RESEARCH PROGRESS ON THE DEVELOPMENT, EVOLUTION, AND INFLUENCING FACTORS OF BLOWOUTS

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Abstract. Blowouts, as a type of negative landform in sandy areas, have long been a central focus in aeolian geomorphology. They serve as key indicators of sand fixation and activation, and reflect how near-surface wind-sand processes respond to environmental changes and human activities. With a growing number of research on the responses of aeolian processes to global change, blowout dynamics in coastal, lacustrine, and semi-arid grassland environments have drawn significant attention. This paper summarizes and reviews studies on the morphological types, developmental patterns, evolutionary processes, dynamic mechanisms, and influencing factors of blowouts. Current research focuses mainly on the development of individual blowouts, often neglecting the group morphology and spatial patterns of blowouts within the same region. Although surface airflow is widely considered the main force shaping blowout morphology—through wind erosion and abrasion—coastal blowouts are also affected by temporary water flow, weathering, and salinization. Thus, the genetic mechanisms of blowouts require further in-depth investigation. Also, studies on influencing factors have largely been qualitative, therefore, future work should emphasize quantitative assessments to support precise desertification evaluation and improved sand-control strategies in blowout-prone regions.
Keywords: *blowouts, development patterns, evolutionary processes, dynamic mechanisms, wind-blown sand landforms*

Introduction

In aeolian geomorphology, blowouts typically refer to depressions, hollows, and channels formed on sandy coasts, lake shores, vegetated fixed sand dunes, or flat grasslands due to wind erosion. Specifically, the soil layer of wind-eroded bare ground is destroyed, exposing the surface layer of loose sand. Under the influence of wind, the soil layer further disintegrates, resulting in sandy landforms (Wu et al., 2020). Melton and Bagnold proposed the concepts of parabolic dunes and blowouts, respectively, stating that dunes are downward depressions of sand surfaces caused by wind erosion, and blowouts are wind-eroded breaches of successive deposits of transverse dunes under the action of wind (Hesp, 2013; Shumack, 2017). The developmental evolutionary process of blowouts disrupts the original material cycle and energy balance patterns, establishing a new landscape erosion pattern (Yan, 2016). In arid and semi-arid regions of inland deserts, blowouts not only directly reflect the activation of fixed sandy areas but also indicate regional ecological changes and the impact of human activities (Liu et al., 2021; Wan et al., 2018). Blowouts can also form on sandy coasts, lake shores, and riverbanks in humid regions, creating coastal blowouts. Due to differences in geographical location and environmental conditions, blowouts exhibit significant regional variations in

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morphological types and characteristics (Dong et al., 2008). The evolutionary processes and influencing factors of inland blowouts and coastal blowouts also exhibit significant differences (Yuan et al., 2022; Cui et al., 2022).

Scholars' research on wind-blown sand landforms has primarily focused on the morphology and movement of sand dunes (Dong et al., 2014), formation conditions and processes (Yang et al., 2014), airflow fields and erosion-deposition characteristics (Marrero-Rodríguez et al., 2022), grain size and structural features (Han et al., 2012), and other aspects. However, research on typical wind-eroded landforms, specifically blowouts, remains relatively limited. Studies on blowouts began in the 1940s (Melton, 1940), initially focusing on the basic morphology and development patterns of wind erosion. Significant progress was made in morphological classification, distribution patterns, sedimentary characteristics, and evolutionary processes (Cai et al., 1983; Lancaster, 1986; Wu et al., 1987). However, due to the relative backwardness of research methods and technologies, studies on the dynamic processes of blowouts remained insufficient. By the 1990s, with the widespread use of measurement instruments such as anemometers, sand collectors, and three-dimensional terrain survey instruments, blowouts entered a new phase focused on morphological-dynamic studies. During this period, scholars from China and other countries focused on exploring the interrelationship between airflow and the morphology of blowouts, conducting extensive fieldwork on airflow field distribution, erosion-deposition rates, and terrain changes (Pye, 1982), providing important references for subsequent comprehensive studies on blowouts. In the 21st century, with the advancement of modern measurement and remote sensing technologies, high-spatial-temporal-resolution morphological monitoring and wind-sand dynamics observation became feasible, propelling wind erosion pit research into a period of rapid development (Dong et al., 2019). During this period, scholars primarily focused on airflow (Hesp, 1996; Fraser, 1998; Pluis et al., 1993), erosion-deposition rates (Hails, 1980), and evolutionary processes of coastal blowouts in the United States (Gares et al., 1995; Jungerius, 1984), the Netherlands, Canada, and other regions, Chinese scholars have conducted relatively systematic research on the formation causes (Zhang et al., 2006), influencing factors (Zhang et al., 2007), development patterns (Yan et al., 2009), evolutionary processes (Zhang et al., 2007), surface sediments (Wang et al., 2008), surface airflow characteristics (Wang et al., 2009, 2007), and airflow-morphology interactions (Li et al., 2012) of blowouts in the inland sandy grasslands of Hulunbuir, China. This paper reviews the research progress and shortcomings in the morphological characteristics, types, evolutionary processes, dynamic mechanisms, and influencing factors of blowouts, aiming to gain a deeper understanding of the morphological change processes, developmental evolutionary patterns, and driving mechanisms of blowouts, and to provide foundational data for advancing the development of the discipline of wind and sand landforms.

Types and characteristics of blowouts

Types of blowouts

The shape of blowouts is influenced by climate change and the disturbance of blowouts by airflow. Additionally, under the influence of regional environmental conditions, initial triggering factors, and the interactions between various variables, blowouts exhibit diverse morphological characteristics (Guo et al., 2024). Scholars have classified blowouts based on their geometric shapes and morphological evolution (Cooper, 1958).

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Hunsandak Desert classifies blowouts into five types based on scale and surface morphology: dish-shaped, trapezoidal, valley-shaped, cup-shaped, and slope-shaped (Yan, 2016). Other scholars use the morphology of the eroded pit body and the accumulated sand body behind the pit as classification criteria, dividing blowouts into elliptical and fan-shaped types (Hesp et al., 2011). Ritchie defined five types of blowouts: cigar-shaped, V-shaped, spoon-shaped depressions, and pot-shaped and trough-shaped blowouts (Ritchie, 1972). Cooper et al. (2021) classified blowouts into two major categories: trough-shaped and dish-shaped. Hesp et al. (2011) and Smyth et al. (2013) classified blowouts into three major categories: bowl-shaped, dish-shaped, and trough-shaped. Field surveys have found that shallow dish-shaped pits generally form on flat grasslands or broad sand dune surfaces, while trough-shaped pits form on steep windward slopes. Wang et al. classified the surface morphology of blowouts on Hulunbuir sand dunes into three types: sand patches, dish-shaped pits, and trough-shaped pits (Wang et al., 2008). Zhang et al. (2006) further classified the surface morphology of blowouts on Hulunbuir sand dunes into eight geometric shapes: oval, bead-like, strip-like or trough-like, kidney-shaped, flower-shaped, gourd-shaped, palm-shaped, and square. Coastal sandy land blowouts were initially classified into two categories: dish-shaped and trough-shaped (Hesp et al., 2002). Recently, they have been further classified into three categories: dish-shaped, bowl-shaped, and trough-shaped blowouts (Smyth et al., 2013; Hesp et al., 2012).

Morphological characteristics of blowouts

During their development, blowouts exhibit varying degrees of change in their morphological parameters. Their morphological characteristics primarily include: an accumulation zone composed of a gently sloping sand slope and a semi-circular-edged sedimentary fan at the rear end of the downwind side of the erosion pit (Wu et al., 2020); a broad erosion basin floor with the strongest airflow activity (Hesp, 2013); steep erosion walls near the erosion mouth (Shumack et al., 2017; Du et al., 2012). Smith et al. (2017) found that blowouts developing on broad foredune ridges are typically shallow dish-shaped, while those developing on steep windward slopes are typically trough-shaped. Despite differences in the geographical location and type of Blowouts, there is a certain relationship between their morphological parameters, with the length of the erosion basin and the length of the sedimentation zone showing a strong correlation, with a correlation coefficient of 0.81. Hesp et al. (1996) found that the width of the erosion pit in the middle of the blowout is also correlated with the length of the sand accumulation area. Overall, as the width of the erosion pit increases, the length of the sand accumulation area also increases, with a ratio of approximately 1:2. Among these, the ratio for trough-shaped blowouts is 1:4, and for dish-shaped blowouts, it is 1:2 to 1:3. Zhang et al. (2018) conducted a more in-depth study of coastal blowouts, concluding that dish-shaped blowouts are commonly developed at the base of open coastal sand dunes, typically shallow and semi-circular in shape (length-to-width ratio of 1.67 to 2.27), with short and steep erosion slopes and steep slopes (length-to-depth ratio of 7.69 to 16.95, width-to-depth ratio of 4.62 to 7.45). The sand accumulation zone is generally flat and round (length-to-width ratio of 2.00 to 3.00) and can evolve into cup-shaped or bowl-shaped pits under further wind erosion. Bowl-shaped blowouts are typically deeper (length-to-depth ratio of 3.67–5.00, width-to-depth ratio of 3.83–5.00), with a semi-circular to circular shape (length-to-width ratio of 0.96–1.00), and generally have only a single sediment accumulation zone. However, under bidirectional or multidirectional wind

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conditions, two or more sediment accumulation zones may exist (Bernard et al., 1998). Trough-shaped blowouts often have a narrow opening referred to as the "throat" of the pit, with an overall elongated slot shape [length-to-width ratio of 2.00–4.00], with narrow, steep erosion walls on both sides of the relatively deep erosion basin (length-to-depth ratio of 5.00–10.00, width-to-depth ratio of 2.50–3.10) (Hesp et al., 2001; Smyth et al., 2019; Smith, 1960; Gares, 1992), and the sand accumulation zone (length-to-width ratio of 4) located at the downwind end (Smith, 1960; Gares, 1992). In addition, trough-shaped blowouts have deeper erosion basin bottoms and steeper erosion side walls; dish-shaped blowouts are typically semi-circular or dish-shaped shallow basins with flat bottoms, shallow depths, short and steep erosion inner walls, flat sedimentation zones, and short and steep concave slopes on the windward side, while the leeward slope is long and gentle (Luo et al., 2019). Further erosion evolves into cup-shaped or bowl-shaped pits; bowl-shaped blowouts evolve from dish-shaped blowouts, being deeper than the latter, with a circular or elliptical shape, typically having only one sediment accumulation zone, but developing two or more such zones when the prevailing wind direction is not unique. Typical trough-shaped blowouts are elongated, with the bottom of the erosion pit being deeper and narrower than that of dish-shaped blowouts, longer and steeper erosion sidewalls, longer and larger sediment accumulation zones, and steeper slopes on the slip surfaces (Zhang et al., 2019, 2024). The morphological characteristics, typical environments, and key formative factors of the main blowout types are summarized in *Table 1* for a clearer comparison.

Table 1. *Summary of main blowout types, their morphological characteristics, and key formative environmental factors*

Type	Representative photograph	Morphological characteristics	Typical environment	Key formative factors
Saucer		Shallow, semi-circular or dish-shaped basin; flat bottom; short, steep erosion walls. Length-to-width ratio: ~1.67-2.27; Length-to-depth ratio: ~7.69-16.95	Flat grasslands; broad dune surfaces; base of foredune ridges	(1) Surface airflow as the dominant force (2) Localized vegetation destruction as the initial trigger (3) Relatively uniform wind regime (4) Weak surface resistance
Bowl		Deeper than saucer type; circular or elliptical shape; often a single depositional lobe. Length-to-width ratio: ~0.96-1.00; Length-to-depth ratio: ~3.67-5.00	Evolved from saucer blowouts; various sandy environments	(1) Continued wind erosion and deepening (2) Bi- or multi-directional winds may form multiple depositional lobes (3) Vegetation stabilization of sidewalls limits lateral expansion and promotes vertical erosion
Trough		Elongated, trough-like shape with a "throat"; deep and narrow erosion basin; long, steep sidewalls. Length-to-width ratio: ~2.00-4.00; Length-to-depth ratio: ~5.00-10.00	Steep windward slopes; areas with strong, unidirectional prevailing winds	(1) Dominance of strong unidirectional winds (2) Airflow acceleration through constriction (Venturi effect) (3) Significant sidewall erosion and collapse (4) High potential for downwind extension
Composite		Irregular shape formed by the merging and coalescence of two or more blowouts; large scale and complex morphology	Areas of intense aeolian activity; where multiple blowouts develop in close proximity	(1) Lateral expansion and linkage of adjacent blowouts (2) Intense and potentially variable wind regimes (3) Widespread vegetation degradation (4) Human activities (e.g., overgrazing) accelerate the merging process

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The development pattern and evolution process of blowouts

Development patterns of blowouts

Currently, the scientific hypothesis regarding the development patterns of Blowouts is that their evolution is controlled by sediment transport processes. When sediment-laden airflow enters a blowout, the terrain within the pit alters the vertical structure and horizontal pattern of the airflow, creating a unique airflow field. The erosive action of the airflow above the side walls causes them to become steeper and leads to collapse, leading to lateral expansion of the blowout. Subsequently, the airflow eroding the pit bottom transports the debris downstream while deepening the pit. Differences in erosion and deposition rates at different locations can lead to changes in the morphology and size of blowouts (*Fig. 1*). Gares suggests that differences in shape, size, and vegetation patterns of blowouts may be due to different developmental stages, and summarizes the developmental patterns of blowouts on coastal foredunes into four stages: (1) Initial erosion. Due to a decrease in vegetation cover along the foredune ridgeline, initial breaches form; (2) Early development. Widening and deepening of the breach, with the formation of initial blowouts; (3) Maturity. blowouts continue to widen, producing nearly vertical asymmetric slopes; (4) Completion of the evolutionary sequence. The typical erosional slopes on the sides of blowouts disappear, and continued accumulation within the pits promotes the cessation of their development. In this stage, the gently sloping sides do not accumulate sediments, vegetation and prevailing onshore winds prevent sand material from being transported seaward (Wang et al., 2009). Luo divides blowouts from embryonic to mature stages into four phases: in the embryonic stage, sand blocks are small; in the initial stage, blowouts begin to deepen and expand, forming deeper types such as dish-shaped and bowl-shaped pits. In the juvenile stage, blowouts further deepen and rapidly expand both laterally and longitudinally. In the mature stage, some adjacent medium-sized blowouts may continue to merge, ultimately forming a blowout with stable external characteristics (Shi et al., 1986). Yan classified blowouts developing on the sandy grasslands of Hulunbuir into four developmental stages: bare sand patches, active development, fixation, and reactivation (Yan et al., 2009). Zhang, however, summarizes the five stages of blowouts on sandy grasslands as bare wind erosion areas, soil layer breaches, actively developing blowouts, fixed blowouts, and the disappearance of blowouts (Zhang et al., 2007).

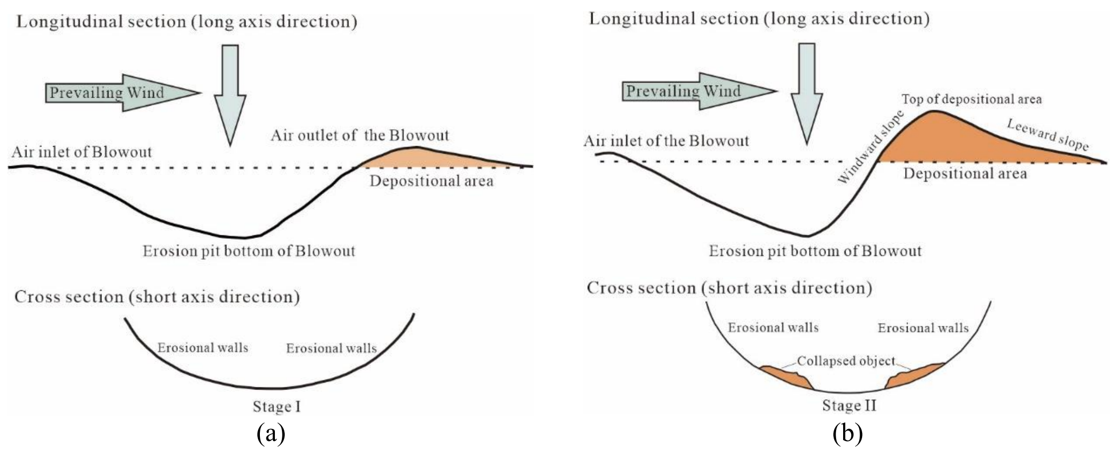

Figure 1. *Schematic diagram of the development pattern of blowouts: (a) developmental stage; (b) mature stage*

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The evolution process of blowouts

Blowouts are not only indicators of the fragmentation of sandy grasslands and the activation of fixed sand dunes, but also serve as a critical threshold for the transformation of sandy grasslands into sandy soils. Therefore, the evolution of blowouts has attracted widespread attention from scholars both domestically and internationally (Smyth et al., 2012). After the destruction of surface vegetation, sandy soil becomes exposed and susceptible to wind erosion, leading to the formation of wind-eroded bare ground. Continued wind erosion causes sand particles in loose areas to be continuously carried away by the wind, the surrounding soil layers disintegrate and collapse, gradually forming blowouts. The sand particles transported by wind erosion gradually accumulate on the rear side of the blowouts, forming sand deposits. As the blowouts deepen, the walls of the pits retreat, causing collapses, and the collapsed material moves toward the bottom of the pits and accumulates, causing the blowouts to become shallower. At the same time, the sand deposits increase in height, enhancing its resistance to prevailing winds, resulting in decreasing wind speeds at the crest and fewer sand particles accumulating there, thus preventing further heightening of the sand accumulation body. Therefore, when external disturbances (human activities) diminish or cease, the development rate of later-stage blowouts declines and cannot continue to expand (*Fig. 2*).

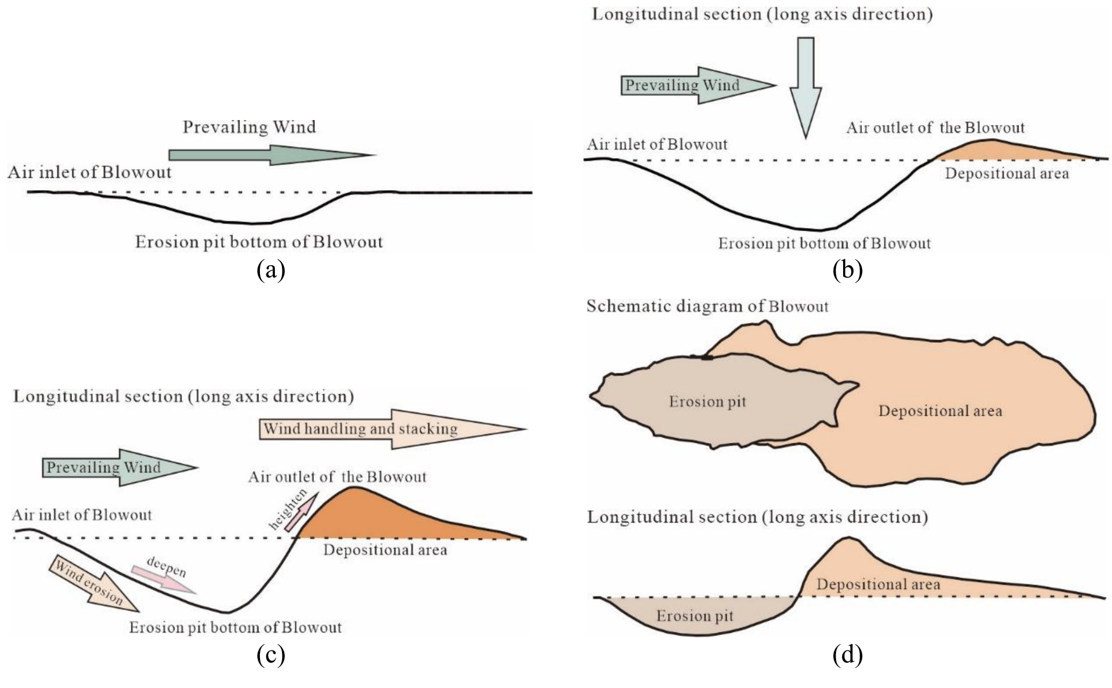

Figure 2. *Schematic diagram of the evolution process of blowouts: (a) early stage; (b) developmental stage; (c) mature stage; (d) schematic diagram of blowouts*

Zhang conducted research on coastal sandy land blowouts, and the results indicated that the evolution of blowouts follows four stages: the formation of sand patches or gaps → dish-shaped blowouts → semi-bowl-shaped blowouts → the expansion and disappearance of trough-shaped blowouts. Among these, the development of dish-shaped blowouts into semi-bowl-shaped blowouts is primarily controlled by the topography and vegetation behind and around the pits, leading to continuous downward erosion of the pit morphology. Under the influence of typhoons and strong winds, sediments are removed

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from the pits, ultimately resulting in the formation of mature semi-bowl-shaped blowouts. When semi-bowl-shaped blowouts erode to a certain depth, the erosion basin bottom is influenced by coarse sand, old red sand, causing the depth to cease developing. Under the influence of prevailing winds, it gradually transitions from a semi-bowl-shaped blowout to a trough-shaped blowout (Zhang et al., 2024). Wang et al. (2009) found through field surveys that dish-shaped blowouts can further develop into trough-shaped blowouts, and multiple small blowouts can form a composite blowout. However, blowouts do not expand indefinitely. Once their area reaches a certain extent, they enter a fixed or stable stage due to resistance from the underlying soil layer and surrounding vegetation, as well as local airflow within the pit. Due to the geographical location of the Dutch coast, the length of blowouts does not exceed 30 m, indicating that blowouts automatically stabilize once they reach a certain extent.

Evolutionary dynamics of blowouts

Airflow characteristics of blowouts

The extent and complexity of airflow changes are controlled by the morphology of blowouts. Observations of blowouts on sand dunes in the Korqin Sandy Land by Shi revealed that changes in wind flow fields vary at different stages. As airflow enters the pit, it first forms a horizontal-axis vortex. As the blowout expands, a vertical-axis vortex forms. During the stage where wind-eroded cavities appear, the wind accelerates at the slope crest due to terrain features, while wind strength weakens on the leeward slope. When the process progresses to the erosion basin stage, the wind field becomes more complex, with horizontal-axis vortices present within the wind-eroded basin. As wind strength further increases, the eroded basin develops into a dish-shaped blowout, and the wind field undergoes significant changes, with the emergence of vertical-axis vortices, which vary depending on wind direction and the long axis of the wind-eroded hollow (Shi, 1986). Hesp also summarized changes in wind speed at different locations within blowouts: the lowest wind speed is at the entrance, while the highest wind speed is on the top surface of the depositional convex angle. Wind speed does not always increase with height; in narrower sections at lower elevations, wind speeds can be higher than in wider sections at higher elevations (Hesp et al., 1996, 2001). Smyth et al. (2012) conducted a statistical analysis of the relationship between vertical wind speed and terrain changes over a 33-day period for a bowl-shaped blowout. The study indicated that airflow movement has a strong correlation with overall terrain changes, with vertical wind speed (including positive and negative) are strongly correlated with negative terrain (erosion) changes, while airflow parameters show only a weak correlation with positive terrain (accumulation) changes. Sun et al. (2016) observed the airflow and sand transport in a fixed dune blowouts at the southern edge of the Hunsandak Sandy Land. The results show that the airflow enters the blowout and undergoes the process of diffusion deceleration-convergence acceleration-separation deceleration-gradual recovery. Hesp et al. (2011) used a three-dimensional anemometer to make three-dimensional observations of the airflow pattern in the bowl-shaped blowout and found that strong offshore winds caused the airflow to be sucked into the pit, eroded at the bottom of the pit, spread and accelerate along the side walls, and undergo significant steering, separation, overturning, and more complex three-dimensional motions. Cui et al. (2022) also found, through simulations, that near-surface air currents exhibit complex responses to the development of trough-shaped and dish-shaped blowout morphologies. The airflow accelerated at the entrance

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of both types of blowouts. After comprehensively obtaining the flow field information of the blowouts, the existence of vortices was confirmed, and the mechanism of wind-sand flow adsorption in the blowouts pits was elucidated (*Fig. 3*). Che et al. (2021) studied the airflow field and morphology feedback on the surface of blowouts at different development stages in the Qinghai Republican Basin, and concluded that there are differences in the internal flow field structure of blowouts at different development stages, and the airflow field of the advected stratum is greatly affected by the morphology of the pits. The sand transport rate is weakly positively correlated with wind speed and shows an insignificant negative correlation with the coefficient of variation of wind speed, which is closely related to the distribution of secondary currents in the blowouts and the surface conditions. There is a feedback relationship between airflow and morphology in the blowouts, the direction of the airflow and the morphology of the pits affect the distribution of the airflow inside the pits affects the development of the morphology of the pits, and the larger the pits, the more obvious the effect of this feedback is. By comparing the structural characteristics of wind and sand flow in blowouts at different development stages in the centralized distribution area of blowouts in the northern sandy grassland of Hulunbeier, Zhang et al. (2018) concluded that in blowouts at the stages of bare ground sand patches, active development, fixation, and re-activation, the wind speed contour basically follows the logarithmic distribution law. Whereas in the blowouts in the un-eroded grassland and the extinction stage, the airflow is disturbed by the underlayment, and shows an “S” shape. “S”-shaped distribution. The optimal fitting model for the sand transport and height of blowouts at each development stage is a negative exponential model, and the difference in sand transport between blowouts at different development stages is more obvious.

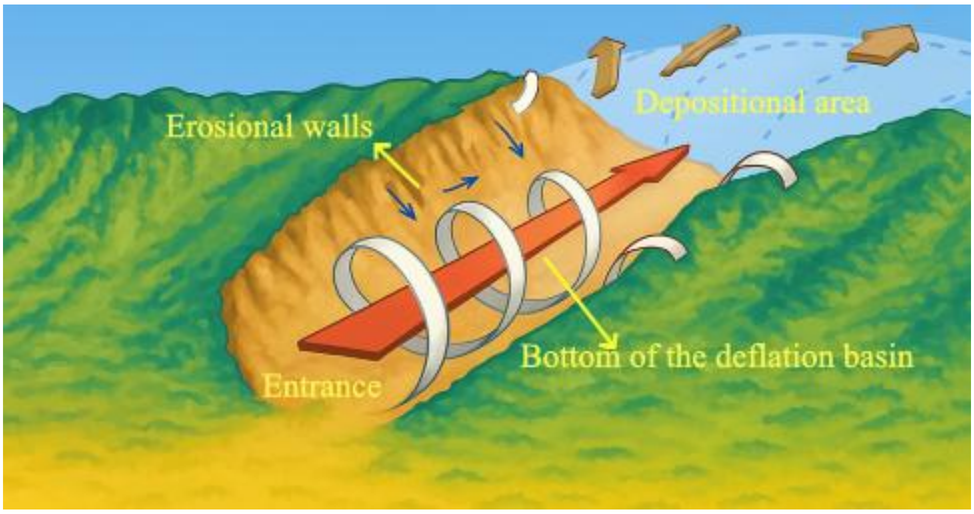

Figure 3. *Airflow patterns in trough-shaped blowouts*

Evolutionary dynamics of blowouts

It is currently widely accepted that the evolution of blowouts is controlled by sediment transport processes. Blowouts are the result of the interaction between atmospheric erosive forces and surface resistance to erosion, with surface airflow serving as the primary driving force shaping the morphology of blowouts. Landsberg and Olson were among the first to study the aerodynamics of blowouts in sand dunes (DaSilva et al.,

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2023). Other scholars have subsequently conducted research on the aerodynamics of blowouts in locations such as the Australian coast, New South Wales, the Netherlands, and the South African coastal plains. It is generally agreed that airflow exhibits varying degrees of change in different parts of blowouts, accelerating on the windward slope of sand dunes, reaching maximum speed at the summit, and decelerating on the leeward slope (Sun et al., 2015). Mir-Gual et al. (2023) investigated the relationship between aerodynamics and wind erosion, and the results indicated that the channelization of water flow caused by blowout topography leads to increased wind speed and sand transport. Zhou et al. (2023) analyzed the morphological changes of blowouts from 2011 to 2020 through field measurements, explaining that there is a close relationship between the morphology of blowouts and airflow patterns, and that these patterns are associated with regional wind direction. Hesp et al. (2011) argued that the diffusion of airflow at the bottom of erosion pits means that all side walls are eroded by winds blowing in a single direction, leading to the expansion of blowouts. Dish-shaped blowouts typically extend toward the upwind direction of the prevailing wind, and the erosion rate at the bottom of the erosion pit is relatively low, while the area with the highest erosion volume is near the ridge line of the erosion sidewall. This may be due to the limited depth and length of dish-shaped pits, which rarely or cannot generate jets under high-speed airflow conditions. Compared to dish-shaped blowouts, trough-shaped blowouts can typically achieve the maximum erosion depth, and can develop over longer distances in the downwind direction (or with the sand accumulation zone moving in the downwind direction). Smyth et al. (2011) was the first to apply computational fluid dynamics (CFD) software to simulate airflow, and he measured and simulated the heterogeneous patterns of airflow above blowouts, enabling the simulation and quantification of a large number of low-frequency storm events. These studies all indicate that there is a feedback interaction between terrain and airflow.

Factors influencing the development and evolution of blowouts

Natural factors influencing the development of blowouts

The development and evolution of blowouts are influenced by various natural factors, including climate change, wave erosion, water erosion, vegetation type, vegetation coverage, and regional wind conditions. Hu et al. (2013) analyzed blowouts in the Hunsandak sandy grassland and found that there is a significant correlation between the area of blowouts and their length, and there is also a correlation between length and width, but not with depth. Jungerius (1984) attributed the morphological evolution of blowouts to the cumulative effects of erosive gusts. Other studies have also found that slope aspect plays a role in the development of blowout morphology and influences the spatial variation in sediment supply. Sun et al. compared morphological measurement data from blowouts in different regions and concluded that the morphology of blowouts is highly correlated with regional environmental factors (Sun et al., 2015). Additionally, vegetation plays a crucial role in altering the near-surface flow field, protecting the underlying sand surface from erosion, and preventing wind erosion and sand fixation by covering the ground surface, dissipating airflow, trapping sand particles, and improving local moisture conditions. Hugenholtz et al. (2006) thinks that vegetation increases the wind speed that causes sand to blow by making the surface rougher, which limits the process of sand transport. Field observations show that when vegetation cover is more than 30%, there is basically no wind erosion. Mckeehan et al. (2023) analyzed changes in coastal sand dunes

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on the eastern shore of Lake Michigan from 1938 to 2018 and found that since 1938, the size of Blowouts has decreased by approximately 37%, with most being replaced by vegetation, suggesting that increased precipitation may be the primary cause of this trend. Wang et al. (2009) indicated that the most direct driving factors influencing changes in blowout morphology are surface airflow and sediment transport rates, as well as differences in the physical and chemical properties of surface soil layers and underlying loose sand (*Fig. 4*). Sand transport within blowouts exhibits seasonal variability. Mir-Gual et al. (2023) conducted relevant research and found that herbaceous vegetation present at the boundaries of beach blowouts effectively reduces sand transport, confirming the importance of vegetation in controlling sediment movement. Additionally, Fraser (1998), Byrne (1997), and others have suggested that collapse blocks, debris slopes, fan bodies, residual mounds, vegetation debris, and exposed soil within blowouts can increase the complexity of airflow and influence the sediment transport process, thereby affecting the evolution of blowouts.

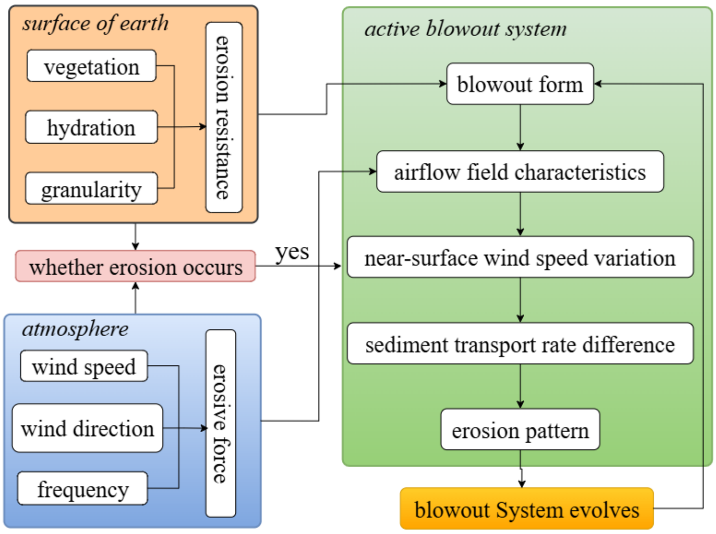

Figure 4. *Conceptual model for dynamic process of blowouts (modified after Wang et al., 2009)*

Human factors influencing the development of blowout morphology

Hu et al. (2019) analyzed the dynamic changes in blowouts along the southern edge of the Hunsandak Desert in Shangdu Town, Zhenglan Banner, using QuickBird imagery data and ground survey data. The study examined the relationship between changes in blowout morphology and human activities, indicating that while construction activities such as industrial and mining roads are detrimental to controlling wind and sand activity, other measures such as grazing bans, tree planting, and other measures are beneficial for the stabilization of blowouts or the restoration of grassland vegetation. Baird et al. (2021) studied blowouts in the Gonghe Basin of the Qinghai-Tibet Plateau, indicating that human activities, including overgrazing, have led to the widespread development of blowouts and formed some of the largest blowouts on Earth. Zhang et al. (2022) conducted a field survey of 187 modern blowouts in the sandy grasslands of Hulunbuir, obtaining morphological indicators, development stages, inducing causes, and modern grazing pressure, and found that 87% of blowouts were caused by human activities. Hu et al.

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(2019) analyzed and discussed the morphological changes of blowouts in fixed sand dunes at the southeastern edge of the Hunsandak Sandland and their relationship with climatic factors and human activities, simply concluding that the increase in regional blowouts is related to human activities. Essentially, various land development and utilization activities, such as grassland reclamation, overgrazing, indiscriminate logging, industrial and mining construction, and road construction, all damage vegetation and increase surface erodibility. However, actions such as grazing bans and afforestation can help stabilize blowouts or restore grassland vegetation. Zhang et al. (2022) conducted field experiments on Pingtan Island in China, and the results showed that human activities can interfere with the bidirectional feedback between blowout morphology and wind-induced processes.

Technological applications in blowout research

The in-depth development of blowout research is closely linked to advances in modern observation and analytical technologies. To overcome the limitations of traditional measurement methods—such as insufficient attention to the spatial patterns of blowout groups, short time series, and a lack of quantitative assessment—it is essential to adopt technical approaches capable of large-scale, long-term, and high-precision monitoring. Integrated technologies such as Geographic Information Systems (GIS), Remote Sensing (RS), Terrestrial laser scanning (TLS), Airborne laser Scanner (ALS), and Unmanned aerial vehicle (UAVs) have demonstrated significant potential in this regard and have become vital tools for advancing blowout research in a quantitative and model-driven direction.

Application of remote sensing technology

Remote sensing technology provides an irreplaceable means for the macroscopic and dynamic monitoring of blowouts. Using high-resolution satellite imagery and UAV photogrammetry, key morphological parameters such as blowout area, perimeter, and length-to-width ratio can be accurately identified and extracted (Smyth et al., 2013). Through the analysis of long-time-series satellite imagery, dynamic processes of blowout activation, stabilization, expansion, or shrinkage can be effectively tracked, and their rates of change quantified (Duan et al., 2014). Furthermore, technologies such as TLS, ALS, and UAVs can generate high-precision Digital Elevation Models (DEMs) through integrated surveys. Calculating the difference between these DEMs (*Fig. 5*) allows for the precise quantification of erosion volumes within the deflation basin and deposition in the accumulation lobe, providing three-dimensional data support for the study of dynamic processes (Joanna et al., 2013). Simultaneously, remotely sensed information, such as vegetation indices and soil moisture, can be spatially overlain with blowout distribution data, enabling the quantitative assessment of the influence of environmental factors on blowout development (Smith et al., 2016).

Application of geographic information systems

Geographic Information Systems (GIS) enable the construction of comprehensive spatial databases for blowouts, facilitating unified management, visualization, and sharing of blowout-related data (Dong et al., 2025). By leveraging high-precision morphological data of blowouts collected through remote sensing imagery, ALS, TLS,

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and other technologies, GIS allows for systematic investigation of the spatial distribution patterns of blowout groups. It also enables quantitative analysis of the spatial correlations between their distribution and environmental factors such as wind direction, topography, vegetation coverage, and human activities (Marcio et al., 2023). Furthermore, by integrating historical blowout distribution with hazard-inducing factors (e.g., wind speed, vegetation coverage, soil erodibility) within a GIS platform and applying models such as machine learning, susceptibility maps of blowout development can be generated. This provides a scientific basis for decision-making in regional aeolian disaster risk assessment and prevention planning (Borrelli et al., 2020).

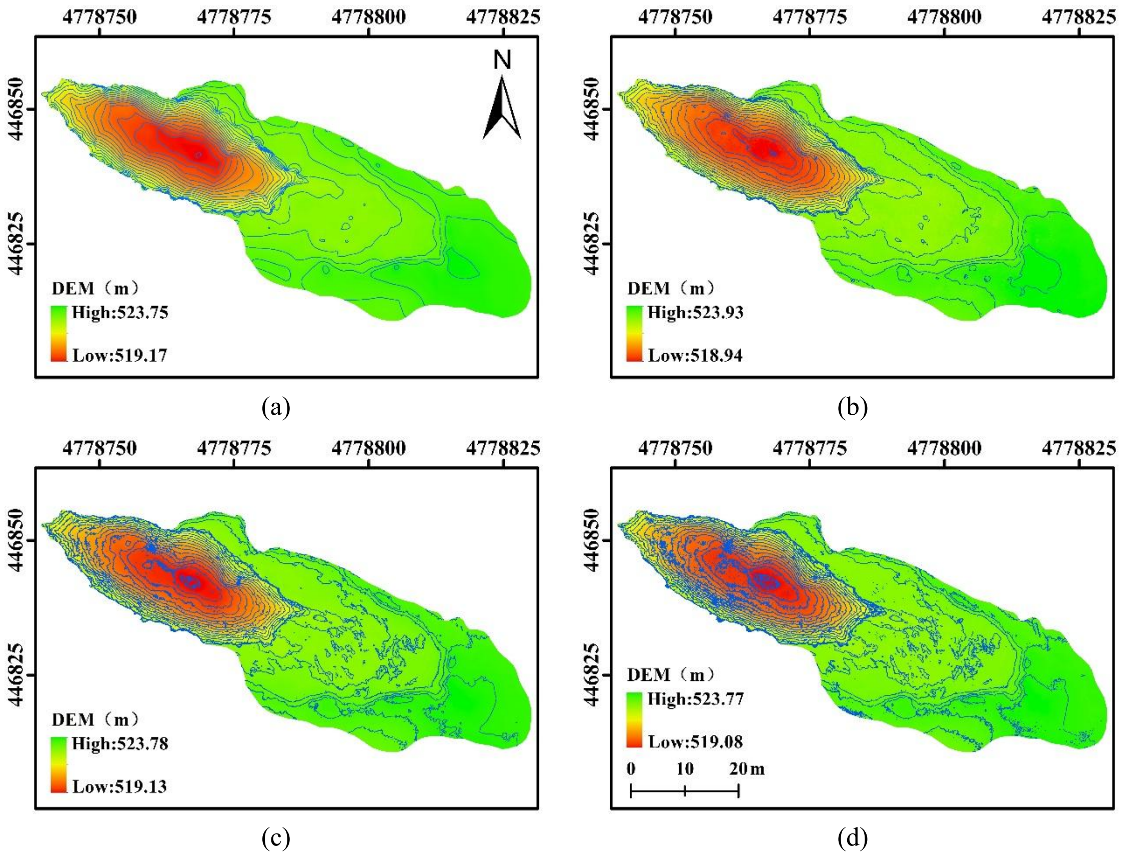

Figure 5. *Model of a typical trough blowout with 0.2-meter contour intervals: (a) RTK-GPS; (b) UAV; (c) ALS; (d) TLS*

Future technological integration

Future research on blowouts will increasingly focus on the integration of multiple technologies and platforms. For example, combining the high spatiotemporal resolution of ALS or UAVs with the extensive coverage of satellite imagery enables multi-scale, high-precision measurement of both basic morphologies and micro-topographic features of blowouts (*Fig. 6*). Promoting the deep integration of numerical simulation technologies like Computational Fluid Dynamics (CFD) with high-precision topographic data will allow more accurate simulation and reconstruction of the complex three-dimensional airflow structures and morphodynamic feedback mechanisms within blowouts, thereby enhancing our understanding of their dynamic formation mechanisms (Smyth et al., 2011).

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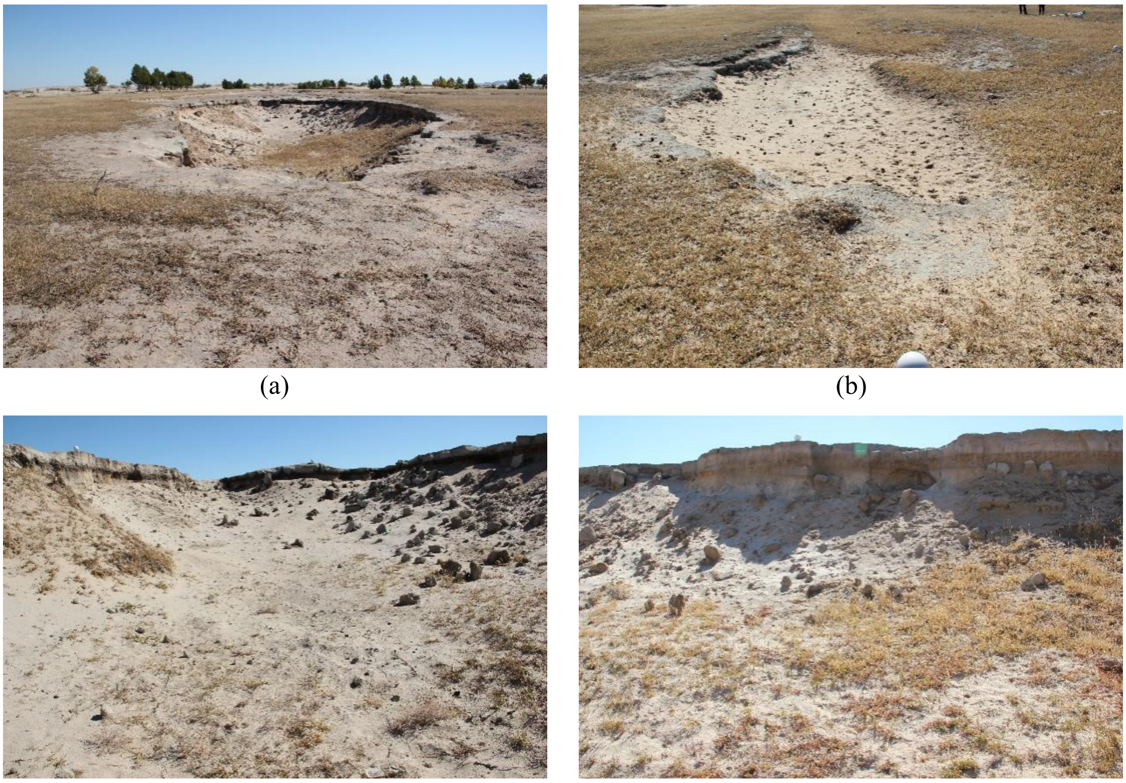

(a) (b) (c) (d)

Figure 6. *TLS-derived typical trough blowout and its micro-topography: (a) deflation basin; (b) depositional area; (c) the bottom of the deflation basin; (d) erosional walls*

Conclusions

Currently, most scholarly research focuses on the development and evolution of individual blowouts, neglecting the developmental status of wind erosion pit clusters in the same region. As underscored by the discussion on technological applications, advancing beyond this limitation and summarizing a more comprehensive evolutionary pattern necessitates the support of large-scale, long-term monitoring technologies such as remote sensing and GIS. While surface airflow is widely recognized as the primary driving force shaping blowout morphology through wind erosion and abrasion, a comprehensive understanding of their genesis, especially in coastal settings where temporary water flow, weathering, and salinization are also influential, requires further integrated investigation.

Research on the influencing factors has predominantly relied on qualitative descriptions of both natural and anthropogenic elements, lacking the quantitative assessments necessary to pinpoint precise driving mechanisms and their interactions. Future efforts must, therefore, prioritize quantitative approaches, leveraging spatial analysis and modeling within a GIS framework to quantify the contribution of various factors and unravel their complex coupled relationships. This shift towards quantification is crucial for developing targeted and effective policy measures to control blowout expansion and combat desertification.

Looking ahead, the integration of multi-technology approaches for combined measurements will be crucial. Combining high-resolution morphological monitoring (e.g., from UAVs and LiDAR) with three-dimensional airflow simulation (CFD) will not

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only enable more precise measurement of blowout morphology and micro-topographic features but also provide clearer insights into the complex dynamic processes and morphodynamic feedback mechanisms governing blowout behavior.

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REFERENCES

[1] Baird, T. R., Bristow, C. S., Luo, W. Y., D, E. J., Bryant, R. G., Mitchell, T. M., Vermeesch, P. (2021): Blowout morphometrics and mass balances. – Frontiers in Earth Science 9: 669440.

[2] Bernard, O. B., Douglas, J. S. (1998): Coastal dune dynamics: problems and prospects. – Aeolian Research 14: 72-103.

[3] Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., Wuepper, D., Montanarella, L., Ballabio, C. (2020): Land use and climate change impacts on global soil erosion by water (2015-2070). – Proceedings of the National Academy of Sciences 117(36): 21994-22001.

[4] Byrne, M. L. (1997): Seasonal sand transport through a trough blowout at Pinery Provincial Park, Ontario. – Canadian Journal of Earth Sciences 34: 1460-1466.

[5] Cai, A. Z., Cai, Y. E. (1983): A study of depositional causation and characteristics of coast aeolian sand in coast areas in China. – Journal of Desert Research 3: 1-10.

[6] Che, X. H., Luo, W. Y., Shao, M., Wang, Z. Y. (2021): Form-flow feedback within blowouts at different developing stages in the Gonghe Basin, Qinghai Province. – Advances in Earth Science 36(1): 95-109.

[7] Cooper, H. M., Wasklewicz, T., Zhu, Z., Lewis, W., Lecompte, K., Heffentrager, M., Smaby, R., Brady, J., Howard, R. (2021): Evaluating the ability of multi-sensor techniques to capture topographic complexity. – Sensors 21: 2105.

[8] Cooper, W. S. (1958): The coastal sand dunes of Oregon and Washington. – Geological Society of America 72: 169.

[9] Cooper, W. S. (1967): Coastal dunes of California. – Geological Society of America 104(1/4): 131.

[10] Cui, K. J., Li, S. Y., Wang, H. F., Fan, J. L. (2022): Three-dimensional flow field characteristics of two typical blowout in the dry lake basin of Taitema Lake and their influence on wind erosion. – Arid Land Geography 45: 1784-1794.

[11] DaSilva, M. D., Bruce, D., Hesp, P. A. (2023a): Post-wildfire coastal dune field response using photogrammetry and satellite indices. – Earth Surface Processes and Landforms 48: 1-24.

[12] DaSilva, M. D., Bruce, D., Hesp, P. A., da Silva, G. M., Downes, J. (2023b): Post-wildfire coastal dunefield response using photogrammetry and satellite indices. – Earth Surface Processes and Landforms: 30 March 2023.

[13] Dong, G. C., Huang, F. X., Zhou, W. J., Fu, Y. C., Li, Y., Xian, F., Yi, C., Caffee, M. W., Liu, X. H. (2025): Towards an understanding of dynamics of blue-ice moraines: a case study in the Grove Mountains, East Antarctica. – Geomorphology 480: 1.1-1.11.

[14] Dong, Y. X., Huang, D. Q. (2014): Typical research on the movement and topographic change of coastal crescent dune. – Scientia Geographica Sinica 34: 863-869.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_693710

[15] Dong, Y. X., Hesp, P. A., Namikas, S. L., Ma, J. (2008): Field measurements of structure of wind-sand flow on coastal transverse ridge in China. – Journal of Geological Education 28: 507-512.
[16] Dong, Y. X., Zhang, Q. N., Huang, D. Q. (2019): Progress and prospect of research on coastal wind-eroded landform. – Advances in Earth Science 34: 1-10 (in Chinese).
[17] Du, H. S., Hasi, E. D., Yang, Y., Sun, Y. (2012): Landscape pattern change and driving force of blowout distribution in the Hulun Buir Sandy Grassland. – Sciences in Cold and Arid Regions 4: 431-438.
[18] Duan, H. C., Wang, T., Xue, X., Liu, S. L., Guo, J. (2014): Dynamics of aeolian desertification and its driving forces in the Horqin Sandy Land, Northern China. – Environmental Monitoring and Assessment: An International Journal 186(10): 6083-6096.
[19] Fraser, G. S., Bennett, S. W., Olyphant, G. A., Bauch, N. J., Ferhugon, V., Gellasch, C. A., Millard, C. L., Mueller, B., O'Malley, P. J., Way, J. N., Woodfield, M. C. (1998): Windflow circulation patterns in a coastal dune blowout, south coast of Lake Michigan. – Journal of Coastal Research 14: 451-460.
[20] Gares, P. A. (1992): Topographic changes associated with coastal dune blowouts at island beach State Park, New Jersey. – Earth Surface Processes and Landforms 17: 589-604.
[21] Gares, P. A., Nordstrom, K. F. (1995): A cyclic model of foredune blowout evolution for a leeward coast: Island Beach, New Jersey. – Annals of the Association of American Geographers 85: 1-20.
[22] Guo, Z. Y., Xie, Y. H., Gao, L., Jiang, H. T., Shi, H. D., Hai, C. X. (2024): A study on the morphology evolution of blowouts in sandy grassland area: taking Dahekou town, Xilingol league as an example. – Acta Ecologica Sinica 44(22): 10401-10410.
[23] Hails, J. R., Bennett, J. M. (1980): Wind and sediment movement in coastal dune areas. – Coastal Engineering 1565-1575.
[24] Han, Z. W., Gou, Q. Q., Du, H. Q., Sun, J. H. (2012): The piecewise fitting of sand flux vertical distribution of wind-sand flow within 100-cm height above the Barchan Dune surface. – Geographical Science 23: 892-897.
[25] Hesp, P. A. (1996): Flow dynamics in a trough blowout. – Boundary-Layer Meteorology 77: 305-330.
[26] Hesp, P. A. (2002): Foredunes and blowouts: initiation, geomorphology and dynamics. – Geomorphology 48(1/3): 245-268.
[27] Hesp, P. A. (2013): Conceptual models of the evolution of transgressive dune field systems. – Geomorphology 199: 138-149.
[28] Hesp, P. A., Hyde, R. (1996): Flow dynamics and geomorphology of a trough blowout. – Sedimentology 43: 505-525.
[29] Hesp, P. A., Pringle, A. (2001): Wind flow and topographic steering within a trough blowout. – Journal of Coastal Research 34(Suppl.1): 597-601.
[30] Hesp, P. A., Walker, I. J. (2011): Three-dimensional aeolian dynamics within a bowl blowout during offshore winds: Greenwich dunes, Prince Edward Island, Canada. – Aeolian Research 3(4): 389-399.
[31] Hu, C. E., Wang, X. J., Zhang, W. J., Liu, Y. H., Hai, L., Zhang, L., Sulenggaowa. (2013): Analysis on spatial pattern of blowouts in Otindag sandy grassland based on ALOS data. – Journal of Desert Research 33: 662-667.
[32] Hu, R. N., Hasi, E. D., Haobisi, H. L. T., Zhou, Y. G., Li, H. Y. (2019): Dynamic changes of blowouts on fixed sand dunes in the southeastern fringe of Otindag Sandy Land. – Journal of Desert Research 39: 34-43.
[33] Hugenholtz, C. H., Wolfe, S. A. (2006): Morphodynamics and climate controls of two aeolian blowouts on the northern Great Plains, Canada. – Earth Surface Processes and Landforms 31: 1540-1557.
[34] Jungerius, P. D. (1984): A simulation model of blowout development. – Earth Surface Processes and Landforms 9: 509-512.

[35] Lancaster, N. (1986): Dynamics of deflation hollows in the Elands Bay area, Cape Province, South Africa. – Catena 13: 139-153.
[36] Li, S. Q., Hasi, E. D., Du, H. S., Zhang, P., Wu, X., Yang, Y. (2012): Interaction between airflow and shape of saucer blowout in sandy grassland. – Journal of Desert Research 32: 1201-1209.
[37] Liu, L., Xie, Y. Y., Chi, Y. P., Kang, C. G., Wu, P., Wei, Z. Y., Zhang, Y. X., Zhang, M. (2021): Geochemical compositions of the Onqin Daga Sand Land and Horqin Sand Land and their implications for weathering, sedimentation and provenance. – Marine Geology and Quaternary Geology 41: 192-206.
[38] Luo, W. Y., Wang, Z. Y., Lu, L. H., Qian, G. Q., Dong, Z. B., Bateman, M. D. (2019): Mega-blowouts in Qinghai–Tibet Plateau: morphology, distribution and initiation. – Earth Surface Processes and Landforms 44: 449-458.
[39] Marrero-Rodríguez, N., Dóniz-Páez, J. (2022): Coastal dunes geomorphosites to develop the geotourism in a volcanic subtropical oceanic island, Tenerife, Spain. – Land 11: 426.
[40] Mckeehan, K. G., Arbogast, A. F. (2023): The geography and progression of blowouts in the coastal dunes along the eastern shore of Lake Michigan since 1938. – Quaternary Research: An Interdisciplinary Journal 115: 25-45.
[41] Melton, F. A. (1940): A tentative classification of sand dunes its application to dune history in the southern high plains. – The Journal of Geology 48: 113-174.
[42] Mir-Gual, M., Pons, G. X., Delgado-Fernández, I., Smyth, T. A. G. (2023): Field-measurement of surface wind and sediment transport patterns in a coastal dune environment, case study of Cala Tirant [Menorca, Spain]. – Journal of Marine Science and Engineering 11: 2361.
[43] Nield, J. M., King, J., Wiggs, G. F. S., Leyland, J., Bryant, R. G., Chiverrell, R. C., Darby, S. E., Eckardt, F. D., Thomas, D. S. G., Vircavs, L. H., Washington, R. (2013): Estimating aerodynamic roughness over complex surface terrain. – Journal of Geophysical Research, D. Atmospheres: JGR 118(23): 12948-12961.
[44] Pluis, J. L. A., van Boxel, J. H. (1993): Wind velocity and algal crusts in dune blowouts. – Catena 20: 581-594.
[45] Pye, K. (1982): Morphological development of coastal dunes in a humid tropical environment, Cape Bedford and Cape Flattery, North Queensland. – Geografiska Annaler: Series A, Physical Geography 64: 213-227.
[46] Ritchie, W. (1972): The evolution of coastal sand dunes. – Scottish Geographical Magazine 88: 19-35.
[47] Shi, P. J. (1986): Discussion on the surface morphological characteristics and development process of desertified land in Daqinggou area, southern Horqin. – Journal of Hangzhou Normal University, Natural Science 1(1): 43-54.
[48] Shumack, S., Hesse, P., Turner, L. (2017): The impact of fire on sand dune stability: surface coverage and biomass recovery after fires on Western Australian coastal dune systems from 1988 to 2016. – Geomorphology 299: 39-53.
[49] Smith, A., Gares, P. A., Wasklewicz, T., Hesp, P. A., Walker, I. J. (2017a): Three years of morphologic changes at a bowl blowout, Cape Cod, USA. – Geomorphology 295: 452-466.
[50] Smith, A. B., Jackson, D. W. T., Cooper, J. A. G. (2017b): Three-dimensional airflow and sediment transport patterns over barchan dunes. – Geomorphology 278: 28-42.
[51] Smith, H. T. U. (1960): Physiography and photo interpretation of coastal sand dunes. Final Report Contract NONR–2242 [00], Office of Naval Research. – Geographical Branch 60.
[52] Smyth, T. A. G., Jackson, D. W. T., Cooper, J. A. G. (2011): Computational fluid dynamic modelling of three-dimensional airflow over dune blowouts. – Journal of Coastal Research 57: 314-318.
[53] Smyth, T. A. G., Jackson, D. W. T., Cooper, J. A. G. (2012): High resolution measured and modelled three-dimensional airflow over a coastal bowl blowout. – Geomorphology 177: 62-73.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_693710

[54] Smyth, T. A. G., Jackson, D. W. T., Cooper, J. A. G. (2013): Three-dimensional airflow patterns within a coastal trough-bowl blowout during fresh breeze to hurricane force winds. – Aeolian Research 9(147): 111-123.
[55] Smyth, T. A. G., Hesp, P. A., Walker, I. J., Wasklewicz, T., Gares, P. A., Smith, A. B. (2019): Topographic change and numerically modelled near surface wind flow in a bowl blowout. – Earth Surface Processes and Landforms 44: 1988-1999.
[56] Sun, Y., Du, H. S., Liu, M. P., Hasi, E. D. (2015): A review on morphodynamic processes of blowouts. – Geographical Science 35: 898-904.
[57] Sun, Y., Du, H. S., Hasi, E. D., Liu, M. P. (2016): Aeolian dynamical process of blowout on the fixed dune. – Acta Geographica Sinica 71: 1562-1570.
[58] Wan, W., Yan, C. Z., Xiao, S. C., Xie, J. L., Qian, D. W. (2018): Process, Spatial Pattern and Driving Mechanisms of the Aeolian Desertification in the Alxa Plateau from 1975 to 2015. – Journal of Desert Research 38: 17-29.
[59] Wang, S., Hasi, E. D. (2008a): Particle size variation in trough blowout on sandy grassland. – Bulletin of Soil and Water Conservation 28: 122-125.
[60] Wang, S., Hasi, E. D. (2008b): Wind regime and blowouts geomorphology in Hulunbuir sandy grassland. – Research of Soil and Water Conservation 15(3): 74-76, 80.
[61] Wang, S., Hasi, E. D. (2009a): Advances in the study of geomorphology and process of wind erosion landforms. – Journal of Earth Sciences and Environment 31: 100-105.
[62] Wang, S., Hasi, E. D. (2009b): Air flow dynamics of the blowout trough in the Hulun Buir Sandy Grassland. – Science of Soil and Water Conservation 7: 80-85.
[63] Wang, S., Hasi, E. D., Zhang, J., Zhang, P. (2007): Geomorphological significance of air flow over saucer blowout of the Hulun Buir Sandy Grassland. – Journal of Desert Research 27: 745-749.
[64] Wu, Y. J., Liu, T. X., Tong, X., Luo, Y. Y., Duan, L. M., Wang, G. L. (2020): Dynamic evolution analysis of land use [land cover] in Horqin sandy land based on long time series Landsat data. – Acta Ecologica Sinica 40: 8672-8682.
[65] Wu, Z., Wu, K. G. (1987): Sedimentary structure and developing model of coastal dunes along the northeastern coast of Hainan Island, China. – Acta Geographica Sinica 42: 129-141.
[66] Yan, D. R. (2016): Impact factors and morphological characteristics of blowouts in Hunshandake Sandland. – Scientia Geographica Sinica 36(4): 637-642.
[67] Yan, X., Zhang, D. P., Xia, X. D., Hasi, E. D. (2009): Morphology and Developmental Mode of blowouts in Hulun Buir Sandy Grassland China. – Journal of Desert Research 29: 212-217.
[68] Yang, Y. Y., Liu, L. Y., Qu, Z. Q., Zhang, G. M. (2014): A review of Barchan Dunes. – Geographical Science 34: 76-83.
[69] Yuan, L. M., Yang, Z. G., Xue, B., Gao, H. Y., Han, Z. R. G. T. (2022): Spatial heterogeneity of soil moisture of blowouts in Hulun Buir grassland. – Arid Zone Research 39: 1598-1606.
[70] Zhang, D. P., Feng, Z. W., Wang, X. K., Sun, H. W., Zhao, J. M., Hu, R. L. (2006): A preliminary study on blowouts in the Hulun Buir Sandy Grassland. – Progress in Natural Science: Materials International 16: 1341-1345.
[71] Zhang, D. P., Wang, X. K., Sun, H. W., Feng, Z. W. (2007a): HulunBuir Sandy Grassland blowouts: influence of human activities. – Journal of Desert Research 27: 214-220.
[72] Zhang, D. P., Sun, H. W., Wang, X. K., Feng, Z. W. (2007b): HulunBuir Sandy Grassland blowouts [II]: process of development and landscape evolution. – Journal of Desert Research 27: 20-24.
[73] Zhang, S. Y., Dong, Y. X. (2019): Research progress on morphodynamics of coastal sandy blowout. – Advances in Earth Science 34: 1028-1037.
[74] Zhang, S. Y., Qiu, X., Fu, S. Y., Fu, J. J., Chen, S. X., Tian, W., Huang, D. Q., Dong, Y. X. (2022): Evolution of blowouts in artificial foredunes on Pingtan Island, China. – Earth Surface Processes and Landforms 47: 2597-2611.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2401_693710

[75] Zhang, S. Y., Dong, Y. X., Hasi, E. D., Huang, D. Q. (2024): Morphodynamics and morphological evolution characteristics of blowouts dunefields: a case study in Haitan Island, Fujian. – Geographical Research 43: 255-271.
[76] Zhang, X. W., Wang, J., Hai, C. X., Ding, Y. L., Bao, C. (2018): Structure of drifting sand flow over the surface of blowouts in the Hulun Buir Sandy Grasslands. – Arid Zone Research 35(6): 1505-1511.
[77] Zhou, Y. G., Wang, Z. R., Qing, D. M. N., Hu, R. N., Yin, J., Wu, Z. F., Hasi, E. D. (2023): Morphological changes and dynamic mechanism of blowouts on fixed dunes in the Otingdag sandy land, China. – Chinese Science Bulletin 68: 1298-1311.

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