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# Morphological and ecological responses of a managed coastal sand dune to experimental notches

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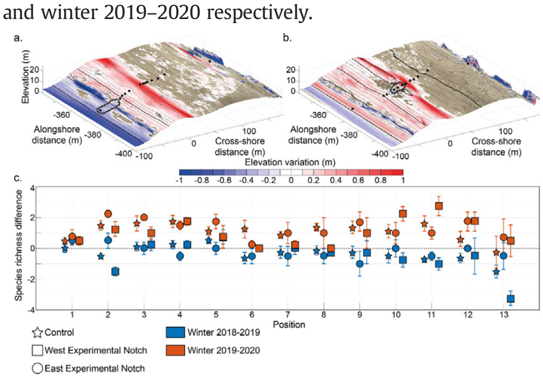
## HIGHLIGHTS

- Excavated notches modify coastal dune profile and vegetation cover.
- Response depends on the dune compartment where the notches were dug.
- Excavated notches increase sand accretion and landward transport.
- Foredune notches drive landward plant community rejuvenation by sand deposition.
- Foredune notches can reinstate biomorphological dynamics in southwest France.

## GRAPHICAL ABSTRACT

Elevation differences for the entire study period surimposed on 3D textured DSM (from November 13, 2018 to May 20, 2020) with example of (a) West Experimental Notch (WEN) #2 and (b) East Experimental Notch (EEN) #2. Black points represent the vegetation quadrats location. Notches are delimited by black and white line and the color bar indicates the elevation difference in meters. (c) Mean species richness difference (± SE) for each position for the control (stars), the WEN (square) and EEN (circle). Blue color and orange color are winter 2018–2019 and winter 2019–2020 respectively.

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## ABSTRACT

In northern Europe, coastal dune remobilization by restoring natural processes is considered by some to maintain the coastal dune in chronically eroding sectors by migrating landward and to restore dune ecology. In wet climatic contexts, this nature-based solution has been shown to induce an increase in both sand bare areas and vegetation diversity. However, it has never been tested in the coastal dunes of southern Europe with a drier climate and, thus, more stressful conditions, where disturbance may inversely decrease vegetation diversity. An original experiment was set up in 2018 on a 4-km stretch of coastal dune in southwest France where Experimental Notches (EN) were excavated in the incipient foredune, referred to as West Experimental Notch (WEN), and in the established foredune, referred as to East Experimental Notch (EEN). Morphological and ecological responses were monitored using UAV photogrammetry and vegetation sampling along transects during two years with contrasted winter storm conditions. During the first winter characterized by calm wind conditions, a rapid filling of the WENs and the initiation of deposition lobes landward of the EENs were observed. Stronger winds during the second winter led to the development of deposition lobes of the EENs, increasing both their volume, up to 6 times, and their cross-shore elongation. The increase in disturbance induced by the notches had a significant impact on vegetation. New sandy bares were colonized by pioneer species leading to an increase in species richness and rejuvenation, in particular landward of the EENs. Although longer-term monitoring is required to draw

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conclusions, these results suggest that the excavation of foredune notches are able to re-establish an ecomorphological dynamic in the dunes of southwest France on the time scales of years, promoting landward sand transport and, thus, the foredune landward translation, while not threatening diversity. Such approach may become a relevant adaptation strategy to sea level rise and increased erosion in this region of the world.


## 1. Introduction

Coastal environments host most of worldwide human population, activity and industry. Such anthropogenic pressure on natural resources can induce ecological and landscape degradation or destruction (Lazarus, 2017). Moreover, in the context of global warming and sea level rise, coastal areas are increasingly exposed to flooding (Lionello et al., 2006; Vousdoukas et al., 2016; Rojas et al., 2012; Alfieri et al., 2015) and marine erosion (Vousdoukas et al., 2020; Cooper et al., 2020). In this context, sandy shores are among the most vulnerable coastal environments.

Along sandy coasts with ample sand supply and dominant onshore winds, beaches are generally backed by coastal dunes. Foredunes develop through complex interactions between marine, aeolian physical (Cohn et al., 2018; Cohn et al., 2019; Nordstrom, 2000; Hesp, 2002) and biotic processes (Zarnetske et al., 2012; Maun, 1998; Maun and Perumal, 1999; Durán and Moore, 2013). Indeed, sand deposition is facilitated by the presence of pioneer plant species which are tolerant to burrowing and salinity. Plant growth can also be enhanced by sand deposition resulting in a positive feedback mechanism (Maun, 2009). Developed foredunes provide habitats promoting plant community succession, increasing vegetation cover and stabilization of the dune system (Barbour et al., 1985; Wilson and Sykes, 1999). Coastal dunes provide a wealth of ecosystem services, such as natural and efficient protection that buffers eroding storms limit flood risk, pollutant filtration and provision of nesting sites (Martinez et al., 2013).

During the past century, most of the European coastal foredunes have been stabilized by reprofiling (Matias et al., 2005; Nordstrom and Arens, 1998), planting vegetation and fence installation (Arens et al., 2001; Ruz and Anthony, 2008) and/or beach nourishment (De Vriend and Van Koningsveld, 2012). The objective was to build stabilized dunes, in order to buffer storm waves and surge, and limit sand transport to the back of the dune, thus protecting human social and economic goods from flooding or sand burial. However, stabilization is often associated with more alongshore-uniform morphology, resulting in weak variations in exposure to swash, wind, sediment transport and salt spray, thus affecting the diversity of habitats. In some regions of the world (such as Netherland, Wales, Northwestern USA), this resulted in a reduction of vegetation dynamics, diversity of natural communities and the reduction of ecosystem services (Martinez et al., 2013). In addition, along sandy coasts under chronic erosion, large erosion scarps can be formed in the stabilized dune during storm wave events. Such high scarp can act as a barrier inhibiting the natural sediment exchange between the beach and the dune, leading to the progressive narrowing or even disappearance of the dune (Castelle et al., 2019). In contrast, in other regions, more natural and alongshore non-uniform dune systems display greater ecological diversity with natural beach-dune sediment exchange allowing the system to translate landward in eroding sectors (Heslenfeld et al., 2004; Castelle et al., 2019; Gao et al., 2020).

Jackson et al. (2019) and Gao et al. (2020) have documented a worldwide increasing dune stabilization and decreasing plant diversity in recent decades, due to increased rainfall, temperatures and decreased wind activity. In wet climates, reinstating natural processes in stabilized foredunes is therefore currently considered by some coastal managers, in particular where dune width is reducing rapidly due to marine erosion. For example, in Northern Europe (e.g., England or the Netherlands), dune systems have been largely affected by human activities. In this context, dune remobilization is currently considered to stimulate dynamic processes that have dramatically decreased due to stabilization and vegetation succession (Creer et al., 2020; Pye and Boltt, 2020; Arens et al., 2020). Additionally, since these dune systems are subject to a temperate and humid climate, plant cover and biomass can be very high in absence of disturbance, inducing intense plant-plant competition and thus low plant diversity (Grime, 1973; Huston, 1979). For example, Brunbjerg et al. (2015) observed a decrease in competition and, thus, increasing plant diversity due to new bare sand induced by blowouts. These positive effects for diversity are consistent with theoretical community ecology models and empirical studies that have proposed or shown that disturbance increases diversity in conditions of low environmental severity through decreased competition (Grime, 1973; Huston, 1979; Touzard et al., 2002; Michalet et al., 2002). However, it is unclear if such positive effect of increasing disturbance in coastal dunes is generic.

In constrained environmental conditions, where competition is low or absent, community ecology models, empirical observations and field experiments have shown that disturbance rather decreases diversity (Grime, 1973; Huston, 1979; Forey et al., 2008; Maalouf et al., 2012). These constraints can be found, in particular, along the Atlantic coast in southwest France, where the climate is drier in summer than in northern Europe. Back-dune communities are highly stressed there (dry and nutrient-poor), dominated by stress-tolerant plant species with a much sparser vegetation cover, preventing any competition between species (Forey et al., 2010; Michalet et al., 2015). Moreover, the Atlantic coast of Europe is exposed to high energy winter waves, generated in the North Atlantic Ocean, which can lead to large beach coastal erosion during severe winter storms (Castelle et al., 2015; Masselink et al., 2016). This winter wave and wind storm activity shows large interannual variability (Castelle et al., 2018a).

The influence of local climate is critical to coastal dune response, especially summer rainfall that promotes plant growth and decreases sand transport compared to drier climates. These climate and biotic effects can strongly influence the response of the system to remobilization experiments (Maun, 2009; Bauer et al., 2009; García-Romero et al., 2019). Dune remobilization can be achieved by several techniques such as foredune vegetation removal (Jungerius et al., 1995; Arens et al., 2004; Eamer et al., 2013; Konlechner et al., 2015; Darke et al., 2016), individual blowout restoration (Van Boxel et al., 1997), or foredune notch excavation (Arens et al., 2012; Arens et al., 2013; Kuipers, 2014) in order to promote sand transport from the beach to the back dune (Gares and Nordstrom, 1995; Hesp, 2002). These notches are aimed to increase the back-dune community diversity, through increasing disturbance and thus inducing local rejuvenation of the vegetation (Nordstrom et al., 2007). A recent experiment on the Dutch coast succeeded to increase the aeolian dynamics and induced a positive landward sand budget by the excavation of five notches (Ruessink et al., 2018). However, in this experiment the effects of the notches on vegetation were not investigated. Such field experiments are rare, and few studies have investigated coastal foredune biological and morphological interactions (Zarnetske et al., 2012; Durán and Moore, 2013; Hesp, 2002; Schwarz et al., 2019). Given that biotic and abiotic processes interactions and feedbacks are complex and occur at different temporal and spatial scales, detailed field experiments addressing both morphological changes and vegetation dynamics are required. To the best of the authors' knowledge, such a combined field study concerning biotic and abiotic processes using artificial notches has never been performed.

An original experiment was designed in southwest France by excavating notches in the foredune in order to investigate the impact of disturbance on coastal dune morphological changes and vegetation dynamics. Eight notches were excavated at two distinct cross-shore positions of the coastal foredune and were monitored during two years with contrasting winter storm conditions. This study aims to investigate the effect of experimental notches on wind dynamics, sediment transport and changes in composition and diversity of plant communities. The effects of experimental notch position and winter wind conditions on these morphological and ecological responses are also investigated.

## 2. Material and methods

### 2.1. Study area

Truc Vert is an open sandy beach located in southwest France (Fig. 1.a). It is a remote beach located a few kilometers from the first car park beach access that has been studied for over a decade (see review in Castelle et al., 2020), including research on sediment transport (Masselink et al., 2008), beach dune morphodynamics (Almar et al., 2010; Castelle et al., 2017b; Laporte-Fauret et al., 2019, 2020), long term shoreline variability and storm impact (Castelle et al., 2014, 2015; Masselink et al., 2016; Robinet et al., 2016; Robin et al., 2020a) and plant-plant interaction and community composition (Forey et al., 2008; Laporte-Fauret et al., 2021; Le Bagousse-Pinguet et al., 2013; Michalet et al., 2015).

Truc Vert is meso-macro tidal with a mean spring and highest tide range of 3.7 m and 5.0 m, respectively (Castelle et al., 2015). The coast is exposed to high-energy waves and storm winds. Waves are generated by extra-tropical cyclones in the North Atlantic, with a dominant WNW direction and a mean significant wave height and peak period of 1.7 m and 10.3 s, respectively, and storm wave height can exceed 10 m (Castelle et al., 2017a). The prevailing winds have a mean velocity and direction of 4.52 m.s$^{-1}$ and 311° in summer and 5.18 m.s$^{-1}$ and 263° in winter, respectively, at Cap Ferret (Appendix 1.a, b).

Winter storm wave and wind conditions show large interannual variability owing to large-scale climate patterns of atmospheric variability in the North Atlantic (Castelle et al., 2017b, 2018a). Such large interannual variability can drive winters characterized by temporal and spatial storm clustering (Castelle et al., 2015; Davies, 2015). Despite intense beach-dune erosion can occur during such winters, Truc Vert beach has been relatively stable over at least the last 65 years (Castelle et al., 2018b).

Truc Vert beach is backed by a large foredune (c. 250 m wide and 20–25 m height), which current shape is largely inherited from large-scale anthropogenic works spanning the last 150 years (Robin et al., 2020b). In the end of the 19th century, the foredune was erected through progressive rising of fences and marram planting to stabilize the dune system and protect the landward forest. During the 20th century, the coastal dune system suffered severe damages due to major winter storms in the 1910s and 1920s and then the Second World War, when the coastal dunes were restricted areas and a source of aggregate for German blockhouses building. In the 1960s–1980s, the coastal dune stakeholders undertook large renovation works involving mechanical reprofiling and marram planting (Robin et al., 2020b). Since then, the coastal dune system has been softly managed by marram grass planting and branching, particularly to prevent the development of blowouts (Barrère, 1992; Prat and Auly, 2010).

The current Truc Vert dune system is composed of four geomorphological units with, from the beach to the forest (i.e., from the most to the least disturbed by sand deposition, see Fig. 1.a): (1) the incipient foredune, with the presence of pioneer species able to grow quickly on bare sand (e.g., *Elymus farctus*, *Euphorbia paralias* and *Eryngium maritimum*); (2) the established foredune, with a dense coverage of *Ammophila arenaria* (used to build the dune); (3) the transition dune, colonized by perennial plant species (*Helychrisum stoechas*, *Artemisia campestris* and *Corynephorus canescens*); and (4) the grey dune, where lichens and mosses are widespread (Forey et al., 2008; Laporte-Fauret et al., 2021).

### 2.2. Experimental design

The experimentation was carried out across a domain covering 4 km and 300 m in the longshore and cross-shore directions, respectively, allowing to cover the entire beach–dune system. This domain was divided into four 500-m blocks separated by 500 m from one another (Fig. 1.b). In each block, two experimental notches were excavated in November 2018: one in the incipient foredune (called WEN for West Experimental Notch, Fig. 1.c) and the other one in the established foredune (called EEN for East Experimental Notch, Fig. 1.d). WENs aim at simulating the erosion of the incipient foredune during severe storms due to the marine and aeolian action. EENs aim at mimicking blowout initiation under wind erosion only. Both notch types were excavated to reinstate landward sand transport and dune mobility. Noteworthy, a first series of eight notches (four WENs and four EENs) were excavated in December 2017, with a horizontal dimension similar to the blowouts naturally present nearby the study area. Coastal dune managers in southwest France have been promoting stabilization and fighting blowout development for decades. Therefore, coastal dune managers supported our experimentation but required that notches with small to moderate size. However, despite beneficial effects on vegetation composition and ecosystem functioning during the first year (Laporte-Fauret et al., 2021), the notches did not develop into blowouts and partially infilled. Thus, hereafter we address the impact of the notches excavated in November 2018, prior to the winter of 2018–2019. WENs were excavated at the same location as in December 2017. In contrast, EENs were excavated further landward across the crest of the foredune (Table 1). The EENs and WENs notches were deeper than in 2017 and were numbered from 1 to 4, from south to north according to the block number.

In order to assess the impact of these experimental notches on vegetation composition, four cross-shore transects, extending from the beach to the grey dune, were placed in each of the four blocks. Such configuration was used to ensure spatial replication for the vegetation dynamics statistical analysis. Two transects in the alignment of notches and two transects, approximately 100 m further south, were used as controls (Fig. 1.e, f). Each transect was composed of 13 sampling positions, positioned at the three ecotones and in the middle of each community type (e.g., incipient foredune, established foredune and transition dune). This approach was chosen in order to better capture vegetation composition changes, which preferentially occur at the ecotones. The number of each position represents the same habitats in all transect, even if the shoreline distance can slightly change among transects. Thus, the design was composed of four WENs, four EENs and height control transects and 208 sampling positions (13 positions x four transects x four blocks).

### 2.3. Aeolian data

We used hourly 10-m wind data collected by Météo France at weather station Cap-Ferret (Fig. 1.a) from January 1, 2003 to April 1, 2020. These data allowed to estimate a potential wind-driven sand flux $Q_l$, using the model of Lettau and Lettau (1978) which, according to Sherman et al. (2013), shows the best agreement with observed transport rates. It reads:

$$Q_l = L\sqrt{\frac{D_{50}}{d}}\,\frac{1}{g}\left(u^*_{z_{0,1}} - u^*_t\right) u^{*2}_{z_{0,1}} \quad (1)$$

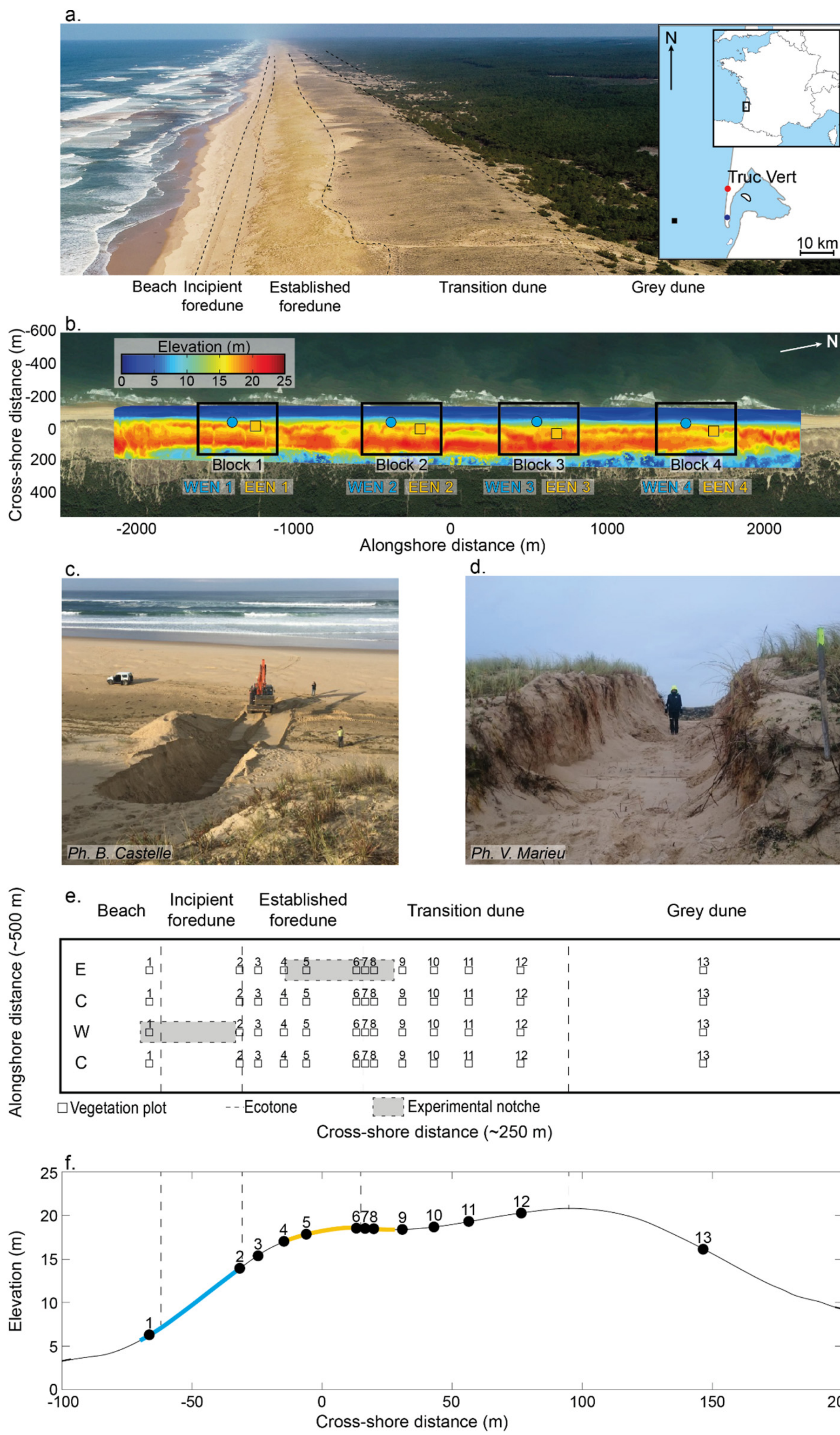


**Fig. 1.** (a) Aerial photograph of Truc Vert beach dune system with the different dune units delimitated by the dashed lines (ph. V. Marieu). The black square and blue point on location map show the Candhis directional wave buoy and the Météo France weather station, respectively, (b) Digital Surface Model (DSM) of Truc Vert beach dune system (generated by UAV photogrammetry). The black rectangles delimit the four blocks where treatments were applied; the blue circles and yellow squares within blocks represent WEN and EEN, respectively, with their numeration, (c) Example of incipient foredune notch excavated on November 5, 2018 (WEN), (d) Example of 2.5-m deep notch excavated in the established foredune (EEN), (e) Design within one block showing cross-shore position of vegetation plots (squares with numbers) along four transects. The letter C, E and W correspond to the control, EEN and WEN, respectively, and (f) 4 km alongshore-averaged beach dune profile at Truc Vert with the mean cross-shore position of vegetation plots and of the WEN in blue, and EEN in yellow.

where $L$ is the Letteau constant (6.7), $D_{50}$ the median grain size, $d$ the reference grain diameter (i.e., 0.25 mm, Bagnold, 1936), $g$ is the gravitational acceleration, $u_t^*$, the threshold shear velocity computed using the formula of Bagnold (1936). The following values were used for Truc Vert: $u_t^* = 0.29$ m.s$^{-1}$, $D_{50} = 0.4$ mm. As most of the potential sand flux is oriented cross-shore

**Table 1**
Characteristics of the 8 experimental notches excavated in 2018.

| | Block 1 | | Block 2 | | Block 3 | | Block 4 | |
|---|---|---|---|---|---|---|---|---|
| | WEN 1 | EEN 1 | WEN 2 | EEN 2 | WEN 3 | EEN 3 | WEN 4 | EEN 4 |
| Volume ($m^3$) | 83.9 | 109.2 | 140.1 | 132.8 | 96.8 | 80.3 | 74.1 | 94.8 |
| Width (m) | 6.2 | 5.5 | 4.4 | 5.2 | 4.7 | 4.4 | 5.6 | 4.2 |
| Length (m) | 15.6 | 27.1 | 34.2 | 28.2 | 39.5 | 37.1 | 19.8 | 41.4 |
| Depth (m) | 2.1 | 2.2 | 2.2 | 2.6 | 1.5 | 2.0 | 2.8 | 1.8 |

(Appendix 1.c, d) we used the cross-shore component (i.e., $Q_{lcs}$) of $Q_l$:

$$Q_{lcs} = Q_l \cos\left(\frac{\pi}{180}(280.8 - \theta)\right) \quad (2)$$

where $\theta$ is the wind direction and 280.8° the orientation of the coast at Truc Vert. The shear velocity at 0.1 m height $u^*_{z0.1}$ was computed using the law wall:

$$u^*_{z_{0.1}} = \frac{\kappa}{\ln\left(z/z_0\right)} u_{z_{0.1}} \quad (3)$$

where $\kappa$ is the Karman constant (0.4), $z_0 = 2.5D_{50}$ is the roughness length, $z$ the elevation (i.e., 0.1 m here), $u_{z0.1}$ is the wind speed at 0.1 m above ground level. The wind speed extrapolation from 10 m to 0.1 m height was computed using the logarithmic law (Eq. (4)) (Arya, 1988; Jacobson, 1999):

$$u_{z_{0.1}} = u_z \frac{\ln\left(z/z_0\right)}{\ln\left(z_R/z_0\right)} \quad (4)$$

where $u_z$ is the wind speed at 10 m height, $z$ the extrapolated elevation and $z_R$ the reference elevation (i.e., 10 m).

However, the sand flux calculated here represents only a maximum potential flux. Indeed, Lettau and Lettau (1978) formula only takes into account wind parameters to calculate the sand flux, but, in coastal environments, many other factors can influence and limit sand flux such as sediment availability, humidity, fetch zone, salinity and vegetation cover (Davidson-Arnott and Law, 1990; Delgado-Fernandez, 2010; de Vries et al., 2014; Lancaster and Baas, 1998). As we do not have access to all these parameters, we only addressed potential sand flux, which were used primarily to compare their orders of magnitude between the different winter periods.

### 2.4. Beach-dune topographic surveys

The topographic surveys of the 4 km beach-dune system were performed using a DJI Phantom 4 Pro quadricopter equipped with a 20 MPix camera. The combination of photogrammetry algorithms from Agisoft Metashape software v1.5 and the presence of permanent ground control points distributed across the system allowed to generate accurate (root-mean-squared vertical error < 0.1 m) and high-resolution (0.1 m) digital surface models (DSMs) enabling the detection of subtle morphological changes induced by marine and/or aeolian processes (Laporte-Fauret et al., 2019). The surveys were performed every three months, with additional surveys after severe storms and before and immediately after the excavation of notches in December 2017 and November 2018. From November 2018 to May 2020, 10 beach-dune topographic surveys were performed.

In order to determine whether the notches promoted landward sand transport, three 12-m wide zones extending from the dune foot (defined at $z = 6$ m according to Castelle et al., 2015) to the middle of the transition dune (at cross-shore position $x = 150$ m) were defined around each notch (Fig. 2). The zone at the center, containing the notch, was used to evaluate the notch impact, the two zones on each side being used as controls. Within blowouts, alongshore and cross-shore wind flow can lead to complex wind circulations (Pease and Gares, 2013). However, given the potential sand flux rose (Appendix 1.c, d) and that sand transport primarily occurs in the alignment of the notches we assume that the gradients in alongshore transport is negligible. The sediment conservation equation in the cross-shore direction links the dune local elevation, $z$, to the cross-shore sand flux Q:

$$\frac{\partial z}{\partial t} + \frac{1}{1-p}\frac{\partial Q}{\partial x} = 0 \quad (5)$$

where $p = 0.4$ is the dune porosity. Eq. (5) was used at first order to estimate the cross-shore flux divergence between two surveys:

$$\frac{\partial Q}{\partial x} = -(1-p)\frac{\Delta z}{\Delta t} \quad (6)$$

where $\Delta z$ is the dune elevation difference and $\Delta t$ the time elapsed between the two surveys. Given that net sand transport is oriented landwards, erosion (accretion) occurs where $\partial Q/\partial x$ is positive (negative).

### 2.5. Vegetation sampling

Plant community composition and cover were assessed with the interception cover technique, using a 1 $m^2$ quadrat with a mesh size of 0.2 m, thus with 36 intersections (Goodall, 1953). This method consists to record plants, or their vertical projections, located at the 36-line intersections to calculate their percent cover. A cover of 0.5 % was assigned to species present in the quadrat but only outside of these intersections (Appendix 2). In order to monitor the impact of each winter on plant community composition, the surveys were performed before and after the winter of 2018-2019 (i.e., in December 5, 2018 and May 20, 2019) and before and after the winter of 2019-2020 (i.e., in January 14, 2020 and May 18, 2020). Then, plant species were gathered into four groups according to their position along the dune stabilization gradient, quantified with their scores along the first axis of correspondence analysis (Forey et al., 2008) and, thus, to their tolerance to sand deposition

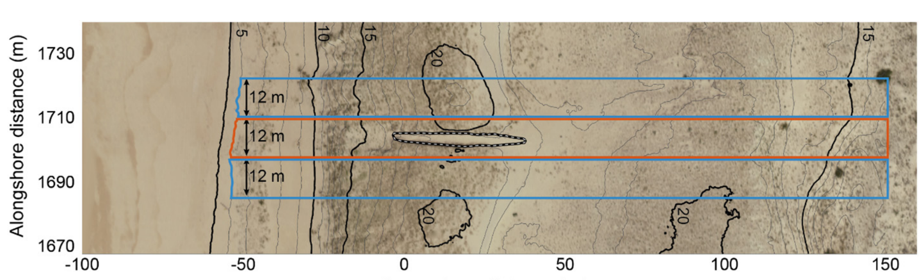


**Fig. 2.** Example (notch EEN 4) of the three 12-m wide transects where landward sediment flux is computed from difference plot $\Delta z(x)$. Experimental notch transect and the two control transects are shown in orange and blue, respectively.

**Table 2**
Classification of vegetation species in 4 groups defined by coastal dune geomorphological unit.

| Group 1 (Incipient foredune) | Group 2 (Established foredune) | Group 3 (Transition dune) | Group 4 (Grey dune) |
|---|---|---|---|
| *Cakile maritima*<br>*Elymus farctus*<br>*Eryngium maritimum*<br>*Euphorbia paralias* | *Ammophila arenaria*<br>*Calystegia soldanela*<br>*Festuca juncifolia*<br>*Galium arenarium* | *Artemisia campestris*<br>*Helichrysum stoechas*<br>*Jasione crispa*<br>*Leontodon taraxacoides* | *Cerastium glomeratum*<br>*Corynephorus canescens*<br>*Lichen*<br>*Moss*<br>*Phleum arenarium*<br>*Senecio vulgaris*<br>*Silene portensis*<br>*Vulpia membranacea* |

(i.e., incipient foredune, established foredune, transition dune and grey dune) (Table 2).

To assess vegetation composition evolution between surveys, the first step was to compute the absolute cover ($P_{Gi}$ in %) of each vegetation group and for each position along transects:

$$P_{Gi} = 100 \cdot \frac{\sum_j A_j}{n} \tag{7}$$

with $P_{Gi}$ the cover percentage of the group i (%), $A_j$ the cover of each specie j (ranging from 0 to 36) of the group i and $n$ the maximum cover allowed for the species ($n = 36$). Then, the cover difference ($D_{Gi}$ in %) of each group was computed as:

$$D_{Gi} = P_{Gi\ date2} - P_{Gi\ date1} \tag{8}$$

$D_{Gi}$ were computed for the winter of 2018–2019 (May 2019 – December 2018) and for the winter of 2019–2020 (May 2020–January 2020).

We used three common indices of diversity, $S$ which is the species richness of the community (number of species in a plot), $J'$ which is the evenness of the community (equitability of dominance among species) (Pielou, 1975), $H'$ which is the Shannon index (Shannon and Weaver, 1949) combining the two former indices. Thus, a high value of the Shannon Index characterizes communities with high species richness and equitability of dominance among species. $H'$ and $J'$ were computed in each quadrat by:

$$H' = -\sum_{i=1}^{S} \left(p_j \ln\left(p_j\right)\right) \tag{9}$$

$$J' = \frac{H'}{\ln(S)} \tag{10}$$

where $p_j$ is the cover ratio estimation of species $j$ in the quadrat. The evolution of $S$, $H'$ and $J'$ during the winters of 2018–2019 and 2019–2020 were computed resulting in $D_S$, $D_{H'}$, $D_{J'}$.

### 2.6. Statistical analyses

A three-way ANCOVA was performed in order to assess the effect of the experimental notches (called EN with East, West or Control treatments), the group (1, 2, 3 or 4), the shoreline distance (called distance hereafter) and their interactions on each $D_{Gi}$. Then, a Correspondence Analysis (CA) was conducted on vegetation cover from position 7 to 13 in order to assess the effect of experimental notches on landward vegetation. Indeed, as shown by Laporte-Fauret et al. (2021), vegetation changes occurred mainly landward of the notches. Plots without species and rare species (appearing less than four times in surveys) were removed before the CA. A four-way ANCOVA was conducted on plot scores along the two first axes of the CA, in order to assess the effects of the year, season, EN, distance treatments and their interactions on species composition. Finally, three two-way ANCOVAs were performed in order to assess the effect of the EN, distance and their interaction on $D_S$, $D_{H'}$, $D_{J'}$ for each winter. Sample t-tests were used to highlight significant differences from zero values. For the position treatment in all ANCOVAs, we used the distance as a continuous variable with also a quadratic expression to detect non-linear shapes (Maalouf et al., 2012). All statistical analyses were performed using the software R (version 1.2.5033).

## 3. Results

### 3.1. Wind and aeolian data analysis

The analysis of 17.25 years (from January 1, 2003 to April 1, 2020) of 10-m hourly wind data collected at Cap Ferret weather station shows a mean wind speed of 4.85 m.s$^{-1}$ with large seasonal variations (Fig. 3.a). The 99th percentile of wind speed is $u_{z,\ 99\%}$= 15.2 m.s$^{-1}$ and maximum hourly wind velocity of 36.2 m.s$^{-1}$ was reached during the winter storm Klaus on January 24, 2009. During this storm the cross-shore potential sand flux peaked at 2.56 m$^3$.s$^{-1}$, that is c. 500 larger than the average cross-shore potential sand flux (0.0054 m$^3$.s$^{-1}$, Fig. 3.b). We defined a storm event when the hourly wind speed exceeded $u_{z,\ 99\%}$ (Debernard Boldingh and Petter Røed, 2008). Then, two storm events separated by less than 48 h were considered as the same storm event. A total of 212 storms events were identified of which 159 (75%) occurred during the winter period (between October 1*st* and April 1*st*). The average wind speed, duration and cross-shore potential sand flux during the winter storm events are 17.5 m.s$^{-1}$, 7.97 h (peaked at 29 h during the winter storm Joachim on December 16, 2011) and 0.22 m$^3$.s$^{-1}$, respectively. For each winter, the cross-shore potential sand flux was integrated during each storm events in order to assess the potential transported sand volume. It shows an average of 16.13 m$^3$, with a maximum and minimum values occurring during the winters of 2019–2020 (44.71 m$^3$) and of 2004–2005 (4.82 m$^3$), respectively (Fig. 3.c).

A zoom onto the winters 2018–2019 and 2019–2020 highlights their contrast in terms of wind intensity, providing an opportunity to understand the evolution of the notches excavated in 2018 under different winter conditions (Fig. 4). The mean and maximum of the main characteristics of winter storms (i.e., duration, wind speed, shear velocity and cross-shore potential sand flux) are presented in Table 3. The first winter was characterized by only one major storm event (named Gabriel on January 29, 2019) for which all three storm characteristics were maximized (Table 3, Fig. 4.a). Relatively calm wind conditions led to few shear velocity values exceeding the threshold shear velocity (Fig. 4.b) and thus to limited sand transport (Fig. 4.c). Several major storm events occurred during the 2019–2020 winter which characteristics largely exceed those of 2018–2019 winter (Fig. 4.b, c and Table 3). These results highlight the strong interannual wind speed variability to which the dune system on the Gironde coast is exposed. Although the winter of 2019–2020 is not characterized by the strongest or longest winter storm events of the 17.25-year time series, it is by far the most efficient in transporting sediment landwards, with cross-shore potential sand fluxes five times larger than during the winter 2018–2019.

### 3.2. Morphological evolutions

#### 3.2.1. Elevation variations

After the two winters, elevation change within the four WENs ranged between +1.0 m (WEN 3) and + 2.0 m (WEN 1, 2 and 4), depicting an overall filling (Fig. 5, right panel). In contrast, the four EENs were characterized by an erosion at the entrance ranging from −0.1 m to −0.5 m, and large sand deposition from +0.8 m (EEN 3 and 4) to +1.5 m (EEN 1 and 2) landward forming lobes with various shapes and elongations (Fig. 6, right panels). Finally, a + 0.5 m to 1.8

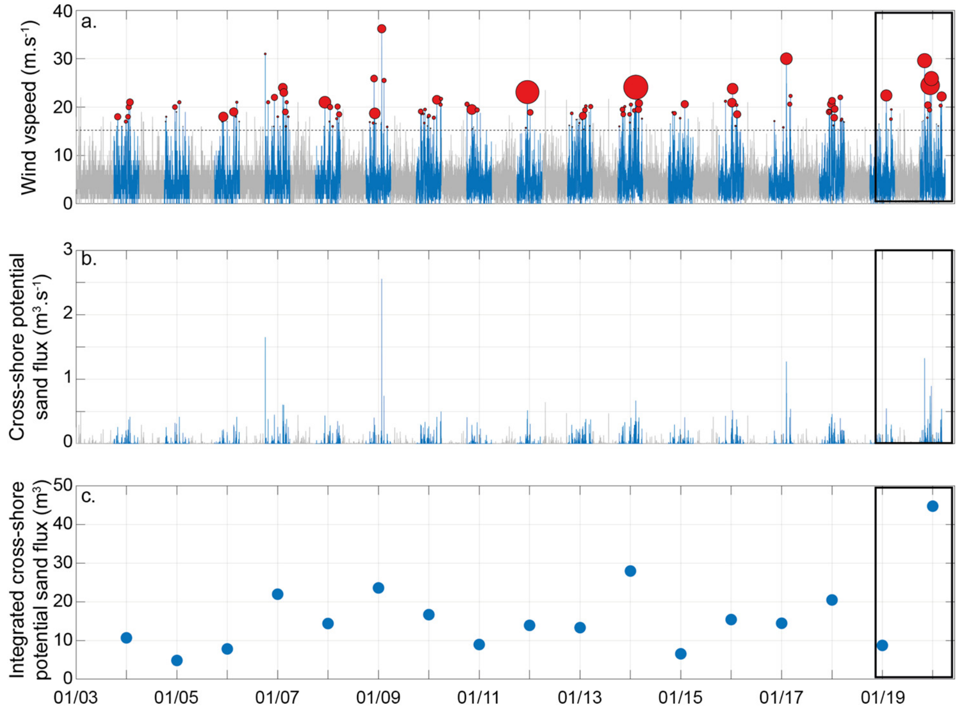


**Fig. 3.** (a) Time series of 10-m hourly wind speed measured at Cap Ferret weather station (Fig. 1.a) with red bubbles indicating the wind speed at the peak of the storm, with its size proportional to the storm duration. The horizontal black dashed line represents the 99th percentile ($u_{z,\ 99\%}$= *15.2 m.s*$^{-1}$), (b) Time series of hourly cross-shore potential sand flux, (c) Integrated cross-shore potential sand flux during winter storm events for each winter. Blue color highlights the winter period (here defined as from October 1st to April 1st), black rectangle represents the study period (from November 13, 2018 to May 20, 2020).

m vertical accretion was observed along the entire stoss slope and lee slope of the established foredune, respectively.

Despite the limited number of storm wind events during the first winter, it drove i) most of the filling of the four WENs and the erosion of the excavated sand deposed southward (Fig. 5, left panel), ii) the initiation of the deposition lobes landward of the EENs (Fig. 6, left panel) and iii) sand deposition ranging from 0.1 to 0.4 m at the incipient foredune and established foredune stoss slope. This rapid initial

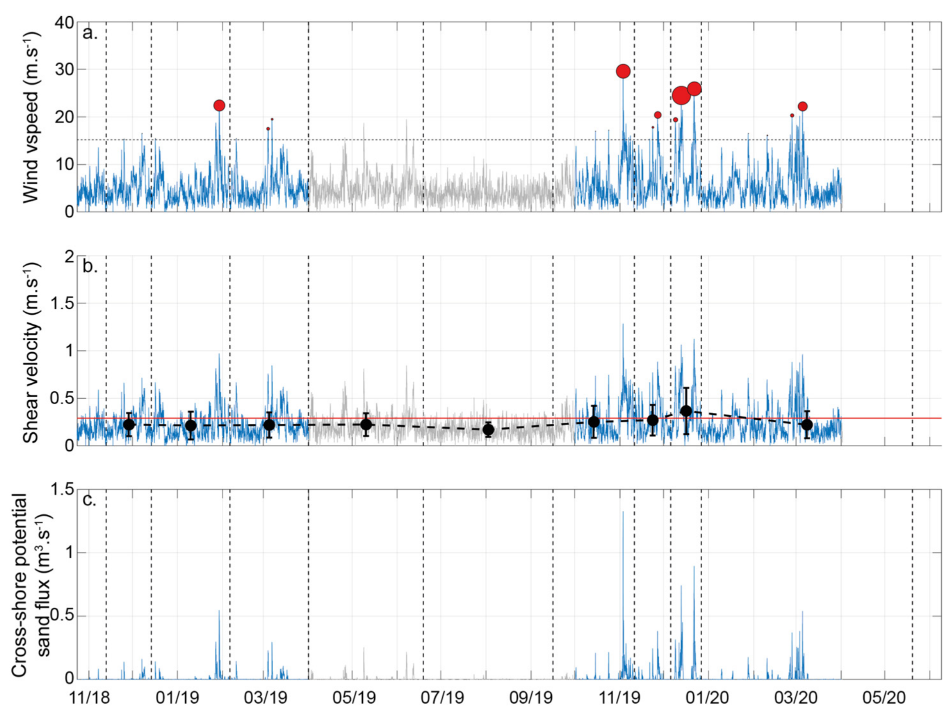


**Fig. 4.** (a) Time series of 10-m hourly wind speed measured at Cap Ferret weather station (Fig. 1.a) with red bubbles indicating the wind speed at the peak of the storm, with its size proportional to the storm duration. The horizontal black dashed line represents the 0.99 quantile ($u_{z,\ 99\%}$= *15.2 m.s*$^{-1}$), (b) Time series of 0.1-m hourly shear velocity, black points and error bars represent the mean shear velocity with their standard deviation between two consecutive UAV survey and the red horizontal line represents the threshold shear velocity ($u_t^* = 0.29\ m.s^{-1}$), (c) Time series of hourly cross-shore potential sand flux. Each UAV survey is represented by vertical black dashed lines, blue color highlights the winter period (here defined as from October 1st to April 1st).

**Table 3**
Mean and maximum characteristics of storms event during the winters of 2018–2019 and 2019–2020.

| Characteristics of storm events | 2018–2019 winter 7 storm events | | 2019–2020 winter 12 storm events | |
|---|---|---|---|---|
| | Mean | Maximum | Mean | Maximum |
| Duration (hour) | 5.29 | 23 | 12.83 | 38 |
| Wind speed ($m.s^{-1}$) | 17.36 | 22.4 | 18.32 | 29.6 |
| Shear velocity ($m.s^{-1}$) | 0.75 | 0.97 | 0.80 | 1.29 |
| Cross-shore potential sand flux ($m^3.s^{-1}$) | 0.23 | 0.55 | 0.29 | 1.33 |

morphological response, especially that of the WENs, despite the reasonably calm wind conditions suggests that the morphological system was in strong disequilibrium with prevailing local wind conditions, and that morphological changes were therefore also governed by the morphological perturbation itself.

The evolution of the WENs during the second winter was limited as they were already mostly infilled (Fig. 5, middle panels), whereas the deposition lobes of the four EENs strongly developed with vertical accretion ranging from 0.6 m to 1.4 m and increased cross-shore elongation (Fig. 6, middle panels). Finally, the almost alongshore-uniform accretion of the foredune stoss and lee slopes mostly occurred during that winter (Figs. 5 and 6, middle panels) under storm winds.

### 3.2.2. Volume evolution

After two winters, the four WENs have filled on average by 79.6% (ranging from +34.4 $m^3$ to +90.1 $m^3$) (Fig. 7.a). In contrast, the EENs show more limited changes with an average filling of 6.12% (ranging from −5.6 $m^3$ to +20.3 $m^3$) (Fig. 7.b). This mean value is strongly influenced by the EEN 3, which filled by 25% while the three others show volume changes smaller than 5%. Finally, the deposition lobes landward of the EENs developed with an average volume of 184.9 $m^3$ (ranging from +77.2 $m^3$ to +301.2 $m^3$) (Fig. 7.c). Volumes were calculated within the areas delimited by the black dashed lines in Fig. 5, for WENs, Fig. 6, for EENs, and Fig. 7.d-g for deposit lobes.

The major storm of the first winter, characterized by winds above 20 $m.s^{-1}$ (on January 29, 2019), drove the WENs filling but had limited impact on the EENs (changes <10 $m^3$). However, it triggered the development of the deposition lobes with volumes ranging from 15.7 $m^3$ to 44.6 $m^3$. During the second winter, the succession of several storm events exceeding 20 $m.s^{-1}$ reactivated WENs 2 and 3 which have slightly deepened (−38.4 $m^3$ and − 41.6 $m^3$, respectively), unlike the two others WENs which were already filled. It is likely that this reactivation is related to their shape which is more elongated and could have better funneled the wind flow in comparison to the two others. The changes of the EENs remained limited (<15 $m^3$), except for EEN 1 (−30 $m^3$). In contrast, the volumes of the deposition lobes were multiplied by 4 (EEN 1) and 6 (EEN 2, 3 and 4) suggesting large transport of beach sand to the back of the EENs during this second winter.

### 3.2.3. Notch impact on local flux

The difference plots in Figs. 5 and 6 indicate substantial alongshore variability in morphological changes. A cross-shore variability is also observed, which clearly depicts the different coastal dune geomorphological units (Fig. 8). The comparison with control areas shows that all EENs enforce an increase $\partial Q/\partial x$ at their entry, which means an increase in landward flux (Fig. 8.b2, d2, f2, h2). In contrast, a large deposition pattern is observed landward of the EENs, which means a decrease in landward sand transport at the exit of the notches (Fig. 8. a1, d1, f1, h1). Interestingly, not only EENs increased the volume of sediment deposited at the back of the foredune, but the sand deposits landward of the EENs are also approximately 8 m further inland than in the control areas, highlighting that EENs locally promoted the landward migration of the foredune. For the WENs, the cross-shore distribution of $\partial Q/\partial x$ over the entire study period shows larger negative values in the notches than in the control areas, which means more sand deposition driving their filling (Fig. 8.a2, c2, e2, g2).

## 3.3. Vegetation dynamics

### 3.3.1. Species composition dynamics

During the first winter, for elevation variation there was a highly significant interaction between the experimental notch (EN) and distance treatments (Table 4). This effect was mostly due to (1) the high sand deposition forming the deposition lobe landward of the EENs (mean sand deposition of 0.5 m in positions 6 to 8, Fig. 9.c), (2) the sand filling of the

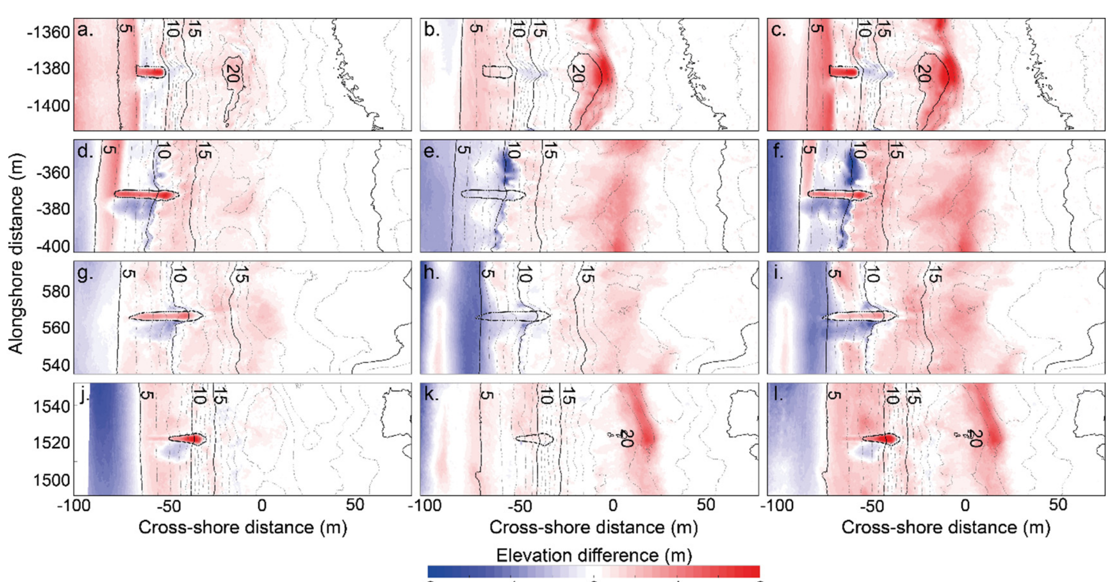


**Fig. 5.** Difference plots zoomed onto the WEN before and after the winter of 2018–2019 (from November 13, 2018 to June 06, 2019, in the left panel a, d, g, j), before and after the winter of 2019–2020 (from September 16, 2019 to May 202,020, in the middle panel b, e, h, k) and for the entire study period (from November 13, 2018 to May 20, 2020, in the right-hand panels c, f, i, l). The WEN number 1, 2, 3 and 4 are presented in lines 1, 2, 3 and 4, respectively.

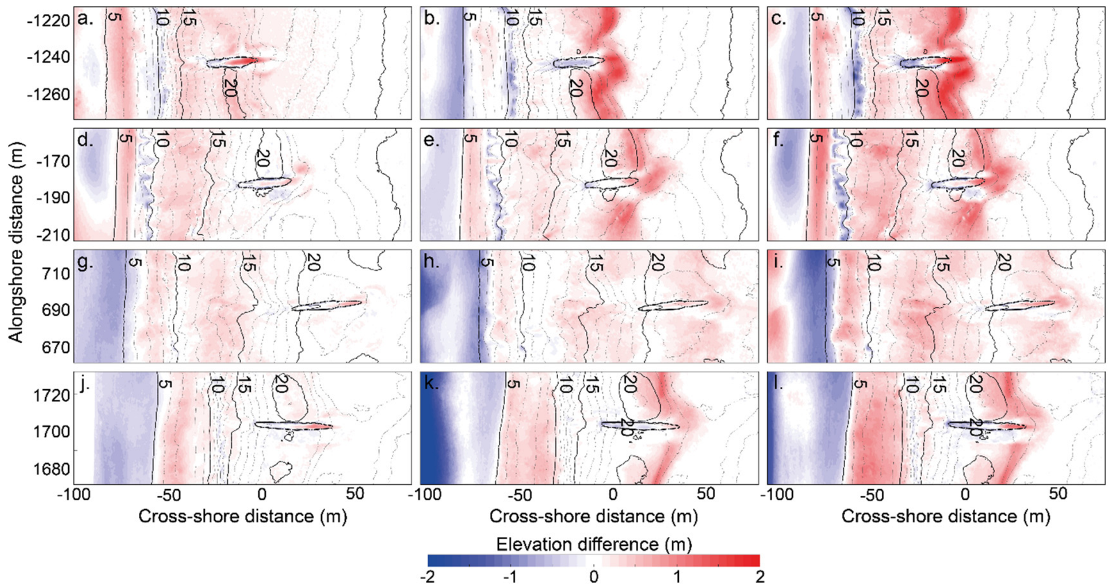


**Fig. 6.** Difference plots zoomed onto the EEN between the winter of 2018–2019 (from November 13, 2018 to June 06, 2019, in the left panel a, d, g, j), between the winter of 2019–2020 (from September 16, 2019 to May 202,020, in the middle panel b, e, h, k) and during the entire study period (from November 13, 2018 to May 20, 2020, in the right-hand panels c, f, i, l). The EEN number 1, 2, 3 and 4 are presented in lines 1, 2, 3 and 4, respectively.

WENs (mean sand deposition of 0.8 m in position 1, Fig. 9.b) and (3) the low sand deposition of +0.25 m to +0.15 m, from positions 1 to 6, in the control treatment (Fig. 9.a). For changes in vegetation cover, there was a weakly significant interaction between the EN, group and distance treatments (Table 4). This significant effect was mostly due to the increase in group 2 cover observed in the established foredune (positions

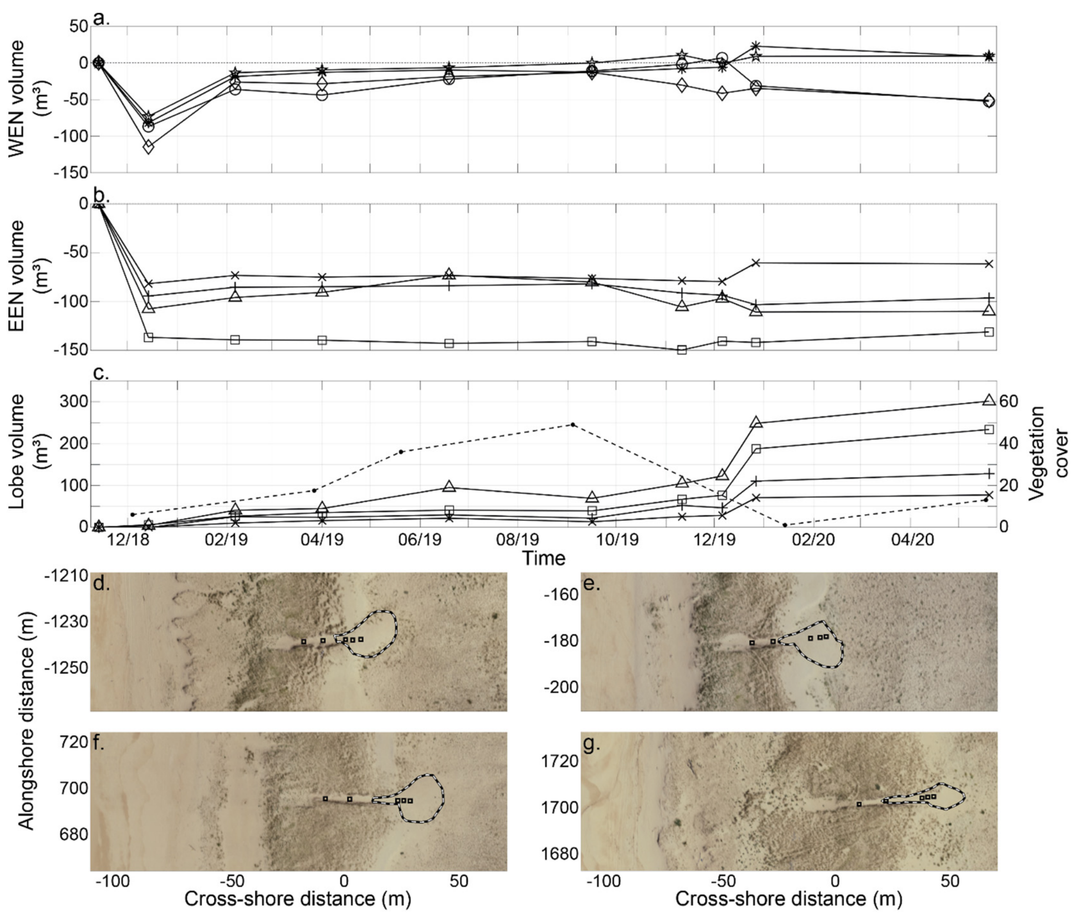


**Fig. 7.** Time series of volume change between each UAV survey of (a) WEN with asterisk, diamond, circle and star for notches 1, 2, 3 and 4, respectively, (b) EEN with triangle, square, cross and plus sign for notches 1, 2, 3 and 4, respectively, (c) the deposition lobe backward to EEN with triangle, square, cross and plus sign for notches 1, 2, 3 and 4, respectively (left axis), and of the sum of vegetation abundance in the EEN with black dotted line point (right axis). Orthomosaic showing the deposition lobe contour (black line with dotted white line) and the location of the vegetation quadrats for the EEN (d) 1, (e) 2, (f) 3 and (g) 4.

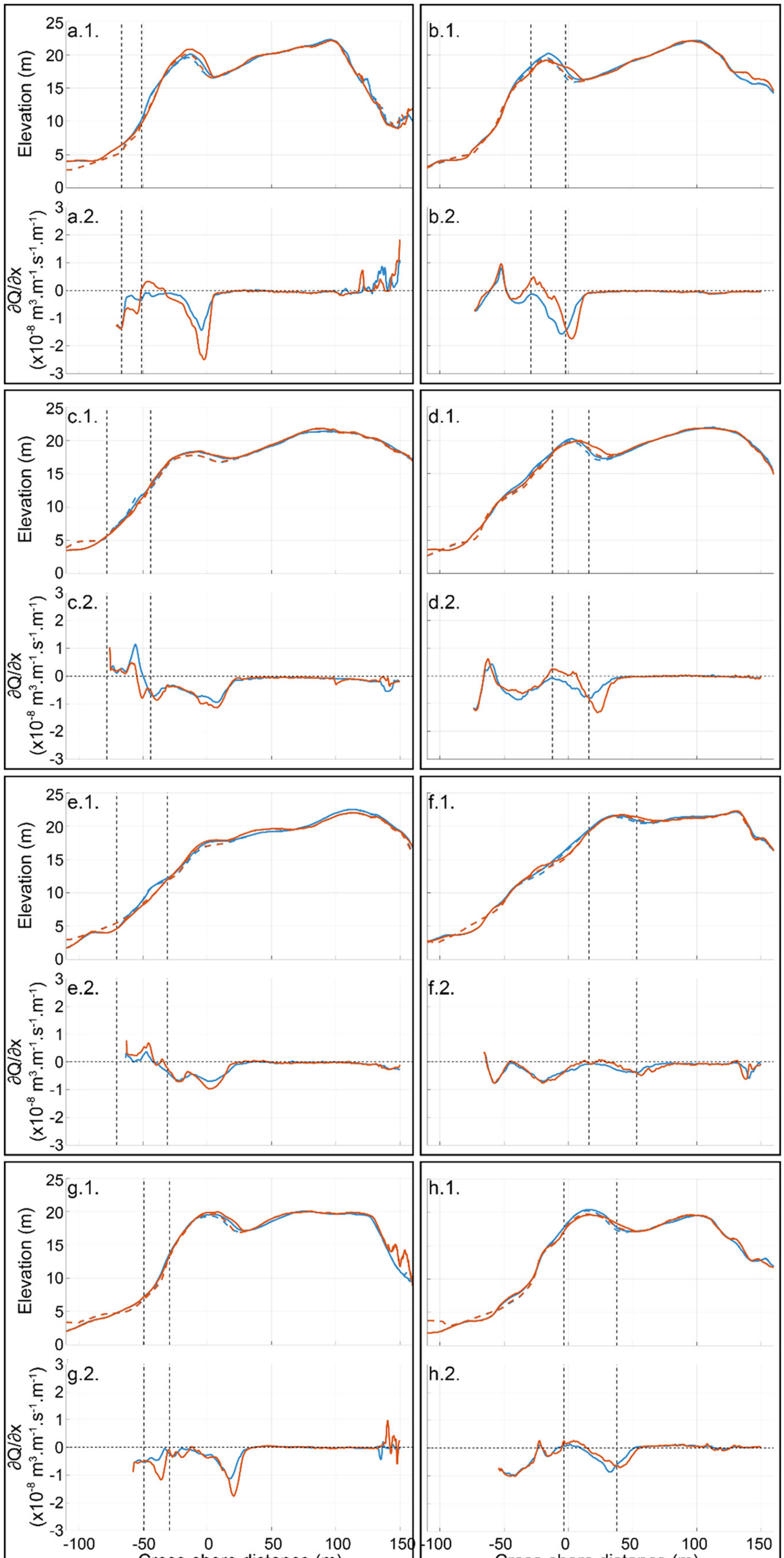


**Fig. 8.** Cross-shore distribution of the elevation changes and local sediment flux gradient with left panels for WENs (a) 1, (c) 2, (e) 3 and (g) 4 and right panels for EENs (b) 1, (d) 2, (f) 3 and (h) 4. Subpanels 1 are the alongshore-averaged profiles of the control area (in blue) and of the experimental area (in orange) in November 13, 2018 (dotted lines) and May 20, 2020 (solid lines). Subpanels 2 are the local cross-shore local sediment flux gradient for the control area (blue line) and the experimental area (orange line). The vertical black dotted lines represent the western and eastern edges of the experimental notches.

**Table 4**
Results of the ANCOVAs on the effects of the Experimental Notches (EN), Group (G), Distance (D), quadratic Distance ($D^2$) treatments and their interactions on vegetation abundance variation and elevation variation during winter 2018–2019 and winter 2019–2020. Significant results are indicated in bold and marginally significant in italics.

| Factors | Winter 2018–2019 | | | | Winter 2019–2020 | | | |
|---|---|---|---|---|---|---|---|---|
| | Elevation variation | | Cover variation | | Elevation variation | | Cover variation | |
| | F | P | F | P | F | P | F | P |
| EN | 32.9 | **<0.001** | 1.62 | 0.18 | 10.1 | **<0.001** | 11.2 | **<0.001** |
| G | 0 | 1.0 | 55.9 | **<0.001** | 0 | 1.0 | 16.7 | **<0.001** |
| D | 12.2 | **<0.001** | 3.39 | *0.06* | 99.9 | **<0.001** | 4.40 | **0.03** |
| $D^2$ | 8.61 | **0.003** | 0.13 | **0.71** | 79.1 | **<0.001** | 6.12 | **0.01** |
| EN x G | 0 | 1.0 | 0.48 | 0.82 | 0 | 1.0 | 1.40 | 0.21 |
| EN x D | 13.0 | **<0.001** | 0.68 | 0.51 | 14.9 | **<0.001** | 1.39 | 0.25 |
| EN x $D^2$ | 7.86 | **<0.001** | 0.89 | 0.41 | 12.3 | **<0.001** | 0.88 | 0.41 |
| G x D | 0 | 1.0 | 1.58 | 0.19 | 0 | 1.0 | 4.52 | **0.003** |
| G x $D^2$ | 0 | 1.0 | 4.60 | **0.003** | 0 | 1.0 | 5.79 | **<0.001** |
| EN x G x D | 0 | 1.0 | 2.60 | **0.01** | 0 | 1.0 | 0.90 | 0.50 |
| EN x G x $D^2$ | 0 | 1.0 | 2.47 | **0.02** | 0 | 1.0 | 0.84 | 0.53 |

5 to 8) in both the WENs (Fig. 9.b) and control transects (Fig. 9.c), but not in the EENs. This lack of increase in group 2 cover in the EENs at these positions, compared to WENs and control transects, was likely due to the excessive disturbance induced by the deposition lobe initiation (as shown in Section 3.2). However, a group 2 cover increase was also observed landward of the deposition lobe in EENs transects (i.e., position 9 to 11), as well as a decrease in groups 3 and 4 (Fig. 9.c). Moreover, these sand deposits landward of the EENs seem to have stimulated the growth of ruderal species during spring-summer season, as shown in Fig. 7.c by the increase in vegetation cover.

During the second winter, the highly significant interaction between the EN and distance treatment (Table 4) on the elevation variation was due to the higher sand deposition in position 7 of WENs (i.e., 0.42 m ± 0.28 m) than the EENs (i.e., 0.21 m ± 0.1 m) and control (i.e., 0.15 m ± 0.06 m) and the higher sand deposition in position 8 of WENs (i.e., 0.27 m ± 0.17 m) and EENs (i.e., 0.26 m ± 0.14 m) than the control (i.e., 0.08 m ± 0.04 m) (Fig. 9, and results of Tukey test not shown). But it should be noted that these large mean deposits in the WENs were mainly due to an extreme sand deposit observed in WEN 3 (>1 m, Fig. 5.k). In contrast to the first year, for changes in vegetation cover, there was a highly significant EN treatment, due to a lower whole cover increase in EENs than WENs and control (Table 4, Fig. 10). Overall, the increase in vegetation cover was particularly important for group 2 and also a little less for group 1 (highly significant group effect, Table 4). However, this increase was not observed in EENs at positions 3 to 8 (both in the notch and the deposition lobe, Fig. 10.c and also Fig. 7.c with the drastic vegetation cover decrease). These differences in changes among EN indicate a strong rejuvenation of the vegetation, whatever the distance in control and WENs and less changes in EENs at positions 3 to 8, likely due to the important sand deposition that occurred here.

Morphological changes related to the calm winter wind conditions in 2018–2019 led sand deposits which induced a moderate rejuvenation of vegetation, mainly localized landward of the EENs. On the contrary, the intense winter wind conditions in 2019–2020 led to higher and more generalized sand deposits throughout the dune system (as seen in Section 3.2) inducing a generalized rejuvenation of the dune vegetation.

In order to focus on the effect of the EN and sand deposition on vegetation composition landward of the notches, only the quadrats of the positions 7 to 13 were further analyzed with a CA. The year, season and distance treatments had all highly significant effects on vegetation composition on both CA axes, but the EN treatment only affected axis 1, in particular in interaction with the distance treatment (Table 5). This latter effect was due to more positive CA axis 1 scores for the EENs than for the WENs and control. This is particularly for the position landward of the deposition lobes in the transition dune (Fig. 11.a). This

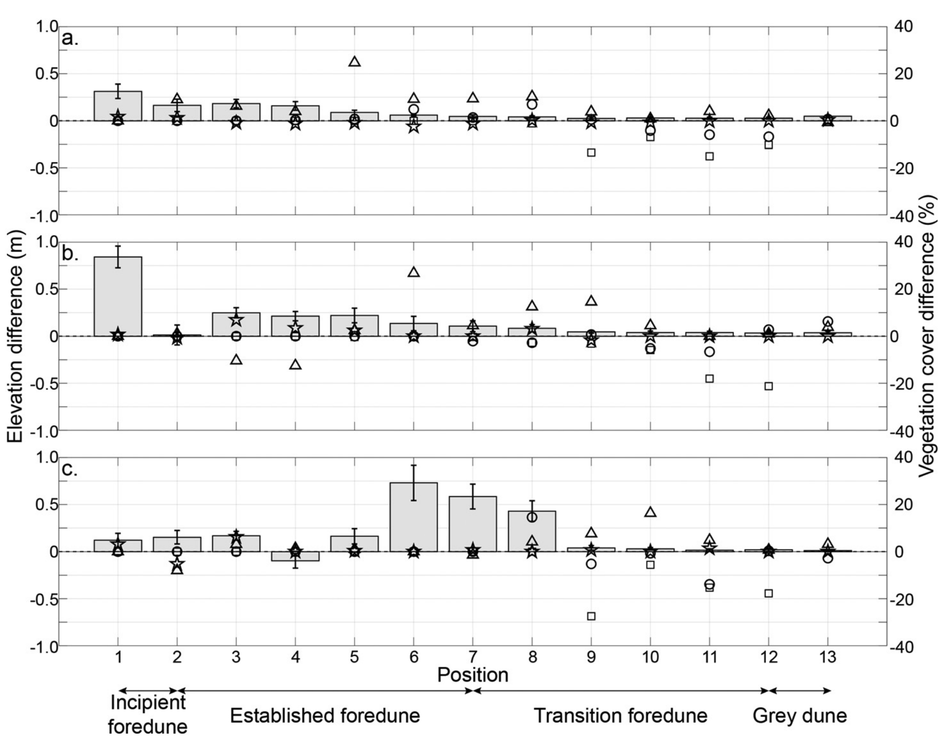


**Fig. 9.** Mean elevation difference (± *SE*) (left axis) and mean vegetation cover difference (right axis) for each position for the treatment (a) control, (b) west and (c) east between December 12, 2018 and May 20, 2019. Star, triangle, circle and square stand for vegetation group 1, 2, 3 and 4, respectively.

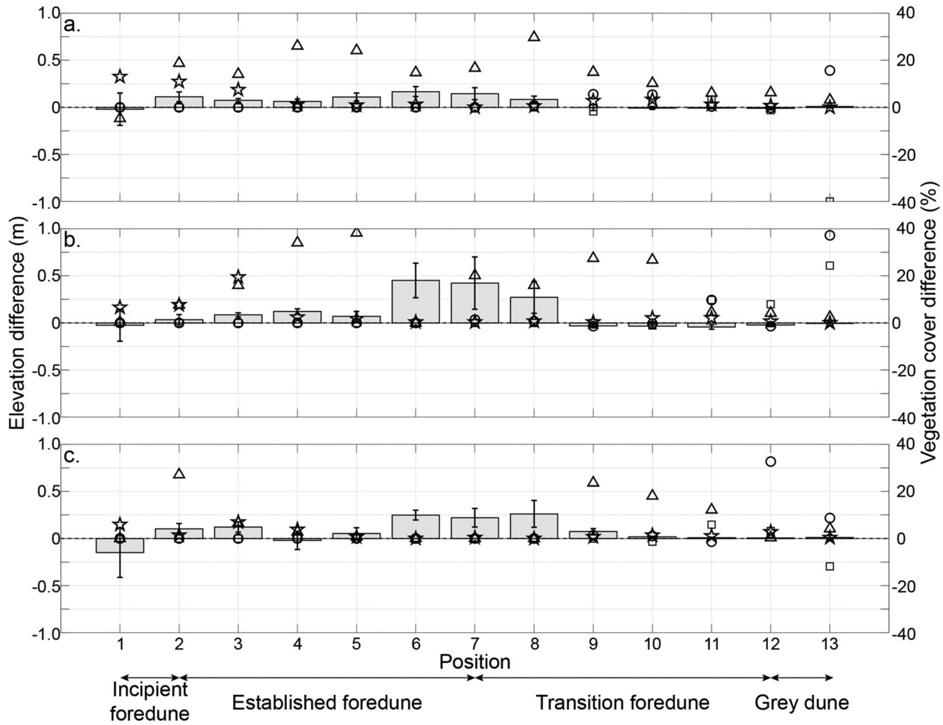


**Fig. 10.** Mean elevation difference (± *SE*) (left axis) and mean vegetation cover difference (right axis) for each position for the treatment (a) control, (b) west and (c) east between January 14, 2020 and May 18, 2020. Star, triangle, circle and square are for vegetation group 1, 2, 3 and 4 respectively.

result is in agreement with the results of Figs. 9 and 10 showing that the EENs significantly induced a rejuvenation of the transition dune. CA axis 2 showed significant interactions between year by distance and year by season. Both interactions are explained by the more positive CA axis 2 scores for the second year and spring season than for the first year and winter season. This effect is mainly observed in the transition and grey dunes (i.e., negative side of both CA axis) (Fig. 11.b). Thus, the CA results nicely separated on the two axes the effects of phenology and year treatments (axis 2) from the effects of the experimental notches (axis 1). These results highlighted that (1) the EENs induced the most rejuvenation of the dunes and (2) the second year had stronger overall effects than the first one.

**Table 5**
Results of the ANCOVAs on the effects of the Year (Y), Season (S), Experimental Notches (EN), Distance (D), quadratic Distance ($D^2$) and their interaction on CA axes 1 and 2 scores. Significant results are indicated in bold and marginally significant in italics.

| Factors | CA axis 1 | | CA axis 2 | |
|---|---|---|---|---|
| | F | P | F | P |
| Y | 10.5 | **<0.001** | 4.67 | **0.003** |
| S | 4.91 | **0.002** | 8.25 | **<0.001** |
| EN | 2.33 | *0.05* | 0.51 | 0.73 |
| D | 62.8 | **<0.001** | 70.4 | **<0.001** |
| $D^2$ | 28.3 | **<0.001** | 79.9 | **<0.001** |
| Y x S | 1.38 | 0.24 | 7.03 | **0.008** |
| Y x EN | 0.01 | 0.99 | 0.18 | 0.83 |
| Y x D | 1.11 | 0.29 | 2.96 | *0.08* |
| Y x $D^2$ | 1.33 | 0.25 | 4.19 | **0.04** |
| S x EN | 0.45 | 0.64 | 0.06 | 0.94 |
| S x D | 1.85 | 0.17 | 1.29 | 0.26 |
| S x $D^2$ | 1.85 | 0.17 | 0.83 | 0.36 |
| EN x D | 4.06 | **0.01** | 0.73 | 0.48 |
| EN x $D^2$ | 3.77 | **0.02** | 0.61 | 0.54 |
| Y x S x EN | 1.02 | 0.36 | 0.41 | 0.66 |
| Y x S x D | 0.22 | 0.64 | 0.37 | 0.54 |
| Y x S x $D^2$ | 0.23 | 0.63 | 0.24 | 0.62 |
| S x EN x D | 0.29 | 0.75 | 0.23 | 0.80 |
| S x EN x $D^2$ | 0.24 | 0.79 | 0.33 | 0.73 |
| Y x S x EN x D | 0.80 | 0.53 | 0.29 | 0.88 |
| Y x S x EN x $D^2$ | 0.75 | 0.56 | 0.25 | 0.91 |

### *3.3.2. Species diversity dynamics*

Changes in species richness were not significantly affected by our treatments during the first year (Table 6), although there were some significant decreases in species richness in the transition dune, in particular at position 13 of the control and EENs (see sample *t*-tests in Fig. 12). In contrast, during the second year there was a significant distance effect (with a slightly more significant distance$^2$ effects, i.e., non-linear effect of the treatment). This effect was due to a general lower species richness at position 6 and 7, and then a landward increase with a tendency for a maximum species richness at positions 11–12 (Table 6 and Fig. 12). Moreover, there was a significant distance X EN interaction because significant increases in species richness occurred in different position thought the EN treatment. Indeed, it increased from positions 7 to 11 in the control, positions 10 and 11 in the EENs and were only marginally significant at positions 9, 11 and 12 in the WENs (see sample t-tests in Fig. 12). These results show (1) the important disturbance induced by the high sand deposition during the second winter as compared to the first one and (2) the significant effect of the EENs on sand deposition in the transition dune, already shown in the results on species composition dynamics, and (3) these statistical analyses significantly confirm the effects of the EENs on the foredune morphological evolutions in Section 3.2. Additionally, results on positions 1 to 6, not included in the previous ANCOVAs, showed that species richness also increased in the incipient and established foredunes only in the second year and more significantly in the control, likely due to the effects of the digging of the notches located at these positions in the WENs and EENs.

Changes in Shannon and Pielou evenness indices were much less significant, in particular landward of positions 7, as shown by the only occurrence the second year for both indices of a marginally significant interaction between the EN and distance treatments (Appendices 3 to 6).

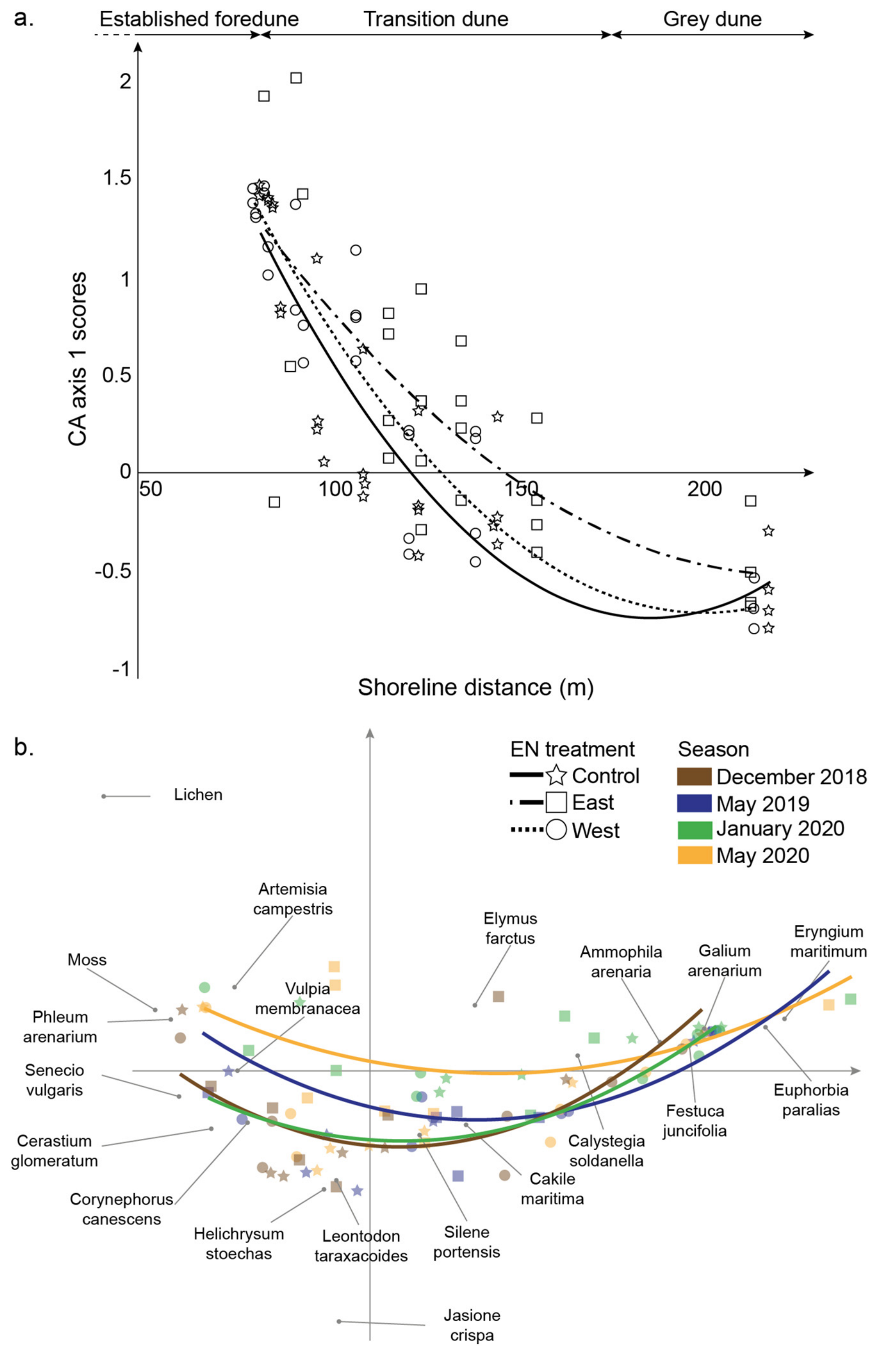


**Fig. 11.** (a) Mean CA axis 1 quadrat scores with their second-degree tendency curve in function of the shoreline distance, (b) CA 1–2 diagram for vegetation quadrats (from position 7 to 13).

Thus, species diversity dynamics was mostly due to increase in species richness, that occurred only the second year and at all positions, except the most stabilized ones (12 and 13) in the control, and mostly from landward of the EENs to position 12. This increase in species richness was mainly due to an increasing occurrence of ruderal species tolerant to sand deposition (*Cakile maritima*, *Elymus farctus*, *Eryngium maritimum*, *Euphorbia paralias*, *Calystegia soldanela* and *Festuca juncifolia*), consistent to results on species composition.

## 4. Discussion

The excavation of the foredune notches affected sediment transport, promoting either vertical accretion or a more landward sand deposition. The disturbance generated by these new sand deposits significantly affected vegetation diversity and composition, inducing an increase in species richness due to the colonization of ruderal species. However, these responses were dependent on the location of the notches, the EENs inducing the most important changes. Finally, morphological and ecological changes were stronger the second year but independent on notches, due to the higher sand deposition that occurred during the second winter characterized by stronger wind storm conditions than the first winter.

### 4.1. Overall physical and ecological responses to notches excavation

Over the entire study period, the excavation of experimental notches in the foredune drove cross-shore-variable morphological responses compared to juxtaposed control areas. These evolutions were mainly

**Table 6**
Results of the ANCOVAs on the effects of the Experimental Notches (EN), Distance (D), quadratic Distance ($D^2$) treatments and their interactions on species richness difference during winter 2018–2019 and winter 2019–2020. Significant results are indicated in bold and marginally significant in italics.

| Factors | Winter 2018–2019 | | Winter 2019–2020 | |
|---|---|---|---|---|
| | Species richness difference | | Species richness difference | |
| | F | P | F | P |
| EN | 0.65 | 0.52 | 0.26 | 0.77 |
| D | 0.01 | 0.94 | 4.46 | **0.03** |
| $D^2$ | 0.34 | 0.56 | 6.09 | **0.01** |
| EN x D | 0.78 | 0.46 | 3.22 | **0.04** |
| EN x $D^2$ | 0.98 | 0.38 | 2.52 | *0.08* |

characterized by a vertical accretion or more landward sand deposition in the alignment of the EENs. The new sand deposits increased disturbance for plants, thus resulting in significant changes in plant community composition and species richness. However, in contrast to our hypothesis, we found a higher diversity, and in particular species richness, with increasing disturbance. This result does not support theoretical community ecology models that predict that increasing disturbance should decrease species richness in stressed environments. It is also opposite to results of observational studies showing in the same system that species richness strongly decreases along spatial gradients of increasing disturbance from the grey dune to the incipient foredune (Forey et al., 2008; Michalet et al., 2015). This divergence is probably related to the response timescale of plant species according to their functional strategies (i.e., competitive, ruderal and stress-tolerant, Grime, 1973). Indeed, divergences between experimental manipulations and natural spatial patterns have yet been found in climate change experiments conducted along water stress gradients (Sandel et al., 2010; Metz and Tielbörger, 2016). During short-term rainfall manipulations of the American Prairie, Sandel et al. (2010) found an increase in small seeded and fast-growing plants with decreasing drought, since ruderal species quickly colonized open spaces. Sandel et al. (2010) argued that larger seeded and nutrient conservative species should competitively exclude ruderal species and dominate in the long-term, as observed in naturally wetter parts of the American Prairie. Thus, we argue that our short-term increase in disturbance due to sand deposition yet only produced a transient biological response. Sand deposits have certainly stimulated the colonization and growth of ruderal plant species (such as *Cakile maritima*, *Elymus farctus*, *Eryngium maritimum*, *Euphorbia paralias*, *Calystegia soldanela* and *Festuca juncifolia*) due to increasing soil fertility (Forey et al., 2008; Laporte-Fauret et al., 2021; Le Bagousse-Pinguet et al., 2013). This induced a slight but significant increase in species richness, likely because this effect was not yet compensated by the mortality of stress-tolerant species (*Helichrysum stoechas*, *Corynephorus canescens*, etc.) buried by the sand. Indeed, in the transition dunes of Truc Vert, where nutrient and drought stresses are high, competition is very unlikely to exclude ruderal species as documented in the American prairie (Forey et al., 2010; Michalet et al., 2015). Thus, we hypothesize that if disturbance is still present in the long- or middle-term, species diversity should decrease due to the disappearance of stress-tolerant species, in agreement to ecological theory and natural observations (Grime, 1973; Forey et al., 2008).

The physical changes induced by the experimental notches affected very locally the morphology and vegetation of the dune. Indeed, despite annual and seasonal variations, the shoreline has been relatively stable over the last 65 years at Truc Vert beach, and the dune volume has

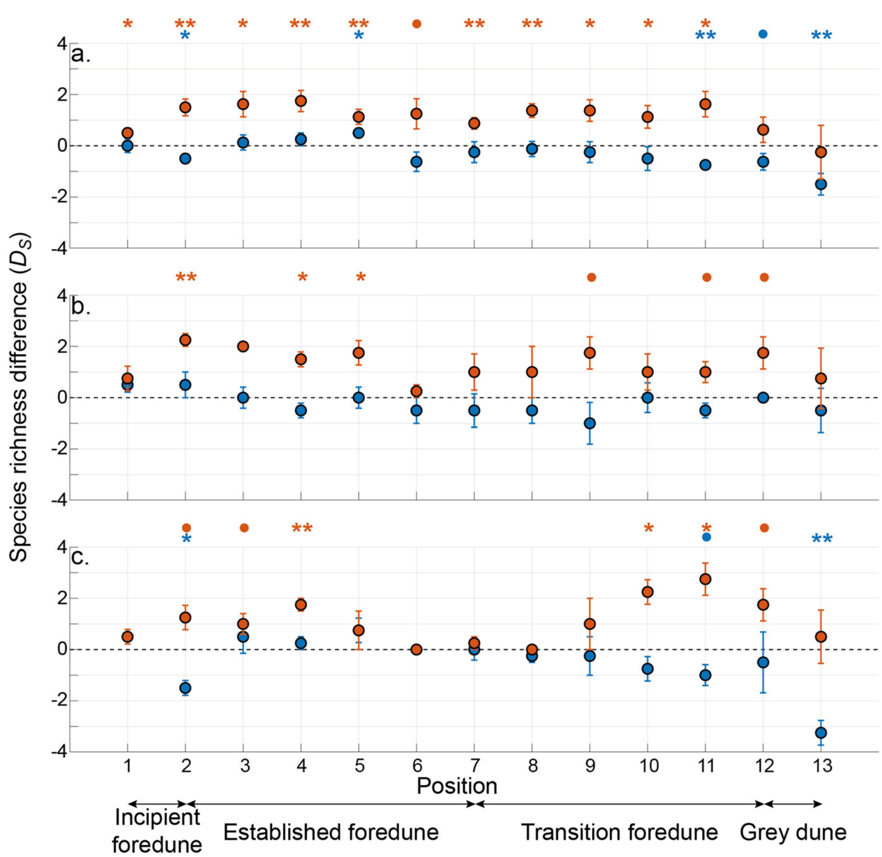


**Fig. 12.** Mean species richness difference (± SE) for each position for the treatment (a) control, (b) west and (c) east. Blue color and orange color are winter 2018–2019 and winter 2019–2020 respectively. Sample t-test (. p < 0.1; * p < 0.05; ** p < 0.01; *** p < 0,001). of morphological and ecological changes in Truc Vert dune system in order to assess the influence of the meteorological winter conditions on a longer time scale.

continuously increased with a landward migration of the dune crest during the last decade (Castelle et al., 2018b; Laporte-Fauret et al., 2020). It is likely that this stable trend and the absence of eroding scrap, in which blowouts are more likely to be formed, could limit morphological and ecological changes, compared to some naturally blowouts which have evolved in parabolic dune in the past few years further north on the Gironde coast. It is important to note that here the large alongshore spacing between notches strongly reduced the impact of the backhoe loader on vegetation. However, in severely eroding areas where lowly spaced notches may be required to increase the landward migration of the dune, it is expected that engineering machinery will have a strong impact on vegetation.

### 4.2. Influence of the position of the notches

The position of the experimental notches in the dune system had a strong influence on morphological and ecological responses. The WENs, located in the incipient foredune, rapidly infilled after their excavation during the first winter storms. Both visual inspection of the WENs, and total water level estimation at the coast including run-up ($<$ 8 m during extreme storms coinciding with spring high tide, Castelle et al., 2017b) with respect to WEN elevation ($>$ 6 m) suggest that impact of wave and overwash events on the WEN morphological evolution was minimal. They promoted the deceleration of the incident flux, inducing a vertical accretion with limited landward evolutions. It is likely that their initial shape was not favorable and that a more landward extension would have more importantly funnel the wind flow and induce higher disturbance. Moreover, their limited impact on vegetation might be due to both the higher nutrient availability of the incipient foredune than the grey dune and, thus, the functional strategies of the species dominating there, mainly ruderal species. In contrast, the EENs affected the overall morphology and sediment pathways. Compared to control sectors, EENs increased the aeolian landward sand transport to the back of the dune, with the formation of a deposition lobe. Similar experiments in other coastal dune systems are scarce. Meerkerk et al. (2007) showed on the Dutch coast a rapid filling of a 60-m wide experimental notch excavated in a foredune. This led to vegetation regrowth and the almost complete closure of the notch after three years. Pye and Blott (2016) monitored the evolution of 27 experimental notches on the Welsh coast. They showed that the most active notches were generally located on wide beaches with a convex shape and positive sediment budget. These notches were typically wider upwind than downwind, thus enhancing acceleration of wind flow velocities landwards and further erosion of the notch. Finally, most of the massive notches excavated in a Dutch national park were found over the years to act as highly effective conduits for aeolian landward transport (Ruessink et al., 2018). Nevertheless, the EENs show a U-shape cross section, erosion at the entrance, erosion of the walls, and formation of the deposition lobe with absence of vegetation colonization. This suggests that these notches are still at the early abiotic stage of the natural development of the though blowouts (Schwarz et al., 2019), which stimulate their continuous monitoring in the coming years. We argue that it is likely the formation of the deposition lobes, landward to the EENs, which is responsible of the increasing disturbance for plants and, thus, short-term increase in ruderals and specific richness. Finally, the EENs acted as an efficient conduit for transporting the beach sand to the back of the dune, it is expected that they act the same for e.g., beach litters as investigated in Andriolo et al. (2020), although it was not addressed herein.

### 4.3. Influence of the meteorological conditions of the year

Morphological and ecological responses were also strongly influenced by winter wind conditions of the year, in particular the frequency and intensity of winter storms. The first winter, characterized by extreme calm wind conditions, filled the WENs and initiated the deposition lobes landward of the EENs, inducing a local plant rejuvenation. In contrast, the stronger winds of the second winter led to an important development of the deposition lobes multiplying their volumes by 4 to 6 and inducing a more generalized vegetation rejuvenation. Interestingly, the strong and general rejuvenation of the dune communities observed only the second year almost deleted differences in effects between the two kinds of notches that were more significant during the calm first year. Thus, meteorological conditions are an important component in the morphological and ecological evolution of coastal dunes. Indeed, if normal wind and waves actions slowly build the foredunes (Hayes, 1979; da Silva et al., 2008), large morphological evolutions can be generated by low frequency and high magnitude storms events as the recent example of the winter 2013–2014. This winter was characterized by extreme storm wave clustering leading to drastic beach-dune systems erosion in western Europe (Castelle et al., 2015; Masselink et al., 2016). In addition, storm events may also have a strong effect on coastal vegetation by reducing species richness as highlighted by Miller et al. (2010) who monitored vegetation changes during nine years in Florida. According to their monitoring, the coastal dune vegetation communities will recover over a 3–5 year period. These results therefore encourage further monitoring of morphological and ecological changes in Truc Vert dune system in order to assess the influence of the meteorological winter conditions on a longer time scale.

## 5. Conclusion

In this study, the strategy of remobilization of coastal dunes by restoring natural processes was tested in a 4-km stretch dune system in southwest France. Experimental foredune notches were excavated and intensively monitored during two years in order to investigate the morphological and ecological responses to this disturbance. Experimental notches affected the morphology and the vegetation by increasing windblown sand transport to the back of the dune, and species richness due to the short-term development of ruderal species. However, the effects of the notches were limited in space, likely because the notches are still at an early stage of blowout development. Effects were strongly dependent on the location of the notches with only EENs promoted landward sand transport while showing similar evolutionary characteristics to natural blowout. Intense winter wind conditions can lead to important and more generalized morphological evolutions at the scale of the system, reducing the difference in effects between the two notches. Further works are necessary to continue monitoring the morphological and ecological changes due to our notches, in particular to assess the long-term vegetation response and, eventually, observe a decrease in species richness, as predicted by the literature on the effect of disturbance in stressed ecosystems.

Finally, the excavation of experimental notches in the foredune crest may, in certain environments, reinstate morphological and ecological dynamics while initiating a foredune landward migration. Future larger experiments should be carried out in sectors which, contrary to the Truc Vert dune system, are chronically eroding in order to try to reintroduce some dynamics in these dune systems. Based on this experimentation, we can suppose that to initiate a generalized landward migration of the dune system, it would be necessary to excavate notches in the dune crest with a short alongshore distance between them. This dynamic could allow the coastal dune to better adapt in a context of sea level rise and increased erosion. However, we cannot exclude that this migration could decrease in the long term the diversity of dune communities.

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## CRediT authorship contribution statement

**Quentin Laporte-Fauret:** Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Bruno Castelle:** Conceptualization, Funding acquisition, Investigation, Methodology, Writing – review & editing. **Richard Michalet:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Vincent Marieu:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Stéphane Bujan:** Methodology. **David Rosebery:** Methodology.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


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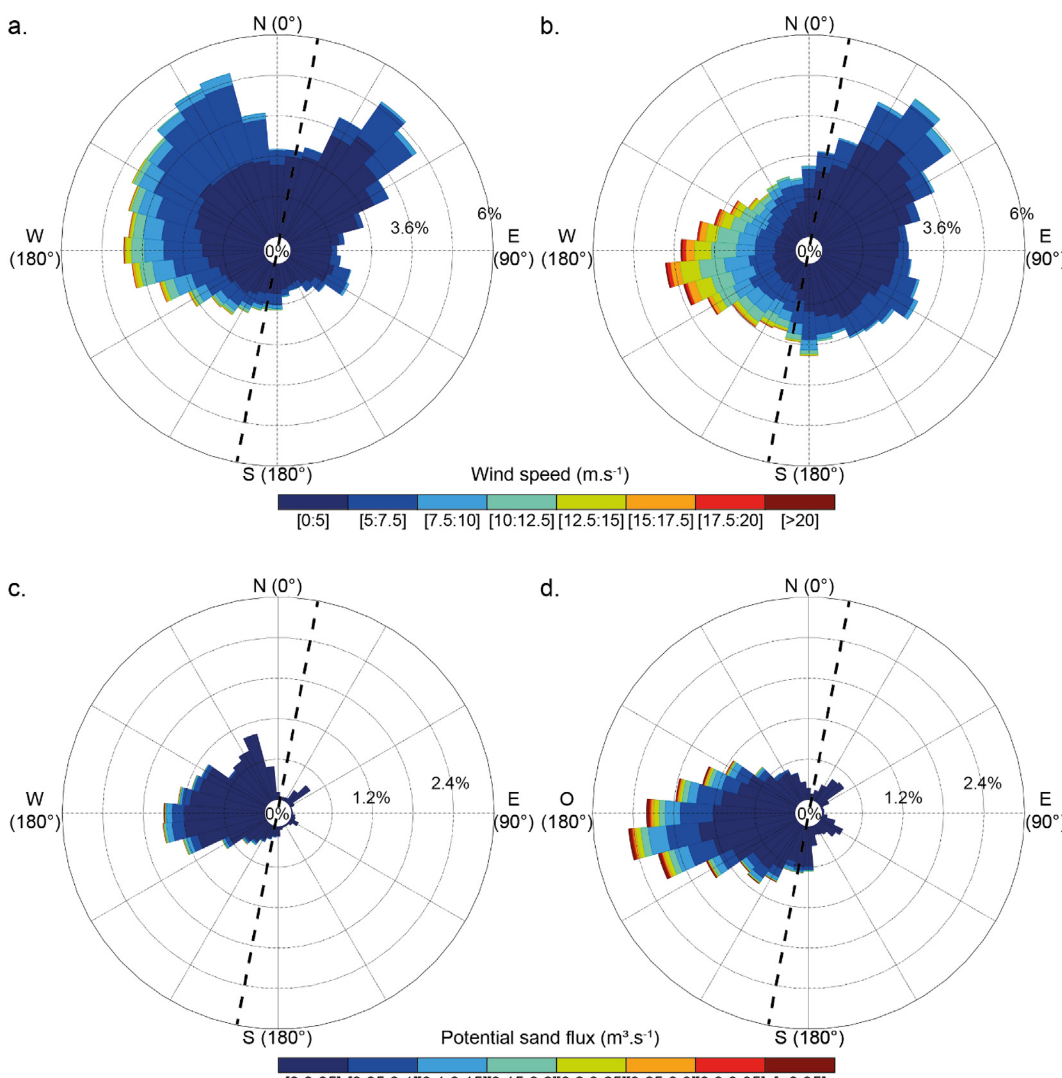
## Appendix A

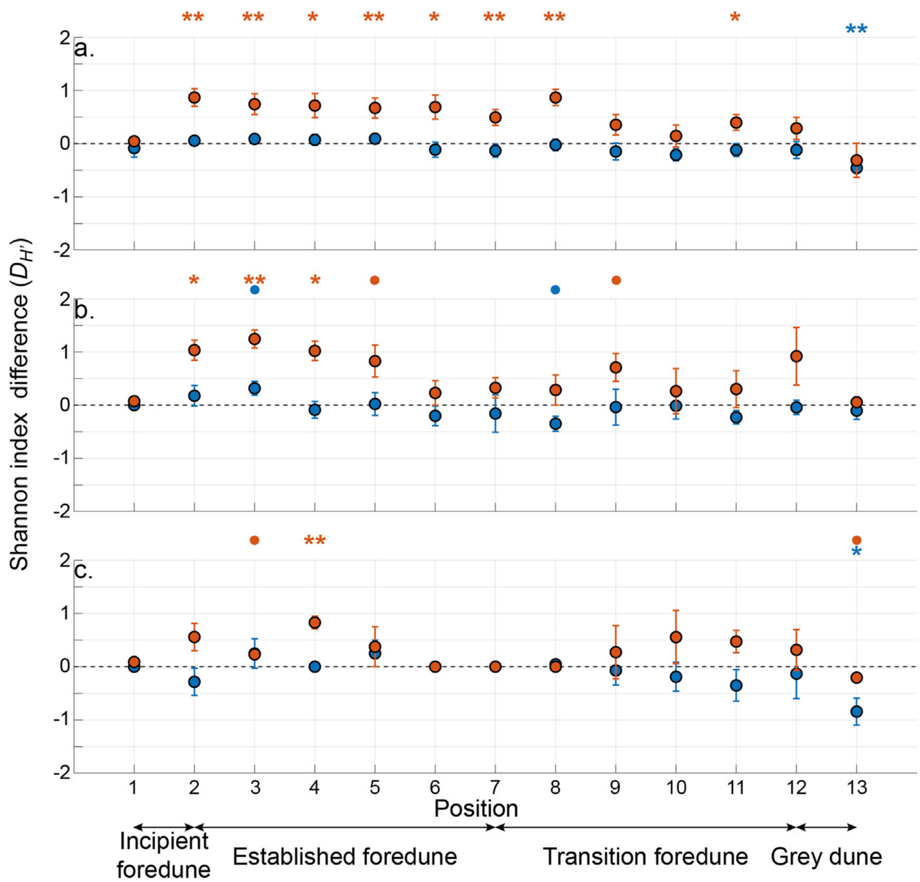



**Appendix 1.** Wind rose from 2003 to 2020 during (a) summer and (b) winter period. Potential sand flux rose from 2003 to 2020 during (c) summer and (d) winter period. The dashed black line represents the main orientation of the Gironde coast (10.8°). Summer period is defined as from April 1st to October 1st and Winter period is defined as from October 1st to April 1st.


**Appendix 2.** Example of sampling quadrat with black circles correspond to the 36 intersections. Following the interception cover technique (Goodall, 1953), the abundance of Galium arenarium, *Ammophila arenaria* and *Eryngium maritimum* are 69.4% (i.e., 25 intersections of 36), 16.7% (i.e., 6 intersections of 36) and 1.4% (i.e., 0.5 intersections of 36), respectively.

**Appendix 3**
Results of the ANOVAs on the effects of the Experimental Notches (EN), Distance (D), quadratic Distance ($D^2$) treatments and their interactions on Shannon index difference during winter 2018–2019 and winter 2019–2020. Significant results are indicated in bold and marginally significant in italics.

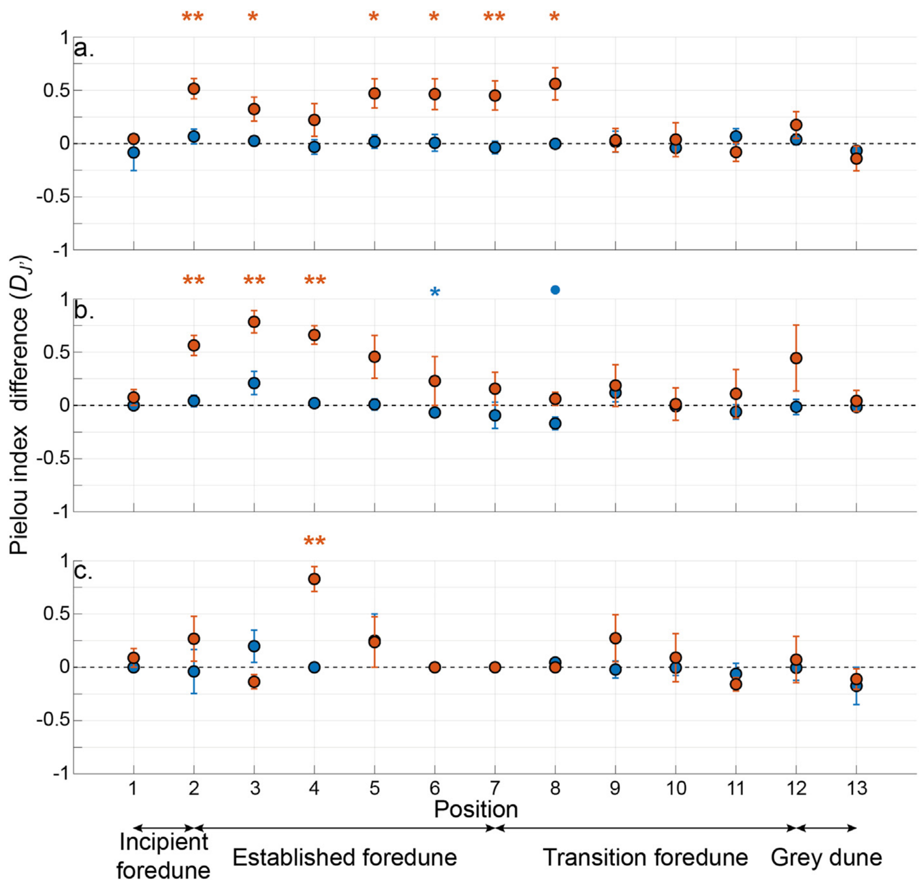
| Factors | Winter 2018–2019 | | Winter 2019–2020 | |
|---|---|---|---|---|
| | Shannon index difference | | Shannon index difference | |
| | F | P | F | P |
| EN | 0.17 | 0.84 | 0.57 | 0.56 |
| D | 0.001 | 0.97 | 0.17 | 0.67 |
| $D^2$ | 0.10 | 0.75 | 0.76 | 0.38 |
| EN x D | 0.15 | 0.86 | 2.35 | *0.09* |
| EN x $D^2$ | 0.03 | 0.97 | 1.74 | 0.18 |




**Appendix 4.** Mean Shannon index difference (± SE) for each position for the treatment (a) control, (b) west and (c) east. Blue color and orange color are winter 2018–2019 and winter 2019–2020 respectively. Sample t-test (. $p < 0.1$; * $p < 0.05$; ** $p < 0.01$; *** p <0,001).

**Appendix 5**
Results of the ANOVAs on the effects of the Experimental Notches (EN), Distance (D), quadratic Distance ($D^2$) treatments and their interactions on Pielou index difference during winter 2018–2019 and winter 2019–2020. Significant results are indicated in bold and marginally significant in italics.

| Factors | Winter 2018–2019 | | Winter 2019–2020 | |
|---|---|---|---|---|
| | Pielou index difference | | Pielou index difference | |
| | F | P | F | P |
| EN | 0.45 | 0.64 | 0.56 | 0.57 |
| D | 0.23 | 0.63 | 1.49 | 0.22 |
| $D^2$ | 0.27 | 0.60 | 0.77 | 0.38 |
| EN x D | 1.24 | 0.29 | 1.75 | 0.18 |
| EN x $D^2$ | 1.11 | 0.33 | 1.22 | 0.30 |




**Appendix 6.** Mean Pielou index difference (± SE) for each position for the treatment (a) control, (b) west and (c) east. Blue color and orange color are winter 2018–2019 and winter 2019–2020 respectively. Sample t-test (. p < 0.1; * p < 0.05; ** p < 0.01; *** p < 0,001).

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