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► **To cite this version:**

Quentin Laporte-Fauret, Bruno Castelle, Vincent Marieu, Alexandre Nicolae-Lerma, David Rosebery.  
Foredune blowout formation and subsequent evolution along a chronically eroding high-energy coast.  
Geomorphology, 2022, 414, pp.108398. 10.1016/j.geomorph.2022.108398 . hal-03831776

**HAL Id: hal-03831776**

**<https://hal.science/hal-03831776>**

Submitted on 27 Oct 2022

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1 **Title:** Foredune blowout formation and subsequent evolution along a chronically eroding high-energy  
2 coast.

3  
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6  
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## 14 **Highlights**

- 15  
16  
17 - Orthophoto, Lidar and UAV surveys allow to assess multi-decade coastal dune changes  
18 - Blowouts preferably develop where marine erosion is the most intense  
19 - Blowouts promote the transport of windblown sand to the back of the dune  
20 - Erosion scarp, paleosols and vegetation prevent landward transport  
21 - Blowouts can help maintaining dune systems in chronically eroding dune systems  
22

## 23 **Abstract**

24  
25 Coastal dune systems provide important ecosystem services, while being vulnerable to marine erosion.  
26 In these environments, blowouts can develop and promote sand transport from the beach to the back of  
27 the dune, but are generally fought by coastal dune managers. There are only few quantitative studies on  
28 the 3D evolution of blowouts and how they can develop into parabolic dune. We investigate the  
29 morphological evolution of a 2-km long freely evolving dune system in southwest France from 1947 to  
30 2021 using historical aerial photos and digital surface models from Lidar and UAV photogrammetry.  
31 The combination of these remote sensing methods shows an alongshore non-uniform erosion with a  
32 mean of 1.26 m/yr, and with erosion rates in the north of the study area four times larger than in the  
33 south. Over the study period, three large blowouts developed in the northern, (more rapidly eroding)  
34 sector and subsequently evolved into parabolic dunes, with a depositional lobe migrating landward into  
35 the forest. Two parabolic dunes naturally stabilized by vegetation colonization, without any reactivation  
36 phase, with the third one still migrating landward with an average migration of 7.2 m/yr. A high-  
37 frequency and high-resolution analysis of the active blowout was performed between 2014 and 2021.  
38 Compared to the adjacent areas, this blowout promoted dune landward migration. Since 2014, the high  
39 erosion scarp in the adjacent southern sector prevented the transport of sand resulting in a loss of dune  
40 volume due to marine erosion. In contrast, in the adjacent northern sector and in front of the blowout,  
41 the presence of vegetation and paleosols at the dune toe favored sand deposition and limited marine  
42 erosion. In chronically eroding sectors, promoting blowouts and thus landward dune migration may be  
43 considered as an efficient management approach to maintain the dune system.  
44

45 **Keywords:** Coastal dune; Remote sensing; Marine erosion; Blowout; Parabolic dune.

## 46 **1. Introduction**

49 With increased anthropic pressure (e.g., demographic expansion of coastal areas, Neumann et  
50 al., 2015; Merkens et al., 2018) and climate change (e.g., sea level rise and increase in storminess, Zappa  
51 et al., 2013; Cazenave et al., 2014), sandy coasts (31% of the world coastlines, Luijendijk et al., 2018)  
52 are among the most vulnerable environments. In the backshore and landwards of sandy beaches with  
53 sufficient sand supply, coastal dunes can develop through many interactions between marine and aeolian  
54 processes on the one hand (Nordstrom, 2000; Hesp, 2002; Cohn et al., 2018), and vegetation growth and  
55 burial on the other hand (Maun, 1998; Maun and Perumal, 1999; Zarnetske et al., 2012). Dune vegetation  
56 traps windblown sand and promotes sand deposition, which, in turn, can promote plant growth. This  
57 positive feedback is responsible for the growth of coastal dunes along many coasts worldwide (Maun,  
58 1998; Emery and Rudgers, 2014; Charbonneau et al., 2021). As coastal dunes develop, they provide  
59 new habitats that promote plant succession, eventually stabilizing the dune system (Barbour et al., 1985;  
60 Provoost et al., 2011; Pye et al., 2014; Charbonneau et al., 2016). Coastal dunes also provide ecosystem  
61 services such as natural and effective barrier against flooding and storm waves, the formation of  
62 ecological niches for plants, the filtration of pollutants, fresh water supply or the expansion of nesting  
63 sites (Martinez et al., 2013).

64  
65 Foredune blowouts are erosional features typical of active dune systems (Black, 1951; Adamson  
66 et al., 1988). These depressions, formed by wind erosion, are characterized by a deflation basin, erosion  
67 walls, and a deposition lobe (Glenn, 1979; Carter et al., 1990; Hesp, 2002). Foredune blowouts can be  
68 classified into two broad categories according to their morphologies: saucer blowouts and trough  
69 blowouts (Cooper, 1958; Cooper, 1967). The formers are shallow with a circular shape while the latter  
70 are more elongated, deeper and with a well-defined deposition lobe. Blowouts are an important  
71 component of dune functioning. Under strong onshore wind, the airflow is topographically accelerated  
72 through the deflation basin, it erodes the base of the deflation basin and transports the sand into the  
73 deposition lobe or beyond to the back dune (Hesp and Hyde, 1996; Fraser et al., 1998; Pease and Gares,  
74 2013). These new deposits generate a disturbance for plants species that can lead to a local vegetation  
75 rejuvenation (Nordstorm et al., 2007, Laporte-Fauret et al., 2021a; Laporte-Fauret et al., 2021b) and a  
76 vertical accretion potentially increasing the back dune resilience to sea-level rise and coastal erosion  
77 (Clemmensen et al., 2001; Hesp, 2002; Petersen et al., 2005; Rhind and Jones, 2009; Arens et al., 2013;  
78 Hesp and Hilton, 2013; Martinez et al., 2013; Kuipers, 2014; Jewell et al., 2017; Pye and Blott, 2017).  
79 For this reason, in recent years (natural or artificial) blowouts have been progressively considered as a  
80 potential means for efficient management approach in some regions of the world (Van Boxel et al.,  
81 1997; Arens et al., 2013; Kuipers, 2014; Pye and Blott, 2016; Ruessink et al., 2018; Laporte-Fauret et  
82 al., 2021b). In particular, naturally (or artificially) stabilized dune systems threatened by chronic marine  
83 erosion can be remobilized and migrate landward through blowout development which, in sector under  
84 severe shoreline erosion, may maintain the dune system (Castelle et al., 2019).

85  
86 Many studies on blowouts have focused on the airflow modification, including acceleration and  
87 steering, using two- and three-dimensional anemometers (Hesp and Hyde, 1996; Hugenholtz and Wolfe,  
88 2009; Hesp and Walker, 2012; Pease and Gares, 2013) and computational fluid dynamics (Jackson et  
89 al., 2011; Smyth et al., 2012) by predominantly focusing on the short-term (event) scale. Studies on  
90 morphological changes on medium (months) to long (annual/decadal) temporal scales, are scarcer and  
91 focus mainly on planview (horizontal) changes using erosion pins, aerial photography or ground  
92 penetrating radar (Jungerius and van der Meulen, 1989; Gares and Nordstrom, 1995; Hugenholtz and  
93 Wolfe, 2006; González-Villanueva et al., 2011; Abhar et al., 2015; Jewell et al., 2017).

94  
95 Blowout evolution depends on complex interactions between abiotic (e.g., windblown sand,  
96 marine erosion) and biotic (e.g., vegetation colonization and growth) processes (Gares and Nordstrom,

1995; Hesp, 2002; Pye and Blott, 2017). Schwarz et al. (2018) developed a conceptual model of blowout evolution highlighting these bio-geomorphological interactions according to three stages. Blowout initiation (Stage 1) is dominated by abiotic (aeolian) processes that increase the size and depth of the blowout. Blowout development (Stage 2) is governed by bio-geomorphological interactions between vegetation development, which inhibits blowout extension, and physical disturbance, which inhibits vegetation development. Finally, closure (Stage 3) is related to biotic processes where vegetation development prevents erosion and promotes deposition in the blowout. However, in stormy environments the constant erosion of the erosion walls, by avalanches of sediment from the crest to the deflation basin, generates significant sedimentary supplies that further feed the deposition lobe. If the disturbance remains too large for vegetation colonization, the lobe may continue to migrate downwind leading to the development of hairpin or long-walled parabolic dunes with trailing arms (Melton, 1940; Cooper, 1958; Wiedemann, 1991; Hesp, 2001; Girardi and Davis, 2010). The size of the parabolic dune may continue to increase if enough sand supply through the deflation basin is sustained. In contrast, the growth may cease if the deflation basin becomes too large, preventing airflow acceleration and sand transport; if it reaches a non-erodible layer (e.g., ground water table, limestone bed, or paleosol); or if it becomes colonized by vegetation (Melton, 1940; Cooper, 1958; Livingstone and Warren, 1996, Hesp, 2002). Yan and Baas (2015) highlighted approximately 20 studies documenting the formation of parabolic dunes from blowout. Most of these studies were based on field surveys, aerial photo interpretation on multi-year to decadal time scales (see Table 4 in Yan and Baas, 2015), or numerical modeling (Baas and Nield, 2007; Nield and Baas, 2008). However, as shown by Delgado-Fernandez et al. (2018), large morphological evolutions can take place on very short time scales (e.g., storm event). Therefore, there is a real lack of quantitative studies at high spatial resolution and on time scales ranging from event to decade on blowouts transformation into parabolic dune.

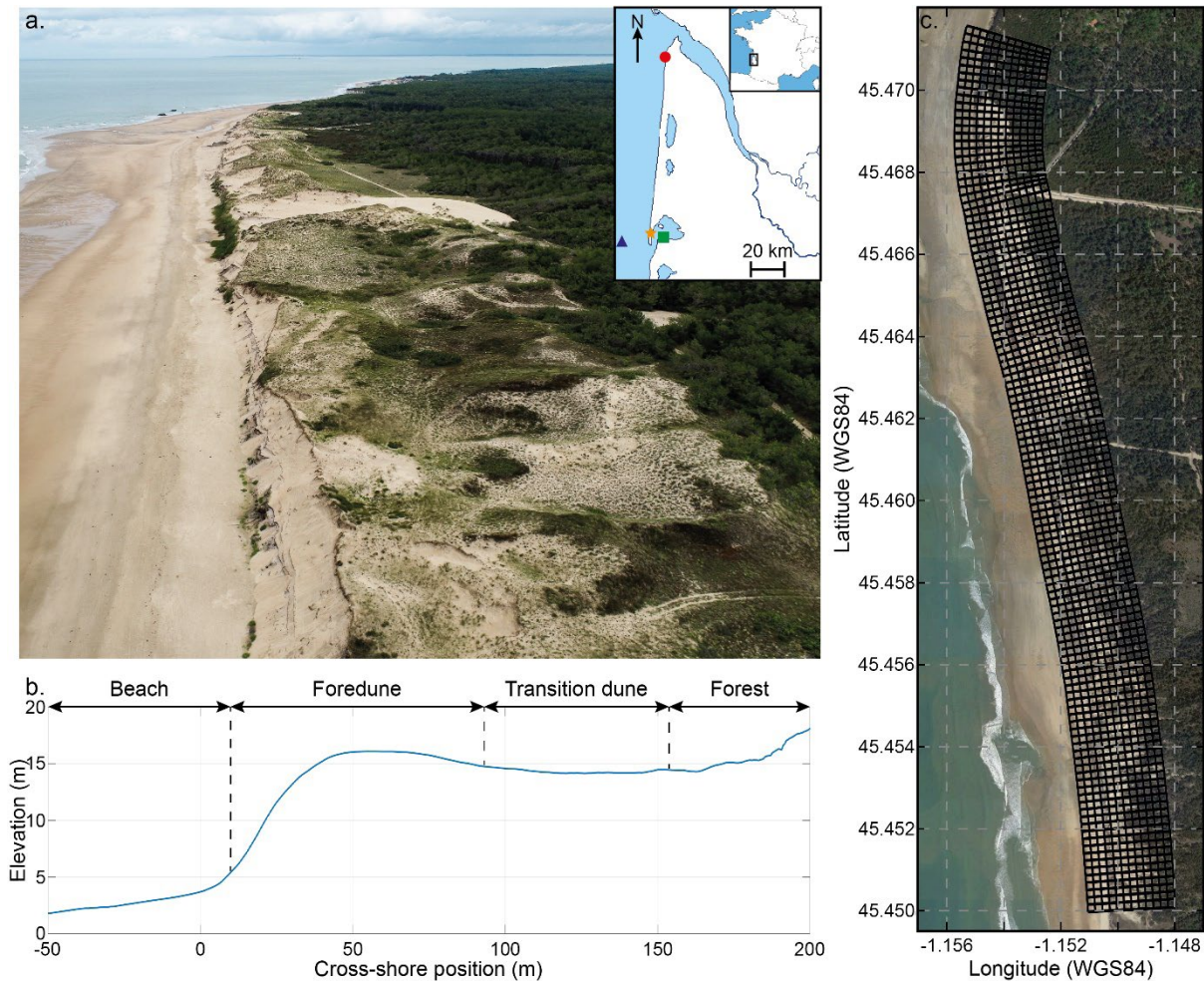
The objective of this study is to investigate the morphological evolution of a freely evolving dune system dissected by many natural blowouts in a chronically eroding sector in southwest France. These investigations are carried out using historical aerial photos to understand these evolutions since 1947 and Digital Surface Models (DSMs) performed by Lidar and UAV photogrammetry on event to seasonal timescales in order to provide fresh and quantitative insight into the 3D dune evolution, focusing on an active blowout that recently developed into a parabolic dune.

## 2. Material and methods

### 2.1. Study site

The study site, l'Anse du Gulp, is located in the northern part of an almost uninterrupted 110-km dune system along the Gironde coast, southwest of France (Figure 1.a). This coast is mainly characterized by open sandy beaches facing W-WNW, turning to WNW-facing to the north at the Pointe de la Négade. The coast is meso- to macro-tidal with an average tidal range of 3.7 m, reaching a maximum of 5 m during spring tides (Castelle et al., 2015, measured at the Arcachon-Eyrac tide gauge, Figure 1.a). The beaches are exposed to an energetic wave climate with waves generated in the North Atlantic Ocean arriving with a dominant W to NW incidence. Incident waves show strong seasonal variability with monthly averages of significant wave heights ( $H_s$ ) and period between peaks ( $T_p$ ) ranging from 1.1 m and 8.5 s in July with a dominant W-NW direction, to 2.4 m and 13 s in January with a dominant W direction (Castelle et al., 2017, measured at the wave buoy, Figure 1.a). This strong seasonal variability is also found in the wind conditions with an average hourly mean wind speed and direction of 4.5 m/s and 311° (NW) in summer and 5.2 m/s 263° (W) in winter, potentially exceeding 36 m/s during extreme storms (Laporte-Fauret et al., 2021b, measured at the weather station, Figure

145 1.a). Winter (wind and waves) conditions also show a large interannual variability due to large-scale  
 146 climate patterns of atmospheric variability. The West Europe Pressure Anomaly (WEPA) was found to  
 147 be a dominant mode explaining the winter interannual variability in the Bay of Biscay of e.g., westerly  
 148 winds, wave height, precipitations, river discharge (Castelle et al., 2017; Jalón-Rojas and Castelle,  
 149 2021). The positive phase of WEPA reflects a southward-shifted and intensified Icelandic Low / Azores  
 150 funneling high-energy waves and storm winds towards the Bay of Biscay (Castelle et al., 2017).  
 151



152 Figure 1. (a) Aerial photograph of l'Anse du Gulp (Ph. Quentin Laporte-Fauret), the red bubble, the  
 153 green square, the blue triangle and the orange star show the location of the study site, the Arcachon-  
 154 Eyrac tide gauge, the wave buoy and the weather station, respectively, (b) 2 km alongshore-averaged  
 155 beach dune profile at l'Anse du Gulp, (c) 2 km curvilinear grid used at l'Anse du Gulp.  
 156  
 157

158 At l'Anse du Gulp, the dune system, located between the beach and the forest, is composed of  
 159 a foredune and a transition dune, both showing large alongshore variability, reaching a mean height of  
 160 16 m with a mean width of 85 m (Figure 1.b). The dune system is composed of medium grain sand from  
 161 300  $\mu\text{m}$  to 415  $\mu\text{m}$  (Bosq et al., 2019; Stéphan et al., 2019). The overall shape of the dune is largely  
 162 inherited from the action of the coastal stakeholders who built the dune systems using fences and  
 163 vegetation planting from the 19<sup>th</sup> century (Buffault, 1942, Bossard and Lerma, 2020; Robin et al., 2020).  
 164 Unlike some other dune systems where soft engineering methods are still applied (e.g., Truc Vert,  
 165 Laporte-Fauret et al., 2021b), the dune system at l'Anse du Gulp has not been managed since the early  
 166 2000s. This area is characterized by a chronic, quasi-steady, erosion since the 1950s (Castelle et al.,  
 167 2018), which prevents the formation of incipient foredune and generates high erosion cliffs. It is a remote

168 system, with only an old and partially destroyed concrete road dating from the German occupation.  
 169 However, despite access is prohibited, the area is often used as attested by paths formed by animals,  
 170 hunters, dissident walkers and even motocross riders (see Figure 4.i). Finally, the dune system is perched  
 171 on Pleistocene paleosols, which are more resistant to marine erosion than sand and locally outcrop at  
 172 the dune toe and/or upper part of the beach, particularly after high-energy winters (Pontee et al., 1998;  
 173 Castelle et al., 2015; Stéphan et al., 2019).

174

175 2.2. Data

176

177 A set of 6 B&W and 3 RGB historical aerial photographs covering the study area were collected  
 178 from the French National Institute of Geography and Forest Information (IGN) (Table 1). These surveys  
 179 cover the period from 1947 to 2012, with a quasi-decadal frequency during the 1900s and then  
 180 approximately every four years in the 2000s, with a pixel size ranging from 0.33 m to 1.87 m.

181

182 Table 1. Characteristics of the aerial photo survey dataset from 1947 to 2012.

Date	Number of photos	Color data	Pixel size (m)
1947-05-29	6	B&W	1.12
1957-06-18	9	B&W	1.87
1969-01-01	9	B&W	0.84
1977-09-10	7	B&W	0.87
1986-07-18	6	B&W	1.33
1998-06-24	22	B&W	0.33
2004-06-14	5	RGB	1.62
2009-06-23	8	RGB	0.79
2012-08-08	14	RGB	0.46

183

184 For each survey, all the photos were assembled and merged using Agisoft Metashape (v1.7.2) in order  
 185 to build a 3D georeferenced model and an orthomosaic following a 4-step workflow, (1) the cameras  
 186 were aligned by the detection of matching points on overlapping image parts, (2) the 3D sparse point  
 187 cloud, generated by the camera alignment, was orthorectified using 13 fixed Ground Control Points  
 188 (GCPs, e.g., crossroads) from the recent IGN referenced images and a camera optimization procedure  
 189 was performed to compute the intrinsic camera calibration parameters by minimizing the error on the  
 190 ground control points, (3) a 3D dense point cloud was generated and (4) interpolated with Matlab on a  
 191 0.2 x 0.2 m regular grid (Figure 1.c) in order to build a textured DSM that can be exploited in geographic,  
 192 projected, or local (cross-shore/longshore) coordinates. The planimetric errors of DSMs from historical  
 193 aerial photos are under 3 m.

194

195 Two topographic surveys performed by airborne Lidar on the entire Aquitaine coast were used,  
 196 the first dated October 23-24, 2014 with a density of 4 points/m<sup>2</sup> and an altimetric error of 0.14 m (Lerma  
 197 et al., 2019), and the second dated October 07, 2021, with a density of 15 points/m<sup>2</sup> and an altimetric  
 198 error of 0.10 m. The second Lidar survey was mainly used to estimate the DSM error due to vegetation  
 199 coverage, in particular at the parabolic dune toe. From January 2016 to January 2018, 17 surveys were  
 200 performed using a DJI Phantom 2 (DP2) quadricopter UAV equipped with 12MPix camera (GoPro Hero  
 201 4 Black), and, from November 2018 to July 2021, four surveys were performed using a DJI Phantom 4  
 202 Pro (DP4P) quadricopter equipped with a 20MPix camera. All surveys were performed according to the  
 203 monitoring strategy designed and validated in Laporte-Fauret et al. (2019). In short, the surveys covered  
 204 2 km of beach/dune system with an automatized fly plan. In order to georectify the DSM, an array of 14  
 205 permanent GCPs were implemented by pairs (one in the foredune and one in the transition dune) every

206 250 m alongshore. Their positions were measured with GNSS before each winter. The DSM generation  
 207 process follows the same workflow as the one applied to the historical aerial photos except that the  
 208 rectification is done with the permanent GCPs instead of crossroads. Laporte-Fauret et al. (2019) showed  
 209 that this protocol leads to altimetric RMSE around 0.13 m and 0.05 m for DP2 and DP4P, respectively.  
 210 Given the curvature of the coast, here the DSMs were computed on a curvilinear, cross-shore/longshore,  
 211 grid (Figure 1.c).

212

### 213 2.3. Coastal dune metrics

214

215 There is a large range of shoreline definitions (Boak and Turner, 2005). In our study, in line  
 216 with previous work in southwest France (Castelle et al., 2017; Lerma et al., 2019), from the LiDAR and  
 217 UAV DSMs we computed the shoreline position the iso-contour  $z = 5.5$  m, which correspond to the  
 218 dune toe on almost the entire site. Given the poor altimetric accuracy of the historical DSMs, the  
 219 shoreline position was digitized by an operator. Given the curvilinear grid used for DSM generation, the  
 220 dune volume from 2014 to 2021 was computed as:

$$V = \sum_{j=j_S}^{j_N} \sum_{i=i_W}^{i_E} S_{ij}(z_{ij} - z_{DT}) \quad (1)$$

221 where  $j_S$  and  $j_N$  are the grid indices of the southern and northern limit, respectively,  $i_W$  and  $i_E$  are the  
 222 grid indices of the western and the eastern limit, respectively.  $i_W$  is defined as the shoreline position  
 223 index of the dune toe and  $i_E$  is defined as the forest limit index, manually digitized on the last drone  
 224 survey (2021-07-09).  $S_{ij}$  and  $z_{ij}$  are the grid cell surface and elevation at grid point (i,j), respectively  
 225 and  $z_{DT}$  is the elevation of the dune toe. The evolution of the alongshore-averaged dune volume through  
 226 the survey was computed as:

227

$$DV = \frac{V_i - V_0}{d_{SN}} \quad (2)$$

228 where  $DV$  is the dune volume difference per beach width ( $\text{m}^3/\text{m}$ ) between the dune volume of the date  
 229  $i$  (i.e.,  $V_i$ ) and the initial dune volume (i.e.,  $V_0$ ) computed from the Lidar 2014, and  $d_{SN}$  is the alongshore  
 230 distance between the northern (i.e.,  $j_N$ ) and the southern (i.e.,  $j_S$ ) limits. All calculations were performed  
 231 using the curvilinear grid shown in Figure 1.c, which allows straightforward computations of  
 232 alongshore-averaged quantities. The cross-shore position  $x = 0$  m corresponds to the shoreline position  
 233 measured in the field along the 110-km Gironde coast using a DGPS-equipped ATV on 2014-11-14  
 234 (Castelle et al., 2015). The models generated by Lidar data and UAV photogrammetry are Digital  
 235 Elevation Model (DEM) and DSM, respectively. In order to correct the DSM-DEM bias, the 2017-10-  
 236 04 airborne Lidar (DEM) survey and the 2017-10-26 UAV photogrammetric (DSM) survey were  
 237 compared, showing an average 0.1-m vertical difference in the vegetated areas. Hence the 2014 initial  
 238 volume  $V_0$  was corrected by rising the DEM elevation by 0.1 m in vegetated areas of the dune, in order  
 239 to be consistent with subsequent photogrammetric DEMs. From the October 26, 2017 survey, a dense  
 240 vegetation zone started to develop in front of the parabolic dune, which could alter the volume  
 241 computation with the DSMs. By comparing the UAV-DSM of July 9, 2021 and the Lidar-DEM of  
 242 October 07, 2021, the vegetation was outlined and its volume computed. Then its effect on the elevation  
 243 was calculated as:

$$D_z = \frac{V_{UAV} - V_{Lidar}}{S_{veg}} \quad (3)$$

244 where  $V_{UAV}$  and  $V_{Lidar}$  are the volume of the outlined vegetation for the UAV-DSM and the Lidar-  
245 DEM, respectively and  $S_{veg}$  is the surface of the outlined vegetation. Then, for each DEM from October  
246 26, 2017, the vegetation was outlined and then a correction was applied by:

247

$$V_{corrected} = V - (S_{veg} D_z) \quad (4)$$

248

249 where  $V$  and  $S_{veg}$  are the initial volume and the vegetation surface for each survey, respectively.

250

### 251 **3. Results**

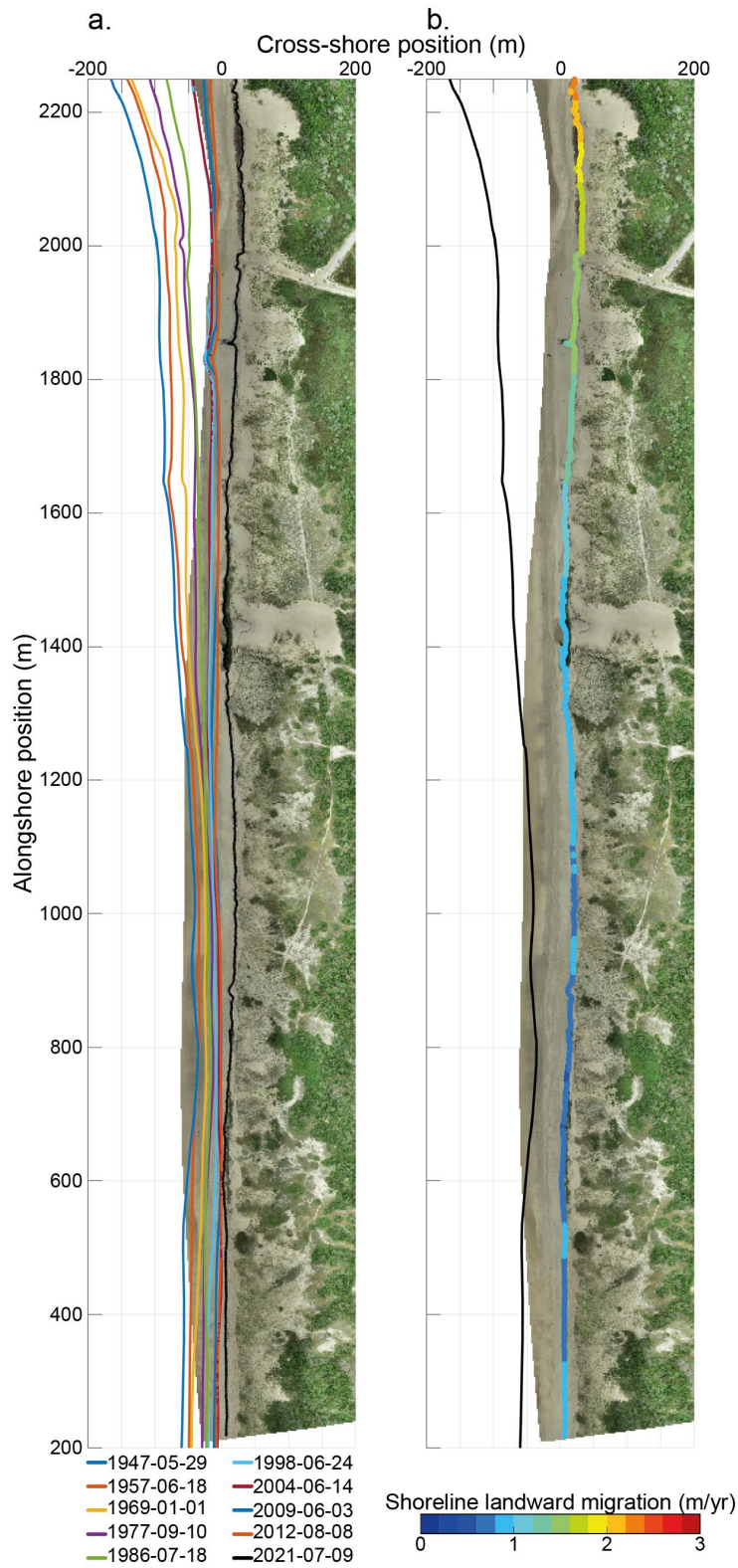
252

#### 253 3.1. Long term spatial coastal dune evolution

254

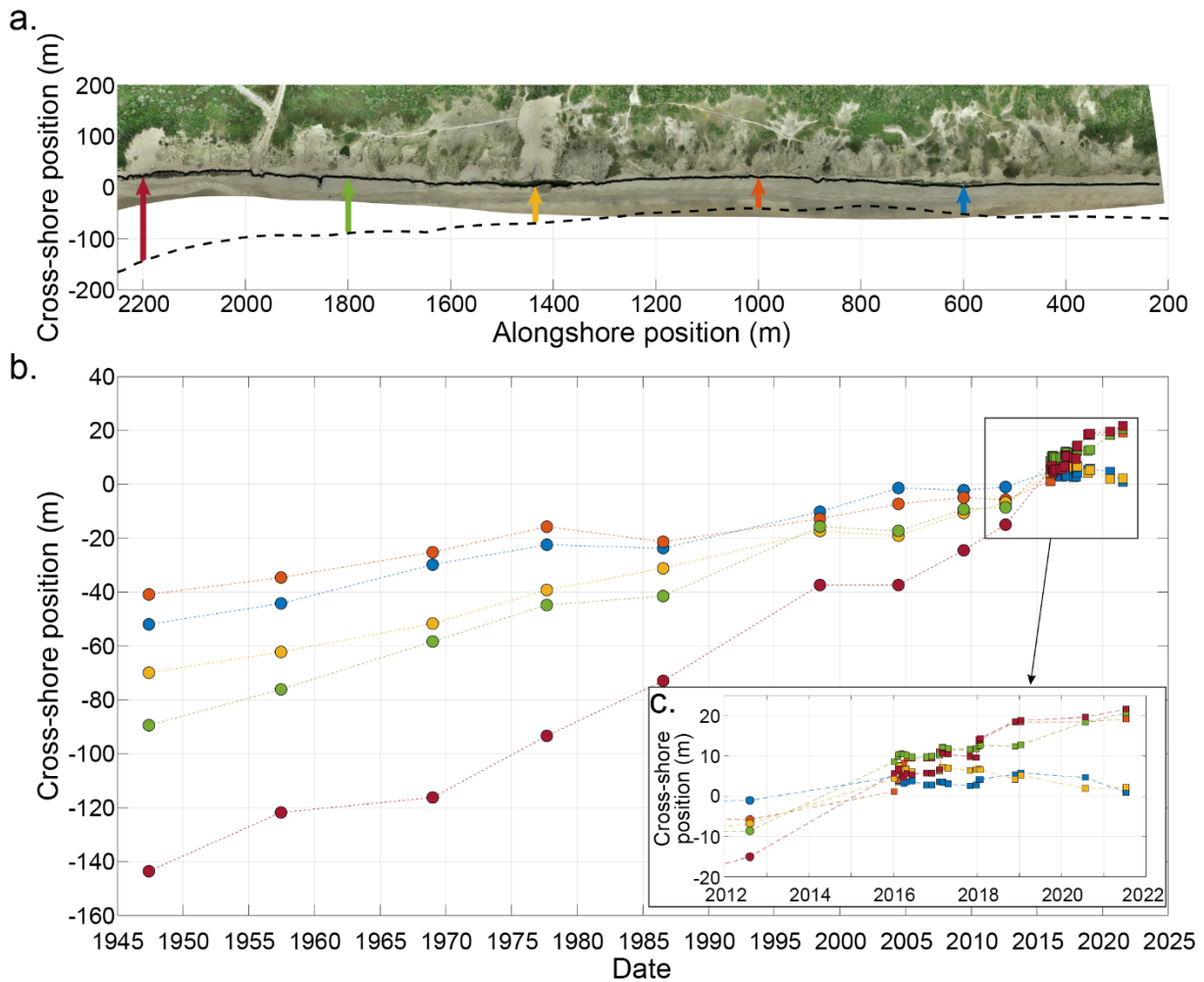
255 Figure 2.a shows the time series of shoreline position from 1947 to 2021, highlighting chronic,  
256 quasi-steady, marine erosion. The shoreline erosion rate increases northwards, from 0.68 m/yr in the  
257 south to 2.72 m/yr in the north (Figure 2.b). Erosion rates are fairly uniform alongshore in the south of  
258 the study zone, before dramatically increasing northwards in the northern part (Figures 2 and 3).





259  
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 261  
 262  
 263

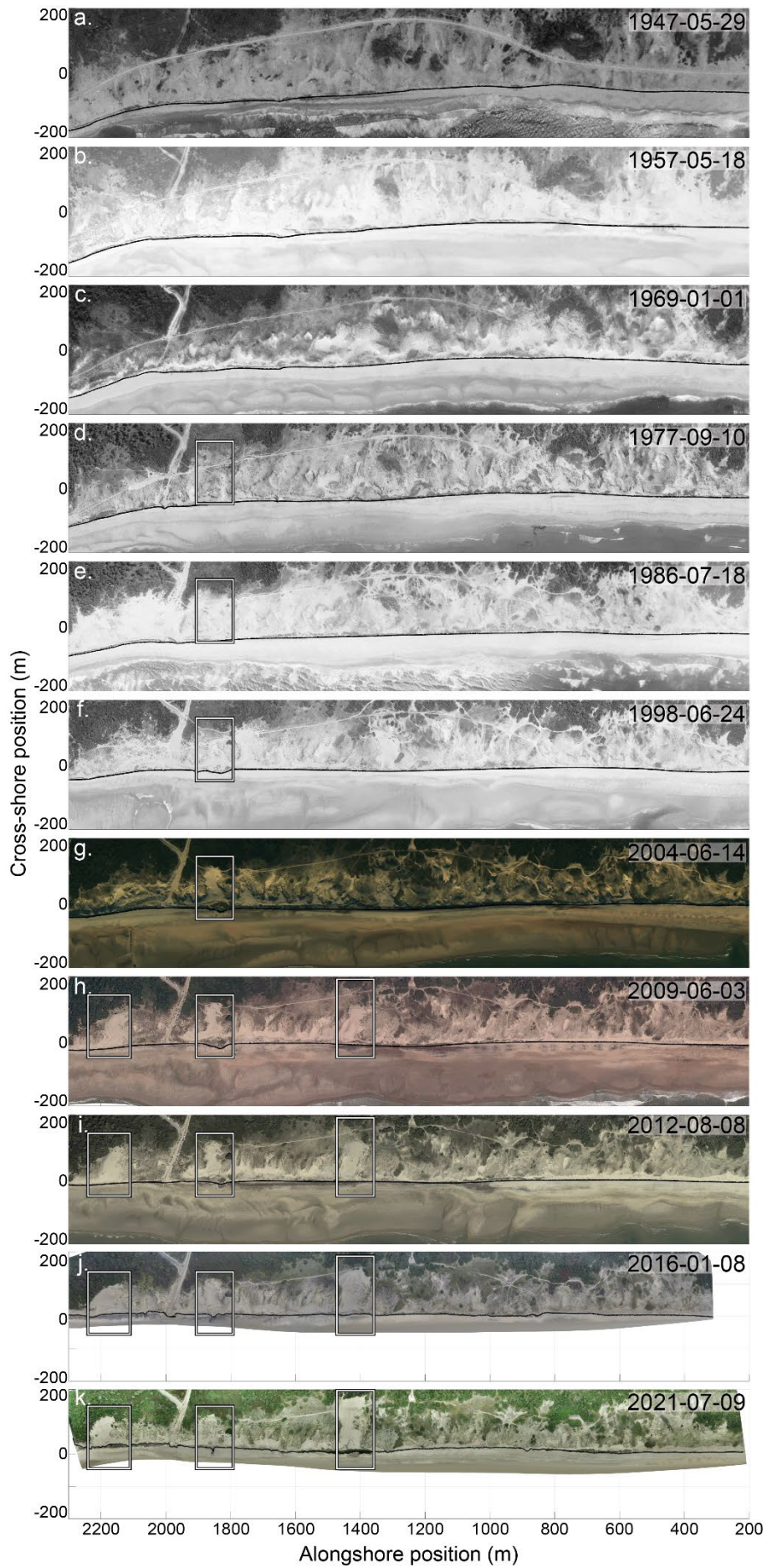
Figure 2. Orthophotos of l'Anse du Gulp in 2021-07-09 with superimposed (a) shorelines from 1947-05-29 to 2021-07-09 and (b) colored shoreline migration rate computed from 1947-05-29 (black line) to 2021-07-09 (colored line).



264  
 265 Figure 3. (a) Orthophotos of l'Anse du Gurd on 2021-07-09 with shoreline position (black line) and  
 266 the shoreline position on 1947-05-29 (black dashed line). The five colored arrows represent the  
 267 shoreline migration at five alongshore position  $x = 600$  m (blue),  $x = 1000$  m (orange),  $x = 1435$  m  
 268 (yellow),  $x = 1800$  m (green) and  $x = 2200$  m (red), (b) time series of the shoreline cross-shore  
 269 position for these 5 alongshore positions from 1947-05-29 to 2021-07-09 with (c) a zoom on the 10  
 270 last years. Circles and squares represent data from aerial photography and UAV photogrammetry,  
 271 respectively.  
 272

273 All the orthophotos since 1947 show a coastal dune system systematically dissected by breaches  
 274 and blowouts (Figure 4), with the notable successive development and evolution of three large blowouts  
 275 (i.e.,  $x = 1450$  m,  $x = 1850$  m and  $x = 2200$  m) at different times from 1977 (white rectangles in  
 276 Figure 4.d-j). The first breach ( $x = 1850$  m) formed around 1977 (Figure 4.d) and further developed  
 277 into a large blowout around 2004 (Figure 4.g). The deposition lobe migrated landward before reaching  
 278 the forest in 2009 (Figure 4.h) and further stabilizing and revegetating after 2012 (Figure 4.i,j,k). The  
 279 second blowout ( $x = 2200$  m) rapidly developed between 2004 and 2012 (Figure 4.g,h,i) when its  
 280 deposition lobe reached the forest. Incipient vegetation colonized the southern part of the blowout  
 281 starting in 2016 (Figure 4.j) and subsequently extending to 2021 (Figure 4.k) suggesting no further  
 282 morphological development. Finally, the third blowout ( $x = 1450$  m) shows an initial development  
 283 concurrent to the previous one (Figure 4.g,h), with the formation of a deflation basin between two  
 284 vegetated erosion walls, and a large deposition lobe. Compared to the two other blowouts, this blowout  
 285 is located in a sector with less intense chronic erosion and a wider dune system. The deposition lobe  
 286 continuously grows, with a quasi-steady landward migration into forest between 2016 (Figure 4.j) and

287 2021 (Figure 4.k). As erosion walls remained vegetated and stable, this blowout transformed into a  
288 parabolic dune which will be analyzed in detail in Section 3.2.2.  
289



291 Figure 4. (a-i) Aerial orthophotos of l'Anse du Gulp and (j-k) UAV orthophotograph, all represented  
292 in the local coordinate system. The black line represents the shoreline position for each date and the  
293 white rectangles indicate the position of large blowouts.

294

### 295 3.2. Coastal dune morphological evolution

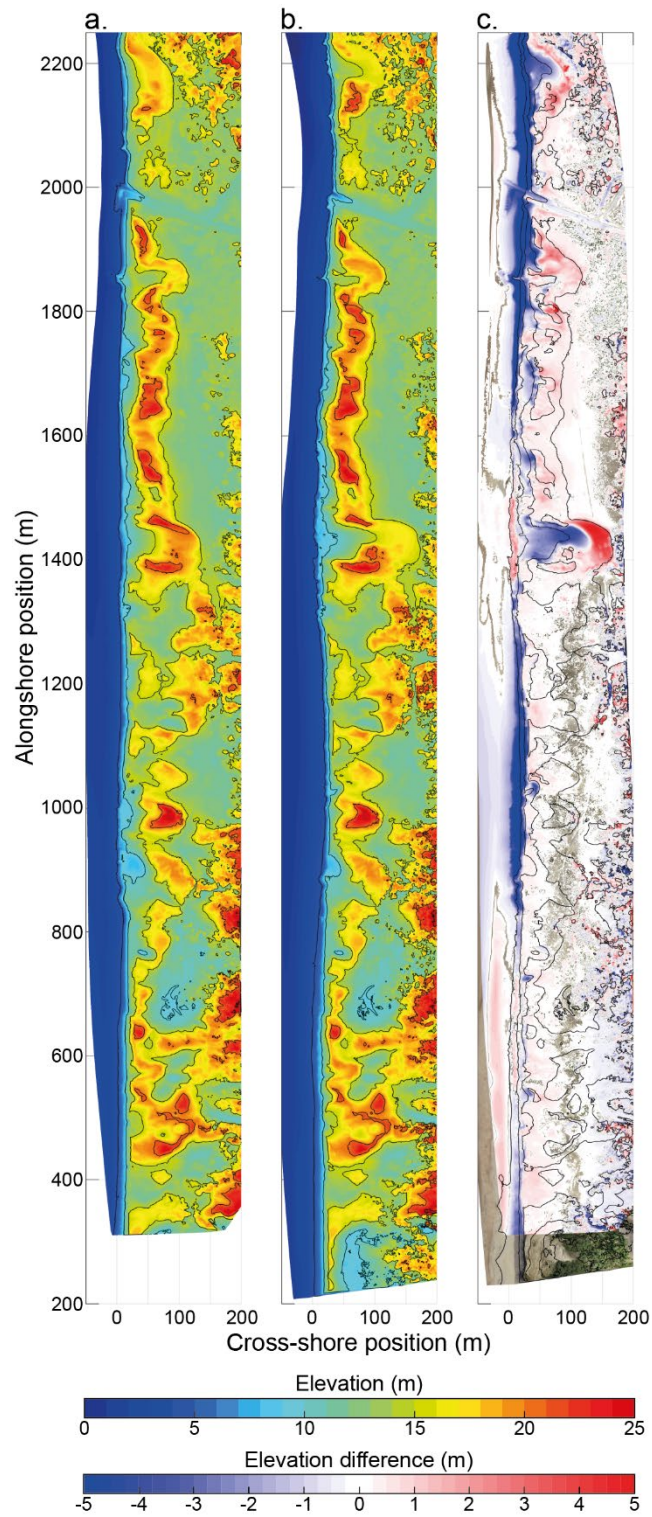
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#### 297 3.2.1. Overall dune system

298

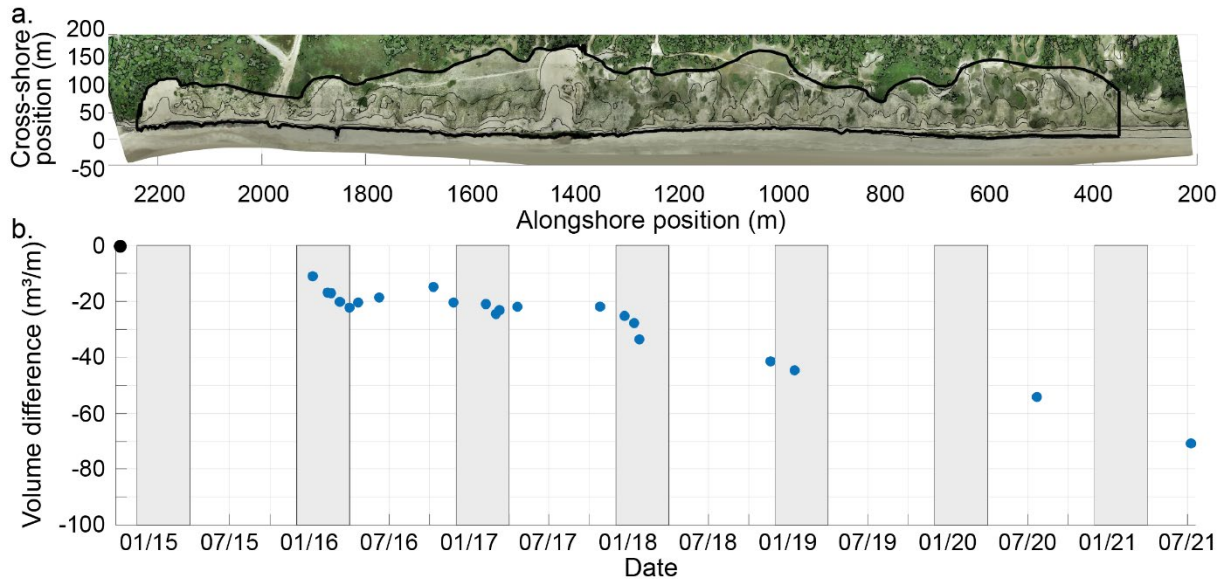
299 The dune system of l'Anse du Gulp is strongly non-uniform alongshore due to the presence of  
300 many breaches cutting the dune, with different sizes and shapes, some of them starting to develop into  
301 trough or saucer blowouts. Between 2016 (Figure 5.a) and 2021 (Figure 5.b), three large blowouts  
302 developed in this 2-km long dune system, at  $x = 1435$  m,  $x = 1850$  m and  $x = 2200$  m. The DSM  
303 difference between 2016 and 2021 (Figure 5.c) highlights two large areas of dune marine erosion with  
304 an average (maximum) vertical erosion of 6 m (11 m). These areas are located between  $x = 850$  m and  
305  $x = 1350$  m with horizontal dune toe erosion reaching 20.8 m, and further north, between  $x = 1625$  m  
306 and  $x = 2250$  m, where the average (maximum) vertical erosion is 10 m (15 m) with horizontal dune  
307 toe erosion reaching 33.8 m. The blowouts at  $x = 1435$  m and  $x = 2200$  m show an average vertical  
308 erosion of 3 m in the deflation basin, reaching 6 m in the center, whereas the blowout at  $x = 1850$  m  
309 shows lower vertical erosion with an average of 1.5 m, reaching 3.5 m in the center. Apart from these  
310 active blowouts, the foredune is mainly characterized by vertical accretion with an average (maximum)  
311 of 0.4 m (1.5 m) between  $x = 320$  m and  $x = 1350$  m, and 0.8 m (2.1 m) between  $x = 1480$  m and  
312  $x = 1950$  m. The largest vertical accretion values are found in the deposition lobe of the three main  
313 blowouts with an average (maximum) of 2 m (5 m) at  $x = 1435$  m, 2 m (4 m) at  $x = 1850$  m and 1 m (3  
314 m) at  $x = 2200$  m. The dune system of l'Anse du Gulp has been continuously losing sand since 2014  
315 (Figure 6.b) with winter marine erosion exceeding the amount of sand recovered in spring-summer-fall.  
316 This results in a net loss of sand of  $70.7 \text{ m}^3/\text{m}$  between 2014 and 2021, i.e., 4.98% of the total volume  
317 with a mean rate of  $10.5 \text{ m}^3/\text{m}/\text{yr}$  (Figure 6.a,b).

318



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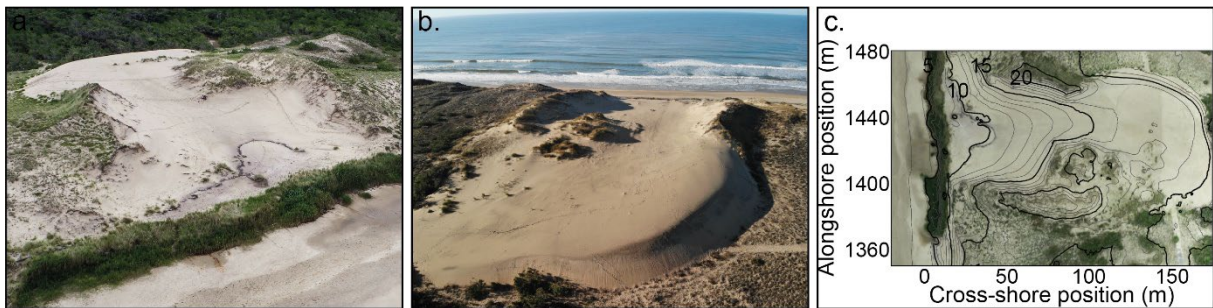
Figure 5. DSM of l'Anse du Gulp in (a) 2016-01-08 and (b) 2021-07-09 and (c) and corresponding difference plot.



323  
 324 Figure 6. (a) UAV-derived orthophotograph of l'Anse du Gulp in 2021-07-09 where the black lines  
 325 delimit the area in which the volumes are calculated, (b) Time series of the volume difference between  
 326 2014 and 2021. Grey rectangles represent the winter periods, blue and black points are for drone  
 327 Lidar surveys, respectively.

### 3.2.2. Zoom onto the parabolic dune

330  
 331 As revealed by the historical aerial photos (Figure 4), the blowout that formed after 2004 (Figure  
 332 4.g-k) has evolved into a parabolic dune (Figure 7). Figure 8 shows the high-frequency morphological  
 333 evolution of this blowout from 2016 to 2021. In 2016, the distances between the base of the erosion  
 334 walls and from the throat to the end of the deposition lobe were 40 m and 118 m, respectively. After 5.5  
 335 years of monitoring, the parabolic dune is still mostly unvegetated, which is characteristic of the first  
 336 stage of the Schwarz et al. (2018) blowout development model, indicating that its current evolution is  
 337 mainly related to physical forcing. Indeed, the deposition lobe continuously migrated landward with  
 338 concurrent widening of the deflation basin, reaching distances between erosion walls of 54 m, and 159  
 339 m between the throat to the end of the deposition lobe. The latter has migrated landward by 39.6 m, i.e.,  
 340 by 7.2 m/yr on average. An average (maximum) vertical erosion within the deflation basin is 2.4 m (5.9  
 341 m), with an average (maximum) vertical accretion of 1.95 m (4.7 m) in the deposition lobe.  
 342



343  
 344 Figure 7. Aerial photograph (a) from the front (taken on July 9, 2021, Ph. Quentin Laporte-Fauret), (b)  
 345 from the back (taken on January 15, 2019, Ph. Bruno Castelle) and (c) drone-derived orthophotograph  
 346 of the parabolic dune at l'Anse du Gulp (from the July 9, 2021 survey).  
 347





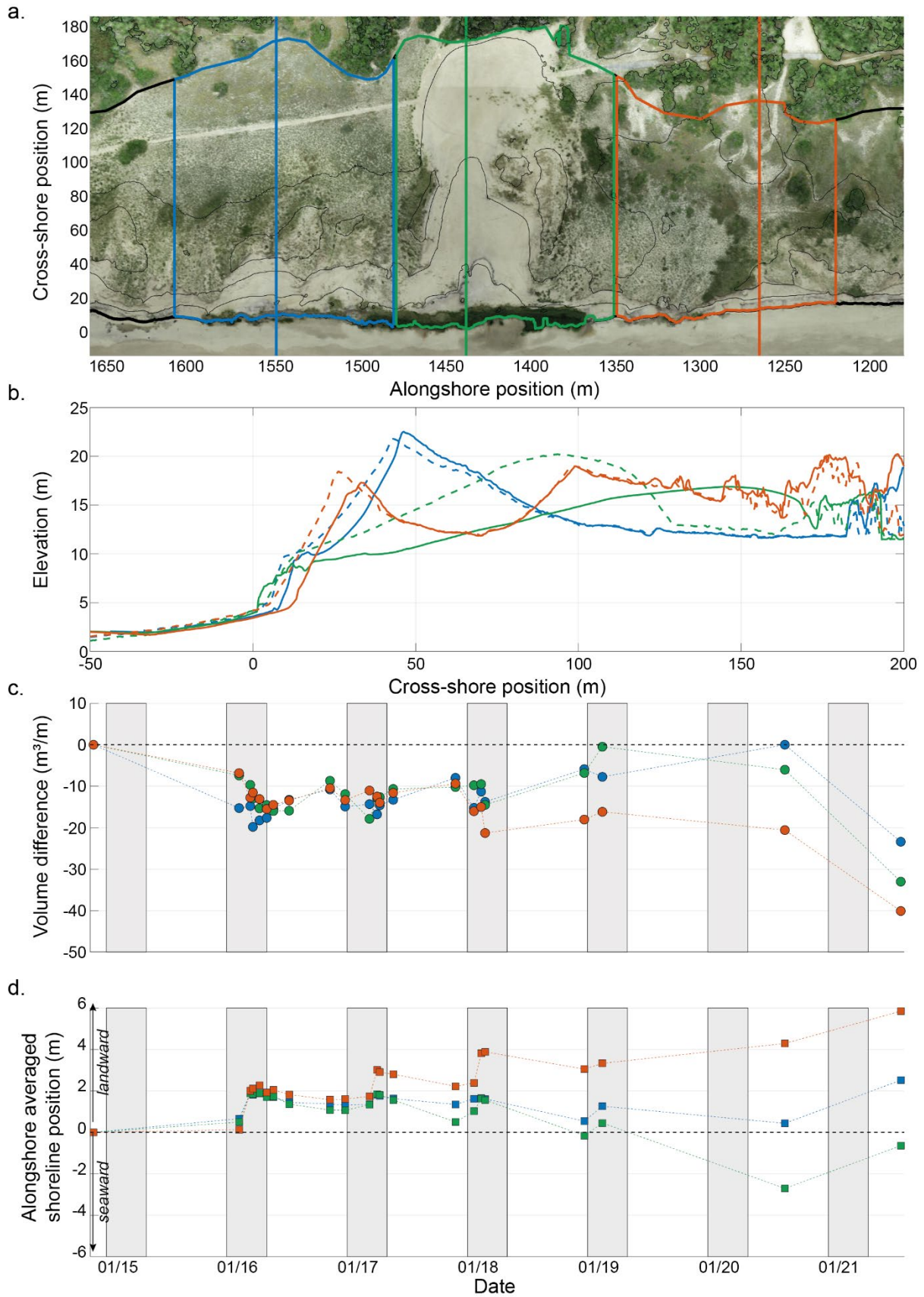
349 Figure 8. **(Left-hand panels)**: DSMs of l'Anse du Gurd zoomed onto the parabolic dune from 2016-  
350 01-08 to 2021-07-09. **(Right-hand panels)**: Elevation difference between two consecutive surveys. **(I)**  
351 Net elevation difference between 2016-01-08 and 2021-07-09. All these DSMs were performed by  
352 UAV photogrammetry.

353  
354 Figure 9 shows the 2014-2021 morphological evolution (i.e., cross-shore profile, volume  
355 difference and alongshore-averaged shoreline position) of the parabolic dune system (green area in  
356 Figure 9.a), compared to two adjacent control areas in the north (blue area in Figure 9.a) and in the south  
357 (orange area in Figure 9.a). The cross-shore profiles in the central area (green curves in Figure 9.b)  
358 highlight the landward migration (by approximately 40 m) of the deposition lobe with crest lowering  
359 (up to 3.3 m). The northern profiles (blue curves in Figure 9.b) are characterized by a dune toe retreat  
360 by 4.9 m. The dune crest migrated landward by 3.2 m and raised by 1.14 m. The northern and central  
361 profiles are characterized by an approximately 5-m high erosion scarp with a slope break around  
362 elevation  $z = 9.5$  m. The southern profiles (orange curves in Figure 9.b) show a retreat of the dune toe  
363 by 5.5 m, with the dune crest migrating landward by 7 m and lowering by 1.14 m. Contrary to the two  
364 other zones, the profile of the southern zone does not show any break in slope around  $z = 10$  m, with a  
365 steep 17.3-m high face from the shoreline to the crest.

366  
367 The time series of volume differences show three periods with different evolution patterns  
368 (Figure 9.c). During the first period (i.e., from 2014 to the beginning of winter 2017-2018) the northern,  
369 the central and the southern areas all show a small decrease in dune volume with seasonal variation  
370 amplitude of approximately  $10 \text{ m}^3/\text{m}$ . At the end of the winter of 2017-2018, the northern, the central  
371 and the southern areas all show an increased volume loss by  $13.8 \text{ m}^3/\text{m}$ ,  $14.5 \text{ m}^3/\text{m}$  and  $21.3 \text{ m}^3/\text{m}$ ,  
372 respectively. During the second period (i.e., from the end of the winter of 2017-2018 to July 2020), the  
373 dune volume of the southern area has remained relatively stable, while the northern and central areas,  
374 although located in slightly more chronically eroding sectors, largely recovered with the dune volume  
375 even exceeding that in 2014. The third period (i.e., from July 2020 to July 2021) shows an alongshore  
376 quasi-uniform dune volume decrease, with  $19.5 \text{ m}^3/\text{m}$  for the southern area,  $23.4 \text{ m}^3/\text{m}$  for the northern  
377 and  $27 \text{ m}^3/\text{m}$  for the central areas. Thus, over the study period, the dune volume decreased by  $23.4 \text{ m}^3/\text{m}$   
378 (i.e., -1.75%),  $33 \text{ m}^3/\text{m}$  (i.e., -2.03%) and  $40.1 \text{ m}^3/\text{m}$  (i.e., -3.72%) for the northern, the central, and the  
379 southern areas, respectively.

380  
381 The three distinct time periods described above are also found in the evolution of the alongshore-  
382 averaged shoreline position (Figure 9.d). The first period (i.e., from 2014 to the beginning of winter of  
383 2017-2018) shows relatively stable alongshore-averaged shoreline position for the three areas with some  
384 seasonal variations in the order of 1.5 m. The winter of 2017-2018 induced a 1.67 m retreat of the  
385 alongshore-averaged shoreline position of the southern area, whereas during the second period (i.e.,  
386 from the end of the winter 2017-2018 to July 2020) the alongshore-averaged shoreline position of the  
387 southern area remained relatively stable. During the same period, the northern and central areas show a  
388 seaward shoreline migration by 1.20 m and 4.25 m, respectively. The alongshore-averaged shoreline  
389 position of the three areas migrated landward by about 2 m during the third period (i.e., from July 2020  
390 to July 2021). Thus, over the study period, the alongshore-averaged shoreline position eroded by 2.51  
391 m and 5.84 m, for the northern and southern areas respectively, and migrated seaward by 0.65 m for the  
392 central area where the parabolic dune is observed, which will be discussed in the next section.

393



394 Figure 9. (a) Orthophoto of l'Anse du Gurg zoomed onto the parabolic dune in 2021-07-09. The green  
 395 area includes the parabolic dune whereas the blue and orange areas are adjacent control areas at the  
 396 north and south of the parabolic dune, respectively, (b) Representative cross-shore profile of each area  
 397

398 (which locations are represented by vertical lines in Figure 9.a), dashed and solid lines are for 2014-  
399 10-23 and 2021-07-09, respectively. Time series of (c) volume difference and (d) alongshore-averaged  
400 shoreline position difference in each area. Grey rectangles represent the winter periods.

401

#### 402 **4. Discussion**

403

404 The main objective of this study was to investigate the morphological evolution of a freely evolving  
405 dune system dissected by blowouts at different stages of development, and the role of blowouts in  
406 sediment transfer to the back of the dune, in a chronical erosion context exceeded 2 m/yr since at least  
407 1947.

408

##### 409 4.1. Historical blowout evolution

410

411 The lifetime of blowouts is dictated by the interactions between physical and biological  
412 processes. A blowout can be considered no longer active when enough vegetation is present to  
413 overwhelm physical processes (e.g., erosion of the deflation basin) (Schwarz et al., 2018). Jewell et al.  
414 (2017) attempted to characterize the initiation and stabilization phases of foredune blowouts in two sites  
415 on the Texas coast (USA) between 1969 and 2010. Over 41 years of monitoring, they highlighted at  
416 least five phases of foredune recovery (i.e., defined as the expansion of vegetation in the deflation basin)  
417 and blowout reactivation, each of them lasting about five years at the first site, and four phases lasting  
418 about 10 years at the second site. The blowout reactivation can occur after severe storms, with strong  
419 and funneled winds rapidly locally eroding the dune where there is disruption of vegetation. At our study  
420 site, the oldest blowout developed in 1977 and was active until 2012 when vegetation began to colonize  
421 the deposition lobe and then the deflation basin. Its evolution is currently primarily controlled by biotic  
422 processes (i.e., ecological stage in the model of Schwarz et al., 2018). The northern blowout developed  
423 between 2004 and 2009 and vegetation began to colonize the southern part of the deposition lobe in  
424 2012 (Figure 4. g-i). It currently appears to be in the bio-morphological stage but if the current physical  
425 conditions persist over time, it is possible that this blowout will stabilize because of its limited  
426 development space with the presence of the forest to the east, and the chronic marine erosion of the dune  
427 to the west. It is also possible that the blowout will disappear due to coastal erosion, which is severe in  
428 the north of the study site. Indeed, from 2009 to 2021, the deposition lobe migrated landward by 2.15  
429 m/yr while the shoreline erosion rate reached 3.65 m/yr. Finally, the third blowout that formed between  
430 2004 and 2009 is still active as it developed into a parabolic dune. Its evolution is mainly controlled by  
431 physical processes (i.e., geomorphologic stage) preventing the establishment of vegetation. Contrary to  
432 Jewell et al. (2017), we therefore did not observe any reactivation phases in any of the three blowouts.  
433 It is possible that our time series is too short to capture reactivation phases as blowout lifetime at l'Anse  
434 de Gulp could be longer, i.e., decades. Indeed, Girardi and Davis (2010) have highlighted stabilization  
435 and reactivation phases over several decades (i.e., three episodes of reactivation between 1969 and 2001)  
436 through their GPR monitoring and aerial photography in the northeast coast of the USA. Another  
437 explanation is related to the local wave and wind climate. The low-energy conditions of the Texas coast  
438 favor stabilization, and occasionally isolated cyclonic events drive reactivation, while the southwest  
439 coast of France is a storm-dominated environment. Local climate drives wind, precipitation, waves  
440 which in turn influence sand transport (i.e., erosion/deposition) and vegetation dynamics (i.e., growth,  
441 colonization) which, in addition to e.g., dune size and shape or chronic marine erosion, are crucial  
442 elements to consider in the blowout life cycle (González-Villanueva et al., 2011; Hesp, 2002; Schwarz  
443 et al, 2018). Finally, as described by Jackson et al. (2019) and Gao et al. (2020), worldwide, and  
444 particularly in temperate climates, coastal dunes tend to stabilize due to global increases in temperature,  
445 precipitation, and greenhouse gases that result in increased vegetation cover.

446

#### 447 4.2. Recent morphological evolution

448

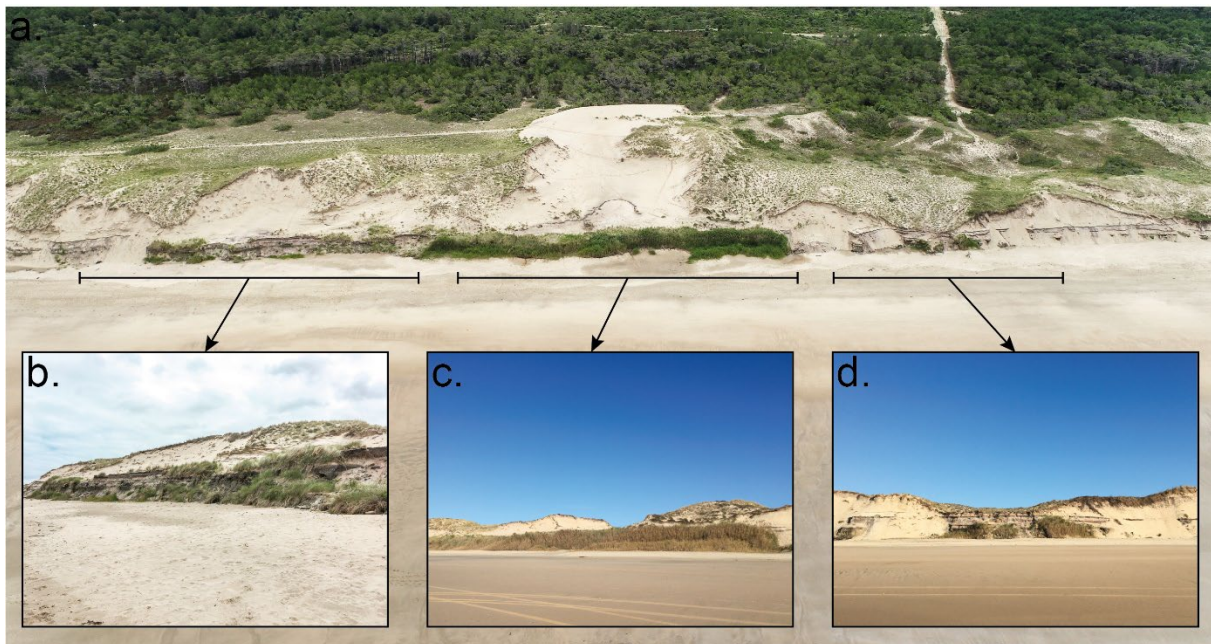
449 The volumetric analyses of the dune system between 2014 and 2021 (Figure 6.b) are discussed  
450 in the frame of the 2013-2014 winter, which was a winter characterized by extreme storm clustering  
451 along the Atlantic coast of Europe driving large-scale coastal erosion (Masselink et al., 2016; Dodet et  
452 al., 2019). During the first years of monitoring, the dune volume showed some seasonal variations with  
453 a decrease during winters and a recovery the rest of the year. Volume evolution shows some interannual  
454 variability, although less pronounced than further south along the coast at Truc Vert (Laporte-Fauret et  
455 al., 2020) where the shoreline has been relatively stable over the last decades (Castelle et al., 2018;  
456 Robin et al., 2020). However, two winters, 2017-2018 and particularly 2020-2021, appear to have had  
457 a larger erosive impact in terms of dune volume (Figure 9.c), which is negatively correlated with  
458 shoreline erosion (Figure 9.d). These two winters are both associated with a positive (+1.0 and +0.59  
459 for the winters of 2017-2018 and 2020-2021, respectively) WEPA index (Castelle et al., 2017), which  
460 reflects a stormy winter in this region. However, the winter of 2019-2020 was also stormy (WEPA of  
461 +0.95), as evidenced in Laporte-Fauret et al. (2021b) by the largest integrated onshore windblown sand  
462 flux over at least the last 17 years and the large coastal dune changes observed at Truc Vert. At this stage  
463 it is unclear why this 2019-2020 winter had a limited impact on the coastal dune at l'Anse du Gurp,  
464 which will need further study.

465

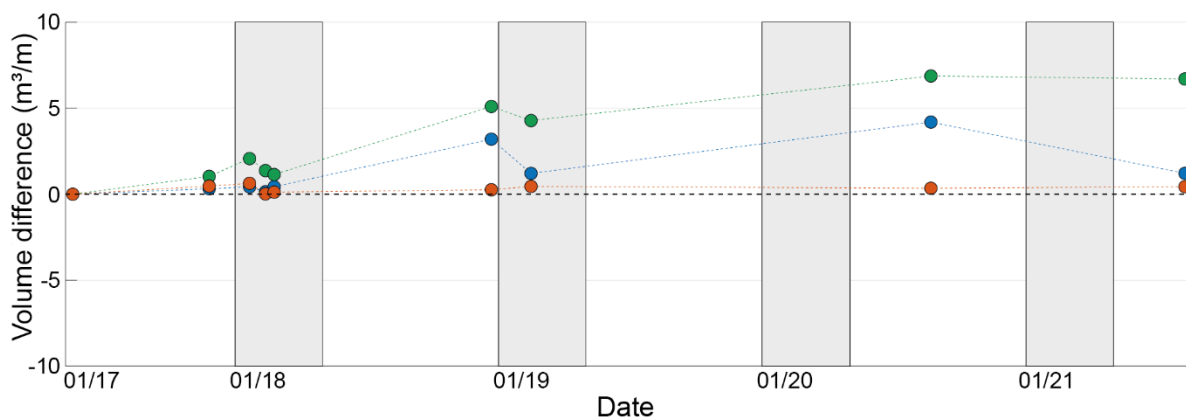
466 Interestingly, although chronic shoreline erosion is less intense in the south, the area in the south  
467 of the parabolic dune is losing more sediment than the two other areas (Figure 9.b,c). Ignoring the last  
468 winter, the central (parabolic dune) and northern areas even show an almost full recovery to their 2014  
469 dune volumes, mostly by either rising in elevation (i.e., northern area) or by migrating landward (i.e.,  
470 central area – parabolic dune). In these two areas, the shoreline erosion is (more than) compensated by  
471 landward transport. On the contrary, the decrease in dune volume and the shoreline landward migration  
472 in the southern part seems to characterize an erosion of the dune according to the conceptual model of  
473 Sherman and Bauer (1993). An explanation can be that higher erosion scarp in the southern area (i.e.,  
474 steep 17.3-m high from the shoreline to the crest) limits the transport of windblown sand from the beach  
475 to the dune, thus preventing its growth and landward migration (Castelle et al., 2019). Accordingly,  
476 erosion scarp height appears to be an important parameter for the landward transport in sectors with  
477 roughly similar chronic erosion rate (Davidson et al., 2020). Another factor controlling the dune  
478 response is the dense and high vegetation at the dune toe that has grown on the paleosols. These  
479 paleosols, which outcropped after the outstanding winter of 2013-2014, are more resistant to marine  
480 erosion than sand (Stéphan et al., 2019; Verdin et al., 2019), with fresh groundwater resurgence also  
481 favoring dense plant growth (i.e., reeds, Figure 10.c). The dense and high vegetation promotes  
482 windblown sand trapping and consolidates the underground by rhizomes system (see review of McGuirk  
483 et al., 2022). This rapid growth since approximately 2017 is evidenced by the large accretion patterns  
484 facing the parabolic dune (central area) in the DSM difference plot (Figure 8). This vegetation is also  
485 present, although less dense, along the northern area (Figure 10.a, b). In contrast, such vegetation is  
486 restricted to an isolated patch along the southern, more eroding, area (Figure 10.d). By comparing the  
487 nearly concurrent UAV-DSM (July 9, 2021) and Lidar-DEM (October 07, 2021), a correction was  
488 applied to the UAV-DSM from October 26, 2017. The estimated vegetation volume facing the parabolic  
489 dune (central area) reaches 5.68 m<sup>3</sup>/m (Figure 11), which is minor compared to the total volume  
490 differences computed in Figure 9.c, and with vegetation volume in the other two areas an order of  
491 magnitude smaller (Figure 11). However, it is possible that vegetation height and density impacted the  
492 landward dune evolution and volume change by preventing the sand transport from the beach to the  
493 deposition lobe. Thus, without new sand input, the deposition lobe may only be fed by the deflation

494 basin with dune volume either constant or slightly decreasing. The latter is especially true during winter  
495 storms causing diffuse deposition landward from the deposition lobe). In contrast, the effect of this  
496 vegetation on the alongshore-averaged shoreline position time series is more complex to estimate due  
497 to the lack of Lidar surveys between 2017 and 2021. Looking only at the differences between the latest  
498 drone and lidar surveys, the alongshore-averaged shoreline position difference for the central zone was  
499 1.56 m, highlighting that there is not a seaward shoreline migration of 0.65 m (Figure 9.d), but a  
500 landward migration of 0.91 m. As the effect of vegetation is negligible in the northern and southern  
501 areas, the slight seaward migration is characteristic of light summer recovery periods related to less  
502 marine erosive action. Finally, the alongshore-averaged shoreline position is characterized by a  
503 landward migration for the three areas, the central area retreating 2.4 times less and 5.7 times less than  
504 the northern and southern areas, respectively. Accordingly, this vegetation, which location and density  
505 is strongly controlled by local paleosol characteristics, is critical to local multi-year shoreline erosion.  
506

507 Our results provide new insight into potential coastal dune management methods in chronically  
508 eroding areas. In our study zone, blowouts can help the dune to maintain by migrating landward. Such  
509 process is limited if the erosion scarp is high, thus acting as a natural barrier for landward sediment  
510 transport from the beach into the dunes. This strategy of coastal dune remobilization is debated because  
511 some authors see it as human intervention that alters the landscape and interferes with natural processes,  
512 and argue that nature should be left alone (Delgado-Fernandez et al., 2019). On the contrary, other  
513 authors defend this remobilization strategy and see it as a way to promote dynamic processes stopped  
514 by plant succession and artificial stabilization in order to create a mosaic of vegetated dunes (Creer et  
515 al., 2020; Pye and Blott, 2020; Arens et al., 2020). Finally, according to Arens et al. (2020), dune  
516 management is not about making good or bad choices. Each choice is valid as long as it is based on a  
517 good understanding of the system. Through our study, we believe that in the chronically eroding sectors  
518 of southwest France, these blowouts can develop and thus promote landward dune migration, they will  
519 evolve through the ecological stage described by Schwarz et al. (2018) and eventually reach  
520 stabilization. Such dune migration should allow the dune system to survive on the long term, in contrast  
521 with some coastal dunes a couple of kilometers further north in more rapidly eroding sectors, which  
522 have now disappeared. However, such blowout systems should be carefully monitored and management  
523 action should be taken (e.g., wind fences) to stabilize the parabolic dunes that migrate too far landward.  
524 Such controlled dynamism strategy, which could also include lowering the dune scarp by mechanically  
525 smoothing the scarp crest, appears as an interesting coastal management avenue in chronically eroding  
526 sectors. However, it is necessary to conduct other quantitative studies in different settings worldwide to  
527 draw conclusions.  
528



529  
 530 Figure 10. (a) Aerial photograph of the parabolic dune and of the adjacent areas in l'Anse du Gulp,  
 531 photography taken from the beach highlighting the presence (or absence) of vegetation and paleosols  
 532 near the dune toe at the (b) northern, (c) central and (d) southern zone. Photos a-b were taken on July  
 533 9, 2021 (Ph. Quentin Laporte-Fauret) and photos b-c were taken on November 10, 2021 (Ph. Bruno  
 534 Castelle).  
 535



536  
 537 Figure 11. Time series of the volume difference of the vegetation in front of the northern (blue line),  
 538 central (green line) and southern (orange line) areas from 2017-04-20 to 2021-07-09. Grey rectangles  
 539 represent the winter periods.  
 540

## 541 5. Conclusion

542  
 543 The 70-year evolution of a 2-km long high-energy, chronically eroding (average of 1.26 m/yr), coastal  
 544 dune system has been studied by combining historical aerial photographs, Lidar and UAV surveys.  
 545 During this period, three major blowouts have developed, all in the northern, more chronically eroding,  
 546 sector. Two of these blowouts have been stabilized by vegetation colonization or are currently  
 547 stabilizing, and the third one rapidly evolved into a parabolic dune, which is still migrating into the  
 548 inland forest. No blowout reactivation phase was observed. Focusing on the 3D evolution of the blowout  
 549 that recently developed into a parabolic and its adjacent sectors, we found that the blowout promoted  
 550 dune inland migration. Despite the southern area (no blowout) was in a less chronically eroding sector,

551 the dune volume in this area decreased by the largest amount during the last seven years of high-  
552 frequency surveys. This can be explained by the presence of the highest erosion scarp in this area, thus  
553 limiting the beach sand transport to the dune. Finally, paleosols outcropping at the dune toe and fresh  
554 groundwater resurgence favoring dense plant growth, can also limit marine erosion but also sand transfer  
555 from the beach to the dune, which could not be addressed here. Further research in other coastal dune  
556 settings is required to explore if and how management of blowout dynamics and potentially scarp  
557 lowering/incising can be a relevant coastal dune management strategy in chronically eroding sectors, in  
558 order to maintain the coastal dune systems and its ecosystem services.

559

#### 560 **Author Contributions**

561 Conceptualization, Q.L.-F., V.M. and B.C.; Formal analysis, Q.L.-F.; Funding acquisition, B.C.;  
562 Investigation, Q.L.-F., V.M., and B.C.; Methodology, Q.L.-F., V.M. and B.C.; Validation, Q.L.-F.;  
563 Writing—original draft, Q.L.-F.; Writing-review & editing, V.M., R.M., B.C., A.N.L. and D.R.

564

#### 565 **Funding**

566 This research was funded by Agence National de la Recherche (ANR) grant ANR-17-CE01-0014  
567 (SONO project).

568

#### 569 **Acknowledgments**

570 This research was funded by Agence National de la Recherche (ANR) grant ANR-17-CE01-0014  
571 (SONO project). Additional funding was provided by Observatoire Aquitain des Sciences de l'Univers  
572 (OASU) and Observatoire de la Côte de Nouvelle-Aquitaine (OCNA) which also provide LiDAR data.  
573 Storage resources for this study was provided by the computing facilities MCIA (Mésocentre de Calcul  
574 Intensif Aquitain) of Univ. Bordeaux and Univ. Pau et Pays de l'Adour.

575

#### 576 **Conflicts of Interest**

577 The authors declare no conflicts of interest.

578

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580

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