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Foredunes and blowouts: initiation, geomorphology and dynamics

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Abstract

This paper reviews the initiation, dynamics, geomorphology and evolution of incipient foredunes, established foredunes, and blowouts. Incipient foredunes may be initiated in a variety of ways leading to the formation of ramps, terraces or ridges depending on progradation rates, vegetation type and cover, sediment transport rates and scale of erosional processes. Vegetation cover, morphology, growth rates, and types combine with aerodynamic processes to determine dune and swale morphology. Established foredunes are classified into five morpho-ecological types, and the flow behaviour over two types is detailed. A new model of foredune evolutionary paths at various possible time scales is presented. Blowout initiation, dynamics and sediment transport, and evolution is examined. Throughout the review, the gaps in present understanding of dune processes and a range of ideas for new research possibilities are provided.

Keywords: Incipient foredunes; Established foredunes; Blowouts; Coastal dunes

1. Introduction

The purpose of this paper is to review the processes of initiation, evolution, dynamics and geomorphology of foredunes, and blowouts. This review does not include dunes that have been partly or wholly built, modified or seriously impacted by humans (see Nordstrom, 1994 for review).

Foredunes are defined as shore-parallel dune ridges formed on the top of the backshore by aeolian sand deposition within vegetation. Foredunes may range from relatively flat terraces to markedly convex ridges. Actively forming foredunes occupy a foremost seaward position in a dune system, but not all foremost dunes are foredunes. Other dune types may occupy a foremost position on eroding coasts or coasts where foredunes are unable to form.

Foredunes have been classified into a wide variety of types (see e.g., Hesp, 1984a,b for review), but generally fall into two main types, incipient and established foredunes, within which there can be wide morphological and ecological variations. Foredunes can form on any shore: beach (open ocean or semienclosed bay), estuary and lake/lagoon (Zenkovich, 1967; Goldsmith, 1989; Nordstrom, 1992; Nordstrom and Jackson, 1994), and in almost any climate from tropical to arctic (Wong, 1978; Ruz and Allard, 1994a,b; Santos et al., 1996).

Incipient and established foredunes have been called a variety of other names including ‘embryo dunes’, ‘frontal dunes’, ‘retention ridges’, ‘beach ridges’, ‘parallel dune ridges’, and ‘transverse’ dunes.

2. Incipient foredunes

Incipient foredunes are new, or developing foredunes forming within pioneer plant communities

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(hence, the term 'embryo' dunes used in the literature). They may be formed by sand deposition within discrete or relatively discrete clumps of vegetation, or individual plants, or driftwood, flotsam, etc. (types 1a and 1b of Hesp, 1989), forming shadow dunes, mounds and nebkha. These may form at various locations ranging from the immediate backshore to back-barrier flats (Carter et al., 1992). Such development often eventually comprises an incipient foredune zone. Incipient foredunes may be seasonal where formed around annual plants and require invasion by perennial plants in order to survive. Plant species type is important in determining morphological development. Species such as the tall, dense *Ammophila* tend to produce higher, more hummocky peaked dune forms than lower, more spreading, rhizomatous plants such as *Spinifex* or *Ipomoea*, which produce lower, less hummocky dune forms (Davies, 1980; Hesp, 1983, 1984a).

Incipient foredunes may also form on the backshore by relatively laterally continuous alongshore growth of pioneer plant seedlings in the wrack line or spring high tide region, and/or by rhizome growth onto the backshore region (types 2a and 2b of Hesp, 1989). Morphological development principally depends on plant density, distribution, height and cover, wind velocity, and rates of sand transport. Secondary factors such as the rate of occurrence of swash inundation, storm wave erosion, overwash incidence, and wind direction can also be important in determining subsequent dune evolution (Cowles, 1898; Ranwell, 1972; Davies, 1980).

2.1. Flow dynamics on incipient foredunes

Shadow dunes, hummocks, and nebkha all form due to high, localized drag (isolated roughness flow) within and behind individual plants, and clumps of plants. Wind velocities experience rapid deceleration on reaching the plants, local acceleration around the plants, and flow separation behind the plants (Bressolier and Thomas, 1977; Hesp, 1981; Greeley and Iversen, 1985; Wasson and Nanninga, 1986; Clemmensen, 1986; Nickling and Davidson-Arnott, 1990; Pye and Tsoar, 1990; Thomas and Tsoar, 1990).

The impact of relatively continuous plant canopies on the wind/sand flow depends on plant density, shape or morphology, distribution, and height (e.g., Buckley, 1987; Aylor et al., 1993; Raupach, 1992; van Dijk et al., 1999). Van Dijk et al. (1999) demonstrate in their modeling that as plant height increases, dune height increases and dune length decreases. Such work verifies field observations (Hesp, 1989). High, dense canopies (e.g., grasses such as *Ammophila* sp., shrubs and trees such as *Atriplex* sp. in Western Australia and poplars on the Great Lakes in Canada) reduce air flow velocities very rapidly (Hesp, 1989; Niedoroda et al., 1991; Jacobs et al., 1995). Sand transport (saltation and traction) is markedly reduced from the leading edge. The greater deposition at the leading edge produces asymmetric incipient foredunes with the short slope to seawards. Lower plant canopies (e.g., *Spinifex* sp., *Uniola* sp.; *Ipomoea* sp.) reduce the airflow and transport more slowly so that there is a gradual down wind reduction in transport. This produces asymmetric dunes with the short slope on the downwind (lee slope) side.

Most vegetation canopies vary along shore in density or distribution either because of variations in the vigor of a particular dominant species, or because the distribution of species varies spatially. As a result, the morphology of the foredune varies alongshore accordingly (Fig. 1). The greater the variations in density or distribution or in sand supply, the greater the morphological variation (Carter, 1988; Carter and Wilson, 1990; Sarre, 1989; Hesp, 1989, 1999; Leys, 1991; Raupach et al., 1993; Hagen and Armbrust, 1994; Musick et al., 1996; Santos et al., 1996; Wilson et al., 1998). Wolfe and Nickling (1993, 1996) demonstrate the flow variations that occur as plant density increases.

Plant density is increased as wind velocities increase because the effective density of a canopy increases as the vegetation bends and streamlines to the wind. High wind velocities may result in canopy changes to such a degree that, for example, wake interference flow may change to skimming flow (Carter, 1988; Nickling and Davidson-Arnott, 1990; Harwood, 1993; Green et al., 1998).

Plant density and distribution also varies seasonally, and therefore seasonal growth rates (low or absent in winter, high in spring) strongly influence patterns of sand transport and deposition on incipient (and established) foredunes.

Fig. 1. An incipient foredune and swale dominated by *Spinifex sericeus*, and formed following relatively rapid accretion of the beach. The swale forms as a low deposition zone following ridge formation at the seaward edge of *Spinifex* growth.

2.2. Other factors affecting incipient foredune development

Beach width (related to: beach-surfzone type, temporal variations in sediment supply (e.g., sand wave migration; delta switching), wind approach direction, and seasonal climatic variations, the potential for development of transverse and barchan dunes on the backshore, lag development, and water table heights, also act as important controls on the rate of sediment supply to foredunes, and therefore foredune development (Carter, 1976, 1988; Hesp, 1988b, 1999; Carter and Wilson, 1990; Law and Davidson-Arnott, 1990; Nordstrom and Jackson, 1992, 1993, 1994; Davidson-Arnott and Law, 1996; Davidson-Arnott et al., 1997). Davidson-Arnott and Law (1990) and Law and Davidson-Arnott (1990) provide an excellent example of seasonal variations in sediment delivery to foredunes as a function of seasonal variations in sediment availability (controlled in part by the degree of snow and ice cover), and beach source width. The degree of sediment delivery to the established foredune and the primary location of sediment deposition is strongly controlled by the presence or absence of the incipient foredune, snow cover, and the presence and location of vegetation (Davidson-Arnott and Law, 1990).

2.3. Incipient foredune morphologies

Incipient foredunes generally display one of three morphological types: ramps, terraces, and ridges. Each of these types forms under fairly specific conditions. Ramps form where: (1) seedlings germinate on a seaward sloping backshore; (2) rhizomatous and/or stoloniferous plants grow seawards from a landward source and gradually trap sand usually on a seaward sloping berm or backshore; and/or (3) where plants germinate or grow on a scarp fill or at the base of a foredune scarp which gradually accretes.

Terraces form where (1) rapid plant growth takes place across the backshore, particularly on rapidly accreting beaches; (2) seaward plant growth roughly matches the accretion rate; and/or (3) plants grow across or on a backshore that experiences little sand accretion (e.g., such as on some tropical, or low energy shores) because the plant density is moderate or because the dominant plant species height is short.

Ridges form where (1) accretion rates are relatively rapid and sand deposition primarily occurs in the seaward portion of the plant canopy; (2) plant density and plant height is high (Fig. 1); (3) seaward growth rates are slow relative to accretion; and/or (4) wave scarping of foredunes results in the relocation of aeolian deposition to the scarp base, and subsequent scarp filling and crestal deposition (Carter, 1977; Carter et al., 1990; Giles and McCann, 1997; Bauer and Sherman, 1999). The last process also leads to the development of ridge morphologies, but is not a critical process for such development as some believe (e.g., Bird, 1985; Bird and Jones, 1988).

2.4. Swale development

Swales (lee dune depressions) are generally created by seaward accretion of a foredune (Fig. 1). They develop as low to limited aeolian deposition zones and become deeper as seaward incipient foredunes become higher (Olson, 1958b; Hesp, 1983; Gares and Nordstrom, 1988). They generally are continuous alongshore where winds are predominantly onshore and the vegetation cover of the incipient foredune is moderate to high. However, where the vegetation cover is more irregular, the dunes more complex, or a variety of offshore and onshore winds occur, localized swale depressions may be formed and are often mistaken for blowouts. Swales may be formed by aeolian deflation as stated by Bird (1985) and Bird and Jones (1988), but this mode of formation is extremely rare.

3. Established foredunes

Established foredunes develop from incipient foredunes and are commonly distinguished by the growth of intermediate, often woody plant species, and by their greater morphological complexity, height, width, age, and geographical position. In some regions/countries, the species that initiate the incipient foredunes also dominate the established foredune. Thus, morphological complexity, height, volume, and geographical position distinguish the incipient from the established foredune.

The morphological development and evolution of established foredunes depends on a number of factors including: (1) sand supply; (2) the degree of vegetation cover; (3) plant species present (a function of climate and biogeographical region); (4) the rate of aeolian sand accretion and erosion; (5) the frequency and magnitude of wave and wind forces; (6) the occurrence and magnitude of storm erosion, dune scarping, and overwash processes; (7) the medium to long-term beach or barrier state (stable, accreting or eroding); (8) sea/lake/estuary water level, and, increasingly (9), the extent of human impact and use.

Foredunes range from very low, scattered dunes less than a meter or so in height to large dune complexes, reaching 30–35 m in height. The low, scattered dunes occur on some barrier islands dominated by overwash and in areas of limited sediment supply. The highest dunes are rare and tend to occur on erosional coasts, where human interference has acted to artificially induce greater foredune heights, by, for example, nourishment and maintaining absolute lee slope stability (e.g., parts of the Dutch coast).

Beach width, sediment supply, and wind velocity act as three (of several) factors controlling or influencing foredune development (e.g., Davidson-Arnott and Law, 1996). The first two factors above are intimately tied to surfzone-beach type in some regions especially where sediment supply is not a major limiting factor (Hesp, 1988b; Short and Hesp, 1982). Foredune height and volume is related to beach-surfzone type. All other factors being equal (e.g., equal potential sediment supply), larger foredunes occur on dissipative beaches (widest beaches and maximum potential sediment supply) and the smaller ones occur on reflective beaches (narrowest beaches and minimum potential sediment supply) (Hesp, 1988b; Ruz et al., 1992; Sherman and Bauer, 1993a; Ruz and Allard, 1994a; Ruz and Allard, 1995; Sherman and Lyons, 1994). Plant successional trends and species richness on foredunes can also be strongly related to surfzone-beach type (Hesp, 1991), and, as discussed above, vegetation characteristics affect foredune morphology.

3.1. Flow dynamics and sand transport

Studies on flow over foredunes have been carried out at two levels. First, there have been detailed studies of flow behaviour within and immediately above plant canopies (see incipient foredunes above and review in Hesp, 1989). Second, larger scale studies have examined flows over various foredune types and morphologies.

The first detailed studies of flow over beaches and foredunes were by Landsberg and Riley (1943), followed by those of Hsu (1974, 1977, 1980). Hsu produced a general model of onshore airflow over both relatively steep, scarped dunes, and ice ridges.

The seaward side was characterized by an area of underspeed, the crest and upper landward slope by an area of overspeed, and the lower landward slope by an area of underspeed. This first approximation of "foredune flow" models relatively steep ridges, but it does not account for dunes with lower, longer stoss, and lee slopes.

Arens et al. have more recently carried out a range of flow and sand transport experiments over various foredune types and under varying wind conditions (Arens, 1994; Arens et al., 1995). These studies found that the wind flow is topographically accelerated over foredunes, particularly up stoss slopes, and over crests, as reported in many other studies of speed-up over ridges (e.g., Jackson and Hunt, 1975; Finnigan, 1988; Wilson et al., 1998; Rasmussen, 1989). However, the variable vegetation cover of foredunes and their topographic variability leads to local decelerations and variations in roughness length (Arens et al., 1995; Fig. 2). Such variations become more pronounced as foredune morphology becomes more complex and the vegetation cover becomes more variable (Hesp, 1988b; Fig. 2). Very dense and tall vegetation results in intensely nonlogarithmic velocity profiles (Harwood, 1993). Estimation of friction velocities and roughness lengths are often difficult and may be both over and underestimated if derived from beach measurements, depending on roughness changes and foredune morphology. While some progress is being made in modeling flow and sediment transport over relatively simple hills (e.g., Kaimal and Finnigan, 1994) and unvegetated transverse dunes (e.g., van Boxel et al., 1999), the addition of vegetation into such models (van Dijk et al., 1999) to simulate realistic foredune development is complicated due to the difficulties involved in simulating plant growth and vegetation type and cover.

The seasonal dominance of wave over wind processes may significantly alter the predominant behavior of the foredune. For example, during storm periods (generally thought to be periods of significant sedimentation and change), aeolian sedimentation was found to be minimal on the foredunes at Schiermonnigoog, The Netherlands, whereas wave erosion processes were notable (Arens, 1996b). The extent of the wet or saturated beach due to waves, tides or rainfall can be very important in determining the amount of aeolian transport to foredunes during storms.

Patterns of sand deposition and erosion are very strongly influenced by wind velocity, surface roughness, foredune topography, and vegetation cover (Carter, 1977; Hesp, 1983, 1984a, 1988b; Sarre, 1989; Raupach, 1992; Raupach et al., 1993; Wolfe and Nickling, 1993; Arens et al., 1995; Arens, 1996a; Wiedemann, 1998). Under low (but above threshold) wind speeds, deposition on the lower seaward portion of the stoss face (or dune toe) is most common where the toe is relatively well vegetated (Davidson-Arnott, 1988; Hesp, 1988b; Sarre, 1989; Davidson-Arnott and Law, 1990, 1996; Gares, 1992; Ruz and Allard, 1994a; Arens, 1996a). As the vegetation density or cover decreases, sand is transported further up stoss faces, and this can increase as foredune height and/or steepness increases (Arens, 1996a). High wind speeds combine with topographic acceleration over dunes (termed 'jettation' by Arens, 1994) to suspend grains and transport sediment far across dunes to lee slopes. On established foredune types 4 and 5 of Hesp (1988b) or Fd and Fe of Short and Hesp (1982) and Carter (1988), the vegetation cover is low, and localized transport and deposition may occur at various locations across the dunes.

Potential (calculated) versus actual sediment transport can vary widely depending on moisture levels, rainfall, fetch (varying with perpendicular versus oblique winds), vegetation cover and species type, ice and snow cover, the role of niveo-aeolian processes, and wind direction (Wal and McManus, 1993; Nordstrom and Jackson, 1994; Ruz and Allard, 1994a,b; Davidson-Arnott and Law, 1996; Arens, 1996b, 1997).

Wind direction is important in determining the degree of sand transport into, versus along the foredune (Svasek and Terwindt, 1974; Rasmussen, 1989). Onshore winds approaching a foredune at an angle of 15–60° are typically deflected and crossover the dune at a lower angle. Maximum bending of streamlines occurs when the wind approach angle is between 30° and 60° (Svasek and Terwindt, 1974; Mikkelsen, 1989; Arens et al., 1995). Winds approaching at a higher angle than 60° are generally deflected parallel to the foredune. Low to moderate angle oblique winds are responsible for localized accretion on the upwind slopes and crests of foredunes and blowouts, thereby increasing topographic variability. High angle oblique winds often result in lower stoss face accretion and

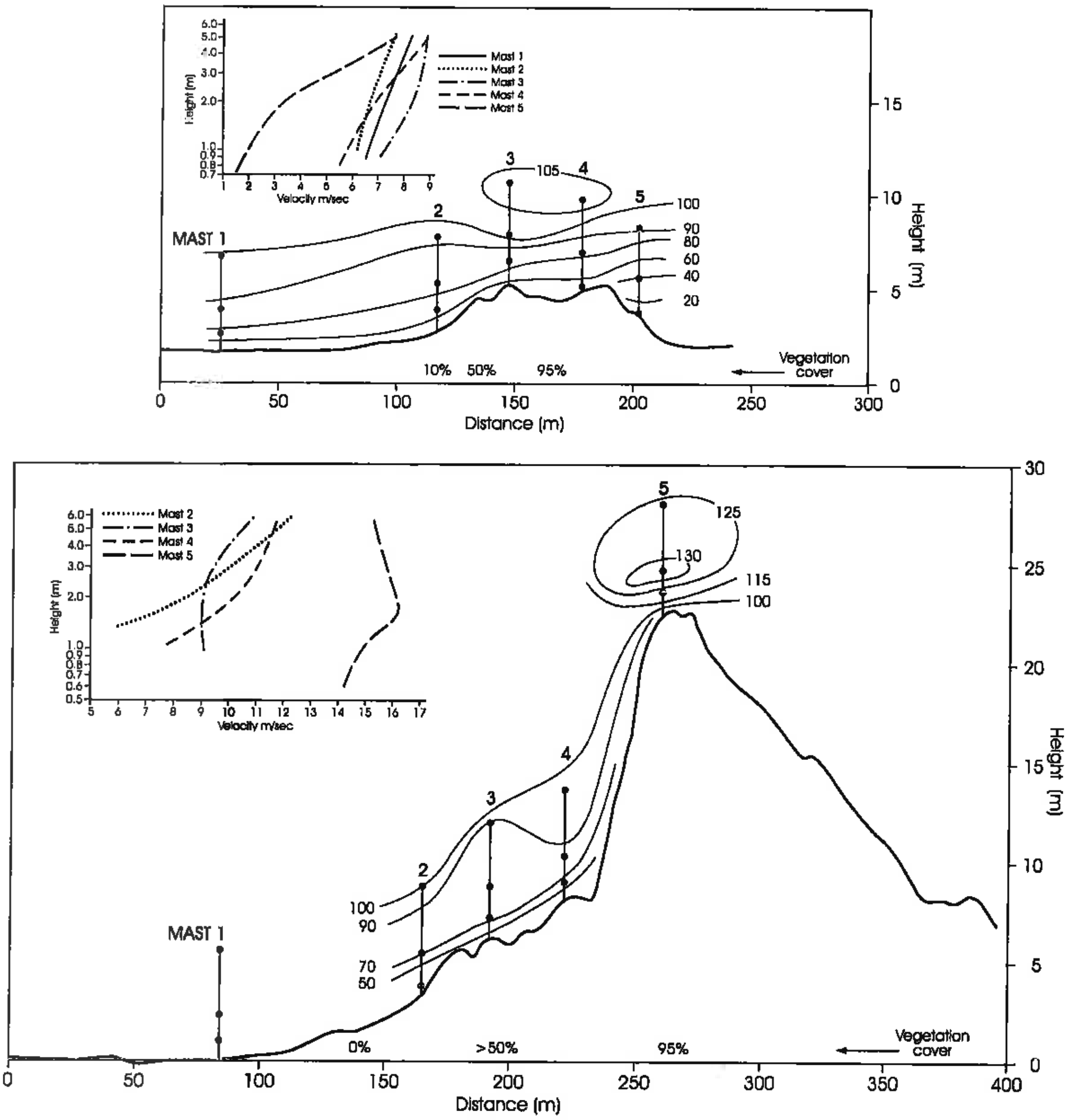


Fig. 2. Topography and percent vegetation cover on a low and a high foredune in the Netherlands. Percent wind speeds (expressed as a percentage of mast 1 velocities) and the wind velocity profiles are shown for the highest wind speeds observed. Considerable relative speed-up occurs even over low foredunes and the velocity profiles are markedly affected by foredune topography and vegetation cover. Raw data kindly provided by Dr. Sebastian Arens (see Arens, 1996a; Arens et al., 1995).

transport, and in some cases, the development of transverse dunes, which extend from the upper backshore up into the vegetated stoss face.

Offshore winds are also important, resulting in the transport of sediment from dune lee slopes and crests back to the stoss face and beach, closure of blowouts and increasing topographic variability (Svasek and Terwindt, 1974; Gares and Nordstrom, 1988; Wal and McManus, 1993; Arens et al., 1995). On the New Zealand east coast where offshore westerly winds predominate, blowouts may be formed in foredunes from both onshore and offshore winds, and the depositional lobes may face seawards or landwards (Shepherd and Hesp, in press).

3.2. *Impacts of sea/lake level change, storminess and sediment supply variation on foredunes*

There are several authors who suggest that sea level rise or fall may have a major impact on dunefield initiation or response (e.g., Thom, 1984; Thom et al., 1992; Clemmensen et al., 1996). Since the foredune is either immediately vulnerable or can potentially become relict during sea level rise and fall, it is often the response of the foredune that predicts what happens to the dunefield as a whole. Some possible scenarios are briefly examined below.

3.2.1. *Sea level fall*

Beach width increases from a small amount to a significant amount depending on beach slope (and therefore surfzone-beach type) and amount of fall.

(a) The foredune stoss slope is supplied with sediment from the wider source area and grows seawards and upwards. A new incipient foredune develops and eventually becomes an established foredune (Saunders and Davidson-Arnott, 1990). The critical factor is whether pioneer vegetation species are able to keep up with beach progradation. If vegetation density is maintained, the sediment is locked up in foredune development rather than being released landwards to initiate a dunefield phase. This is, in essence, the same as minor to major beach progradation without any change in sea level (e.g., Hesp, 1984a,b). Increased storminess has little effect because the foredune is able to recover by scarp filling and revegetation.

(b) The foredune stoss slope and crest is supplied with an excess of sediment off the wider foreshore. This leads to either local and/or more widespread burial of vegetation as sediment is delivered faster than vegetation growth can accommodate, and sediment bypasses the foredune. Subsequent blowout development (or supply of sediment through blowouts already present) and initiation of a phase of foredune instability and breakdown may occur.

(c) The foredune is severely scarped at the time sea/lake level starts to fall. Pioneer vegetation is absent (Saunders and Davidson-Arnott, 1990) and the additional supply of sediment from the widening beach is transported over the foredune and a phase of dune instability begins. Blowout, parabolic, and transgressive dunefield development is possible. A period of increased storminess would aid this process despite water level fall.

3.2.2. *Sea level rise*

Beach width decreases from a small to a significant amount depending on the amount of sea level rise and surfzone-beach type.

(a) The foredune stoss slope erodes, blowout development occurs, the crest increases in height, and the foredune gradually retreats landwards (e.g., Saunders and Davidson-Arnott, 1990; Psuty, 1992; Ritchie and Penland, 1990; Giles and McCann, 1997).

(b) The foredune is scarped, and subsequently destabilised to form blowouts, parabolics, sand sheets or transgressive dunefields of various sizes. Increased storminess merely quickens the process.

(c) Sediment supply to the system is still significant and progradation takes place despite sea level rise. A series of foredunes is built overtime to form a foredune plain (e.g., the distal ends of some barriers and spits; Davidson-Arnott and Law, 1996; Hesp and Short, 1999).

Some of these scenarios have been observed in the short-term (over 10–60 years), while others are merely suspected, but do explain observed dunefield patterns. None of these scenarios account for environments and coastal dune development where foredunes are absent or very poorly developed. What is remarkable is that scenario 1(a) (item (a) of Section 3.2.1) occurring during water level fall has the same result as scenario 2(c) (item (c) of Section 3.2.2) where water level is rising. A significant additional complication not examined here is regional wind velocities (and general climatic factors). If regional wind velocities are high, for example, foredunes may always be erosional due to regular blowout development even where sea level is falling.

3.3. *Foredune morphological spatio-temporal evolution*

Hesp (1982, 1988b) classified foredunes into five morpho-ecological stages. Carter (1988) used the original type descriptions in Short and Hesp (1982) to create a similar, somewhat broader classification. Arens (1994) and Arens and Wiersma (1990, 1994) classified foredunes according to their longer-term temporal state of accretion, stability or erosion. Saunders and Davidson-Arnott (1990) and Law and Davidson-Arnott (1990) illustrates schematic models of foredune response to high water levels, storm wave action, and seasonal patterns of sediment supply. Giles and McCann (1997) describe four types of foredunes in a predominantly erosional setting, and Ritchie and Penland (1990) illustrates the five typical washover to prograding foredune morphologies common to many barrier islands.

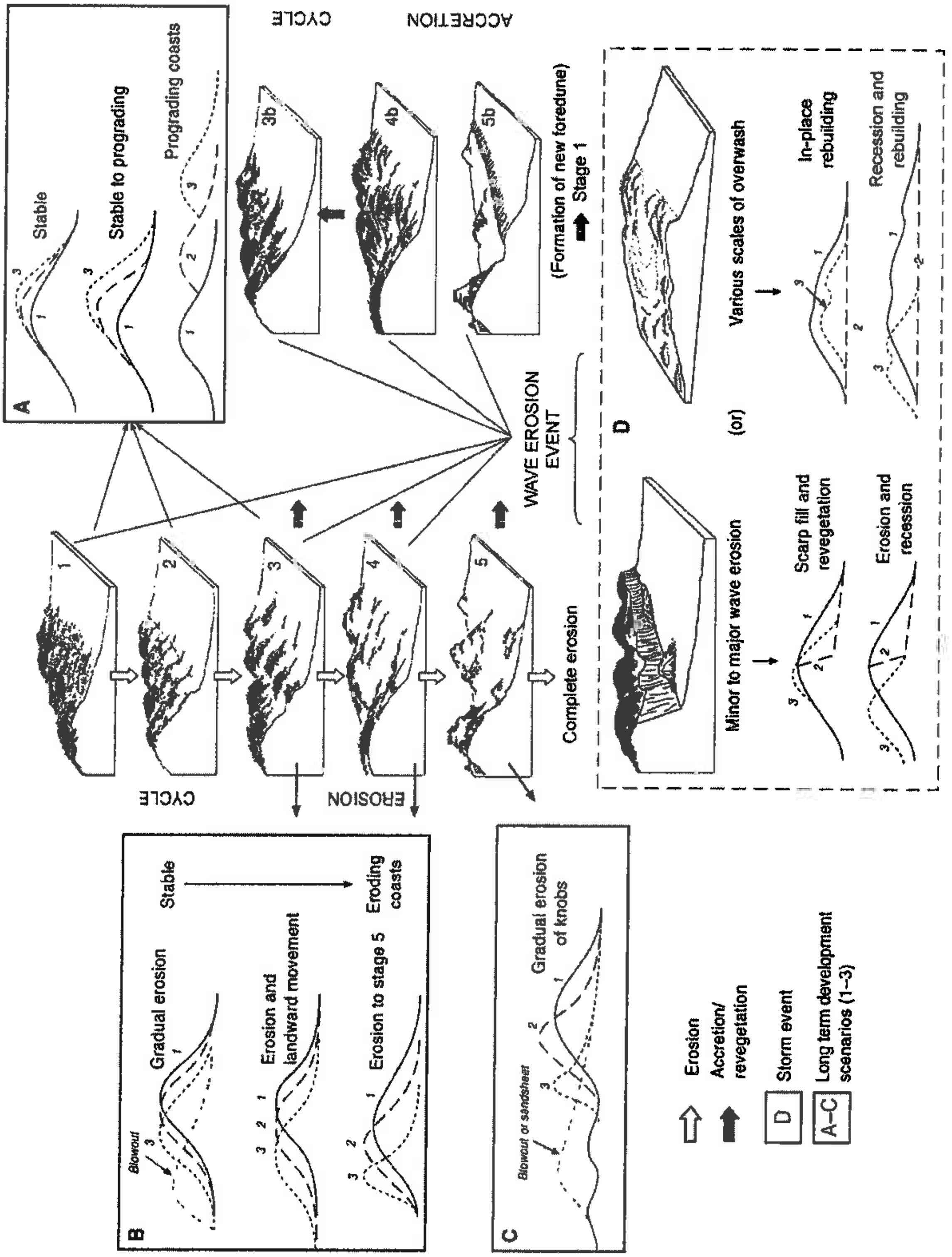
The former classifications of Hesp (1988b) and Carter (1988) comprises elements of Arens (1994) types. Fig. 3 is an attempt to meld the classifications of the authors listed above (Hesp, 1999). In this scheme, foredune stages indicate the stage a foredune may remain in for most of its existence, but also the stages through which a foredune may progress in an evolutionary sequence as aeolian erosion, reduction in vegetation cover, and possibly wave erosion takes place. This evolutionary progression may be reversed, if certain conditions, such as revegetation and stabilization, or reduced aeolian erosion (e.g., due to changes in climatic conditions) take place. It is unlikely that a stage 5 foredune would ever eventually revert to a stage 1 or 2 stage foredune, as it is difficult to envisage a situation where all topographic lows and erosion hollows are filled in by sand accretion. However, it is reasonable to expect that a stage 5 foredune might at least revert to a stage 4 foredune if the right conditions are met. Fig. 3 shows that a stage 5 foredune could continue to erode while a new incipient foredune forms to seaward, and eventually becomes a stage 1 foredune.

At any time, mild change (e.g., minor wave scarping) or catastrophic change may be introduced by moderate to severe storm events (see e.g., Saunders and Davidson-Arnott, 1990; Giles and McCann, 1997). Such events force the foredune to jump to a more potentially erosional form (e.g., major wave formed scarps, slumping and dieback of vegetation), or to partial or complete removal by overwash processes. The subsequent development of the foredune (and its stage) depends on the degree of revegetation and reestablishment.

Fig. 3 also provides a general model of the medium to long-term evolution of a coastal region dominated by foredunes experiencing long-term beach stability, erosion, or accretion/progradation. It attempts to synthesize the findings and diagrams of Hosier and Cleary (1977), Cleary and Hosier (1979), Godfrey et al. (1979), Hesp (1988b), Psuty (1988, 1989, 1992), McCann and Byrne (1989), Ritchie and Penland (1990), Saunders and Davidson-Arnott (1990), Barrere (1992), Arens (1994), Arens and Wiersma (1994), Ruz and Allard (1994a,b) and many others while accepting the inherent problems in such an attempt at synthesizing a complex system (Sherman, 1995; Bauer and Sherman, 1999). The coastal, regional evolutionary paths (based principally on sediment budgets, but also on sea level rise, fall or stability), are indicated for each foredune stage where that morpho-ecological stage is maintained, at least until a new foredune is formed to seaward of it, or it is removed by landward erosion.

With decreasing vegetation cover (stages 2 to 5), aeolian processes transport sand to higher parts of the dunes and over the leeward slopes (cf. Arens', 1994, stable foredune types; Nickling and Davidson-Arnotts', 1990 stable dunefield type). The stage 1, 2, and 3 foredunes either continue to slowly build (Arens type P1 or P3), or new foredunes form to seawards as beach progradation takes place (cf. the "progradational dunefield type" of Nickling and Davidson-Arnott's, 1990). The stage 5 foredune, being highly erosional, may retreat landwards (cf. the regressive types of Saunders and Davidson-Arnott, 1990; Arens, 1994; or Giles and McCann, 1997), or slowly disappear as aeolian erosion continues.

Fig. 3. A model of established foredune morphology, dynamics and evolutionary trends on stable, accreting, and eroding coasts. A foredune may develop towards and remain in a particular morpho-ecological stage (Types 1 to 5), or it may evolve to another stage overtime (e.g., from types 1 to 2 in the erosional cycle, or types 3 to 3b in an accretional/revegetational cycle). Wave erosion events may occur at any time leading to minor to major scarping and/or overwash. Foredunes may recover, rebuild landwards or possibly be completely removed. In the long-term, foredune may be relatively stable gradually building in place [Box A] (stable coasts), slowly build up and seawards (stable to prograding coasts), or be replaced by new foredune development (prograding coasts). Other long-term evolutionary scenarios are indicated in Boxes B and C for the increasingly erosional foredune stages.


A
Stable
Stable to prograding
Prograding coasts
1
2
3
3b
4b
5b
ACCRETION CYCLE
EROSION CYCLE
1
2
3
4
5
Complete erosion
WAVE EROSION EVENT
(Formation of new foredune) → Stage 1
D
Minor to major wave erosion
(or)
Various scales of overwash
Scarp fill and revegetation
Erosion and recession
In-place rebuilding
Recession and rebuilding
B
Blowout
Gradual erosion
Erosion and landward movement
Erosion to stage 5
Stable
Eroding coasts
C
Blowout or sandsheet
Gradual erosion of knobs
Erosion
Accretion/revegetation
D Storm event
A–C Long term development scenarios (1–3)

In the case of large-scale wave erosion and scarping or overwash, foredunes at any stage may lose a significant quantity of sediment (Carter and Stone, 1989) and follow a number of possible courses. They may be completely destroyed. They may also revegetate and reform to various degrees (Fig. 3) via echo dune development, dune crest deposition, scarp slumping, filling and revegetation (e.g., Hosier and Cleary, 1977; Tsoar, 1983; Carter and Stone, 1989; Carter et al., 1990; Saunders and Davidson-Arnott, 1990; Byrne and McCann, 1990; Wiedemann, 1998). They may gradually retreat as a steep, scarped, landward rebuilding foredune (McCann and Byrne, 1989; Carter, 1990; Borowka, 1990; Christiansen et al., 1990; Nickling and Davidson-Arnott, 1990; Psuty, 1993). Alternatively, they may be established as a new foredune zone or ridge some distance behind the erosional foredune (Carter et al., 1992).

Thus, a relatively wide range of medium to long-term responses are possible for a relatively small range of initial established foredune stages.

3.4. Further research/new directions

In regard to incipient foredunes, we need to conduct further field and wind tunnel experiments which link the aerodynamics of modelled and actual plant canopies (similar to those conducted by Wilson et al., 1998), with sand transport processes. Such research also needs to examine incipient foredune development under varying wind speeds and plant types (varying plant height, density, distribution, and plasticity).

Wilson et al. (1998, p. 705) state that the "most important scientific challenge facing micrometeorology, is to improve our understanding of, and means to calculate, the spatial variation of the turbulent wind flow over complex terrain". This is particularly true for established foredunes (and most other coastal dune types). While the findings of Arens et al. and Rasmussen (1989) have gone some way to improving our understanding of flow over vegetated foredunes, we appear to be a long way from general and specific models of flow over foredunes. This is particularly so because it is either difficult to model or physically express the actual vegetation species type and density present on each foredune examined (but not impossible—see e.g., Musick and Gillette, 1990; Musick et al., 1996) or few authors have done so.

Since foredunes are the foremost dune at the edge of the backshore, they reflect the short-, medium- and long-term surfzone-beach-dune processes operating on any particular beach (Hesp, 1982, 1988b; Short and Hesp, 1982; Psuty, 1988, 1992; Carter et al., 1990; Davidson-Arnott and Law, 1990, 1996; Saunders and Davidson-Arnott, 1990; Sherman and Bauer, 1993a; McCann and Byrne, 1994; Bauer and Sherman, 1999). At a global scale, we need to examine further the relationships between foredune development and dynamics and surfzone-beach models and sediment supply. In this, we must be particularly careful to isolate local or regional factors (sea level rise or fall; alongshore variations in sediment supply—especially in sediment deficit systems) from other variables (beach-surfzone type).

4. Foredune plains

Foredunes may gradually, or rapidly become isolated from accretion and erosion processes by the seaward development of a new incipient foredune which itself may evolve into an established foredune. The original foredune then becomes a relict foredune as it is largely or wholly removed from a foremost beach position.

Systematic beach progradation over time frames of 10s to 1000s of years may lead to the development of wide foredune plains (Hesp, 1984b, 1991, 1999). Such plains may also develop during sea level regression, and during sea level transgression as long as there is a significant sediment supply. Progressive soil development and plant community succession is common, particularly in regions with a temperate climate and siliceous sediment (Hesp, 1991; McLachlan, 1991). Examples may be found around the world (Hesp and Short, 1999) including South Africa (Weisser and Backer, 1983), Ireland (Carter and Wilson, 1990), Australia and New Zealand (Hesp, 1984a; Shepherd, 1990), England (Salisbury, 1952; Ranwell, 1972), European coasts (e.g., Carter, 1990; Arens, 1994), Russia (e.g., Zenkovich, 1967), the USA east and south coasts (e.g., Nordstrom and Jackson, 1994; Otvos, 1995), Sweden (known as 'sand hammaren'; Wallen, 1980), arctic and subarctic coasts (Martini, 1986; Ruz and Allard, 1994a,b; Hellemaa, 1998; Giles and King, in press), and South America (Suhayda et al., 1975).

Many foredune plains around the world resemble beach ridge plains in plan form and morphology, and vice versa. It is clearly important to establish the genesis of the form by stratigraphic, stratification, and process studies prior to ascribing an origin or term to the feature. It is quite wrong, in this authors opinion, to term all wave built berms, storm ridges, and foredunes, "beach ridges" as Otvos (2000) suggests.

5. Blowouts

5.1. Definition, types and spatio-temporal variability

A blowout is a saucer-, cup- or trough-shaped depression or hollow formed by wind erosion on a preexisting sand deposit. The adjoining accumulation of sand, the depositional lobe, derived from the depression, and possibly other sources, is normally considered part of the blowout (Glenn, 1979; Carter et al., 1990; Hesp, 1996).

Blowout morphology may be highly variable. Ritchie (1972) defined four types of blowouts including cigar-shaped, v-shaped, scooped hollow, and cauldron and corridor. Smith (1960) notes that blowouts may range from pits to elongated notches, troughs or broad basins. Cooper (1958, 1967) defined two primary types, namely saucer and trough blowouts, and although there exists a wide range of types in aeolian environments, many blowouts can be classified into one of these two types. Figs. 4 and 5 illustrate these two types. Saucer blowouts are semicircular or saucer-shaped and often appear as shallow dishes. Deeper cup- or bowl-shaped blowouts may evolve from these. Trough blowouts are generally more elongated, with deeper deflation floors and basins, and with steeper, longer erosional lateral walls or slopes (Fig. 5).

In nature, there is a large degree of spatial and temporal variability in blowout morphologies. The initial shape, size, and location of blowouts and their subsequent development may depend on several factors. For example, Smith (1960) notes that blowouts initiated on the broad crests of foredunes are generally shallow saucer types, while those initiated on steep stoss faces are generally elongate trough types. While observations in Australia and New Zealand confirms this view (Carter et al., 1990), there are many places where it is not obvious why the blowout is one particular morphology rather than another.

Once initiated, the subsequent morphologic development may depend on the size of the initial constriction (see below), the height and width of the dune in which the blowout is developing, the degree and type of vegetation cover (Melton, 1940; Esler, 1970), the magnitude of regional winds (Cooper, 1958; Jennings, 1957; Marta, 1958; Davies, 1980), and the degree of exposure to winds from various directions (Jennings, 1957; Gares, 1992; Gares et al., 1979; Gares and Nordstrom, 1987; Shepherd et al., 1997).

Blowouts have been described in the literature since at least 1898 (see Cowles, 1898 and review in Carter et al., 1990). Along with 'links' and 'machair', they have been utilised by humans for sport for generations, and are the "prototype of the golf bunker" (Cooke et al., 1993, p. 360). Blowouts have been observed in desert and semiarid terrains where they occur as wind-scoured gaps in transverse dunes (e.g., Bagnold, 1941), as evolutionary forms, which develop into parabolic dunes (e.g., Melton, 1940; Verstappen, 1968), as secondary forms developed on linear dunes (e.g., Eriksson et al., 1989) and on other dune types (Hack, 1941), and particularly as saucer-shaped deflation depressions on partially vegetated and/or semiarid to hyperarid sand plains associated with human, animal, and natural disturbance. They have also been described from subantarctic and glacial environments (e.g., Adamson et al., 1988).

5.2. Initiation

Blowouts are common in coastal dune environments, particularly where beaches and foredunes are occasionally eroded and/or receding, but also occur in stable and accretionary environments where wind and wave energy is high.

The blowouts may be initiated in a variety of ways including: (1) wave erosion along the seaward face of the dune; (2) topographic acceleration of airflow over the dune crest; (3) climate change; (4) vegetation variation in space or change through time; (5) water erosion; (6) high velocity wind erosion, sand inundation and burial; and (7) human activities.

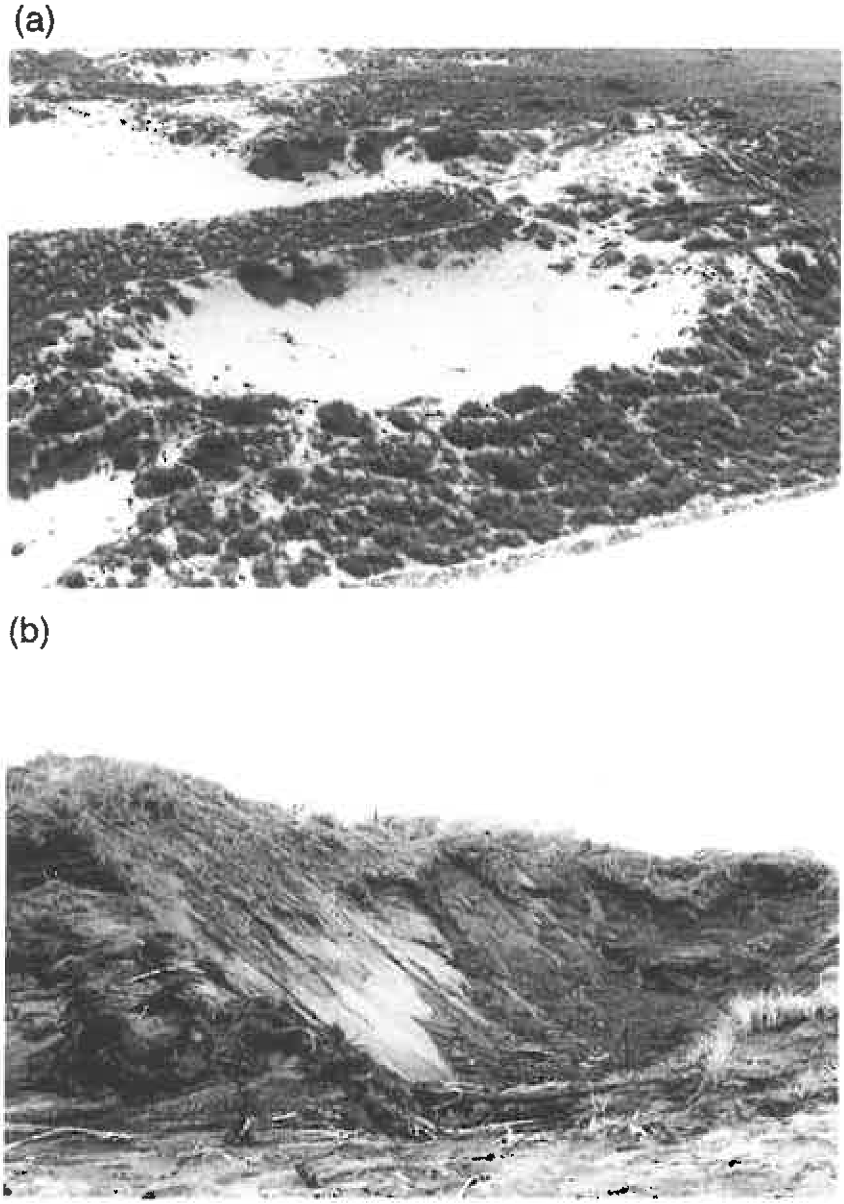


Fig. 4. (a) Saucer blowout developing in the crest of a relict parabolic dune. The primary depositional lobe is to the right, but deposition also occurs on the left-hand margin when offshore and onshore winds occur. (b) A deep, narrow trough blowout showing the steep, collapsing northern wall, and the upwind erosional stoss slope of the depositional lobe (at right).

Wave erosion along the seaward face of the dune generally narrows the dune sufficiently to cause a breach in the dune, as follows.

(1) Irregular scarp slumping typically occurs following laterally continuous alongshore wave erosion of foredunes or other dune types (see e.g., Fig. 10 in Psuty, 1989). Subsequent airflow acceleration and deflation up the slump bowl results in blowout development. Alternatively, wind erosion of poorly vegetated "weak spots", or transport through low points

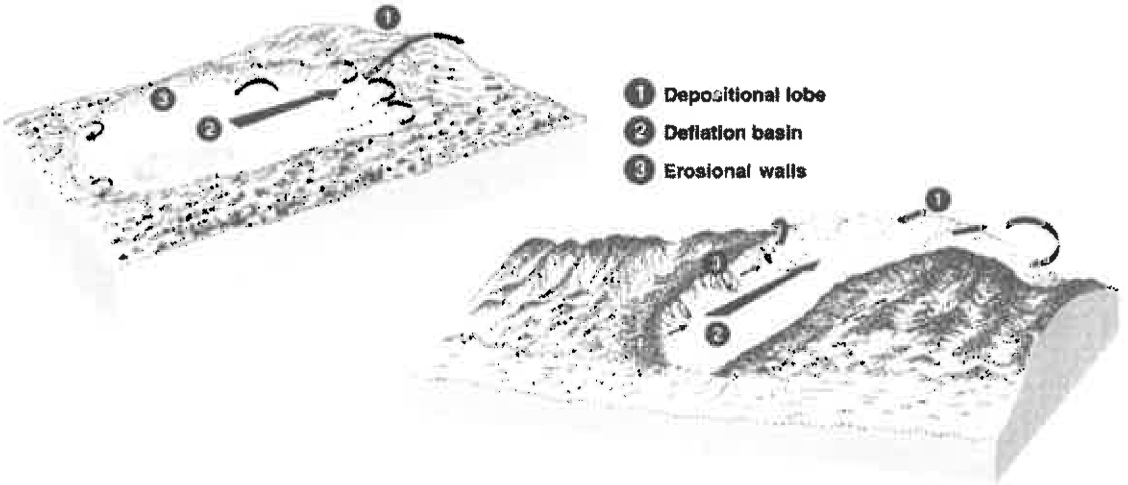


Fig. 5. Schematic diagrams of a saucer and a trough blowout with typical wind flow patterns indicated.

along the scarp crest may occur (Ritchie, 1972; Carter, 1990; Saunders and Davidson-Arnott, 1990; Giles and McCann, 1997).

(2) Discontinuous, localised, arcuate, concave scarp faces are produced by discrete rip erosion, which may become sites for local flow acceleration and blowout formation (Hesp, 1982, 1996).

(3) Continuous longshore wave scarping may result in the complete removal of the pioneer vegetation zone. Subsequent dieback of the then exposed 'intermediate' shrub and woodland vegetation leads to a reduction in surface cover and the potential development of blowouts (Hesp and Hyde, 1996).

(4) Overwash hollows and fans may develop into blowouts, if the vegetation cover is slow in reestablishing (Leatherman, 1976; Godfrey et al., 1979; Ritchie and Penland, 1990; Saunders and Davidson-Arnott, 1990).

There are numerous ways, in which topography accelerates airflow often as a function of the irregular nature of the dune morphology and these may produce blowouts.

(1) In the cases cited above topographic acceleration of wind flow over scarps and cliffs, and through arcuate bowl-shaped topography, is an integral process in the development of the blowouts. Blowouts, however, may also be initiated purely by topographic acceleration of flow.

(2) In the Head of Bight region in southern Australia, blowouts are systematically formed on the downwind edge of arcuate, embayed, high cliffs. Adjacent linear (straight) cliff sections do not have attendant blowouts (Hesp and Hyde, 1996).

(3) Where topographic high spots alternate with topographic lows along, for example, a foredune crest, aerodynamic flows will be laterally and horizontally compressed and accelerated and erosion may result (Esler, 1970; Ranwell, 1972; Goldsmith, 1978; Carter, 1988). This may occur in conditions where winds blow onshore or offshore (e.g., Gares and Nordstrom, 1995).

Climate changes in the past have contributed to blowout development and may be expected to do so in the future.

(1) Blowouts may be initiated where the vegetation cover is weakened, reduced or dies due to a prolonged dry or arid period (Jelgersma and van Regteren Altena, 1969; Ahlbrandt et al., 1983; Thom et al., 1994). Pluis (1992) found that blowouts developed following long periods with dry weather and strong winds followed by short, heavy rainfall.

(2) More windy periods occur during certain ENSO phases. In New Zealand in 1991, El Niño westerly winds were much stronger than the average, and observations indicates that significant blowout

development took place during that year compared to subsequent years.

Vegetation density varies both spatially and temporally and these variations contribute to blowout initiation.

(1) Where the degree of vegetation density, cover or species type varies alongshore, areas of low vegetation cover may be eroded in moderate to high velocity events (Hesp, 1982; Tinley, 1985). A lack of; or reduction in vegetation cover is considered by many authors to be a critical factor in blowout initiation (e.g., Melton, 1940; Jennings, 1957; Steers, 1964; Bird, 1984; Tinley, 1985; Carter et al., 1990).

(2) Vegetation dieback due to soil nutrient depletion may lead to the disintegration of the soil, subsequent deflation and saucer blowout development (Jungerius et al., 1981).

(3) Localized aridity (e.g., on dune crests) may result in a reduction in vegetation cover and blowout development (Rutin, 1983). Dune crest sites (especially on high dunes) are also sites of maximum flow acceleration and high potential erosion, thinnest soil development, and often high salt spray inundation which all act to increase the potential for erosion.

(4) The activities of animals may be significant in reducing or removing the vegetation cover on coastal dunes. Rabbits are commonly cited as initiators of surface erosion (Ritchie, 1972; Jungerius and van der Meulen, 1988), but sheep and cattle (Thom et al., 1992), bears (Martini, 1981), and various other domesticated, feral and wild animals (e.g., goats and kangaroos) have been implicated.

Water erosion is not widely recognized as a mechanism of blowout formation, but it may contribute. Moderate to intense rainfall events may result in surface erosion by sheet wash and raindrop splash, and rills and gullies with attendent debris fans may be formed (e.g., Thompson and Bowman, 1984). Blowouts may be formed where the surface vegetation cover is reduced and where wind may be accelerated within such gullies (Jungerius and van der Meulen, 1988).

Very high velocity winds and hurricanes may remove, or undermine, erode, and bury vegetation. Blowouts may then be initiated on the bare sand surface (Marta, 1958; Bird, 1974).

Finally, the impacts of humans on coastal dunes can be significant. Dune erosion and/or blowouts have developed as a result of pedestrian trampling and track creation (Carter, 1988; Pye, 1990; Bate and Ferguson, 1996), forest felling (Jelgersma and van Regteren Altena, 1969), offroad 4WD activity (Brodhead and Godfrey, 1977; Godfrey et al., 1978), housing and resort development (Nordstrom and McCluskey, 1984), sand extraction and military training (Marston, 1986), and fires (Tinley, 1985).

5.3. Flow dynamics

The first study of wind flow within a blowout appears to have been carried out by Landsberg and Riley in 1943. This, and a subsequent study by Olson (1958a,b) (see Fig. 47, p. 146 of Ranwell, 1972), demonstrated that winds are topographically accelerated over high dune terrain, that flow separation is common over lee slopes, and that jet flow occurs in some circumstances.

Hails and Bennett (1981) conducted flow experiments within a saucer blowout in South Australia. They found that under conditions where the approach flow was at right angles to the blowout entrance, flow within the blowout formed a large reversing rotor. When approach winds were oblique, but more normal to the blowout, they observed the highest wind speeds on the deflation floor and topographic steering of flow by the blowout topography.

Sand movement within blowouts has been examined by a number of authors. Harris (1974) monitored sand movement within three blowouts in South Wales measuring surface changes from 1 to 107 cm over a year. A detailed study of surface change in six, shallow, mostly saucer blowouts in 'De Blink' was conducted by Jungerius et al. (1981). They found that sand erosion and deposition occurred in a complex manner as a result of varying wind speeds and directions and other climatic factors, although, in general, deflation basins deepened in most of the blowouts over the study period (cf. their Fig. 16). Similar findings were described by Jungerius and van der Meulen (1989) (cf. van der Meulen and Jungerius, 1989). In particular, they found that blowouts commonly grew in length upwind against the prevailing wind. Lancaster (1986) examined saucer blowouts on a coastal plain in the Elands Bay area, South Africa. Lancaster found that most erosion and deposition took place on the "dune fronts" (i.e., depositional lobes) and blowout throats, with relatively little taking place in the blowout center.

Pluis (1992) analysed the relationships between deflation in a saucer blowout and near surface wind velocity at Meijendel in the Netherlands. He found that less erosion occurred in the windiest (winter) period (higher surface moisture levels) than in summer. Deflation rates were higher than indicated by nett, measured surface change due to the delivery of rainwashed sand supply from adjacent slopes. Wind direction and velocity were considered to be of major importance in determining the degree of surface change.

Jungerius (1984) constructed a 2D computer model, which simulated the effects of wind gusts along the central axis of a saucer blowout. After successfully modeling a shallow blowout profile, he concluded that "blowouts could result from the cumulative effect of erosive wind gusts" (p. 511).

Gares and Nordstrom (1987, 1995) examined wind flow and sand transport in a small, enclosed, saucer blowout located in a lee foredune swale. They found that windspeeds were lowest in the blowout base and highest on the upwind foredune crest, and along the southern rim of the blowout. The greatest sand transport actually took place within a small gap (incipient blowout?) in the more seaward foredune crest.

Hesp (1996) and Hesp and Hyde (1996) examined flow dynamics and sand transport in a trough blowout. Measurement of wind speeds up the blowout axis under axis-parallel winds indicated that the flow was topographically accelerated, and displayed a marked nonlogarithmic behaviour with single and double jets. Relatively, high speed flows occurred along the deflation basin and lateral erosional walls, corkscrew vortices over the lateral erosional wall crests, and flow over the depositional lobe crest experienced rapid flow deceleration, lateral expansion, and flow separation. There was considerable variability in the flow structure because of the variable presence of vegetation, and the turbulent roller vortices present (cf. Robertson-Rintoul, 1990).

During oblique approach wind conditions, there was significant topographic steering of wind within the blowout by the erosional walls, and this increased as approach winds become more oblique to the blowout entrance. The degree and complexity of steering was dependent on the blowout topography. Recent work (Hesp and Pringle, 2001) indicates that high angle oblique approach winds, normal (alongshore) approach winds, and even offshore winds are "sucked" into trough blowouts and transport sediment at up to 100° opposite to that of the approach wind. This may be because the blowout is a very low-pressure zone, there can be significant flow separation over the foredune/blowout wall, and deflection of approach flows by the foredune.

Byrne (1997) examined seasonal sand transport patterns in a trough blowout in Ontario. She found a general pattern of erosion in winter and fall (plants dead or dormant), and slight accretion during spring and summer. The blowout faced northwest, but prevailing winds were south and SSW and topographic steering of flow was common. Maximum sand transport occurred on the upper, erosional, windward slopes of the depositional lobe.

Fraser et al. (1998) examined wind flow patterns under different wind directions in a blowout on the south shore of Lake Michigan. They found that during up-axis onshore winds, the flow separated as it entered the blowout and a helical flow formed. A zone of stagnation developed up the depositional lobe and flow redeveloped at the depositional lobe crest. Wind flow during oblique approach winds resulted in significant flow separation within the blowout and large helical vortices were generated.

Hesp and Hyde (1996) found that within blowout wind speeds can be significantly greater than remotely sensed wind speeds. Estimates of potential sand transport within a blowout indicate that sand transport rates estimated from regional or remotely sensed wind data may be up to two orders of magnitude lower than actual within—blowout rates.

5.4. Blowout development, geomorphology and evolution

Flow separation and/or deceleration around the entrance regions of trough blowouts is sometimes observed and echo dunes and nebkha may be formed in these entrance areas (see e.g., Fig. 15 in Carter et al., 1990; Gares, 1992; Fraser et al., 1998).

The topographically accelerated flow and common presence of jets in trough blowouts results in maximum erosion potential along the deflation basin floor (Hesp and Hyde, 1996; Fraser et al., 1998). In trough, and many saucer blowouts, deflation basins tend to continue to erode until a base level such as the seasonally lowest water table level, a calcrete (or other cemented/indurated) layer, or an armoured surface such as a pebble, shell, pumice or artifact surface (Ritchie, 1972; Carter, 1976; Hesp and Thom, 1990; Gares, 1992) is reached. Over time, blowouts may become too wide for effective creation of jets and sand transport may lessen. In contrast, flow deceleration rather than acceleration apparently occurs in the deflation base of shallow saucer blowouts.

Where upper slopes are partially to fully vegetated, the unvegetated (or less vegetated) slope sediment is removed, the erosional wall is oversteepened, slumping occurs, and the wall retreats (Gares and Nordstrom, 1987; Carter et al., 1990; Gares, 1992). Flow within the deflation basin then results in downwind transport and removal of the slumped sediment. Lateral expansion of trough blowouts generally occurs by this process. In saucer blowouts, observations indicate that reversing flows are common over the surrounding erosional walls. Such flows lead to undermining, wall collapse and retreat. Saucer blowouts are more likely to expand upwind by this process compared to trough blowouts (Hesp and Hyde, 1996; Fig. 4).

Slump blocks, debris slopes and fans, remnant knobs, vegetation stumps and fallen or exhumed logs, and palaeosols within blowouts increase flow complexity, effect sand transport paths and patterns, and influence blowout evolution (Carter et al., 1990; Byrne, 1997; Fraser et al., 1998).

There is often flow "escape" out the top of the lateral walls where roller vortices transport sand from the upper part of the walls laterally out over the wall crests forming rim dunes (Carter et al., 1990). Maximum transport occurs up the middle axis of trough blowout depositional lobes and radially decreases leading to the development of parabolic-shaped depositional lobes. Rapid deceleration downwind of either end (upwind or downwind depending on wind direction) of saucer blowouts leads to the development of short, wide, radial depositional lobes (Carter et al., 1990; Gares, 1992; Gares and Nordstrom, 1995).

The evolution of blowouts, and in particular, their orientation, may be influenced to various degrees by the degree of variation in regional approach winds strength and direction (Gares and Nordstrom, 1995; Byrne, 1997). In trough blowouts, it is common to see skewed blowout orientations, where the regular occurrence of an oblique approach wind has resulted in the preferential erosion of one erosional wall compared to the opposite wall (Byrne, 1997). In saucer blowouts, observations indicate that flow separation around the blowout walls for any given wind direction, results in undermining, wall collapse, blowout expansion, and depositional lobe development at various locations (Fig. 4), making it very difficult to predict long-term evolution and correlate dune development with regional wind conditions. Thus, the greatest erosion zones are located around the crests of the erosional walls in saucer blowouts as Jungerius et al. (1981) and others have found.

Blowouts may evolve in various ways, the pattern depending on wind speeds, dominant wind direction, vegetation types and revegetation processes and potential, magnitude and occurrence of beach/dune erosion and storm events, and barrier/beach status (receding, stable, prograding). Many blowouts become larger overtime and may evolve into parabolic dunes (Carter, 1990; Carter et al., 1990; Battiau-Queney et al., 1995). Blowouts may advance through evolutionary stages from erosional notches to incipient blowouts to large blowouts to decaying and revegetating blowouts (Gares and Nordstrom, 1995). On some high energy wind coasts, blowout closure by incipient foredune development across the throat may occur, but the blowout continues to enlarge and evolve into a parabolic dune. Subsequent dune erosion and removal of incipient foredunes can lead to reactivation of blowouts.

5.5. Blowout dynamics and morphometrics

Hesp (1982) theorised that trough blowouts may behave somewhat like rivermouths debouching into ambient lake waters or nearshore waters. Both commonly have relatively narrow, constrained channels or troughs, within which the flow is typified by turbulent jet flows. Mid-axis flows are the regions of highest velocity, the velocity profile transverse to the centreline conforms to a Gaussian distribution decreasing outwards from a maximum at the centreline, and when the flow exits the channel or trough, rapid deceleration and flow expansion takes place leading to the deposition of parabolic-shaped deltas or depositional lobes.

Borichansky and Mikhailov (1966) and Wright (1977) indicate that in the case of rivermouths and delta formation, the following physical laws and morphometric properties apply: (i) deceleration and lateral expansion increases as the depth of the outlet decreases (plane turbulent jet diffusion); (ii) the distance from the outlet to the bar (or delta) crest decreases, and (iii) the bifurcation angle increases as the depth to width ratio of the river mouth decreases (mouth widens or depth decreases).

The Manawatu coast (lower west coast, North Island, NZ) provides an excellent region to examine whether blowouts follow similar 'rules', since there are on average 20 blowouts/km of foredune length. In a 2-km stretch, extending north from Foxton Beach, a variety of morphometric data was gathered in 26 blowouts. Fig. 6 indicates some preliminary results from these blowouts. Note that the relatively large number of small blowouts is probably biasing the results. The length of blowout deflation basins and blowout depositional lobes are quite strongly correlated (Fig. 6a). Apart from the very small blowouts (less than 20 m deflation length), there is almost a one to one relationship. This presumably reflects an evolutionary trend, where as the deflation basin extends, the sediment derived from the deflation zone and the stoss slope of the depositional lobe is transported further down the depositional lobe, thereby extending it also.

Fig. 6b indicates that for the limited data collected, the midblowout depth is not correlated with depositional lobe length. If the analogy above follows, the downwind length of the blowout should decrease as midblowout depth decreases. Blowout width is reasonably correlated with depositional lobe length, such that as width increases, depositional lobe length increases by a ratio of around 1:2 (Fig. 6c). Trough blowouts have a ratio of 1:4, while saucer blowouts have a variable ratio of approximately 1:2 to 1:3 (Fig. 6c). Again, this reflects an obvious evolutionary trend: as blowouts become wider, they generally become longer. While the blowouts examined here do not reflect the trends indicated by Wright (1977), there

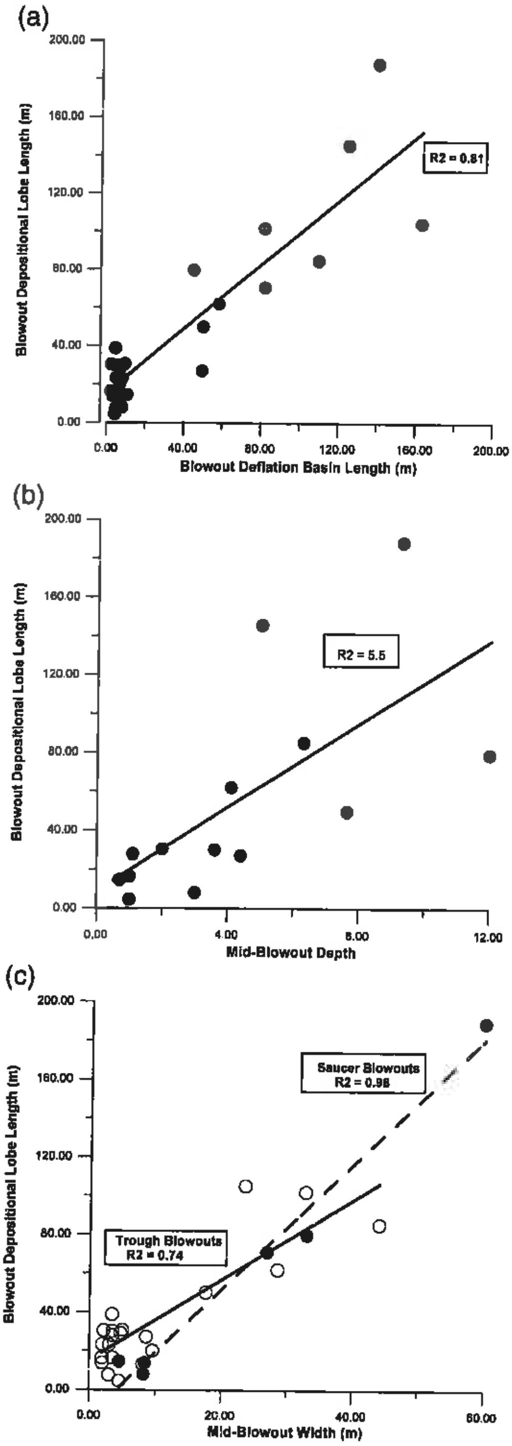


Fig. 6. Morphometric data for blowouts along the Manawatu coast, New Zealand. (a) Deflation basin length versus depositional lobe length. (b) Mid-blowout depth versus depositional lobe length. (c) Mid-blowout width versus depositional lobe length.

are some scaling relationships, which warrant further investigation. Further analyses need to be tempered by thoughts that the entire analogy is incorrect, that the flow in blowouts is considerably more complex than in the case of simple rivermouths, or that longer term evolutionary trends dominate over short-term jet flow behaviour in controlling blowout morphology.

5.6. New research/future directions

While saucer and trough blowouts are common, there is a large degree of spatial and temporal variability in blowout morphologies. As yet, we still know little about the role of various factors such as topographic position, wind regime, wind directional variability, and vegetation cover and species in determining blowout type and morphological evolution.

Hesp and Hyde (1996) stated that some of the major apparent differences between saucer blowouts and trough blowouts were that the latter (i) displayed high to jet velocities in the deflation basins (and in many parts of the blowout), (ii) usually eroded down to a maximum base level, and (iii) could continue to develop (or migrate on the depositional lobe front) downwind for significant distances (and possibly develop into parabolic dunes). Saucer blowouts tend to exhibit low rates of erosion in the deflation basin, limited deflation depths and maximum lengths (Jungerius et al., 1981; Lancaster, 1986; Gares and Nordstrom, 1987; Jungerius and van der Meulen, 1989; Pluis, 1992). In reality, we do not know if these differences are related to fundamental differences in flow dynamics between the blowout types, or other controlling factors.

Very few detailed flow and sand transport experiments have been conducted in either trough or saucer blowouts. It is necessary to further examine and quantify the occurrence and role of helicoidal, corkscrew or vortical flow in trough blowouts, and the nature of wind flow within saucer blowouts. Further research is required on analyzing the relationships between regional wind velocities and local, within blowout velocities and sand transport, and the nature of saucer blowout evolution (e.g., why some blowouts apparently do not respond to storm winds in the way we might expect).

We know little about the dynamics of natural vegetation processes and change in blowout dune environments, rates of dune erosion/movement in different wind regimes and different vegetation communities.

Furthermore, comparative studies are required in order to compare dune evolution, dynamics and migration rates on different coasts—windy coasts, low energy coasts, eroding, stable, and accreting coasts. Only then we be able to define, for example, what is a low rate versus a high rate of dune development and migration.

6. The big picture—foredunes, blowouts, and coastal dunes

Bauer and Sherman (1999, pp. 99–100) were of the view that one of two most pressing needs for advancing the state of the science was the following:

> ...the development of a robust conceptual framework or grand, unifying theory that can serve as the template upon which we may inscribe our piecemeal contributions.

Jack Davies once told me that Australia represented the best laboratory in the world for studying beach and dune evolution, morphology, and dynamics. All tidal ranges, most climatic types, all sediment sizes, virtually the entire range of wave and wind energy, and every beach and dune type are represented. In addition, sediment supply during the Holocene transgression was not generally limited and sea level has been roughly stable (near or at stillstand) for around 7000 years. Thus, barrier and dune development has been largely driven by wave and wind energy variations (although a minimum sediment supply is, of course, required) and the wave-beach-dune model of Hesp (1982, 1988a), and Short and Hesp (1982) reflects this (see Sherman and Bauer, 1993a,b, and Bauer and Sherman, 1999 for reviews).

The USA east coast represents another laboratory (and is similar, e.g., to the Gulf Coast; The Netherlands, Germany) where the system is generally sediment deficient, and sea level has continued to slowly rise since 5000+ years ago. In this environment, Psuty (1992) sees little utility in the wave-beach-dune model, and prefers a model driven by sediment supply. In his construction, blowouts and parabolic dunes, for example, are created in "negative" beach and foredune sediment supply conditions. While this scenario works for some USA barriers, blowouts and parabolic dunes can be, and have been initiated anywhere there is foredune scarping, or where wind energy is sufficient, even just occasionally, to erode some part of a foredune or other dune, regardless of sediment supply. For example, the largest parabolic and transgressive dunefield in NZ (the Manawatu: 18 km wide maximum, 150 km long) has been formed, and continues to form along a prograding, but high wind energy coast.

The Great Lakes provide us with another laboratory where sediment supply varies alongshore and over various time scales (months to years), and where lake levels can vary by 1+ m (Davidson-Arnott and Law, 1996).

So how do we incorporate these various coastal environments and their attendant dominant process signatures into a grand unifying theory? I am reminded of my father's old HMV bakerlite radio, which had a row of large tuning knobs along the front. Perhaps in a new model, each of five knobs would represent a major controlling variable: wave energy/surfzone type; wind energy; sediment supply; sea level state; and climatic region/vegetation cover. By tuning four of the knobs at a constant position (low, moderate or high), we can tune the remaining knob to attempt to understand the control each knob has in the system. Then, just maybe, we might be in a position to better understand coastal dune evolution in different coastal settings. In order to do this, we first need to classify our coastal environments using a universal system: i.e., when we refer to "high" wind energy or "high" sediment supply, we need a common system for determining the values and bounding limits placed on "high". Secondly, we need to obtain and collate data on each of the five variables above (and probably other variables also; e.g., tidal range) in order that reasonable comparative studies can be conducted.

7. Conclusions

Foredunes and blowouts occur almost everywhere in the world from the tropics to the arctic. Throughout this review, I have attempted to indicate some research aims that might be useful in progressing our knowledge of the functioning of coastal dunes. These generally relate to specific questions and problems associated with each dune type.

At the big picture level, we need to continue to examine the meso-scale interactions between surfzone, beach and dune dynamics, sediment supply, sea level changes, and barrier histories.

Finally, there is a need for greater crossover and interaction between subdisciplines and fields. With a few exceptions, the "aeolian" and "desert" research scientists are not apparently reading (or at least referencing) the "coastal" scientists literature and vice versa to the cost of better communication and scientific endeavour and progress.

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