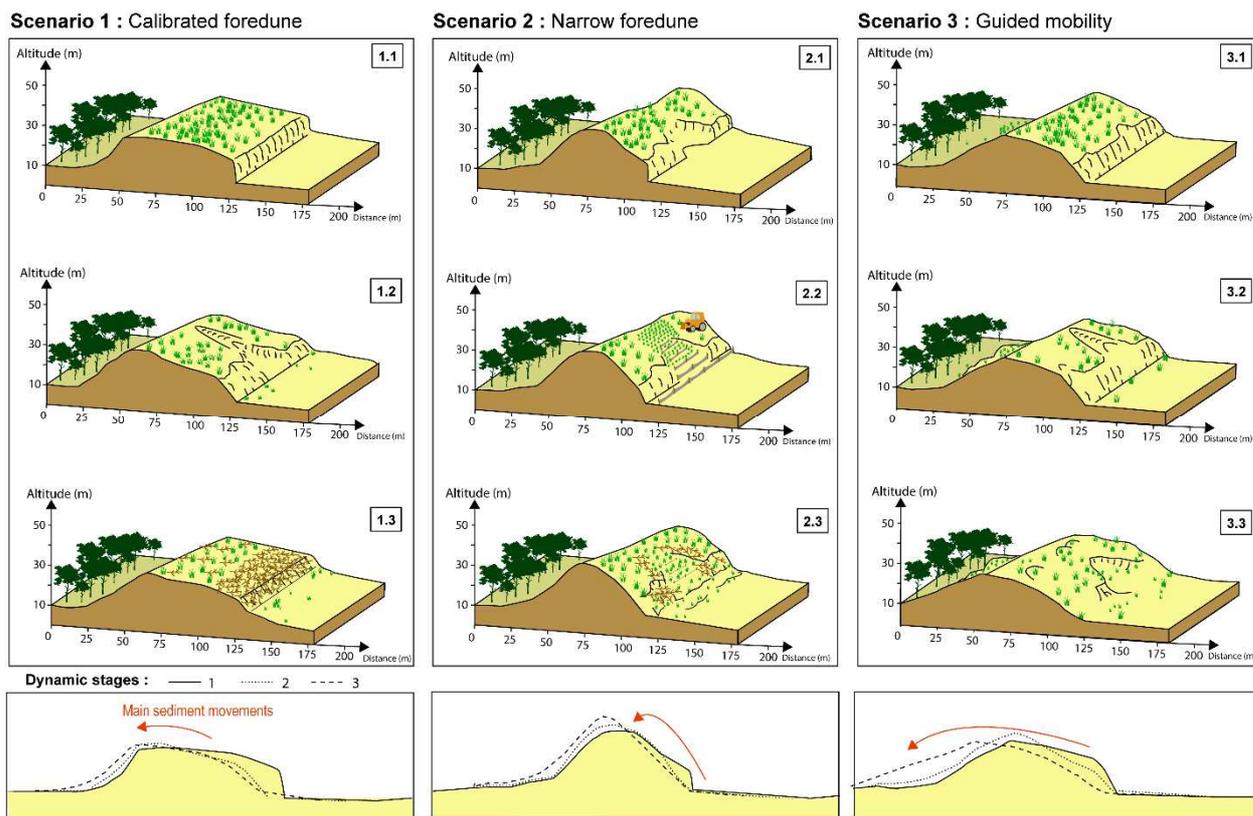
18 At regional scale, data processing and mapping emphasise on different aspect of intervention strategies
19 (synergy between intervention types, important use of branches cover) but quantitatively analysing dune
20 management has clear limits. For instance, information on intervention's goals and context is mainly
21 lost through data processing. Results at the regional scale show no distinct relationship between
22 management intensity and actual dune morphology or sediment dynamics, though it would be expected
23 considering management purposes. The main reason is that current dune management strategies do not
24 focus on part of the coast where erosion processes (both marine and aeolian) are the most important or
25 where the dune is the narrowest. Considering the massive dimensions of the Aquitaine coast and the
26 relatively limited manpower and financial resources, interventions are mostly focusing on beach
27 accesses or on very local spots where dune dynamics are directly affecting stakes (infrastructures or
28 urbanized area).

1 Dune management depends a lot on the person in charge of its planning and particularly when global
2 strategy is based on soft actions. Current management actions mostly rely on individual appreciation
3 because a single person is responsible for several kilometres of coastline and has a certain degree of
4 freedom to plan their actions. Consequently, ways of monitoring dune evolutions can vary significantly
5 depending on the sectors, experiences and sensibility of each ONF agent. Additionally, some parts of
6 the coast (very limited extensions close to urbanized area) are more specifically managed by district
7 services. They can be managed differently going so far as the use of mechanical tools.

8 Examples of Lacanau's and Cap Ferret's foredunes underline management influence on maintaining
9 dune global cohesion. The two dunes are contextually different, though, both situations highlight the
10 efficiency of soft management strategies in limiting dune mobility. Organized and repeated actions on
11 dunes helped them to recover after storm induced perturbations. In both studied situations, it took around
12 4-5 years after the event to reach a satisfying situation where dune mobility and erosion are limited and
13 considered as stabilized. However, this success greatly relies on the fact that winters were mostly low
14 to moderately energetic between 2014 and 2018.

15 Summing up management strategies conducted on the Aquitaine coast, three scenarios, detailed in Fig.
16 18, are generally considered to face the consequences of severe marine erosion. In the light of chronic
17 erosion and relatively low sediment availability dynamics, these scenarios integrate into a "natural"
18 evolution path also called "stable to receding coast" in *Hesp (2002)*.

19



1
2 *Fig. 18: Foredunes evolution scenarios associated to management strategies. Scenario 1 : The*
3 *presence of calibrated and well dimensioned foredunes facilitates soft management practices ;*
4 *Scenario 2 : The presence of narrow dunes forces managers to engage in rapid interventions and*
5 *potentially use hard engineering ; Scenario 3 : the absence of human activity or issues encourages*
6 *managers to support dune mobility*

7
8 **Scenario 1: Calibrated and well dimensioned foredunes facilitates soft management practices**

9 In presence of a large calibrated dune, managers have enough flexibility to observe and adapt to dune
10 natural evolution. Following marine erosion, the dune front is usually cut into a scarp (1.1). The resulting
11 slope offers greater resistance to winds, enhancing sediment transport (*Houser et al., 2015, Hesp and*
12 *Smith 2019*). Managers can take advantage of the situation by letting gravitary processes (sand slide)
13 and aeolian processes (smoothing the upper part of the cliff and creating a dune front blowout) soften
14 the dune front (1.2). As dune morphology naturally evolves towards an equilibrium state (*Hoyt 1966;*
15 *Howard et al., 1978, Arens et al., 1995*) interventions can act to reduce sediment movements and fix the
16 dune shape (1.3). Having this transition stage allows interventions to be more effective. In our example

1 located in Cap-Ferret, it took 3 years before intervening on the dune front. As its slope was too steep to
2 be covered, new plantations were rapidly buried by the sand carried from the uncovered dune front.
3 Once branches were installed on the dune front, sand transportation and carriage were limited and
4 vegetation was able to develop.

5

6 **Scenario 2:** *Narrowed foredune forces managers to rapid interventions and potentially use hard*
7 *engineering*

8 If dune dimensions are reduced and stakes are potentially directly exposed as the Lacanau's foredune
9 example highlights, time can rather be a constraint. When dunes are narrower or present chronic erosion,
10 risks of breaching or global destructuring are greater (2.1). Current protocols generally promote quick
11 interventions to avoid more erosion. On the *Dune Rambaud*, wind-fences associated with marram grass
12 planting aimed to compensate sand loss and fill up the active blowout (2.2, 2.3). This strategy reduces
13 dune erosion, though, hardly limits landward sand transportation. It also allows sand catching from the
14 beach and progressive accumulation. In case of high sediment supply on beaches, dune stocks can be
15 gradually recovered. As we have seen in the past example, the dune progressed landward more than 10
16 meters within 5 years. In presence of urbanised or exploited areas, stakes sometimes are too important
17 to only rely on soft engineering. Mechanical tools are then used to nourish the dune and soften its profile.

18

19 **Scenario 3:** *Absence of human issues or global relocation policies encourages managers to support*
20 *guided mobility*

21 The absence of urbanized area or human activity can lead to an intentional absence of management or
22 more precisely, a controlled or guided remobilization (e.g. [Arens et al., 2004](#); [Arens et al., 2013](#);
23 [Ruessink et al., 2018](#); [Castelle et al., 2019](#)). In this situation, managers do not seek to maintain dune
24 cohesion but rather survey and study its natural evolution. In a chronic erosion dynamic (3.1), aeolian
25 sediment flows result in a natural dune migration. Those sediment transfers are usually made through
26 blowout development (3.2). As dune migrates landward, sediment transport due to wind exposure
27 reduces. Vegetation cover adapts to these changes and a natural balance between dune mobility and
28 stability develops throughout time (3.3). This equilibrated state presents a more chaotic morphology

1 than calibrated dunes. In a context a of narrow fist line dune as observed in Cell 3, this kind of
2 management (survey in case of spontaneous activation or mechanic activation with evolution control
3 actions) (*Arens et al., 2013; Ruessink et al., 2018; Castelle et al., 2019*) can be an alternative to maintain
4 protection as well as the ecological role played by the dune. These kind of surveyed and potentially
5 artificially promoted dynamics appear as a relevant option in non-urbanized areas and an alternative to
6 limit sediment loss caused be chronical coastline retreat. It also potentially allows sand storage in the
7 dunes due to the restoration and reinforcement of sand transfers between beaches and dunes.

8

9 **6. Conclusions**

10 Regional analysis of foredunes geomorphology and natural processes driven evolution (marine and
11 aeolian), can serve different purposes. Pluri-annual airborne LiDAR data offer relevant and precise data
12 source to analyse dune evolution at different time and space scale. In a large-scale analysis, it allows
13 spatial comparison of dunes characteristics along the coast and provides a useful management tool to
14 identify vulnerable areas or prioritize interventions. The present work proposed a classification of
15 foredunes along the Aquitaine coast. Based the relationship between their width and maximum height,
16 dunes were grouped into three classes: stable, narrowed and extended. A reference profile used to
17 formerly manage dunes, called “ideal profile”, was used to define these clusters. Combined with
18 information related to dunes geomorphologic features, sediment dynamics and response to coastal
19 hazards, this analysis provides a regional overlook of dunes characteristics, evolutionary paths and
20 vulnerability. Calibrated dunes appear as the dominant type of dunes along the coast, highlighting their
21 relative stability and efficiency of ecodynamic approach based on soft management on the long term
22 (around 50 years). Emphasis is put on the North and centrer Gironde region whose dunes are facing
23 important and chronic erosion dynamics that has been resulting in a rapid coastline retreat for several
24 decades and a poor beach recovery at interannual scale. The integration of management strategy into
25 our analysis highlights the influence of human intervention on maintaining dune stability. The study of
26 two specific dune areas underlined the efficiency of soft management practices as a response to winter
27 2013-2014 perturbations. It also highlights the time required (4 to 5 years) to efficiently and durably
28 control dune evolution and aeolian sediment mobility. However, if dune soft management efficiency

1 has been secularly demonstrated along the Aquitaine coast, management actions are nowadays
2 concentrated close to local human stakes or beach entrances. They do not focus on areas where dune
3 shape and erosion dynamic seem worrying in view of the evolution trends and expected impacts of
4 climate change. In many parts of the coast, chronic coastline erosion and low sediment availability in
5 the nearshore area questions the viability of current strategies for the coming decades. As the Aquitaine
6 coast is today mostly eroding and that the effect of sea level rise should probably increase coastline
7 erosion, the maintenance calibrated foredune protection service is the next challenge for scientists and
8 managers. Further research should emphasis on dune natural evolution under chronic erosion dynamics
9 to propose extensive adaptation strategy and probably promote so-called “controlled dynamic strategy”
10 or guided remobilisation in order to adapt these environments to actual and future pressure.

11

12

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