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Review

Feedbacks between Biotic and Abiotic Processes Governing the Development of Foredune Blowouts: A Review

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Abstract: This paper reviews the initiation, development, and closure of foredune blowouts with focus on biotic-abiotic interactions. There is a rich body of literature describing field measurements and model simulations in and around foredune blowouts. Despite this abundance of data there is no conceptual framework available linking biotic and abiotic observations to pathways of blowout development (e.g., erosional blowout growth or vegetation induced blowout closure). This review identifies morphological and ecological processes facilitating the transition between blowout development stages and sets them in the context of existing conceptual frameworks describing biotic-abiotic systems. By doing so we are able to develop a new conceptual model linking blowout development to the dominance of its governing processes. More specifically we link blowout initiation to the dominance of abiotic (physical) processes, blowout development to the dominance of biotic-abiotic (bio-geomorphological) processes and blowout closure to the dominance of biotic (ecological) processes. Subsequently we identify further steps to test the proposed conceptual model against existing observations and show possibilities to include it in numerical models able to predict blowout development for various abiotic and biotic conditions.

Keywords: blowout; bio-geomorphology; aeolian sand transport; conceptual model

1. Introduction

The coastal zone, an interface between marine, terrestrial and atmospheric processes is shaped through the dissipation of marine energy and modification of atmospheric processes [1]. The most dynamic coasts are found along high-energy wave-dominated shorelines, such as along the Dutch coast [2], the French coast [3], the west coast of the United States [4], the east coast of New Zealand [5] or the south coast of Australia [6]. At these environments, the dynamics in the nearshore zone, the beach and the dunes are unequivocally intertwined, (e.g., [7,8]). Coastal dunes are important multifunctional landscapes, providing habitats for flora and fauna, and protecting the hinterland from flooding, facilitating drinking water, and serving as recreational space [9]. Foredunes are shore parallel dune ridges located at the landward edge of the backshore, formed on beaches through the deposition of aeolian sand within and around vegetation. Their morphologies range from flat terraces to convex ridges. Foredunes are the most seaward-located dune feature, and are therefore regarded as the primary defense against flooding of the hinterland during storms [10,11].

Currently many coastal foredune systems around the globe experience stabilization of their foredune morphology through increased vegetation cover [9,12–17], while others undergo continuous stabilization-activation cycles [18–20]. Increased vegetation cover increases the stability of the foredune surface inhibiting the development of blowouts and thus dynamic changes in the dune morphology [18,21]. Foredune blowouts, a characterizing feature of active natural foredunes, are erosional features that allow aeolian flow-through of siliciclastic sand from the beach into the back dunes (Figures 1 and 2). This facilitated beach-dune interaction enhances back dune biodiversity due to disturbance driven local vegetation rejuvenation, (e.g., [22]), and vertical accretion potentially increasing back dune resilience in the face of sea-level rise, (e.g., [10,23–29]). As such, foredune blowouts contribute to dynamic, resilient, and species-rich coastal habitats, whereas closed or stabilized blowouts were shown to reduce back dune biodiversity [9]. Previous studies indicated that dynamic natural foredunes are characterized by continuously closing and incising blowouts referred to a stabilization-activation cycles [18]. However, the underlying mechanisms favoring either stabilization-activation cycles or continuous stabilization are still unclear.

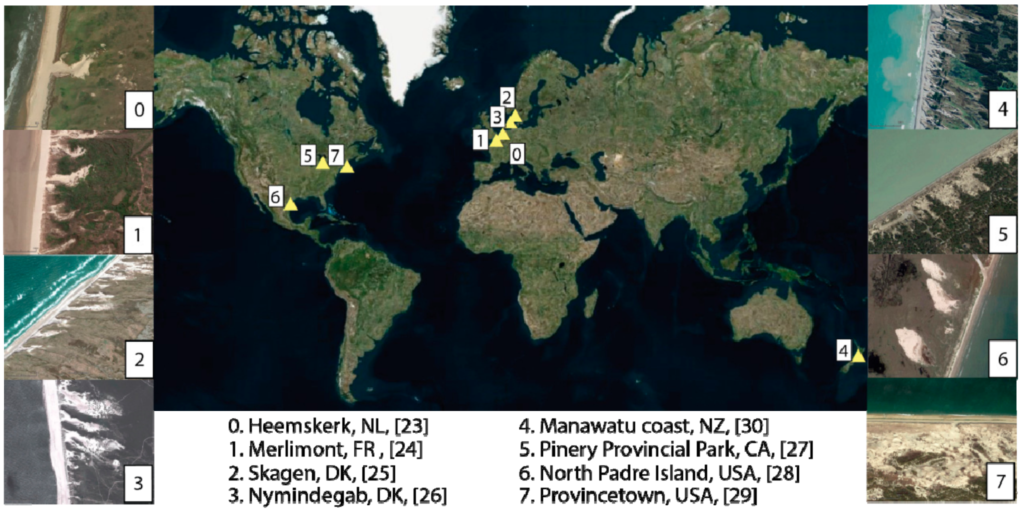


Figure 1. Examples of different blowout systems around the world, which were found in various studies indicated by the different numbers.

Notwithstanding the importance of blowouts in natural coastal dune systems, they are also crucial for applied coastal management purposes. Along many low-lying densely populated coasts, such as in the Netherlands, coastal management traditionally has focused on dune stabilization, including closing gaps in the foredune, planting vegetation, (e.g., [21,30,31]), and nourishments on the foreshore, the foredune and the beach, (e.g., [32,33]). Aside of dune stabilization by maintaining the foredune shape (by adding plants or sand), the stabilizing effect of foreshore- and beach nourishments on foredune morphology is based on the connection between nearshore-, beach morphology, aeolian sediment transport, and dune dynamics as shown by Short and Hesp [8]. Foreshore and beach nourishments at high-energy dissipative beaches get transported onto the foredune by prevailing high aeolian transport rates supporting the effectiveness of sand binding vegetation [13]. The combination of the above stated measures resulted in high and continuous vegetated foredunes, physically separating the beach (the main source of sediment input) from the back dunes, lead to loss of biodiversity (e.g., dune and dune slack habitats being replaced by fixed dune grassland and scrub) and extinction of rare plants and invertebrates which require open mobile conditions (e.g., [14,23,30,33,34]). However, recently, headed by examples from European coasts, a shift in coastal management strategy towards maintaining and reintroducing natural dynamic foredune systems with higher biodiversity and increased resilience against climatic changes and coastal erosion was observed, (e.g., [14,21,23,32,35–39]) (Figure 2). Initiation of artificially induced foredune blowouts turned out to be the most successful and sustainable management measure for dune reactivation [15,23,40]. This is due to the fact that foredune blowouts re-introduce interactions between the beach and the back dunes, (e.g., [23,38,41]). This reintroduced connection is intended to elevate stress factors (wind speed, sand supply, salt spray) in the back dunes, resulting in a sustainable increase in sand input and biodiversity. Re-establishment of extensive mobile foredune surfaces is unlikely to occur naturally at these stabilized systems. However it is possible to increase the mobility of the foredune system locally by either manually creating foredune blowouts or allowing natural blowout formation by discontinuing stabilization measures [14]. Unfortunately, in depth knowledge on blowout development over space and time at natural and managed coasts is still lacking.

Figure 2. Coastline near Heemskerk, the Netherlands. The used Terminology indicates the location of the intertidal zone, dry beach, foredune, back dunes and a natural blowout (photo: Rijkswaterstaat/Rens Jacobs, 2005).

Foredune and foredune blowout evolution reflect the aggregation of both environmental (abiotic) and ecological (biotic) processes. Abiotic processes such as aeolian sand transport, wind speed, rainfall, and temperature, and biotic processes, such as vegetation establishment, growth (rate and period) and competition are important determinants for the presence of blowouts, their development cycles and thus active or stabilized dune development, (e.g., [10,14]). However, biotic and abiotic processes do not operate independently, leading to the recognition that abiotic-biotic feedbacks are critical for some stages in dune and blowout development. Previously, Corenblit et al. [42] proposed four bio-geomorphic succession-phases for biotic-abiotic systems as river floodplains, salt marshes, mangroves, and coastal dune systems: geomorphic, pioneer, bio-geomorphological, and ecological. However in respect to the development of foredune blowouts we here merge the pioneer phase with the bio-geomorphological phase since small seedlings can already create shadow dunes and thus facilitate bio-geomorphological feedbacks (Figure 3) [42]. We thus propose three successional phases depending on the relative importance of biotic and abiotic processes in blowout dynamics: geomorphologic, bio-geomorphological, and ecological [42–44] (Figure 3). The geomorphologic phase is dominated by physical disturbances such as floods, storms or tsunamis, with landform dynamics being dominated by hydrodynamic and aerodynamic forces and intrinsic cohesiveness of the sediment. During this phase, the dispersal of plant diaspores (e.g., seeds or rhizome fragments), their germination, growth, and survival on bare sediment is controlled by the geomorphic environment [42]. The bio-geomorphological phase is characterized by bio-morphodynamic feedbacks, where morphology and biomechanical plant properties interact with the substrate and geomorphic flows (e.g., aeolian sand transport). In the absence or low frequency of major physical (abiotic) disturbances, changes in the geomorphic environment are controlled by plants (ecological phase), resulting in changes in physiochemical soil properties, stabilization of the ecosystem and the increased importance of ecological interactions (e.g., competition, facilitation) [42,45]. In the context of blowouts these three successional stages can be linked to morphological development. Blowout initiation is governed by abiotic processes such as wind and sediment transport indicating the geomorphologic phase. Blowout development is governed by the interaction between sediment transport and vegetation indicating the bio-geomorphological phase. And blowout closure is mainly governed by vegetation re-colonization indicating the ecological phase.

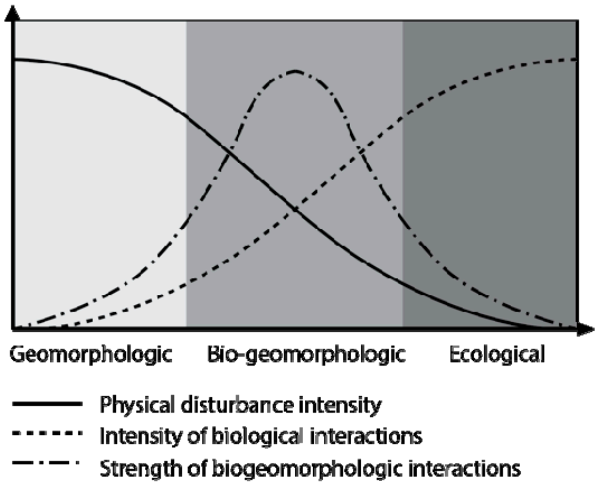


Figure 3. Conceptual model of bio-geomorphological succession in blowout systems. Physical changes related to early stages of the bio-geomorphological phase correspond to sediment accretion and topographic rise; those associated with late stages of the bio-geomorphological phase and to the ecological phase correspond to changes in physiochemical properties of the soil (altered based on the concept of Corenblit et al. [42]). This figure has been adapted from [42], with permission from John Wiley and Sons.

The aim of this paper is to provide a review of the current knowledge on the initiation, evolution and dynamics of foredune blowouts with focus on interactions between abiotic (i.e., physical) and biotic (i.e., biological) processes. While a considerable amount of research was conducted on the initiation of natural blowouts, blowout development has received much less attention. For this reason, this review identifies relevant feedbacks between abiotic and biotic processes in blowout development and summarizes them into a new conceptual model facilitating the prediction of different pathways of blowout development (active vs. stabilized). The proposed conceptual model should be seen as a starting point to create an exploratory predictive model framework able to simulate blowout develop pathways and time scales in response to changes in abiotic and biotic factors. We first give an overview of factors influencing blowout initiation (Section 2.1), development (Section 2.2), and closure (Section 2.3). Then we link these factors in a conceptual model (Section 3.1) and finally we discuss its application in regard to existing approaches (Section 3.2).

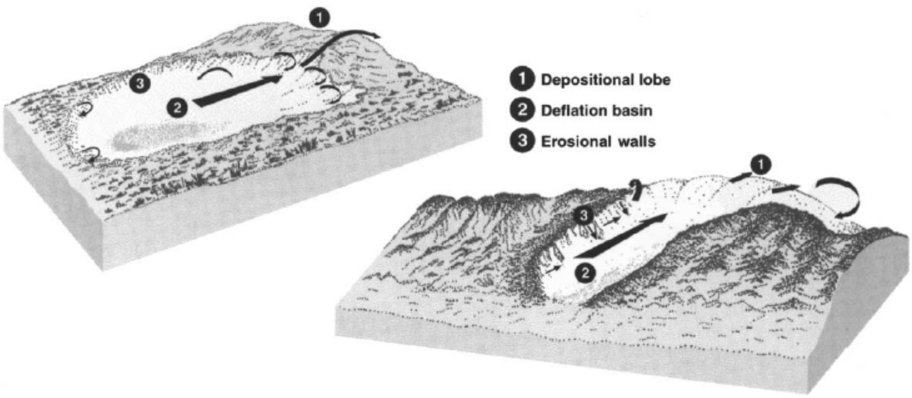
2. Blowouts

2.1. Initiation

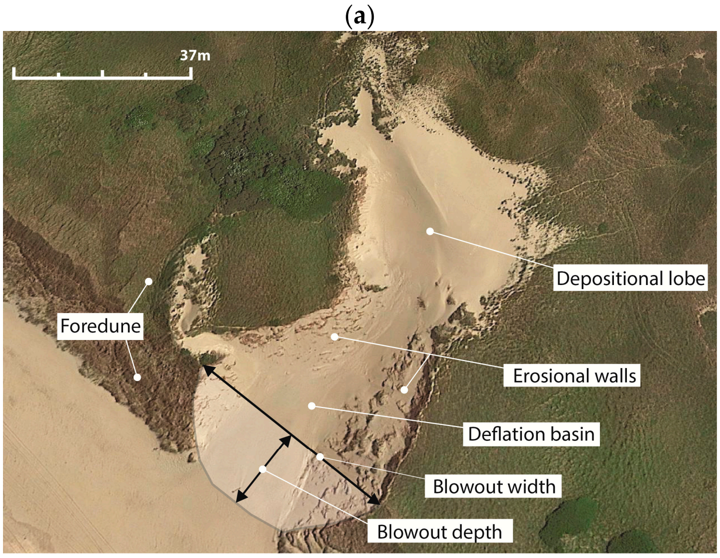
Blowouts are defined as erosional features formed by the wind in sedimentary deposits (e.g., foredunes) and are usually categorized based on their geometry, which is typically either saucer- or trough-shaped (Figure 4a [10]). Their initiation depends on processes disturbing the dune surface, for instance the wind field at the crest of a foredune, which partly depends on the foredune topography and vegetation cover of the foredune slopes. Processes initiating blowouts are wave-, overwash-, topographical acceleration of wind over the foredune crest, or sediment burial [10,46]. The location of blowout initiation is in principle determined by (1) geomorphologic or (2) vegetation induced discontinuities in the foredune and is part of the geomorphological phase described in Figure 3.

Geomorphologic discontinuities in the front of the foredune can form during storms due to alongshore differences in dune erosion [47,48] and can result in discontinuities in the flow field at the dune crest [49]. Previously, blowout formation was observed downwind of embayments in high dune-cliffs at an Australian coast [50] or through storm-related erosion due to wave over-topping or overwash, (e.g., [28]). Blowouts can also form on locations where precipitation-driven overland flow formed gullies in the topsoil. This can particularly occur where the topsoil is hydrophobic due to the presence of organic matter [51].

Vegetation induced discontinuities can be caused by several factors: increased plant mortality due to local sand erosion or excessive accumulation, degeneration of older patches of vegetation due to soil nutrient depletion [52] and due to an increased soil water repellency related with the accumulation of plant-derived hydrophobic compounds [53,54], human induced weakening or removal of vegetation (e.g., trail formation [55–57]), as part of coastal management strategies, (e.g., [15,38,41,58,59]), animal grazing or a decrease in water availability due to a climatic change, (e.g., [13]). This discontinuities caused by vegetation result in a local increase of the bed shear stress and exposure of underlying sand to erosion. This is due to the fact that vegetation generally reduces bed shear stresses and protects the soil from being eroded.



(**a**)



(**b**)

Figure 4. (**a**) Morphological units of saucer (**left**) trough blowouts (**right**). From Hesp [10]. This figure has been adapted from [10], with permission from Elsevier (**b**) Schematic overview of a trough blowout, located in the Zuid-Kennemerland along the Dutch coast, source: Google Earth.

The wind strength is of major importance and thus blowouts are particularly initiated during strong wind seasons [60,61]. During the initial stage, blowouts tend to extend or contract in relation to the dominant wind direction. In principle two possible responses during blowout initiation have been observed [62]. On the one hand, in the absence of a predominant wind direction erosion and deposition has been observed to occur radially in multiple locations and directions resulting in a more complex initial shape. On the other hand, if a dominant wind direction is present, erosion and deposition occur primarily in response to the predominant wind direction and result in enlargement and extension in that direction and a more elongated shape [46,63].

2.2. Development

2.2.1. Morphology

Developed blowouts, trough- or saucer-shaped, can be characterized by the following morphological features: a deflation basin, a depositional lobe, and erosional walls (Figure 4a,b [10]). Blowout topography becomes more pronounced throughout its development when sand is removed from the deflation basin and the walls, transported downwind and deposited on the depositional lobe or further in the back dunes. Its development marks the transition between the geomorphological and bio-geomorphological phase described in Figure 3. Distinct processes drive the development of (a) trough and (b) saucer blowouts.

Trough Blowouts

Sand transport through a trough shaped foredune blowout is governed by the dominating wind direction, which in most cases is onshore [10,55]. Previously observed high erosion rates in the deflation basin of trough blowouts, up to 1 m year^{-1} [64], are explained by steering and acceleration of wind by the blowout topography, often resulting in jet flow. The deflation basin erodes continuously until a base level is reached often related to an immobile layer or the groundwater level [65,66]. The establishment of jet flow within a blowout is dependent on the wind direction. Oblique winds up to 50 degrees from the blowout axis can be redirected [50,67,68] and potentially drive sand transport rates up to two orders of magnitude higher than on the beach [50]. This results in a positive feedback between the topographical evolution and the wind field, stimulating trough blowout erosion. As the deflation basin deepens, the blowout widens through undercutting and slumping of the side-walls. The material from the side-walls is further transported downwind through the blowout to the depositional lobe, (e.g., [41,50]) (Figure 4a,b). The wind speed also accelerates over the side-walls and the stoss (i.e., windward) side of the depositional lobe. Flow separation and deceleration at the crests of the side-walls results in the deposition of sand along the edges of the blowout [65], forming rim dunes and making the blowout topography even more pronounced. Similarly, flow separation and deceleration at the lee-side (i.e., downwind side) of the depositional lobe results in deposition, and a landward-directed migration of the depositional lobe [23,68] (Figure 4).

Saucers Blowouts

Both wind flow acceleration [69] and deceleration [70] have been measured over the deflation basin of saucer blowouts showing that erosion at the deflation basin is probably mainly driven by the availability of sand. Typically, erosion occurs at the deflation basin and the windward located blowout edge (Figure 4a), and subsequently forming the depositional lobe at the downwind edge. Saucer blowouts are thus growing against the prevailing wind direction [71]. The location of erosion and deposition is not fixed when the wind climate is multi-directional (e.g., [15,52]).

The positive feedback between blowout deepening and flow acceleration in a trough and saucer blowout reduces and becomes negative when the blowout reaches a critical size in terms of depth, length (distance from beach to depositional lobe), and mouth width [18,72]. The negative feedback results in a reduced acceleration or even in deceleration of airflow in the blowout mouth, accretion of sand in the deflation basin and eventually in blowout closure.

Regarding the importance of wind magnitude and frequency on blowout evolution, literature shows opposing observations, Jungerius et al. [62] underlines the major importance of low-magnitude high-frequency winds, whereas Abhar et al. [61] links blowout evolution to the occurrence of high-magnitude storms (e.g., hurricanes).

2.2.2. Morphological Impacts on Vegetation

The dominant factor determining plant survival within an existing blowout system is the stability of the sediment bed, (e.g., [72,73]). Related to blowout morphology, two distinct controls on vegetation survival can be identified, (1) the deflation basin where sand erosion dominates plant survival and (2) the depositional lobe where sand accretion dominates (Figure 4b). The susceptibility of plants to sand erosion and accretion depends on the species, development stage and season [74].

Erosion in the Deflation Basin

Focusing on the individual plant, erosion has different effects on different development stages (seeds, seedlings, or developed plants). For seed establishment, episodic erosion can be beneficial, as the burying depth of seeds in the seed bank can become small enough, 2–7 cm [75,76], for seeds to germinate. Seed banks will only be present in relatively fresh deposits, as buried seeds will only remain viable for up to 5 (e.g., *Ammophilia breviligulata*)–20 (e.g., *Cakile edentula*) years [74,77]. Thus, blowout re-colonization from seed banks will primarily take place in relatively fresh deposits. Continuous erosion, however, always leads to seedbank depletion and the death of existing seedlings [73]. Seedlings and developed plants were shown to be unable to survive on eroding surfaces owing to desiccation of their root system [78]. However, McLeod et al. [79] found that partial erosion did not significantly affect seedlings of *Ptelea trifoliata*, suggesting that certain plant species might only respond negatively to erosion after a certain threshold has been surpassed.

Focusing on the morphological configuration, increased erosion of the deflation basin will lead to oversteepening of its walls due to increased sediment-cohesion at the wall rim originating from vegetation-roots. These oversteepend walls of the deflation basin will tend to collapse leading to mass slumping of vegetated blocks into the deflation basin (Figure 4b) [80]. Moreover, Barchyn et al. [66] showed that initially increased erosion in the deflation basin also reduces the proximity to the subjacent ground water table. However after erosion has reached a certain depth this increased proximity to the groundwater table increases soil moisture, reducing further erosion of the deflation basin and facilitating vegetation colonization.

Accretion on the Depositional Lobe

On an individual plant level, seedlings and developed plants were classified by Maun [74] based on their tolerance to sand accretion (Figure 5): (I) burial-intolerant, (II) burial-tolerant, and (III) burial-dependent (Figure 5 [73]). While burial-intolerant (I) species decrease in fitness upon burial, burial-tolerant (II) plant species will be unaffected by sand accumulation up to a certain threshold, above which plant health deteriorates. Plant health is not directly affected by the accumulated sand as long as vital parts for photosynthesis are not buried. But accumulated sand affects soil properties around the roots [78], by increasing soil moisture, decreasing available oxygen concentration, reducing soil porosity due to compaction and decreasing temperature. The decrease in available oxygen was indicated to be the most stressful [73,81] therefore plants must be able to survive episodes of low oxygen before adventitious roots can be grown into fresh deposits. While burial-tolerant species maintain vigor up to a certain deposition rate, the vigor of burial-dependent (III) species increases with burial depth up to a sand accretion threshold (Figure 5 [73]). As a general rule, complete burial of the seedling (i.e., the aboveground plant material completely buried) can be equated with certain death [73,76]. However partial seedling burial of burial-dependent species temporarily increases recovery time, but more importantly will increase plant performance (e.g., plant biomass, carbon uptake) compared to the antecedent condition [75,76].

On a morphological level, the ability of airflow to erode sediment in the deflation basin is related to the blowout shape. Once a critical shape of the blowout cross-section is reached airflow over the deflation basin is no longer accelerated but being reduced (Figure 4b) [82]. It can also be expected that the accretion at the depositional lobe will be reduced as soon as a critical blowout shape is reached, facilitating improved circumstances for vegetation establishment. Moreover, studies showed that vegetation establishment on the depositional lobe over time can lead to a morphological transformation into a parabolic dune with arms pointing upwind colonized by plants [83,84].

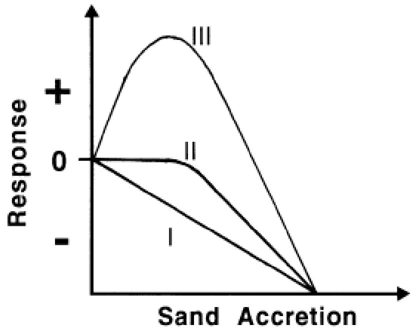


Figure 5. Plant response to sand accretions for three different vegetation types: (I) burial-intolerant, (II) burial-tolerant, and (III) burial dependent. From Maun [74]. This figure has been adapted from [74], with permission from Canadian Science Publishing.

2.3. Closure

Blowout stabilization occurs when the blowout reaches a critical size (length, width, and/or depth), so its morphometry is no more capable of supporting sediment transport along the deflation basin (Figure 4b). This leads to partial surface stabilization by vegetation, visible by contraction of the blowout shape, and can culminate in its closure, (e.g., [61,72]). We define blowout closure, through vegetated incipient foredune development across the throat of the blowout, which prevents further erosion of the deflation basin or erosional walls. Blowout closure marks the transition from the bio-geomorphological to the ecological phase described in Figure 3.

Through the ability of vegetation to engineer blowout topography, it plays an important role in blowout closure [44]. The influence of vegetation on sand mobility results in a hysteresis [66,85–87]. More specifically, wind energy needed for blowout initiation in a vegetation-covered area is significantly higher than the wind energy threshold at which vegetation can re-establish. This was previously also linked to vegetation-altered physical sediment structure, such as adding organic matter by plant roots or trapping relatively fine inorganic sediment particles of the aboveground biomass [88,89]. Thus maintenance or reactivation of blowouts needs disturbances such as overwash, high wind, fire, aridity, biogenic, or other disturbance [15,66,90]. Moreover, studies on inland dune fields showed that dunes are constantly adjusting and are therefore lagging behind a continuously changing climate. Lag times between morphological adaptation of dune fields, being typically out of sync with present climate, also affect closure and reactivation dynamics and are strongly dependent on vegetation characteristics [91].

2.3.1. Spatial Aspect of Vegetation Re-Colonization

Re-colonization of bare blowout areas can originate from germinating seeds, broken of rhizome fragments or clonal lateral rhizome growth [92]. The deflation basin, being the highest disturbed area within a blowout, is most likely to be re-colonized through clonal rhizomes or rhizome fragments of bordering vegetation. This is due to the fact that plants originating from rhizome nodes grow faster and are much less vulnerable than seedlings [73]. Clonal rhizomes usually grow perpendicular to the stem, but can also grow vertical if burial occurs, and new sprouts can form at each node, leading to re-colonization from the blowout edges. Rhizome fragments originate from mass slumping from the rim of the deflation basin walls. The walls of the deflation basin tend to oversteepen due to lateral wall erosion and vegetation stabilization at the top of the wall [80] (Figure 4b). Rhizome fragments reaching the blowout through mass-slumping can form new islands of colonized vegetation within the blowout (i.e., removed from the wall), which can subsequently colonize through lateral rhizome growth. Apart from colonization by rhizomes, colonization by seeds or seedlings is potentially more important at the depositional lobe being less disturbed by wind-sand blasting. Moreover disturbance by accretion potentially favors establishment of burial-tolerant and burial dependent species [24].

Whether colonization of the deflation basin and/or the depositional lobe leads to blowout closure is dependent on factors impeding or facilitating plant growth, which in turn depends on the plant stress response shown in Figure 5. For instance, saucer blowout closure was observed through colonization by *Ammophilia sp.* which started from the depositional lobe, and was aided by high freshwater availability in the deflation basin due to proximity to the groundwater table [24]. Another study observed recolonization by vegetation in the deflation basin, which could potentially lead to formation of embryo dunes through increased sediment capture and closing of the blowout from the beach [93].

These examples illustrate that blowout closure depends on interactions between colonizing plant species and environmental factors. Previously three main factors driving blowout stabilization where identified: (i) availability of sediment outside the blowout, (ii) vegetation type (in relation to plant-sediment-flow interaction, burial tolerance, and colonization rates), and (iii) climate variability (magnitude and duration of precipitation, i.e., moisture, and wind events) (see for example [18,21,82]). As already seen in the above-mentioned examples, the consequences of these factors for blowout development are very specific on the governing abiotic-biotic interactions. For instance, increased soil moisture generally increases plant growth (e.g., burial-intolerant- and burial-tolerant species) [74], but it can also impede plant growth, by reducing sand transport and therefore increasing stress for burial-dependent species [74].

2.3.2. Temporal Aspects of Vegetation Re-Colonization

As described above, the potential of stabilization of an active dune field or blowout by vegetation is dependent on whether the deposition/erosion rates exceed the vegetation deposition/erosion tolerance [40,91]. However, since plant stress tolerance, as shown above, is dependent on the life-stages (i.e., seed, seedling, or mature plant), temporal variation in seedling emergence potentially plays an important role on dune fields and blowout development (activation/stabilization).

More specifically, across temperate systems seedling emergence is either related to an increase in temperature in early spring, or to a coinciding decrease in temperature and increase in rainfall in autumn. Most herbaceous plants in temperate systems, such as *Ammophila breviligulata* or *Cakile edentula*, reach maturity and start seed dispersal in summer and autumn. This leads to seedling emergence in late spring of the next year. Plants like *Aira caryophyllaea* or *Saxifraga tridactylites*, in contrast, reach maturity and start seed dispersal in spring, leading to seedling emergence in autumn [73]. Thus, not only magnitude and frequency but also timing of disturbances, such as storms, will constitute a major constraint on the survival of blowout colonizing species [94]. Moreover, the combination of factors such as strong winds, low precipitation, short growing season, high physical disturbance (e.g., tourism, grazing) and nutrient deficiency were previously identified to facilitate active mobile (un-vegetated) dunes and potentially blowouts, whereas the opposite of above mentioned factors was linked to stable vegetated dune- and blowout systems [13,95]. As a possible explanation for this phenomenon, the windows of opportunities concept was proposed. It states that seeds need a disturbance free period to build up their stress resilience which consequently drastically increases their survival [96]. Consequently, climate conditions and their potential to create disturbance free recruitment periods (i.e., windows of opportunities) can potentially also shape the morphologic development of blowouts.

2.3.3. Ecological Aspects of Vegetation Re-Colonization

Plants able to tolerate sediment burial not only differ in their morphology, as explained above (Figure 4), they also differ in metabolic pathways which has important ramification on their competitive strength. For instance, the burial-dependent C3-plant *Ammophilia brevingulata* has a lower efficient nitrogen- and water use efficiency than the burial tolerant C4-plant *Uniola paniculata*. This results in a competitive advantage for the latter during co-occurrence. As shown at the North American Atlantic coast, a climate-induced change in habitat range can result in a transition of the dominating species depending on metabolic efficiency [97]. Moreover, it was shown that direct interactions between burial-tolerant plants might lead to reduced functional traits, for instance leaf elongation [98]. Thus in the context of blowout closure, it is expected that during the transition between the bio-geomorphological and ecological phase the importance of physical interactions will reduce, while the importance of ecological interactions (e.g., competition) will increase, for selecting dominant plant species (Figures 3 and 6).

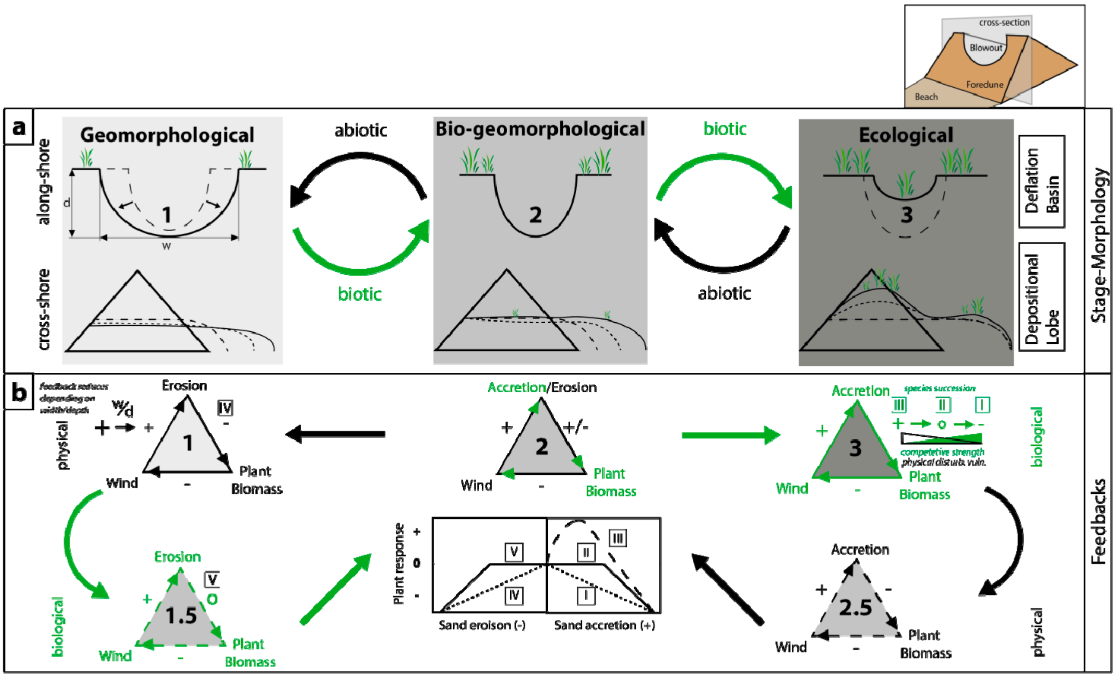


Figure 6. Conceptual model for blowout development: (**a**) shows relation between blowout development stages (1: geomorphological, 2: bio-geomorphological, and 3: ecological) and blowout morphology (deflation basin, along-shore: top and the depositional lobe, cross-shore: bottom); dashed lines indicated development over time. (**b**) Shows the governing feedbacks loops present at the respective development stages: 1 blowout development is governed by erosion at the walls of the deflation basin, suppressing establishment of erosion-intolerant plants (IV), 1.5 as erosion proceeds morphological funneling is reduced which also reduced the stress on plants which now start to colonize favoring erosion-tolerant species (V), 2 as soon as vegetation establishment reaches a sufficient biomass to further reduce wind speed and entrap sediment the bio-geomorphological phase is reached. This stage is governed by ecosystem engineering efficiency and stress tolerance of the establishing plant species, (I) burial-intolerant, (II) burial-tolerant, or (III) burial dependent. Vegetation establishes in the deflation basin and the depositional lobe reducing blowout depth and culminating in the ecological stage 3. At this stage vegetation induced sedimentation in the deflation basin closes of the sediment transport to the depositional lobe. This process is accompanied by succession in plant species selecting for plants high in competitive strength, which generally are more susceptible to physical disturbances. Physical disturbances can lead to reversal to stage 2.5 and further to 1.5 and 1 reopening the blowout.

3. Discussion

3.1. A New Conceptual Model for Dynamics of Existing Blowouts

Several studies conceptualize environmental factors driving dune formation and dynamics, (e.g., [9,10,99,100]). Here, we combine current knowledge on foredune blowout development by focusing on the feedbacks between abiotic and biotic processes based on the above-described concept of successional stages (Figure 3). Although previous studies, (e.g., [42]), used and named stages successional, i.e., consecutive, we apply it in a more general way (further referred to as development stages), where stages can shift back and forth due to external and internal factors. The conceptual model including erosive and accretive trends follows the approach of Hesp [10] for dune formation and consists of two main parts. The "stage-morphology" part (Figure 6a), showing the impact of development stages on morphological units of the blowout (deflation basin: cross-shore and depositional lobe: long-shore). (Color of the arrows between development stages indicates whether biological (biotic) or physical (abiotic) factors need to be dominant to provoke a stage change). And the "feedbacks" part (Figure 6b), showing the governing feedbacks loops at a given development stage indicated by triangles filled with integer numbers from 1 to 3, as well as transitional stages indicated by triangles filled with real numbers (1.5 and 2.5).

A newly incised blowout starts its development at the geomorphologic stage (1) where blowout development is mainly driven by erosional sediment transport processes increasing the depth (d) and the width (w) of the blowout (Figure 6a, geomorphological, along-shore, dashed and closed line) (Figure 4) [18,82]. At the initial stage, an increase in wind speed leads to an increase in blowout erosion (d and w) through morphological funneling suppressing the establishment of erosion intolerant plant species (IV), which in turn facilitates wind speed (Figure 6b), (e.g., [50,82]). Increased funneling and wind speed leads to the extension of the depositional lobe (Figure 6a, geomorphological, cross-shore, dashed to close line). As erosion proceeds, the w/d ratio is reducing the amount of morphological funneling and subsequently reducing the negative feedback on plant biomass. This leads to the transitional stage (1.5) at which erosion caused by morphological funneling of wind becomes low enough for vegetation to establish, favoring erosion-tolerant species (V in Figure 6b), (e.g., [40,66,73]). As soon as vegetation establishment reached a sufficient level to reduce wind and entrap sediment, a shift to the bio-geomorphological stage (2) takes place.

At the bio-geomorphological stage vegetation is able to colonize the walls of the deflation basin, constraining the width of the blowout, and starts to establish in the deflation basin and the depositional lobe engineering its environment (Figure 6a). At this stage, a reversal to the geomorphological stage can take place through major disturbances (e.g., high wind during storm, overwash) removing established vegetation. Morphological development is governed by the interaction between biological and physical processes, where erosion suppresses plant establishment while accretion facilitates it (Figure 6a, bio-geomorphological, cross-shore, dashed to closed line). Blowout development is then heavily dependent on the stress-tolerance of the colonizing species, wind magnitude, and sediment transport. As previously proposed by Maun [73], accretion tolerance ranges from (I) burial-intolerant, (II) burial-tolerant, and (III) burial-dependent (for details see Figure 5). However, since airflow and sediment transport in the deflation basin is dependent on sediment availability and morphological flow acceleration, erosional tolerance will also be crucial. Based on Maun [78] and McLeod et al. [79], we therefore suggest adding the response to sediment erosion, (IV) erosion-intolerant, and (V) erosion-tolerant. Erosion-tolerant (V) species only reduce their fitness after a certain erosion threshold is surpassed, whereas erosion-intolerant species are immediately affected by the occurrence of erosion (IV) (Figure 6b). In the bio-geomorphological stage, vegetation can establish on the depositional lobe, which can lead to transforming its morphological configuration into a parabolic dune [83]. This transformation will reduce deposition along lateral edges of the parabolic dune, facilitating a competition driven transition to burial-tolerant (II) and burial-intolerant (I) plants. If more and more vegetation is able to establish in the blowout, shear stresses are further reduced at the sand surface and thus higher wind stresses are needed to induce erosion and vegetation removal. Continuous sedimentation will reduce blowout depth and width resulting in a transition to the ecological stage (3) [66,85,87].

At the ecological stage, the established vegetation induces sedimentation in the deflation basin and thereby reduces sediment transport to the depositional lobe (Figure 6a, Ecological cross-shore and along-shore dashed and closed line). This is caused by the positive feedback between sediment accretion and plant biomass, which consequently reduces wind speed (Figure 6b). The positive feedback between accretion and plant biomass does not only influence the morphology, it also influences species composition within the blowout. At the start of vegetation colonization only burial-dependent (III) plants are able to colonize due to high levels of accretion, but with reducing accretion rates and wind speeds an ecological succession from burial-dependent (III) to burial-tolerant (II) to burial-intolerant (I) takes place. This is caused by the inverse relation of stress tolerance to competitive strength with the most tolerant (burial-dependent (III)) plant species possessing the least competitive strength and vice versa (Figure 6b). The vegetation succession and simultaneous soil development results in higher soil stability and reduces the susceptibility of sand to erosion. However, increased competitive strength of successional species is accompanied by an increased vulnerability to physical disturbances (physical disturb. vuln.), (e.g., [101,102]) (Figure 6b). In this stage, big storms generating high input of aeolian sand can kill the established burial-tolerant (II) and burial-intolerant (I) vegetation, facilitating the onset of erosion and reversing the blowout back into the bio-geomorphological stage. Thus, occurrence of a disturbance can reverse the positive feedback between accretion and biomass and move the system to transitional stage (2.5) (Figure 6b). At the transitional stage (2.5), the established vegetation community is not adapted (lagging behind) to the current physical conditions. This results in a negative feedback between accretion and plant biomass, further inducing a transition back into the bio-geomorphological stage (2). In the bio-geomorphologic stage, it again depends on the relative importance of physical or biological processes whether a transition toward the geomorphological (1) or ecological (3) stage occurs.

3.2. Predictive Model Framework

Previous attempts to model vegetation-dune interactions shaping foredune morphology, which involve the same processes as shaping blowout development, were based on two main model approaches: Cellular automata (CA) and process-based models.

The first realized Cellular automata approach (further referred to as CA) describes dune formation based on simple rules instead of complex aerodynamics and sand transport processes [101]. Sand is represented as slabs which can be picked up at random, transported in the downwind direction and deposited depending on a probability based on the local abundance of sand, or in the lee of dunes. Sand slabs have a higher deposition probability at a location where at least one slab is already present, as the likelihood for the continuation of saltation on a rocky surface is higher than on a sandy surface. This model was well able to reproduce qualitatively the formation of barchan, crescentic, linear, and star dune fields [103–105] by varying the sand supply and wind directions. Baas [106] added the impact of vegetation on the probability of sand slabs being picked up and deposited. Both a deposition-dependent type of vegetation and a type not tolerant to deposition were included, for each type the growth-rate and the probability of establishment depends on the degree of local erosion and deposition. This model proved a useful tool to study the effect of the presence of vegetation on dune formation and fixation, and subsequently many studies were conducted based on this approach, (e.g., [91,107–109]). Keijsers et al. [107] extended the model of Baas [104] to include the sand supply from the subaqueous part of the beach profile in order to study long-term dune response to climatic changes and sea-level rise.

Process-based models including the effect of the topography and vegetation on wind dynamics were simultaneously developed. For instance, van Dijk et al. [110] and van Boxel et al. [111] modeled the airflow and sand transport across transverse dunes with a 2-dimensional (x,z) approach, including the effect of vegetation on wind and sand dynamics [110,111]. This model showed reasonable results in reproducing morphodynamics during an experiment which was designed to study the effects of different densities of bundles of reed stems planted on the front of the foredune [112]. Later, barchan dune development was reproduced with models including a detailed three-dimensional representation of the wind field over the dune form (see [113,114] for an overview). These models include the effect of topography on the wind field, with flow acceleration at the windward slope and flow deceleration in the lee of a dune. The sand flux is estimated from the wind field and increases downwind until it saturates and reaches the maximum sand flux at a characteristic distance, both the maximum sand flux and the characteristic distance depend on wind flow and sand grain properties. Subsequently, process-based approaches using computational fluid dynamics to simulate airflow over blowouts were used, showing the importance of local wind dynamics in comparison to conditions of the incoming wind-field, (e.g., [115,116]). To simulate morphodynamic development, morphological updating was linked with dune airflow, modeled with the RANS-equations, and sediment transport, modeled based on empirical relationships, (e.g., [117]) for aeolian sediment transport. Vegetation was incorporated as roughness elements that absorb part of the momentum transferred to the soil by wind, thus reducing local bed shear stress, (e.g., [7,83]). These models included simplified vegetation properties such as growth, sensitivity to erosion and accretion, maximum plant height, and plant establishment, as a function of distance to the shoreline. These are able to reproduce the different dune dynamics on a reflective and dissipative beach, showing vegetation mediated differences in the maximal dune height and the development of blowouts [7].

Given the variety of previous used model approaches, a potential method to incorporate biotic and abiotic processes into a predictive model framework for foredune blowouts would be a combination of a process-based approach and a CA-approach to incorporate feedbacks between morphology, stages and transitions described in the conceptual model (Figure 6). The processes-based part covers morphodynamic modeling, combining for instance RANS-equations for wind with empirical equations for sand transport, in combination with morphological updating. This would enable to simulate the impact of landforms, such as blowouts, on the wind field and sediment transport including morphological feedbacks at different blowout stages. Including the complex local wind field to simulate blowout development is essential, as it differs substantially from the wind climate for a larger area [50]. The presence of vegetation reduces the local wind speed and can be incorporated as increased shear stress in the physical model [83]. Its dynamic component, such as growth and stress tolerance, can be based on rules using a CA-approach [83]. This mixed approach allows incorporating different species with various stress tolerance, growth strategies, and including inter-species competition. However considering other previous approaches on modelling bio-morphodynamics found in systems such as tidal wetlands, vegetated floodplains, deltas, or peatlands [118–121] could also prove valuable. Independent of the chosen approach calibration of essential species dependent physical and biological interactions such as flow reduction and sediment trapping or plant growth rate and plant stress tolerance need to calibrated and validated through experiments and/or measurements.

3.3. General Discussion

The proposed conceptual model allows focusing on processes (i.e., accretion, erosion, wind, plant growth), which are part of feedback loops facilitating or hampering the transition between different developmental stages of foredune blowouts. As a consequence, it allows to explain cyclic (e.g., 1-2-3-2-1-2..) as well as non-cyclic (1-2-3) behavior described by Gares et al. [18]. It also allows incorporating the impact of colonizers [90] and dynamics of the sedimentary systems on blowout development as described by Hesp [10]. Thus the new framework describing blowout development using multiple paths governed by biotic-abiotic processes open novel opportunities to look at blowout development.

Nevertheless, one needs to be aware that environmental factors as well as ecological factors exert a major control on the emergence and magnitude of the described feedback loops. Environmental factors, such as magnitude, direction and frequency of winds; magnitude and frequency of waves, tides and precipitation controlling soil moisture and aeolian sediment transport; relative elevation above mean sea level controlling storm surge height and occurrence of overwashes; prograding or transgressing beach state controlling sediment supply, (e.g., [10]). Ecological factors, such as species dependent establishment probabilities, seasonal emergence times; vertical and horizontal growth rates in relations to nutrients and water; sensitivity to disturbances (frequency and duration) such as sediment burial or erosion, (e.g., [72]). These factors need to be included in our conceptual model through adapting the strength of described feedback loops or as boundary conditions.

Not only the magnitude of environmental and ecological factors influences the above described feedback loops and successional stages but also the frequency and time scales of their occurrence. For instance frequent strong winds, wave erosion or overwash, together with low rainfall and short vegetation growing season will facilitate dynamic blowout development transitioning between stage 1 and 2. On the other hand low wind speeds, infrequent wave erosion and overwash, together with high rainfall and long vegetation growing season will facilitate a more static blowout development transitioning between stage 2 and 3 and eventually leading the blowout closure (stage 3) [13]. Moreover the time-scales of successional stages are can also vary in response to environmental factors, for instance increased disturbance can extend the time scale of geomorphological (1) and bio-geomorphological (2) successional stages but reduce the time scale of the ecological stage (3).

The conceptual model can be an important tool in predicting blowout development under different environmental and ecological conditions. A first step towards application could be revisiting existing field datasets (e.g., [9,13,14,22,122,123]) and evaluating measured interactions between blowout form and vegetation colonization within the lens of the new conceptual model. Subsequently we need to include these concepts into a predictive model framework able to represent the aforementioned stages and transitions. However this predictive model would necessitate calibration and validation with additional field data and observations.

Calibration and Validation

Validation of our conceptual model should start by revisiting existing field observations (e.g., [9,13,14,22,122,123]). However, to investigate time-scales and occurrences of stage transitions across various foredune systems around the globe additional field observations on blowout dynamics become crucial. More specifically, detailed remote sensing analysis will be necessary to study growth and stress tolerance of different plant species and their preferred spatial organization within the blowout and in relation with other species. For this application, we advocate to utilize state of the art remote sensing techniques, such as Google Earth Engine, able to resolve vegetation growth over time and space at a high resolution. In addition, detailed field studies will be necessary to ground-truth remote sensing analysis, quantify blowout volume changes in relation to plant types, and test the applicability of previous concepts such as windows of opportunities [96].

4. Conclusions

Blowout development is inextricably linked to vegetation-morphology feedbacks which are shaped by ecological and physical characteristics. Cyclic and non-cyclic behavior in blowout development can be linked the transitions between blowout stages governed by the dominance of geomorphological, bio-geomorphological or ecological processes. Our proposed conceptual model provides a framework able to link transitions in blowout morphology and –development stages to ecological and physical processes. Long-term (decades) observations of blowout development are needed to better understand relevant processes and to develop and validate practical models.

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