Journal of Coastal Research	28	1	112–122	West Palm Beach, Florida	January 2012

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The Impact of *Ammophila arenaria* Foredune Development on Downwind Aerodynamics and Parabolic Dune Development

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ABSTRACT

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HART, A.T.; HILTON, M.J.; WAKES, S.J., and DICKINSON, K.J.M., 2012. The impact of *Ammophila arenaria* foredune development on downwind aerodynamics and parabolic dune development. *Journal of Coastal Research,* 28(1), 112–122. West Palm Beach (Florida), ISSN 0749-0208.

Ammophila arenaria (marram grass) is highly invasive in temperate, southern hemisphere dune systems. *Ammophila arenaria* is known to form relatively large, uniform foredunes. However, the impact of *A. arenaria* invasion on adjacent transgressive dune systems is relatively poorly understood. This study (1) documents foredune and parabolic dune development and *A. arenaria* invasion at Mason Bay, New Zealand and (2) investigates the impact of *A. arenaria* foredune development on aerodynamic flow patterns and resultant parabolic dune sedimentary dynamics.

Over a period of 40 years, *A. arenaria* invasion in Mason Bay transformed foredune morphology from an irregular and hummocky morphology to a continuous, densely vegetated foredune complex up to 11 m high. An incipient parabolic dune, initiated from a large blowout, was present prior to *A. arenaria* invasion. Parabolic dune development occurred through downwind migration of the depositional lobe at an average of 24 m y^{-1} between 1958 and 1978. Subsequent parabolic development occurred through decreased depositional-lobe migration (0.79 m y^{-1} between 1989 and 2002) and deflation surface enlargement as *A. arenaria* increased in extent and density across the dune. Significant vertical accretion and increased stability of the foredune occurred during this period.

Computational fluid dynamics was used to model flow over foredune topographies associated with the native sand binder *Desmoschoenus spiralis* and the exotic *A. arenaria*. *Ammophila arenaria* foredune development has significantly altered the aerodynamic and sedimentary dynamics of the parabolic dune. During onshore SW flows, higher sheltering was modelled in the lee of the *A. arenaria* foredune with velocities reduced to between 60% and 70% of ambient across the deflation surface. Flow recovery downwind of the *A. arenaria* high foredune was 81%, compared to 94% for the *D. spiralis* low foredune with flow influenced up to 40–45 times the *A. arenaria* foredune height. Reduced flow velocities, increased foredune stability, and stabilisation of the parabolic dune have resulted in a transition from a highly mobile to a highly stable dune.

ADDITIONAL INDEX WORDS: Desmoschoenus spiralis*, computational fluid dynamics (CFD), sedimentary dynamics.*

INTRODUCTION

Ammophila arenaria (L.) Link (marram grass) is now widely established in many temperate transgressive coastal dune systems outside its natural range (Hertling and Lubke, 1999; Heyligers, 1985; Huiskes, 1979; Johnson, 1982; Owen, 1996; Pickart and Sawyer, 1988; Wiedemann, 1987), including the west coast of the United States, South Africa, southeastern Australia, and New Zealand. In this case the term "transgressive" means mobile or migrating dunes or sand sheets. *Ammophila arenaria* has been associated with the development of relatively massive and continuous foredunes, in many cases where none previously existed (Cooper, 1958; Heyligers, 1985). For example, the development of stable foredunes up to 10 m in height along the Oregon coast has been associated with the invasion of *A. arenaria* (Wiedemann and Pickart, 1996). In comparison, foredunes formed in association with indigenous sand binders are often low and discontinuous features (Holland, 1981). In New Zealand, *A. arenaria*–dominated dunes are generally steeper and higher than dunes formed in association with the indigenous foredune species *Desmoschoenus spiralis* (A. Rich.) Hook. f. (pingao or pikao) and *Spinifex sericeus* R. Br. (see Esler, 1970). The tussock habit of *A. arenaria* creates eddies or vortices in the lee of the plant, forming pyramidal shadow dunes (Hesp, 1981), as well as encouraging high rates of deposition, resulting in rapid dune development.

To date, few studies have investigated the impact of *A. arenaria* on foredune development or on the dynamics of the transgressive dune systems that lie downwind. Here we use the term "transgressive" to indicate a dune system comprising mobile or migratory dunes. The development of large deflation surfaces and reduced rates of parabolic dune migration along

DOI: 10.2112/JCOASTRES-D-10-00058.1 received 13 April 2010; accepted 19 April 2010.
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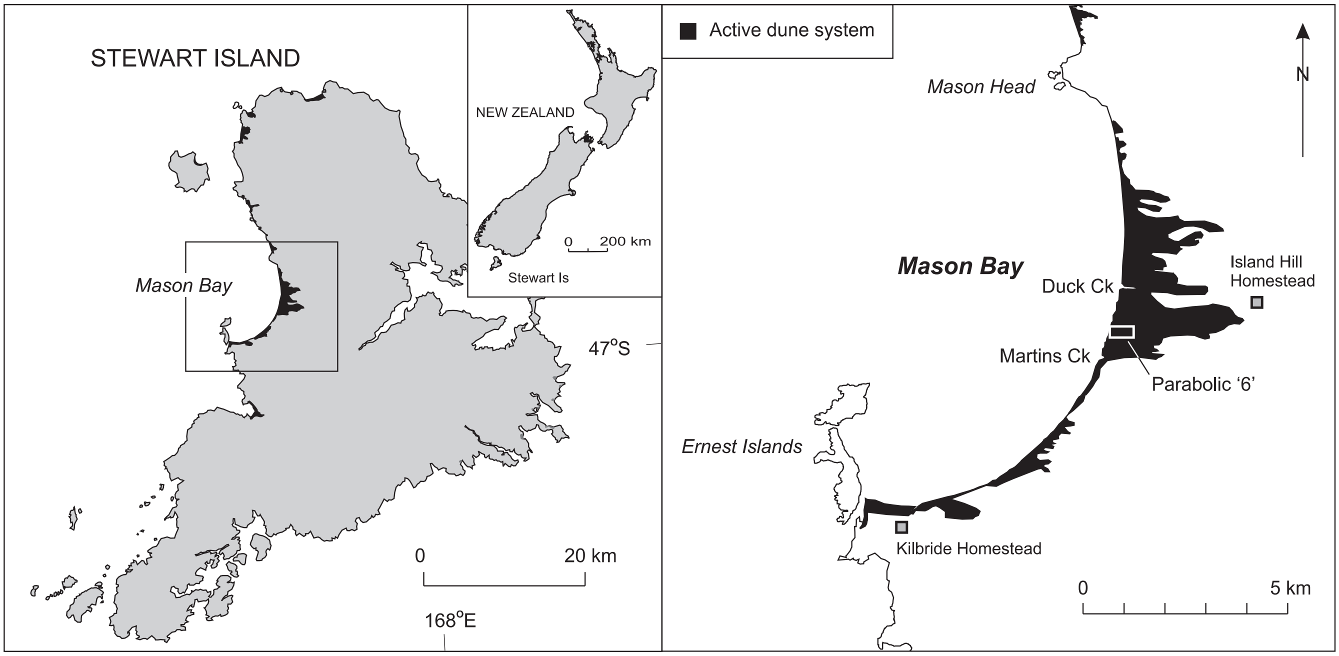

Figure 1. Study area location, Mason Bay, Stewart Island.

the Oregon coast have been linked to the development of a large *A. arenaria* foredune (Wiedemann and Pickart, 1996), but research elsewhere has been limited. The present study investigates *A. arenaria* foredune development and the impact on parabolic dune evolution at the west coast of Stewart Island, southern New Zealand. The impact of *A. arenaria* in New Zealand is not well documented, partly because most dune systems were completely occupied by *A. arenaria* by the mid 1900s (Hilton, Duncan, and Jul, 2005). Today, *A. arenaria* is now the dominant foredune species in most dune systems south of lat 38° S in New Zealand, and it is the primary threat to the geomorphology and ecology of these coastal dune systems (Hilton, Duncan, and Jul, 2005). Indeed, the active dune systems of Stewart Island represent one of the few remaining areas of largely unmodified temperate transgressive dunes in the country. Here, *A. arenaria* invasion has occurred relatively recently, since the early 1930s, and is documented by aerial photography, which provides an exceptional opportunity to understand the impact of *A. arenaria* foredune development on the dynamics of a temperate, exposed-coast, transgressive dune system.

The present study (1) documents the invasion pattern of *A. arenaria* and the concomitant landform development of the foredune and adjacent parabolic dune field at Mason Bay, (2) documents the development of the individual morphological units of the parabolic dune in relation to foredune development, and (3) uses computational fluid dynamics (CFD) to determine the impact of *A. arenaria* foredune development on the downwind flow field through the parabolic dune and discusses these results in relation to the sedimentary dynamics of the system.

METHODS

Study Site

The active dune systems of the west coast of Stewart Island are some of the least modified dune systems remaining in New Zealand and are recognised as nationally significant (Johnson, 1992). Mason Bay contains the largest of these active dune systems, extending up to 3 km inland between Duck Creek and Martins Creek (Figure 1). Parabolic dunes and sand sheets are the most prevalent dune form in the Mason Bay dune system. Climbing, imbricate forms occur most widely, usually modified by the underlying bedrock. However, a series of long-walled parabolic dunes has developed in a relatively flat section of the central dunes of Mason Bay between Duck Creek and Martins Creek. This study focuses on these dunes, which are located immediately landward of the foredune. The contemporary parabolic dune field comprises a series of six U-shaped, long-walled parabolic dunes (after Pye, 1983; Hesp and Thom, 1990) between 600 and 800 m in length (Figure 2). These parabolic dunes are transgressing a gently sloping, stony deflation surface immediately landward of the foredune. The contemporary foredune is 11 m high and extends up to 150 m inland. The foredune, vegetated by a dense cover (~80%) of *A. arenaria*, forms a continuous barrier along the seaward edge of the dune system (hereafter known as the "*A. arenaria* foredune").

The local wind regime was measured during the study period (June 2002 to February 2004) using a permanent Vector 3-cup anemometer at a height of 2 m located on the foredune crest immediately seaward of the subject parabolic dune. The predominant direction of sediment transport is onshore; the wind regime is dominated by strong W-SW winds throughout

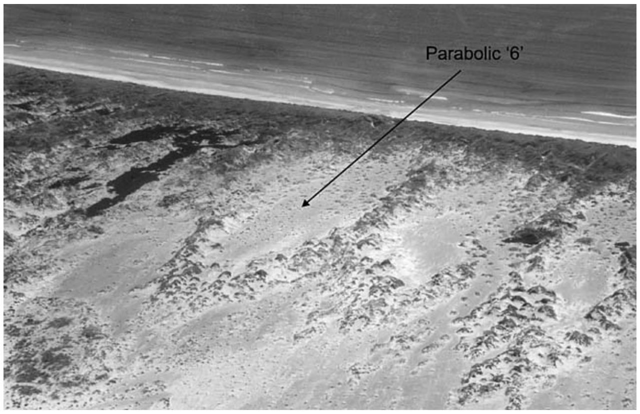

Figure 2. Oblique aerial photograph (2005) showing the series of parabolic dunes transgressing an active deflation surface (the "stonefield") in the lee of the *A. arenaria* foredune. Parabolic 6 can be seen in the centre of the photograph.

the year. Annual average wind speed is 6.4 m s^{-1} with <1% calm conditions. During the period of the study, winds above the accepted sand transport threshold of 6 m s^{-1} (Fryberger, 1979) occurred 46% of the time. Potential aeolian activity is classified as low to intermediate (after Fryberger, 1979), with a total sand drift potential (DP) of 260 vector units (VU), thus classifying the site as a "high energy" environment (Bullard, 1997). This classification is consistent with other documented drift potentials in previous parabolic dune studies (Anderson and Walker, 2006; Bailey and Bristow, 2004; Tsoar, 2000). The resultant drift potential vector (RDP) is 226 VU aligned NE (51°), reflecting the dominant SW winds. The ratio of RDP to DP is 0.87, ideal for parabolic dune development. The west coast of Stewart Island has a "wet winter temperate" climate (Van der Maarel, 1993) with a mean annual precipitation at South West Cape, 40 km south of the study site, of 1324 mm between 1995 and 2003 (NIWA, 2004).

Landform Development

Ammophila arenaria was intentionally introduced to Mason Bay during the 1930s to stabilise dunes on Kilbride farm, at the southern end of the bay (Figure 1). Subsequent dispersal probably occurred through the natural spread of rhizome fragments from north to south (Hilton, Duncan, and Jul, 2005). A time series of aerial photographs documents *A. arenaria* invasion and concomitant landform development in the central dune system of Mason Bay. The first photograph was taken in 1958, with subsequent images obtained in 1978, 1989, and 2002. These images enable the examination of (1) parabolic dune development in association with the native sand-binding species *D. spiralis spiralis*, (2) the invasion history of *A. arenaria* and concomitant indigenous species displacement, (3) the physical development and changing morphology of the foredune and parabolic dunes, and (4) changes in the density and extent of *A. arenaria* and *D. spiralis*. Further, we were able to interpret the pre–*A. arenaria* morphology of the foredune in Mason Bay by combining evidence from ground photographs dating from the 1930s; descriptions by Cockayne (1909), an eminent New Zealand botanist with a particular interest in dune flora; the 1958 aerial photograph; and small sections of *D. spiralis*–dominated foredune (hereafter referred to as the "*D. spiralis* foredune") that survive in Mason Bay north of Duck Creek.

The 1958 aerial photograph clearly shows six adjacent parabolic dunes transgressing a gently sloping deflation surface immediately landward of the foredune. While the majority of these parabolic dunes displayed a classic U-shaped, long-walled parabolic dune morphology, the most southerly of these dunes, henceforth referred to as "parabolic 6," was at an early stage of development.

Measurements of the main morphological units of parabolic 6—the length of the trailing arms, the area and length of the deflation surface, and the area of the erosional face and depositional lobe—were derived from the aerial photographs. Changes in the morphology of parabolic 6 were then assessed using these measurements. Rates of migration were calculated for the deflation surface, erosional face, and depositional lobe for each of the periods between the aerial photographs. Changes in the width of the foredune were also measured using the aerial photographs. Measurements of the contemporary foredune and parabolic dune morphology were validated against field survey data collected using a Leica 305 total station.

Aerodynamic Flow Patterns

The paucity of *D. spiralis* foredunes remaining in New Zealand limits the ability to directly measure aerodynamic flow patterns over and in the lee of such systems, or to compare aerodynamic flow patterns over and in the lee of *A. arenaria* and *D. spiralis* foredune morphologies. Numerical modelling is a tool that is increasingly being used in geomorphological applications (Bates and Lane, 1998) and has been shown to produce realistic and applicable results (Parsons *et al.*, 2004). This study utilises the numerical modelling technique of computational fluid dynamics to model flow over foredunes. In this study we do not model variations in flow associated with the surface roughness related to differences in vegetation.

Computational fluid dynamics models enable simulation of important fluid processes, thereby providing prediction fields that enhance insight into the spatial distribution and sedimentological significance of these processes (Parsons *et al.*, 2004). Such models can provide details of the flow field that are often difficult to measure and offer controlled conditions in which certain aspects of the experimental setup can be varied rapidly, such as changes in vegetation density and roughness.

This study employed the CFD software program FLUENT 6.1. The model used in this study solves the elliptical form of the Navier-Stokes equations, simplified to two dimensions, with a finite volume method. These equations are then discretised and solved on a mesh that covers the fluid space of interest. Various assumptions are made due to the complex, nonlinear nature of the equations, for example, the use of models for turbulence and wall roughness. Modelling the turbulence using time-averaged equations of fluid flow, the so-called Reynolds-Averaged Navier-Stokes technique, is standard practice in

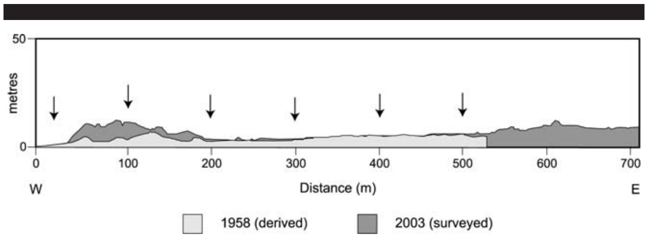

Figure 3. The 1958 (derived) and 2003 (surveyed) profiles used in the CFD model. Profiles are shown within the modelled flow domain. The arrows mark the anemometer locations.

many complex situations. Previous studies (Parker and Kinnersley, 2004; Wakes *et al.*, 2005) have established that the renormalisation group k-ε two-equation turbulence model, recommended for simulating flows with significant mean strain and shear, is the most suitable for simulations of this type.

Aerodynamic flow patterns were modelled over two profiles from 1958 and 2002 (Figure 3). The effect of vegetation on flow was not modelled. Interpolation of the surface was made using the Non-uniform Rational Basis Spline function in GAMBIT, the preprocessor, to enable a smooth surface to be constructed between the points and so produce a profile similar to the natural profile.

Sensitivity analysis was conducted to determine the ideal mesh structure that allowed for accurate modelling but which did not consume large amounts of computational time. Results from this analysis showed that a mesh spacing of 0.2 m was ideal over all surfaces (Table 1); the 2003 profile was meshed with approximately 656,000 cells, and the 1958 profile was meshed with approximately 500,000.

Initial velocity was set at a constant velocity along the inlet wall of 11 m s^{-1}. This velocity was used because it facilitates a direct comparison of the modelled results with data obtained from field anemometer experiments. The model was set up such that a logarithmic profile was developed in the domain prior to any interaction with the foredune. The top and end walls of the domain were set as outflow, thereby ensuring that they exerted minimal influence on the flow structure at the point of contact.

Aerodynamic flow patterns at a landscape level were the focus of this study; therefore changes in surface roughness related to the presence or absence of vegetation were not considered. Indeed, the chosen mesh size of 0.2 m for the profile surface did not allow for a level of detail sufficient to account for vegetation changes. A constant roughness height of 0.004 m, the value for bare sand (Oke, 1987), was applied for the full length of the profile. This value also conforms to the requirement in FLUENT for the cell height to be at least twice the specified roughness height.

Ammophila arenaria Invasion

Analysis of the available photographs indicated that by 1958 *A. arenaria* had established between Martins Creek and Duck Creek (hereafter "central Mason Bay"), where it occurred in small patches within 400 m of the high-water line. The area dominated by *A. arenaria*, where canopy cover exceeded 50%, was 1.4 ha, representing 0.6% of the area of central Mason Bay (Jul, 1998; see Figure 4).

Table 1. *Mesh size and boundary type used for each model surface.*

Surface	Mesh Size (m)	Boundary Type
Profile surface	0.2	Wall
Input	0.2	Velocity inlet
Outlet	0.2	Outflow
Top	1.0	Outflow

The area occupied by *A. arenaria* increased exponentially between 1958 and 1978. By 1978, *A. arenaria* had established within most of the foredune environment, between Martins Creek and Duck Creek, although the cover was discontinuous. At this time *A. arenaria* extended up to 750 m inland and dominated 17.8 ha of the hinterland dunes, an increase of 1137% over 20 years (Jul, 1998). A significant increase in both the extent and density of *A. arenaria* occurred between 1978 and 2000 (Figure 4). During this period *A. arenaria* achieved almost total cover between Martins Creek and Duck Creek, eventually forming a continuous foredune and displacing all *D. spiralis*. By 1998 *A. arenaria* covered 74.9 ha of the central dunes (Jul, 1998). This represents an increase in area dominated by *A. arenaria* of 5204% in the 40 years between 1958 and 1998.

Foredune Development—Central Mason Bay

Ammophila arenaria invaded the central dune system from south to north and inland from the foredune. During this process, the morphology of the foredune changed from a low, sparsely vegetated and hummocky foredune that was discontinuous alongshore (Stage IV after Hesp [1988]) to a relatively massive, densely vegetated, uniform and continuous alongshore foredune complex (Stage I). We have a good understanding of the foredune landscape prior to *A. arenaria* invasion. Cockayne (1909, 18) described the foredunes of Mason Bay, prior to the introduction of *A. arenaria*, as comprising "6–10 ft (1.8–3.0 m) tall, haystack-like dunes." That is, the foredune comprised a series of isolated nebkha or shadow dunes (Type 4–5, Hesp [1988]), formed in association with *D. spiralis* (with some *Austrofestuca littoralis* (Labill.) E. B. Alexeev and *Euphorbia glauca* G. Forst.). Three dunes of this type still occur in Mason Bay, north of Duck Creek (Figure 5a). Cockayne's descriptions accord with ground photographs of the foredune environment near Duck Creek, taken during the 1930s. The 1958 aerial photograph is of poor quality, but it also shows that the vegetation cover at this time was patchy with numerous nebkha or shadow dunes (Figure 6a). The irregular alongshore topography of the *D. spiralis* foredune in 1958 suggests that blowout formation through the foredune occurred from time to time.

Ammophila arenaria invasion and foredune development progressed rapidly between 1958 and 1998, culminating in a relatively massive, stable, continuous foredune. *Ammophila arenaria* had formed a semiuniform cover by 1978 (Figure 6f), creating a continuous, though topographically irregular,

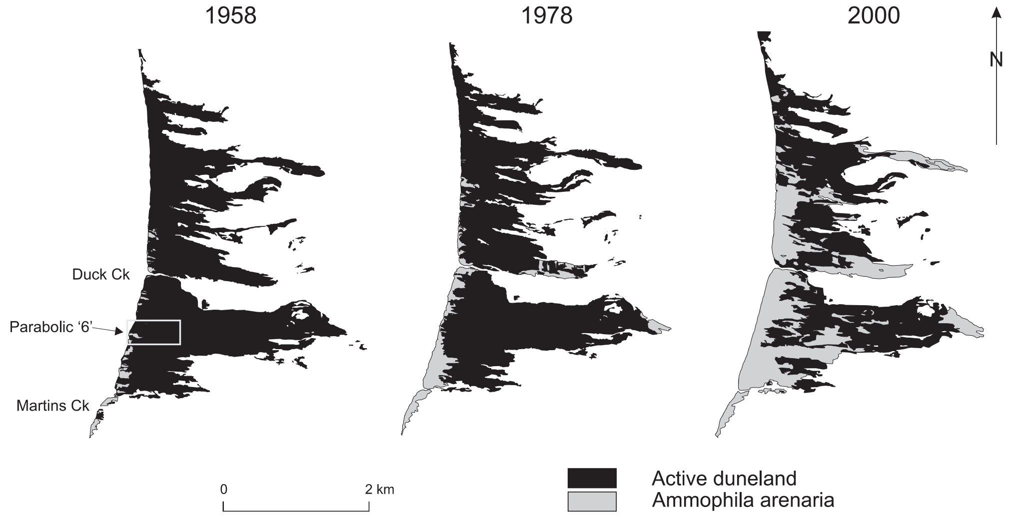

Figure 4. Pattern of *A. arenaria* invasion north of Martins Creek, Mason Bay, Stewart Island, as derived from aerial photographs (1958–2000).

foredune (Stage III, Hesp [1988]). Development of the foredune during this period occurred through the coalescence of adjacent *A. arenaria* shadow dunes as the vegetation cover increased (Hilton, Duncan, and Jul, 2005). *Desmoschoenus spiralis* had been displaced from the stoss face of the foredune during the period 1958 to 1978, as the new *A. arenaria* foredune prograded seawards and accreted. *Ammophila arenaria* increased in extent and density through the back-dune environment, with a corresponding decline in the area of unvegetated and *D. spiralis*–dominated habitat. By 1989, *A. arenaria* had formed a dense, uniform cover across the stoss face, foredune crest, and lee slopes, to within 300 m of the high-tide line (Figure 6g). During the period from 1989 to 2002, the density of *A. arenaria* increased to form an extensive monospecific (>80%) cover (Figure 6h). The contemporary foredune is characterised by a steep stoss face; a broad, relatively flat terrace; and a gently sloping lee face (Figures 5b and 7) equivalent to Stage I of Hesp (1988). The overall morphology of the foredune in 2003 was very different from the pre–*A. arenaria* foredune (Table 2). Lateral growth has occurred primarily through seaward progradation, averaging 50 m between 1958 and 2002 and probably encouraged by high rates of deposition and stabilisation under *A. arenaria*.

The massive *A. arenaria* foredune between Duck Creek and Martins Creek appears to be stable. The numerous corridors and depressions that dissected the foredune at the time of *A. arenaria* invasion have now closed. Two narrow blowouts adjacent to parabolic 6 persisted until 1989 (Figure 6c). During the initial stages of *A. arenaria* invasion, the width and depth of these blowouts were enhanced, providing a major pathway for sediment input into the back-dune system. Closure of the blowouts occurred between 1989 and 2002 as the density of *A. arenaria* increased, stabilising the throat of the blowout and reducing rates of sediment transport. Narrow channels still occur along the stoss face of the foredune, but these are ephemeral features, a few metres wide and 20 m or so deep (Hilton, Duncan, and Jul, 2005). To date, none of these depressions has developed into a substantial blowout.

Foredune–Parabolic Dune Development—Mason Bay

Parabolic 6 evolved from a blowout some time prior to, or coincident with, *A. arenaria* invasion, probably in the late 1940s. The formation of relatively steep-sided *A. arenaria* shadow dunes may well have caused the development of such blowouts by accelerated local flow. In 1958, the blowout lacked trailing arms (Figure 6a). The depositional lobe of the incipient parabolic dune would probably have been a relatively low, sparsely vegetated feature (Table 3). *Ammophila arenaria* had established a sparse, patchy cover within the foredune by 1958 and had started to colonise the more stable walls of the blowout/incipient parabolic 6 (Figure 6a). The characteristic features of a long-walled parabolic dune had formed by 1978. The northern trailing arm and a deflation surface are clearly defined, along with a sparsely vegetated depositional lobe (Figure 6b). Development of the deflation surface occurred primarily through elongation, increasing in length 7.91 m y^{-1} between 1958 and 1978 (Table 4). Widening of the surface also occurred, which resulted in an increase in the area of the deflation surface from 0.35 ha to 1.15 ha between 1958 and 1978, a 226% increase. *Ammophila arenaria* had formed a near-continuous cover across the foredune by 1978, but it was still absent from the parabolic dune (Figure 6f).

Parabolic 6 became increasingly sheltered by the rapidly accreting *A. arenaria* foredune between 1978 and 1989. Downwind migration continued between 1978 and 1989; however, the rate of advance declined (Table 4). During this period the deflation surface became significantly larger, with a corresponding decline in the length and area of the depositional lobe (Table 3). The deflation surface increased in length at a rate of 6.02 m y^{-1} between 1978 and 1989, with an increase in area from 1.15 ha to 2.14 ha, an 86% increase.

Figure 5. (a) One of three surviving *D. spiralis* shadow dunes located north of Duck Creek (viewed from about the high-water line, looking inland), with the contemporary *A. arenaria* foredune in the background. (b) The *A. arenaria* foredune at the edge of parabolic 6 (looking south to Martins Creek).

Ammophila arenaria had established throughout the parabolic dune by 2002, although some remnant areas of *D. spiralis* on the northern trailing arm persisted (Figure 6h). Between 1989 and 2002 the rate of landward advance of the depositional lobe was almost negligible (Table 4). At the same time, the deflation surface increased in length at an average rate of 15.60 m y^{-1} and increased in area to 5.20 ha, a 143% increase over 13 years. The length of the depositional lobe decreased as the eroding face advanced. Development of the depositional lobe during this period occurred through vertical accretion, rather than downwind extension. The depositional lobe now comprises a series of large *A. arenaria* shadow dunes 3–5 m high.

Parabolic 6 has been relatively stable since *A. arenaria* invasion. However, the development of a massive *A. arenaria* foredune has caused a decline in available sediment within the parabolic dune system. The development of the deflation surface and concomitant reduction in length of the depositional lobe occurred as the foredune evolved. The development of large deflation surfaces through a similar process has also been observed in Oregon (Carter, Hesp, and Nordstrom, 1990). However, the ongoing formation of nebkha dunes across the seaward half of the deflation (and former deflation) surface indicates some sand is still in circulation. We have observed significant suspension over the foredune (after Arens, 1996), during strong westerly winds, that provides sand for ongoing nebkha development across the rear slopes of the foredune and former deflation zone of the parabolic dune (Figure 6d).

MODEL VERIFICATION, AERODYNAMIC FLOW PATTERNS, AND SEDIMENTARY DYNAMICS

Modelled results were verified against anemometer measurements at the field site. Instruments were set up at regular intervals (Figure 3) along a profile running down the long axis of parabolic 6 (Figure 6d). Ambient wind conditions were consistently just south of shore normal (288°) and averaged 11 m s^{-1}. Velocity profile measurements were recorded using Vector-type three-cup anemometers, connected to a Campbell CR10 data logger, at elevations of 0.05, 0.1, and 0.4 m above the dune surface. Wind direction was recorded via a Vector wind vane at 0.4 m. Wind speed and direction were recorded at 1-second intervals for multiple 10-minute periods. Ambient wind conditions were measured using a permanent anemometer (SIWS) established on the crest of the foredune. Wind speed data at each site were normalised by concurrent measurement of the ambient conditions at SIWS.

Regression analysis was used to verify the modelled velocities against the measured velocities. The smaller number of observations from the measurements limited the power of the regression. However, visual analysis against the 1 : 1 line showed a high degree of fit between modelled and measured velocities, with the level of agreement being higher for velocities above 0.4 m. The modelled velocities were significantly lower below 0.4 m, which could be attributed to the initial mesh size close to the model surface being set at 0.2 m. A higher level of detail could be achieved, but this would require a significant trade-off in terms of the computational time required. Despite this, the verification provided a degree of confidence that the model was able to produce results similar to field conditions.

Topographic acceleration over the two foredune morphologies was compared (Figure 8). The modelled aerodynamic flow patterns showed significant differences between the *A. arenaria* and *D. spiralis* foredune morphologies with respect to flow over and downwind of the foredune. Previous studies measuring flow patterns over steep foredunes have shown flow acceleration occurs up the stoss face of steep foredunes (Arens, Van Kaam-Peters, and Van Boxel, 1995). In our study, significant topographic flow acceleration was observed near the seaward edge of the foredune crest (at 90 m) for the *A. arenaria* foredune, with relative velocities in the order of 113% (ambient equals 100%). Comparatively, velocity profiles over the *D. spiralis* foredune indicate minimal topographic acceleration. Some retardation of flow was modelled below 0.4 m.

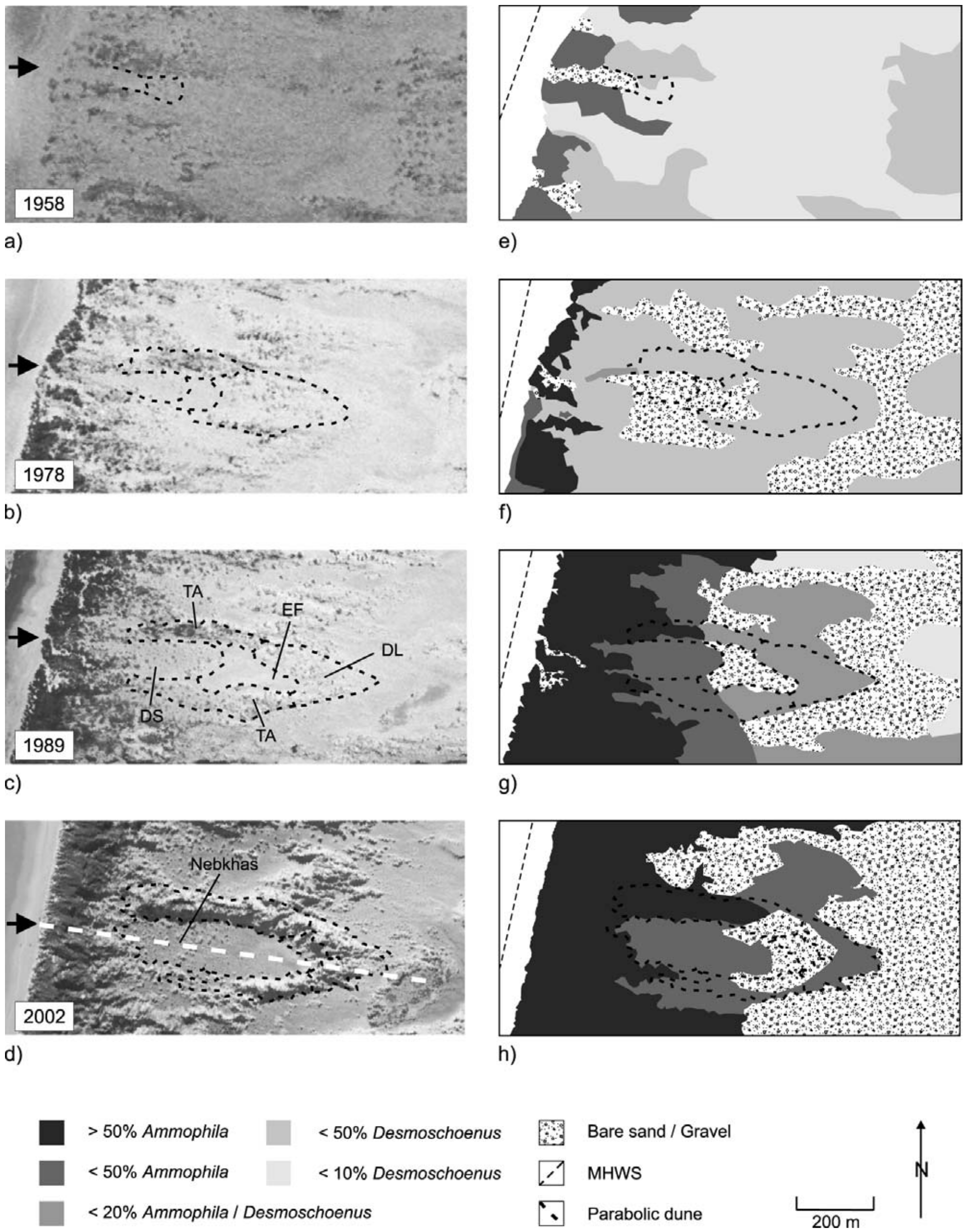

Figure 6. (a–h) A sequence of aerial photographs and vegetation maps highlighting the rapid spread of *A. arenaria* and concomitant development of foredune and parabolic dune landforms and vegetation cover. The outline of the parabolic dune (parabolic 6) at each stage of development is highlighted by the dashed black line. The arrow indicates the closure of the blowout which gave rise to the central parabolic dune. TA = trailing arm, EF = erosional face, DL = depositional lobe, DS = deflation surface. The location of parabolic 6 is indicated in Figure 1. The location of the profiles shown in Figure 3 is indicated by the dashed white line in (d).

However, above this height the profile closely mirrored the ambient profile. The similarity of the modelled profiles against the ambient velocity profile suggests minimal topographic acceleration across and through the *D. spiralis* foredune. However, it is likely that some topographic acceleration did occur over and around individual hummocks (Hilton, Duncan, and Jul, 2005). This level of analysis is beyond the scale of this model. The flow retardation exhibited below 0.5 m is most likely a function of the location of the profile extracted from the model being situated slightly in the lee of a hummock. The simulated flow patterns show reduced velocities in the lee of both foredune morphologies, with a greater sheltering effect evident in the lee of the *A. arenaria* foredune (Figure 9).

The highest degree of sheltering in the lee of the *D. spiralis* foredune was modelled at a distance 200 m downwind of the inlet wall with an average velocity 84% of ambient. The sheltering effect was greatest close to the surface at the 200 m distance, with a modelled velocity of 77% of ambient at 0.5 m.

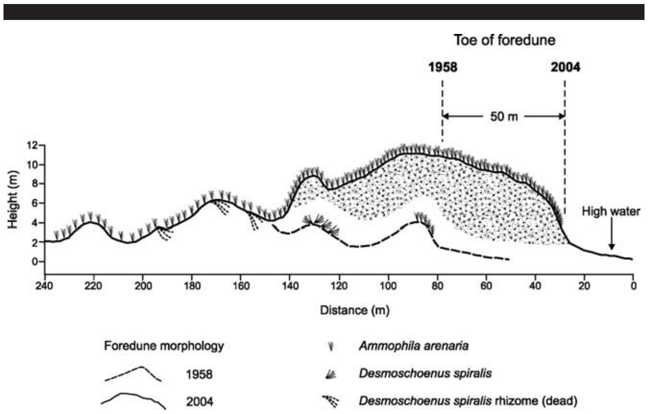

Figure 7. Comparison of the foredune morphology before and after *A. arenaria* invasion for the central dune system of Mason Bay. The morphology of the *D. spiralis*–dominated foredune is derived from the descriptions of Cockayne (1909), field observations of remnant (dead) *D. spiralis* rhizome, and the 1958 aerial photograph.

The sheltering effect was minimal with increasing height; at 2 m the velocity was 90% of ambient, similar to downwind velocities. This suggests that the influence of the *D. spiralis* foredune on the wind flow is exerted at the scale of the individual hummocks that compose the foredune environment rather than the foredune as a singular landform. At distances of 300 m, 400 m, and 500 m downwind, minimal influence is exerted by the *D. spiralis* foredune, with velocities between 90% and 92% of ambient.

A greater degree of sheltering was evident in the lee of the *A. arenaria* foredune (Figure 9). In the immediate lee of the *A. arenaria* foredune, at a distance of 200 m (100 m downwind of the foredune crest), the modelled velocities were between 67% (0.2 m) and 85% (2 m) of the ambient flow, with an average of 81%. The modelled velocity profiles suggest the *A. arenaria* foredune produces a relatively uniform sheltering effect. Downwind of the 200 m mark, corresponding to the flat and relatively smooth deflation surface, the profiles exhibited a high degree of similarity. The average velocity across all sites was between 80% and 83%, with the latter at a distance of 300 m downwind of the foredune crest.

Flow-recovery distances were significantly longer in the lee of the *A. arenaria* foredune. Flow recovery is defined as the point at which velocities recover to 99% of the ambient velocity (Parsons, Walker, and Wiggs, 2004). At a distance of 400 m downwind of the inlet wall, approximately 300 m downwind of the foredune crest, velocities in the lee of the *A. arenaria* foredune recovered to 81% of ambient. Velocities in the lee of the *D. spiralis* foredune recovered to 94% at the same stage. This represented the highest degree of flow recovery simulated over the 1958 morphology. However, flow recovery in the simulated *A. arenaria*–dominated morphology reached a maximum of 87% at a distance of 450 m downwind from the foredune crest. This corresponds relatively well with the maximum relative velocity measured in the anemometer experiments, 84% at 610 m from the foredune. This indicates that the *A. arenaria* foredune influences velocities up to at least this distance downwind of the foredune. Based on an average height h of the *A. arenaria* foredune of 11 m, the downwind influence on aerodynamic velocities is around $40h$–$45h$.

Table 2. *Changes to foredune morphology, 1958 to 2002. Foredune dimensions are derived from Figure 5. Volume calculations assume a 2 km foredune length.*

Year	1958	2002
Dominant species	*D. spiralis*	*A. arenaria*
Vegetation cover	10%–30%	>80%
Hesp (1988) foredune stage	IV	I
Maximum height (m)	3	11
Width (m)	80	150
Area (m^2)	240	1650
Volume (m^3)	4.8×10^5	3.3×10^6

Table 3. *Temporal and spatial changes in the morphology of parabolic 6.*

Year	1958	1978	1989	2002
Total length (m)	176.12	600.71	657.83	664.50
Length of trailing arm, north (m)	—	308.40	343.70	468.40
Length of trailing arm, south (m)	—	—	325.60	325.60
Length of deflation surface (m)	92.34	183.74	285.60	452.20
Length of depositional lobe (m)	90.44	355.10	329.39	243.71
Area of deflation surface (ha)	0.35	1.15	2.14	5.20
Area of erosional face (ha)	—	0.68	1.68	0.61
Area of depositional lobe (ha)	0.51	4.35	2.62	2.34

The Impact of *A. arenaria* on Foredune Development

Ammophila arenaria invasion has resulted in the formation of a major foredune that forms a barrier to aerodynamic flows to the backdune environment. *Ammophila arenaria* has significantly altered the morphology of the foredune and the sedimentary dynamics of the system. Computational fluid dynamics modelling showed an increase in flow acceleration up the stoss face of the *A. arenaria* foredune. Relative velocities at the foredune crest were 113% of the ambient velocity. Arens, Van Kaam-Peters, and Van Boxel (1995) report accelerated flows of up to 150% of the ambient flow over *A. arenaria* foredunes 10–20 m in height. Increased flow velocities up the stoss face of the foredune encourage sand transport over the foredune (Hesp, 2002). However, the presence of *A. arenaria* increases the surface roughness, reducing near-surface velocities and encouraging deposition (Hesp, 1983). Consequently, velocities at the surface were reduced and deposition is encouraged. This positive feedback between vegetation and deposition has resulted in high rates of vertical accretion of the foredune and the development of the contemporary foredune complex.

Table 4. *Calculated migration rates (m y^{-1}) of parabolic 6.*

	Year		
Landform	1958–1978	1979–1989	1990–2002
Deflation surface	7.91	6.02	15.60
Erosional face	—	16.29	7.00
Depositional lobe	24.19	5.56	0.79

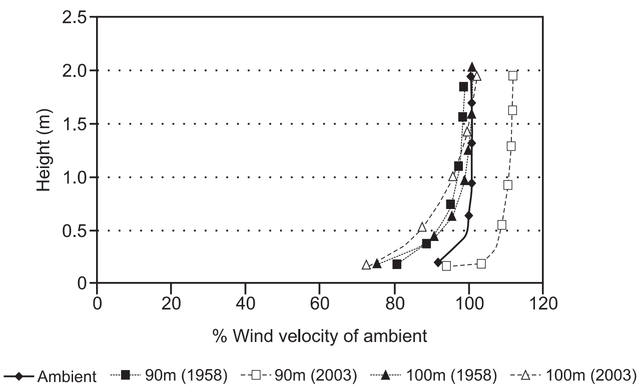

Figure 8. Comparative modelled topographic acceleration over the (nonvegetated) *D. spiralis*–type (1958) and *A. arenaria*–type (2003) foredune morphologies. The distances are downwind from the inlet wall, and the locations are shown relative to the foredune morphologies in Figure 3.

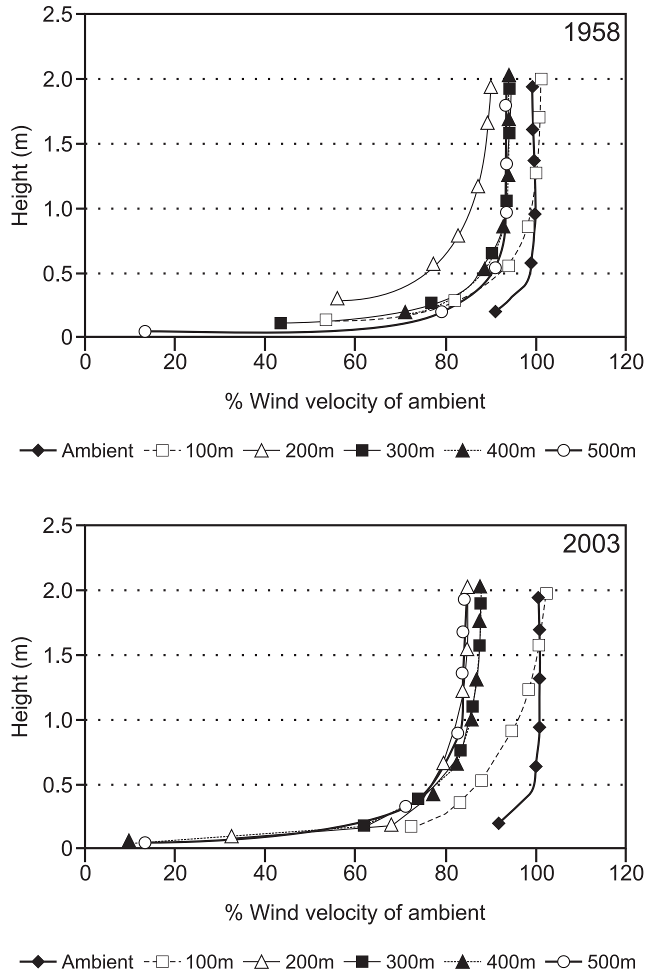

Figure 9. Modelled velocity profiles over and in the lee of nonvegetated *D. spiralis*–dominated (1958) and *A. arenaria*–dominated (2003) foredune morphologies. Velocity is expressed as a percentage of the ambient (inlet) velocity.

Flow modelling over the 1958 *D. spiralis*–type foredune morphology showed a significantly different pattern. Minimal topographic acceleration was modelled over the low and irregular foredune morphology. The results do suggest, however, that acceleration occurs over and around individual hummocks, but due to the sparse cover of *D. spiralis*, increased rates of sediment trapping do not occur (Hesp, 1983). Consequently, vertical accretion of the foredune does not occur, foredune stabilisation is inhibited, and there are high rates of sediment transport to the backdune environment.

A limitation of the CFD model was the use of two-dimensional modelling of flow patterns over topography that is three-dimensional. This is particularly important in the case of the *D. spiralis* foredune. Two-dimensional modelling cannot take into consideration the irregular and discontinuous morphology of this foredune. Flow acceleration is likely to be significantly higher between individual hummocks rather than over the hummocks. Consequently, flow velocities through the foredune may be higher than are simulated by this model.

The CFD simulations document a longer flow-recovery distance in the lee of the *A. arenaria* foredune compared to the *D. spiralis* foredune. Velocities had recovered to 94% at a distance 300 m from the *D. spiralis* foredune crest. In comparison, at the same distance in the lee of the *A. arenaria* foredune, flow recovery was only 81%. The flow-recovery distance exhibited in the lee of the *A. arenaria* foredune suggests that the influence of the *A. arenaria* foredune on wind velocities may extend up to 40*h*–45*h*. This is significantly higher than the estimate of 10*h*–15*h* of Oke (1987). The increase in flow-recovery distance is probably related to the foredune being a solid barrier to flow. The model of Oke (1987) was developed for relatively simple barriers, such as shelterbelts. The large and complex morphology of the *A. arenaria* foredune increases the disruption to flow patterns, resulting in a significantly larger zone of turbulence (in which surface velocities are reduced) downwind of the foredune.

Limitations of the CFD Model

Application of the CFD results, with regard to rates of sediment transport, needs to be tempered by the limitations of the current model. The scale of modelled landform required a number of simplifications, primarily related to the mesh size and structure. Previous CFD studies of dune morphologies have modelled aerodynamic flows over simple, scaled, and idealised dune morphologies, allowing for small, regular mesh sizes and detailed modelling of aerodynamic flows (Parsons, Walker, and Wiggs, 2004). However, investigating flow patterns at this scale for the present study was not possible given the size of the domain to be modelled (700 m $\times$ 45 m) and the resulting mesh grid for the domain.

The final mesh structure, therefore, represents a balance between a structure that produces realistic and usable results, accommodates the complex topography, and does not consume large amounts of computational time. This mesh size, however, did limit the accuracy of the modelled velocities close to the surface, particularly in relation to the future effect of vegetation. The relatively large mesh size (0.2 m) close to the surface does not allow for a detailed investigation of the velocities immediately above the surface. This is critical in that it is within this area that the greatest changes in the near-surface velocity will occur; this area is also the zone of maximum sand transport. However, given that the scale investigated is at the landscape level of the foredune and parabolic dune, such issues were regarded as beyond the scope of this study. Further research has subsequently been undertaken in order to address these issues, as well as expand the modelling to three dimensions (Wakes *et al.*, 2010).

Sediment Transport and Landform Development

Flow modelling over the 1958 (*D. spiralis*) foredune showed that the topography exerts minimal influence on the near-surface velocity profiles. Velocities over and directly in the lee of the foredune experience little reduction in magnitude, such that velocities were maintained closer to the ambient. This suggests that even at ambient velocities close to the threshold velocity for sediment transport, rates of transport may still be significant.

As ambient velocities increase, the rate of sediment transport through the *D. spiralis* foredune increases. The moderate sand-trapping capacity of *D. spiralis* and the high velocities experienced between individual hummocks resulted in high rates of sediment transport through the foredune to the backdune environment. It seems probable that, given the geomorphological stage of the foredune, characterised by frequent small blowouts, much of the sediment supplied to the foredune from the beach is transported into the back-dune system.

The CFD simulations indicated that the low profile of the *D. spiralis* foredune does not significantly reduce velocities in the lee of the foredune. Consequently, rates of sediment transport through the back dune are likely to be high. Under these conditions, establishment of *D. spiralis* would be limited. Subsequently, rates of parabolic dune development would be high.

Measured and modelled flows in the lee of the *A. arenaria* foredune showed reduced velocities in the lee of the foredune. During periods when the ambient velocity averaged 11 m s^{-1}, mean velocities were reduced to around 6 m s^{-1}, the critical velocity for sediment transport, resulting in reduced sediment transport through the parabolic dune. Anemometer measurements in the lee of the contemporary *A. arenaria* foredune showed that maximum velocities were often much higher than mean velocities. Small-scale sediment transport was observed to only occur during wind gusts.

Field studies conducted in parallel with this study highlighted that the supply of sediment from the beach over the *A. arenaria* foredune is minimal and occurs primarily through suspension during periods of high-velocity (>10 m s^{-1}) winds. The stability of the *A. arenaria* foredune also limited the supply of sediment to the back dune *via* the breakdown of the foredune and blowout development. Low rates of sediment transported over the foredune, in association with the low velocities in the lee of the foredune, resulted in the formation of the large nebkha across the deflation surface. The deposition of sediment in the lee of the foredune, in conjunction with decreased exposure to high winds, has created an ideal environment for vigorous *A. arenaria* growth. Consequently, stability has increased and the amount of sediment available to be transported downwind has decreased. This process occurred progressively as *A. arenaria* increased in density and extent through the foredune after 1978. This decrease in the amount of sediment transport landward of the foredune and the increasing protection given by the establishing *A. arenaria* foredune is evident in the massive increase in the size of the deflation surface. The growth of the deflation surface coincided with a decrease in the rate of downwind migration of the depositional lobe and stabilisation of the trailing arms, and a corresponding increase in the extent of *A. arenaria* in these areas. The contemporary deflation surface is extending downwind as a result of the limited supply of sediment from upwind sources and deflation of the erosional face of the depositional lobe.

In 1958, the *D. spiralis*–dominated depositional lobe of the developing parabolic dune was a relatively low feature. Simulated flow conditions indicate that velocities were relatively high through this area. Rates of sediment transport were likely to be high, forcing high rates of depositional-lobe migration. The morphology of the depositional lobe evolved following the establishment of *A. arenaria* in the depositional lobe between 1978 and 1989. In 2003 the lobe comprised a series of large shadow dunes. The exposure of the windward face of the lobe to strong onshore winds during this time decreased as *A. arenaria* established in the foredune and the foredune experienced vertical accretion. Low velocities enhanced deposition and reduce the potential for erosion. Since 1978, the depositional lobe has primarily developed vertical accretion, with negligible downwind migration.

CONCLUSIONS

In summary, *A. arenaria* invasion has significantly altered the dynamics of the Mason Bay dune system, particularly in relation to the continued existence of active, transgressive parabolic dunes. *Ammophila arenaria* has formed a massive, continuous, stable foredune. The impact of this is twofold. Firstly, there is a significant reduction in the supply of sediment to the back dune from the beach, resulting in the starvation of sediment to species that require moderate rates of sand deposition. Secondly, the large *A. arenaria* foredune described in the present study has significantly reduced near-surface velocities in the lee of the foredune. In association with continued *A. arenaria* invasion, this has inhibited sand transport through the parabolic dune. Under these conditions, parabolic dune development occurs primarily through deflation surface enlargement.

Active, transgressive parabolic dunes are a characteristic feature of temperate, southern hemisphere dune systems. *A. arenaria* represents a significant threat to the continued existence of these dunes and the environments they create. Parabolic dune mobility has been shown to decline downwind of the *A. arenaria* foredune. Further, the continued presence of *A. arenaria* significantly reduces the potential for future transgressive dune formation following foredune disturbance.

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