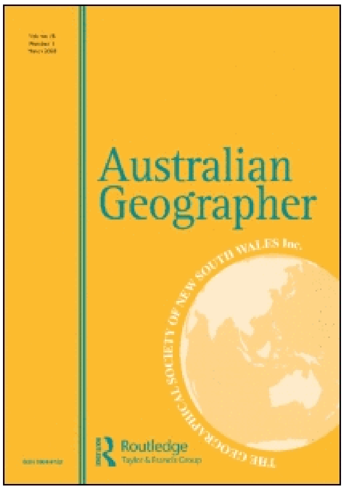

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The Impact of Exotic Dune Grass Species on Foredune Development in Australia and New Zealand: a case study of Ammophila arenaria *and* Thinopyrum junceiforme

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ABSTRACT *Marram grass (*Ammophila arenaria*) and sea-wheat grass (*Thinopyrum junceiforme*) have been introduced to Australia and New Zealand. This study examines the morphology of incipient foredunes and established foredunes associated with these species at two sites, Mason Bay in southern New Zealand, and the Younghusband Peninsula in South Australia. Both species invaded the existing foredunes very rapidly. In both cases the antecedent topography comprised relatively sparsely vegetated, irregular foredunes. Invasion resulted in continuous, regular, evenly vegetated foredunes. At Mason Bay a massive foredune has formed since 1958, in conjunction with* Ammophila. Thinopyrum *has formed an incipient foredune, with a ramp or terrace morphology, along the Younghusband Peninsula, South Australia. In both cases gaps in the former foredune have been closed and the indigenous foredune vegetation has been displaced. Both species may decrease the frequency and severity of blowout development. They are likely to be resilient to aeolian processes of sedimentation compared with dunes formed by indigenous species.* Ammophila *survives burial, is tolerant of drought and is resistant to erosion associated with storm surge and high waves.* Thinopyrum *is very tolerant of salinity. These species may adversely affect the long-term development of coastal barriers by inhibiting transgressive dune development.*

KEY WORDS *Marram grass; sea-wheat grass; invasive species impacts; coastal dune development; Australia; New Zealand.*

Introduction

The development and morphology of established foredunes has been well documented in relation to climate, sediment supply and type, wave climate and onshore winds (see Hesp 2002 for a review), but less attention has been paid to the important role of sand-binding grasses, sedges and herbs. Dense, tall, erect grasses

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are associated with high, steep-sided, asymmetric foredunes (Hesp 1983, 1989; Van Dijk *et al*. 1999). In contrast, species with a lower, more spreading rhizomatous growth form tend to produce lower, less hummocky dunes (Hesp 2002). The alongshore morphology of established foredunes is likewise influenced by vegetation cover, which may be more or less uniform, depending on patterns of species type, vigour or cover (Carter 1988; Hesp 1999). Over the last 50 years there is evidence for the global redistribution of dune grass species (Hilton & Harvey 2005) which may change the dominant foredune grass species and hence affect the dune morphology. This paper explores such changes using examples from Australia and New Zealand, and considers the long-term implications of these species for dune system and barrier genesis, in particular the impact of these grasses on transgressive dune systems.

The beaches and dunes of the temperate coasts of Australia and New Zealand contained only a handful of marine-dispersed species capable of colonising and occupying the back-beach, between the strandline and the established foredune: *Spinifex sericeus*, in both countries; *Atriplex billardierei* in Australia; and *Atriplex hollowayi* (a crystalwort) in New Zealand. In contrast, the established foredune and back dune floras of both countries contain a rich diversity of species. Of those indigenous species capable of forming incipient foredunes and established foredunes, just four are widespread. *Spinifex sericeus* (spinifex) and *Austrofestuca littoralis* (sand tussock) occur in both countries. *Desmoschoenus spiralis* (pingao or pikao), a sedge, is endemic to New Zealand. *Spinifex longifolia* is dominant in Western Australia. In addition, *Atriplex cinerea* (grey salt bush), is locally important in southeast Australia.

The dune flora of Australia and New Zealand changed rapidly over a 50-year period, from the late 1800s, with the introduction of European, American and South African dune plants (Heyligers 1985; Hilton & Harvey 2005). Sea spurge (*Euphorbia paralias*), European sea rocket (*Cakile maritima*) and American sea rocket (*Cakile edentula*) were accidentally introduced in the ballast of ships. The seeds of these species apparently survive in sea water for long periods. Sea wheatgrass (*Thinopyrum junceiforme*) and marram grass (*Ammophila arenaria*) were deliberately introduced to New Zealand and Australia to stabilise mobile dunes. Two South African species, bitou bush (*Chrysanthemoides monilifera*) and pyp grass (*Ehrharta villosa*) were also introduced for this purpose. *Arctotheca populifolia* (beach daisy), another South African plant, was probably brought to Australia as an ornamental. These introductions contributed four new species to the strandline–back-beach community in southeast Australia (the two sea rockets, beach daisy and sea spurge); two new species capable of forming incipient and established foredunes (*Ammophila* and *Thinopyrum*) and two species more commonly associated with backdune environments or established foredunes (bitou bush and pyp grass). Sea spurge occurs in all environments, but has limited dune-building capability.

We are concerned primarily with *Ammophila* and *Thinopyrum* in the present paper, in particular the ability of these plants to form incipient foredunes and established foredunes that are resilient to disturbance. The potential for *Ammophila* to trap large volumes of sand in massive foredunes has previously been noted (Esler 1970; Heyligers 1985). More recent work has suggested that *Ammophila* and *Thinopyrum* may also inhibit or prevent blowout and transgressive dune development (Hilton & Harvey 2002; Hilton *et al*. 2005). Suppression of blowouts might have a significant impact on the natural development of sandy coasts in Australia and New Zealand. Transgressive dune activity is critical to the physical development of coastal barriers on windward coasts in both countries. Transgressive dune activity is also closely linked with dune habitat and species diversity, since such activity inevitably leads to topographic and environmental diversity. We examine the impact of these species on foredune formation through two case studies: *Ammophila* invasion in a large transgressive dune system on the west coast of Stewart Island, New Zealand and, secondly, *Thinopyrum* invasion along the Younghusband Peninsula, South Australia. Finally, we examine the proposition that these species develop incipient foredunes and established foredunes that are more resilient to environmental disturbance than foredunes associated with indigenous species.

Methods

Fieldwork was undertaken at two locations on the Younghusband Peninsula, South Australia (see Figure 1) and one location at Mason Bay, Stewart Island (see Figure 2), during 2003 and 2004. The purpose of this work was to describe,

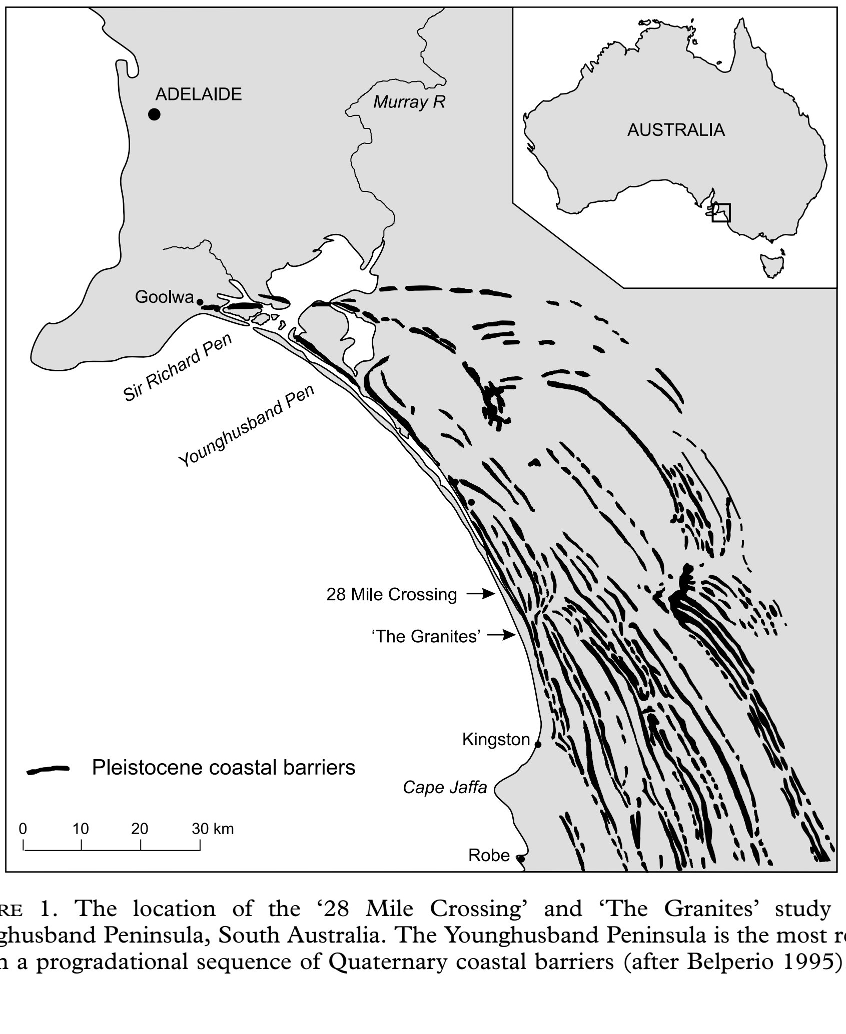

FIGURE 1. The location of the '28 Mile Crossing' and 'The Granites' study sites, Younghusband Peninsula, South Australia. The Younghusband Peninsula is the most recent in a progradational sequence of Quaternary coastal barriers (after Belperio 1995).

through systematic survey, the morphology of established foredunes associated with *Ammophila* and *Thinopyrum*, as well as the morphology of the adjacent hinterland; and to map and classify the associated beach-dune flora. Surveying was accomplished using a Leica 305 total station. Shaded relief plots, contour maps and profiles were generated for each site using Surfer 3D (Golden Software). Historic aerial photographs were used to determine the invasion history of these species, change in vegetation cover and community type and landform development. Ground photographs taken by Andy Short and Patrick Hesp during survey work in 1979 were compared with recent photography.

Foredune morphology and vegetation cover were surveyed at two sites on the Younghusband Peninsula—'The Granites' and '28 Mile Crossing' (see Figure 1). These sites were chosen to examine the morphology of *Thinopyrum* incipient foredunes on quasi-stable and eroding coastlines, respectively. 'The Granites' site is located within the relatively low energy 'Coorong III' morphodynamic class of Short and Hesp (1980). Compared with '28 Mile Crossing' (Coorong II), this site is relatively sheltered from the prevailing southwest winds by Cape Jaffa. In contrast, foredune scarping appears to have occurred frequently over a period of some years at '28 Mile Crossing'. It has not been possible to reconstruct the invasion history of *Thinopyrum* along the Younghusband Peninsula, in part because it established rapidly, in part because it is associated with narrow (5–10 m) incipient foredunes, which are difficult to identify on the earlier aerial photographs. We do know it established some time after 1979, when Short and Hesp (1980) undertook a systematic study of the established foredunes along the Younghusband Peninsula. We utilised a series of ground photographs, made available by Andy Short, to determine the foredune morphologies that existed prior to *Thinopyrum* invasion.

A sequence of aerial photographs records the invasion history of *Ammophila* at various sites along the west coast of Stewart Island. Mason Bay has a record of aerial photography dating from 1958 with subsequent images available for 1978, 1989 and 2002. *Ammophila* established in the study area in the early 1950s. These data document (i) the invasion history of *Ammophila* and indigenous species displacement; (ii) the physical development and changing morphology of the

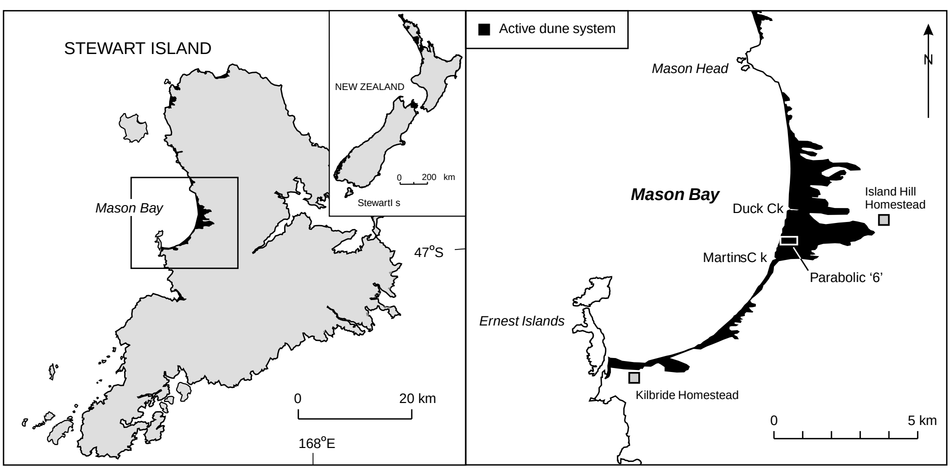

FIGURE 2. Location of Mason Bay study site, Stewart Island, New Zealand.

established foredune; and (iii) associated coastal progradation. Changes in the density and extent of *Ammophila* and *Desmoschoenus*, the dominant indigenous foredune species, are mapped for the period 1958–2002. *Ammophila* appears as a relatively uniform vegetation cover in the aerial photographs, in contrast to the variable texture of bare sand and scattered *Desmoschoenus*.

The pre-*Ammophila* morphology of the established foredune in Mason Bay was interpreted from photographs dating from the 1930s, descriptions by Leonard Cockayne, an eminent New Zealand botanist with a particular interest in dune flora, the 1958 aerial photograph, and small sections of *Desmoschoenus* foredune that survive in Mason Bay north of Duck Creek. The elevation and position of former nabkha associated with *Desmoschoenus* are indicated by the presence of rhizomes of this species (as indicated in Figure 5).

Ammophila arenaria and *Thinopyrum junceiforme*

Ammophila is a perennial rhizomatous dune grass that forms dense erect tufts with the aerial shoots taking a tussock form. The plant has an extensive rhizome network that extends both horizontally and vertically. The primary mode of reproduction of *Ammophila* is vegetative (through spreading rhizomes), although seed production is locally important. Rhizomes are easily broken into fragments by storm waves that are then transported by currents and washed onshore at new locations (Aptekar & Rejmänek 2000). Vegetative reproduction can occur from buds attached to the parent plant or from the long-distance dispersal of rhizome fragments that contain viable buds (Pavlik 1983; Buell *et al*. 1995). Rhizome fragments can be dispersed over long distances by strong winds or sea currents in this way (Baye 1990). *Ammophila* is native to the coasts of Europe and North Africa (between 63° N and 30° N latitude), where it is abundant on mobile and semi-fixed dunes (Huiskes 1979).

Ammophila responds positively to burial. The leafy shoots of *Ammophila* are able to grow vertically following sand deposition. However, once a burial threshold is reached for an individual plant, auxiliary buds develop to create vertical shoots with long internodes (vertical rhizomes). With further growth, the vertical rhizomes reach the sand surface with the apex becoming a new leafy shoot (Gemmell *et al*. 1953). Aerial shoots form along the vertical rhizomes creating dense tufts. These clusters of tillers decrease the wind speed around the plant resulting in increased sand deposition (Willis *et al*. 1959; Huiskes 1979). This increased deposition of sand is counteracted by the rapid production of elongated internodes along the stems of the vertical rhizomes, resulting in *Ammophila* being able to tolerate burial of up to 1 m (Ranwell 1972; Sykes & Wilson 1990). *Ammophila* not only responds positively to burial but actively encourages burial by sand for maximum growth and full completion of its life cycle (Kent *et al*. 2001).

Ammophila builds high and often steep foredunes across its home range (Doing 1985). Along the coasts of Australia and the Pacific coast of the USA, *Ammophila* has been shown to build larger and more continuous dunes than the native sand-binders (Wiedemann & Pickart 2004). Along parts of the Victorian coast, low and wide foredunes, characteristic of areas dominated by native grasses, are replaced by *Ammophila* foredunes up to 5 m high (Bell 1988). These changes have been attributed to differences in plant morphology and habit between *Ammophila* and the native sand-binders. In New Zealand, *Ammophila* tends to build higher and steeper dunes compared to *Spinifex* or *Desmoschoenus*. In a study of Manawatu foredune profiles, Esler (1970) found that dunes formed under *Ammophila* had slopes less than 28° and heights over 6 m, whereas dunes formed under *Desmoschoenus* had slopes less than 14° and were approximately 0.5 m in height. These differences were attributed to the ability of the dense *Ammophila* cover to trap and bind sand more effectively than the sparse *Desmoschoenus* cover.

Ammophila can cause major changes to the structure and composition of indigenous plant communities related to alterations to dune morphology, sand budgets and nutrient supply (Pickart & Sawyer 1998; Duncan 2001; Hilton *et al*. 2005). *Ammophila* excludes other species unable to cope with high rates of burial (Maun 1998) or burial/erosion during shadow dune development (Hilton *et al*. 2005). The impact of *Ammophila* on indigenous dune systems in New Zealand has been recognised largely in the context of its potential to displace indigenous species and degrade habitats. This is reflected in *Ammophila* being rated as the most invasive species in New Zealand (Owen 1996). To date, there has been little consideration of the long-term loss of dune system function as a result of *Ammophila* invasion. *Ammophila* may reduce or prevent phases of instability that create habitat for specialist dune species (Hilton *et al*. 2005). These phases of instability are characteristic of transgressive dune systems and favour the continued dominance of native dune species. *Ammophila*-dominated dune systems are unlikely to respond to climate fluctuations and vegetation stress (such as drought) in the same way as pre-*Ammophila* systems (Dixon *et al*. 2004). Hence, we postulate that *Ammophila* is likely to prevent or inhibit episodes of foredune instability and accelerate vegetation succession, to the detriment of dune system function.

Thinopyrum is an erect, perennial, rhizomatous grass, native to the Baltic, Atlantic and western Mediterranean coasts of Europe. It has a wide latitudinal home range, from Finland (62° N. Lat.) to the Cadiz region of Spain (36° N. Lat.). It is also known as 'sea couch', 'sand couch-grass' or 'Russian wheatgrass' (in the USA). It was formerly identified as '*Elymus farctus*' in Australia, where it was first observed in Port Phillip Bay, Victoria, in 1933 (Heyligers 1985). The circumstances of the introduction of *Thinopyrum* to Australia (and New Zealand) are unclear; however, it probably arrived in Australia with ballast water (Heyligers 1985; Mavrinac 1986). Since 1933 *Thinopyrum* has spread naturally or with human assistance to South Australia and the northern coasts of Tasmania. It is capable of dispersal by sea-rafted fragmented rhizome or seed (Harris & Davy 1986).

Thinopyrum grows closer to the sea and lower down the beach than any indigenous Australian foredunes species. It is exceptionally tolerant of salinity and occasional tidal inundation (Heyligers 1985). Mavrinac (1986) states that it grows closer to the sea than any other 'British' dune grass. It is capable of rapid tiller and lateral/oblique rhizome growth and has excellent sand-trapping and dune-forming abilities. In Europe, *Thinopyrum* often forms embryonic dunes or the first (frontal) dune (zone 3 of Doing 1985), which seldom exceed 1 m in height (see Plate 1). The morphology of *Thinopyrum* foredunes in Australia has not been described systematically. Heyligers (1985) describes *Thinopyrum* as forming 'low wide foredunes' in low to moderate energy conditions. As wind conditions increase *Thinopyrum* dunes become increasingly hummocky. It tends to form a dune with a steep stoss face when growing in front of a former dune or a terrace if the beach is prograding

PLATE 1. Low *Thinopyrum* incipient foredunes on the southern coast of Texel Island (De Hors), Netherlands, in a situation of rapid coastal progradation (24 June 2005). Marram grass occurs on the first established foredune, further inland.

(Heyligers 1985). The vigour of *Thinopyrum* is much reduced where it grows at higher elevations on foredunes.

Foredune development following *Ammophila* invasion, Mason Bay, Stewart Island

Ammophila was intentionally introduced to Mason Bay during the 1930s to stabilise dunes on Kilbride farm, at the southern end of the bay (see Figure 2). Subsequent dispersal probably occurred through the natural spread of rhizome fragments from north to south (Hilton *et al*. 2005), although there is anecdotal evidence that some *Ammophila* was planted in the vicinity of Duck Creek in the 1950s. By 1958 *Ammophila* 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 *Ammophila*, where canopy cover exceeded 50 per cent, was 1.4 ha, representing 0.6 per cent of the area of central Mason Bay (Jul 1998) (see Figure 3).

The area occupied by *Ammophila* increased exponentially between 1958 and 1978. *Ammophila* had established across most of the foredune environment between Martins Creek and Duck Creek by 1978, although the cover was discontinuous. At this time *Ammophila* extended up to 750 m inland and dominated 17.8 ha of the central dunes, an increase of 1137 per cent over 20 years (Jul 1998). A significant increase in both the extent and density of *Ammophila* occurred between 1978 and 2000 (see Figure 3). During this period *Ammophila* achieved almost total cover between Martins Creek and Duck Creek, eventually forming a continuous foredune and displacing all *Desmoschoenus*. By 1998

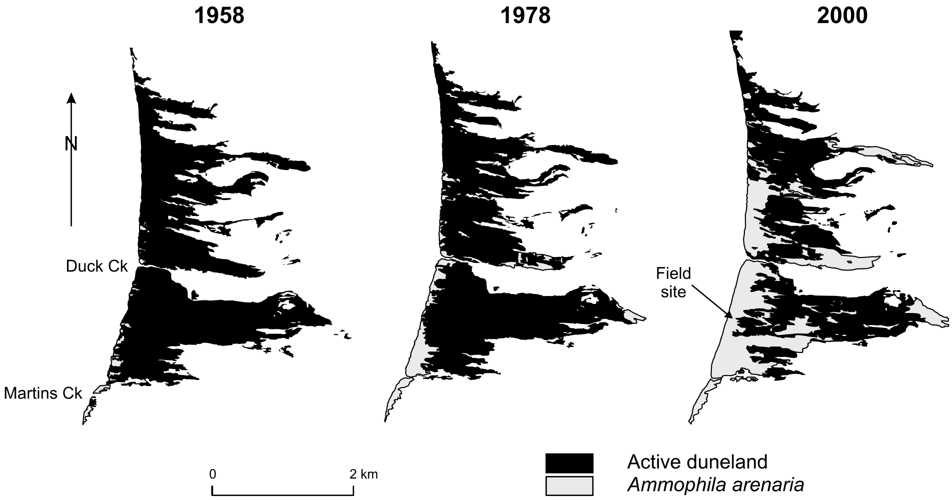

FIGURE 3. Pattern of *Ammophila* invasion north of Martin's Creek, Mason Bay, Stewart Island, 1958–2000 (Hilton *et al*. 2005).

Ammophila covered 74.9 ha of the central dunes (Jul 1998). This represents an increase in area dominated by *Ammophila* of 5204 per cent in the 40 years between 1958 and 1998.

Foredune development—central Mason Bay

Ammophila invaded the central dune system from south to north and inland from the established foredune. During this process, the morphology of the foredune changed from a low, sparsely vegetated and hummocky foredune, 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 *Ammophila* invasion. Cockayne (1909, p. 18) described the foredunes of Mason Bay, prior to the introduction of *Ammophila*, as comprising '6–10 ft (1.8–3.0 m) tall, haystack-like dunes'. That is, the foredune comprised a series of isolated nabkha or shadow dunes (Type 4–5; Hesp 1988), formed in association with *Desmoschoenus* (with some *Austrofestuca littoralis* and *Euphorbia glauca*). Three dunes of this type still occur in the foredune environment in Mason Bay, north of Duck Creek (see Plate 2a). Cockayne's descriptions accord with ground photographs of the foredune environment near Duck Creek, taken during the 1930s. The 1958 aerial photograph is of average quality, but also shows that the vegetation cover at this time was patchy with numerous nabkha or shadow dunes (see Figure 4a). The irregular alongshore topography of the *Desmoschoenus* foredune in 1958 suggests that blowout formation through the foredune occurred from time to time (see Figure 3).

Ammophila invasion and foredune development progressed rapidly between 1958 and 1998, culminating in a relatively massive, stable, continuous foredune (see Figure 5). *Ammophila* had formed a semi-uniform cover by 1978 (see Figure 4f), creating a continuous, though topographically irregular, foredune (Stage III, Hesp 1988). Development of the foredune during this period occurred through coalescence of adjacent *Ammophila* shadow dunes, as the vegetation cover

PLATE 2. (a) One of three surviving *Desmoschoenus* foredunes north of Duck Creek (viewed from about the high water line, looking inland) and (b) the *Ammophila* foredune between Duck Creek and Martins Creek.

increased (Hilton *et al*. 2005). *Desmoschoenus* had been displaced from the stoss face of the established foredune during the period 1958–1978, as the new marram foredune prograded seawards and accreted. *Ammophila* increased in extent and density through the backdune environment, with a corresponding decline in the area of unvegetated and *Desmoschoenus*-dominated habitat. By 1989, *Ammophila* had formed a dense, uniform cover along the stoss face and had become the

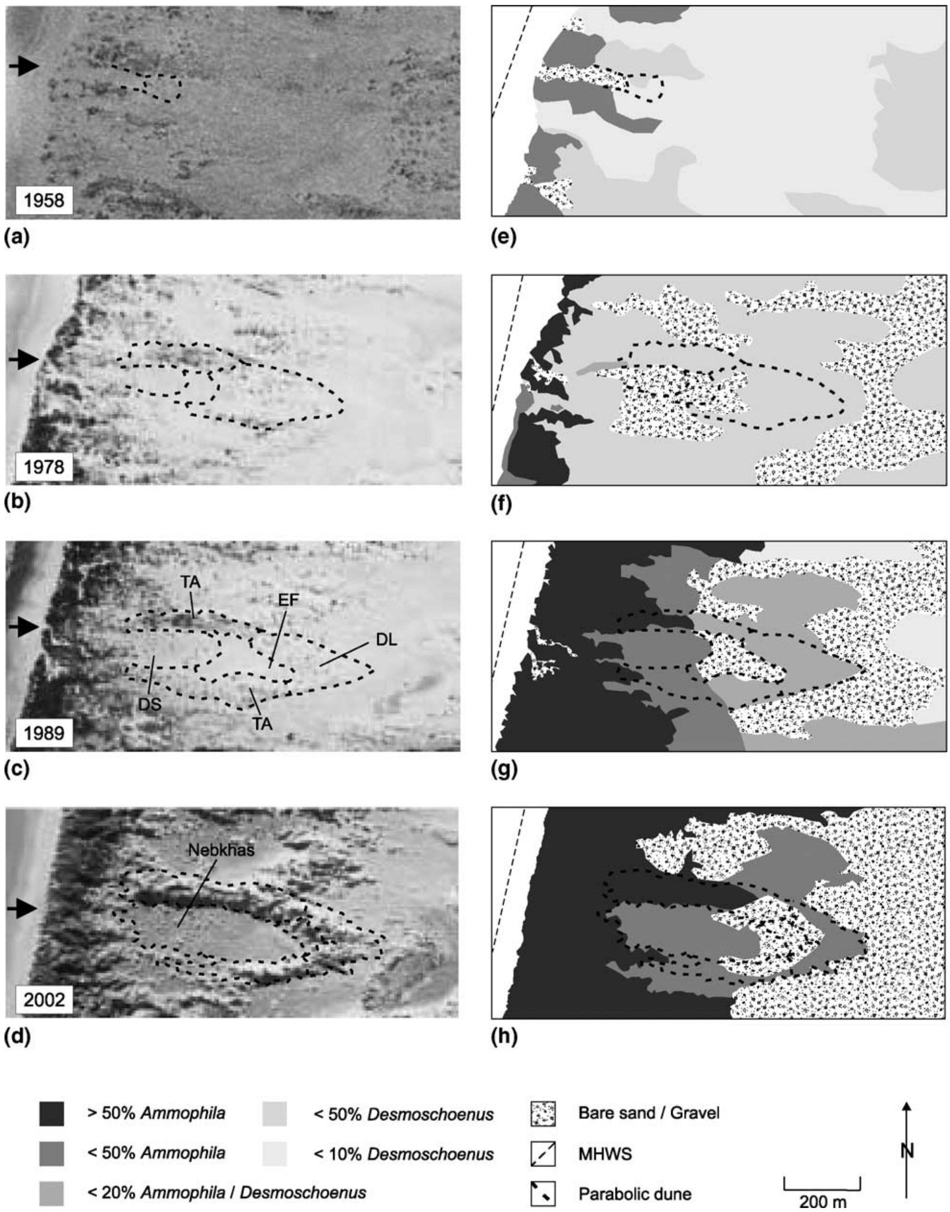

FIGURE 4. A sequence of aerial photographs and vegetation maps highlighting the rapid spread of *Ammophila* and concomitant development of foredune and parabolic dune landforms and vegetation cover. The outline of the parabolic dune ('parabolic 6') at each stage of development is highlighted by the dashed 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.

dominant cover through the lee face of the foredune (see Figure 4g). During the period 1989–2002, the density of *Ammophila* increased to form an extensive mono-specific (>80 per cent) cover (see Figure 4h). The contemporary foredune is

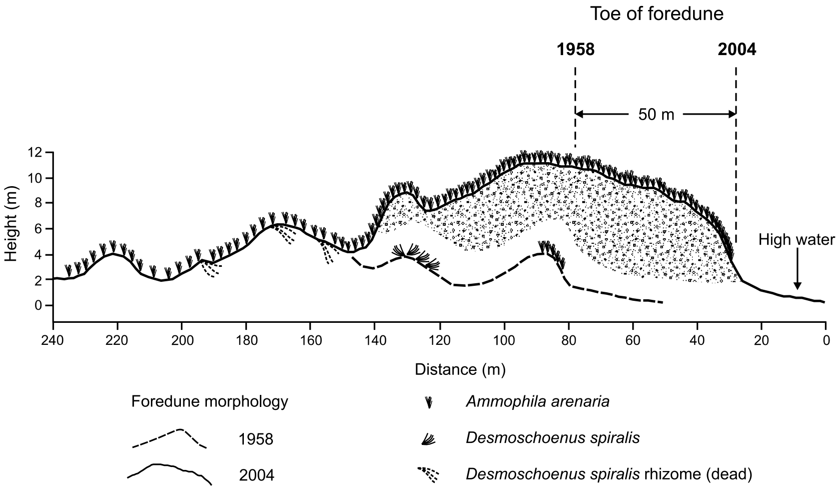

FIGURE 5. Comparison of the foredune morphology before and after *Ammophila* invasion, for the central dune system of Mason Bay. The morphology of the *Desmoschoenus*-dominated foredune is derived from the descriptions of Cockayne (1909), field observations of remnant (dead) *Desmoschoenus* rhizome and the 1958 aerial photograph.

characterised by a steep stoss face, a broad, relatively flat terrace and a gently sloping lee face (see Plate 2b and Figure 5) equivalent to Stage I of Hesp (1988). The overall morphology of the foredune is now very different from the pre-*Ammophila* foredune (se Table 1). Lateral growth has occurred primarily through seaward progradation, averaging 50 m between 1958 and 2002, probably encouraged by high rates of deposition and stabilisation under *Ammophila*, rather than any change to the beach-dune sediment budget.

The stoss face of the massive *Ammophila* foredune between Duck Creek and Martin's Creek appears to be stable. The numerous corridors and depressions that dissected the foredune at the time of *Ammophila* invasion have now closed. Two narrow blowouts adjacent to 'parabolic 6' persisted until 1989 (see Figure 4c). During the initial stages of *Ammophila* invasion, the width and depth of these blowouts was enhanced, providing a major pathway for sediment input into the backdune system. Closure of the blowouts occurred between 1989 and 2002 as the density of *Ammophila* increased, stabilising the throat of the blowout and reducing

TABLE 1. Changes to foredune morphology,[a] 1958–2002

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

Notes: [a]Dimensions are derived from Figure 5.
[b]Assuming a 2 km foredune length.

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 *et al*. 2005). To date none of these depressions has developed into a blowout.

Case study I: foredune parabolic dune development, Mason Bay

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 (terminology after Pye 1983) has developed in a relatively flat section of the central dunes of Mason Bay. The contemporary dune system between Duck Creek and Martins Creek comprises six adjacent parabolic dunes transgressing over a low gradient stonefield. The most southerly of these parabolic dunes ('parabolic 6') is the best defined of these dunes (see Figure 2).

'Parabolic 6' evolved from a blowout, some time prior to or coincident with *Ammophila* invasion, probably in the late 1940s. The formation of relatively steep-sided *Ammophila* shadow dunes may well have caused the development of such blowouts. In 1958 the blowout lacked trailing arms (see Figure 4a). The depositional lobe of the incipient parabolic dune would probably have been a relatively low, sparsely vegetated feature (see Table 2). *Ammophila* 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' (see Figure 4a). The characteristic features of a long-walled parabolic dune had formed by 1978. The northern trailing arm (TA) and a deflation surface (DS) are clearly defined, along with a sparsely vegetated depositional lobe (DL) (see Figure 4b). Development of the deflation surface occurred primarily through elongation, increasing in length at 7.91 m/year between 1958 and 1978 (see Table 3). Widening of the surface also occurred, which resulted in an increase in area of the deflation surface from 0.35 to 1.15 ha between 1958 and 1978, a 226 per cent increase. *Ammophila* had formed a near-continuous cover across the foredune by 1978, but it was still absent from the parabolic dune (see Figure 4b).

'Parabolic 6' became increasingly sheltered by the rapidly accreting *Ammophila* foredune between 1978 and 1989. It continued to migrate downwind between 1978 and 1989; however, the rate of advance declined (see Table 3). During this

TABLE 2. Temporal changes in the morphology of 'parabolic 6'

	1958[a]	1978	1989	2002
Total length[b] (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

Notes: [a]Best estimate only, due to poor image quality.
[b]Excluding foredune.

TABLE 3. Calculated migration rates (m/year) of 'parabolic 6'

	1958–78	1978–89	1989–2002
Deflation surface	7.91	6.02	15.60
Erosional face	–	16.29	7.00
Depositional lobe	24.19	5.56	0.79

period the deflation surface became significantly larger, with a corresponding decline in the length and area of the depositional lobe (see Table 2). The deflation surface increased in length at a rate of 6.02 m/year between 1978 and 1989, with an increase in area from 1.15 to 2.14 ha, representing an 86 per cent increase.

Ammophila had established throughout the parabolic dune by 2002, although some remnant areas of *Desmoschoenus* on the northern trailing arm persisted (see Figure 4f). Between 1989 and 2002 the rate of landward advance of the depositional lobe was almost negligible (see Table 3). At the same time the deflation surface increased in length at an average rate of 15.60 m/year and increased in area to 5.20 ha, representing a 143 per cent 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 *Ammophila* shadow dunes, 3–5 m high.

'Parabolic 6' has been relatively stable since *Ammophila* invasion. The development of a massive *Ammophila* 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 established foredune evolved. The development of large deflation surfaces of this type in this context has also been observed in Oregon (Carter *et al*. 1990). However, the ongoing formation of nabkha dunes across the seaward half of the deflation (and former deflation) surface indicates that some sand is still in circulation. We have observed significant jettation (terminology after Arens 1996) across the foredune, during strong westerly winds, that provides sand for ongoing nabkha development across the rear slopes of the foredune and former deflation zone of the parabolic dune (see Figure 4d).

Ammophila invasion and foredune development may have contributed to the subsequent stabilisation of 'parabolic 6' and the adjacent parabolic dunes. This foredune has trapped a great deal of sand that might otherwise have contributed to parabolic dune development and reduced rates of sedimentation in its lee. *Ammophila* has also established in almost all elements of the parabolic dunes, with the exception of the erosional face, forcing stability. However, it may be that these parabolic dunes were close to completing their life cycle at the time *Ammophila* was introduced.

Case study II: sea-wheat grass, Younghusband Peninsula

The coastal plain between the Murray River mouth and Naracoorte in southeast Australia contains a sequence of at least eight coastal barriers, which have been stranded and preserved by uplift. The oldest barrier, approximately 800,000 years old, is situated around 90 km from the coast. The youngest and active barrier, the Younghusband Peninsula (see Figure 1) is less than 7000 years old (Harvey 1981; Belperio 1995). This sequence is widely regarded as one of the classic records of Quaternary sea-level change and barrier development.

The Younghusband Peninsula is a modern analogue for the formation of the older barriers (Bourman *et al*. 2000). Short and Hesp (1984) propose a five-stage model for the Sir Richard and Younghusband Peninsulas (see Figure 6), involving: (1) the formation of Pleistocene barriers below modern sea level; (2) Holocene sea-level transgression and formation of the initial Holocene shoreline; (3) barrier progradation, as foredune ridges; (4) depletion of nearshore sand supplies and initial dune transgression and shoreline erosion; and (5) continued dune transgressions and barrier regression. Episodes of transgressive dune development, following foredune disturbance were, therefore, central to barrier and dune system development.

Short and Hesp (1980) describe the morphology of incipient foredunes and established foredunes between Kingston and the Murray Mouth, in relation to variations in beach–surfzone morphodynamics. At the time of the field survey

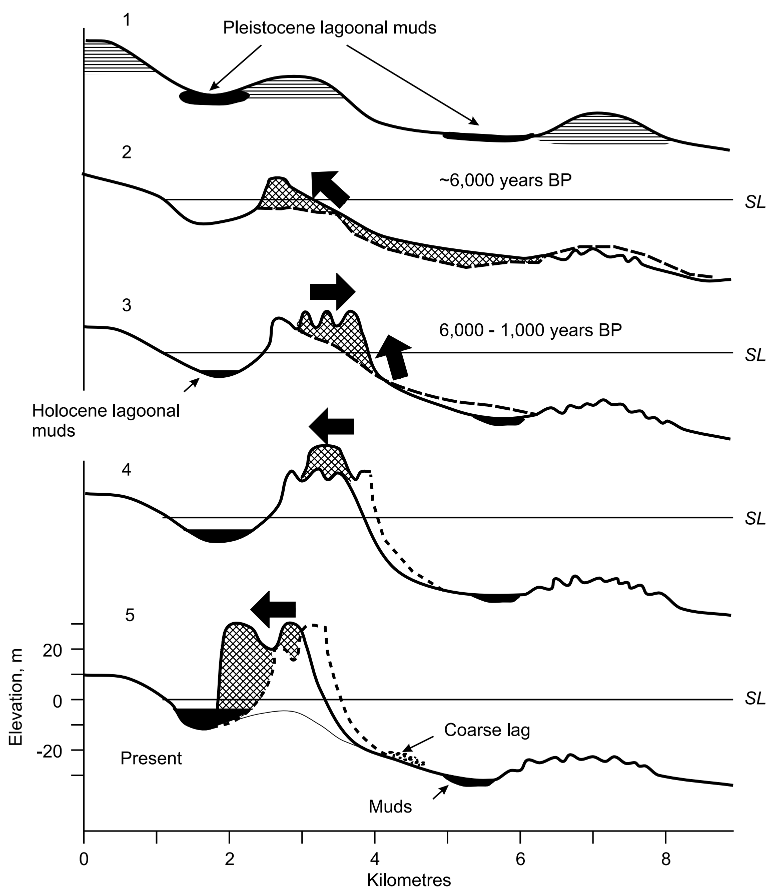

FIGURE 6. An interpretation of the genesis of the Younghusband Peninsula (after Short & Hesp 1984).

Spinifex sericeus and *Austrofestuca littoralis* were associated with incipient foredunes. A wide range of incipient foredune and foredune morphologies were present. In 1979, when Short and Hesp conducted fieldwork, topographically variable and highly eroded foredune morphologies (types Fd and Fe) occurred widely between the Murray Mouth and 'The Granites', as might be expected with a regressive barrier. Incipient foredunes were intermittent, particularly in the region extending between 95 and 123 km south of the Murray Mouth. They observed foredune stability to increase towards Kingston and transgressive dune development to decrease, consistent with declining levels of wave and wind energy in the lee of Cape Jaffa.

Thinopyum *invasion*

Thinopyrum established along much of the length of the Younghusband Peninsula with remarkable rapidity. It was not observed by Short and Hesp (1980) during a systematic survey of foredune morphology between Kingston and the Murray River mouth in 1979. *Thinopyrum* was observed soon after, in 1986, at Butcher Gap Drain and Blackford Drain near Kingston and the Murray Mouth (Mavrinac 1986). It was also present at this time along sections of the Adelaide coast (Torrens Outlet and Bungaloo Creek). *Thinopyrum* had formed a substantial incipient foredune at each of these sites, 15–20 m wide, 1.0–1.5 m high, seaward of the existing *Spinifex* foredune.

Thinopyrum appears to have occupied the coast between the Murray Mouth and Kingston, a distance of about 170 km, during the early to mid-1980s. There has been no work, to date, on processes of *Thinopyrum* dispersal. There is no evidence that this species was deliberately planted in South Australia, and it almost certainly established along the Younghusband Peninsula without assistance. It most likely spread by fragmented rhizome, which is likely to enter the sea in large quantities during storm-forced erosion of the incipient foredune. The low elevation of *Thinopyrum* foredunes would ensure this process occurs frequently.

Incipient foredune development in conjunction with *Thinopyrum*, Younghusband Peninsula

'The Granites'

'The Granites' site is located in the relatively sheltered 'Coorong III' sector of Short and Hesp (1980). This is a stable site, with no significant trend of progradation or erosion over the period 1945 to the early 1980s, prior to the arrival of *Thinopyrum*. The site is situated 250 m south of the public car park and beach access point. The incipient foredune at this locality is typical of the dune for some kilometres north and south of 'The Granites'. It exhibits a 'terrace' form (described in Hesp 2002), with a high cover of *Thinopyrum* (>75 per cent) (see Figure 7). This feature is 10 m wide and 1–2 m high and continuous alongshore. The backdune comprised a former blowout, now well vegetated with *Leucophyta brownii*, *Olearia axillaris*, *Carpobrotus rossii* and other species. The new *Thinopyrum* foredune partially overlies the stoss face of the former *Spinifex* foredune. *Spinifex* occurs throughout the surveyed area, though nowhere is it particularly dense (see Figure 7).

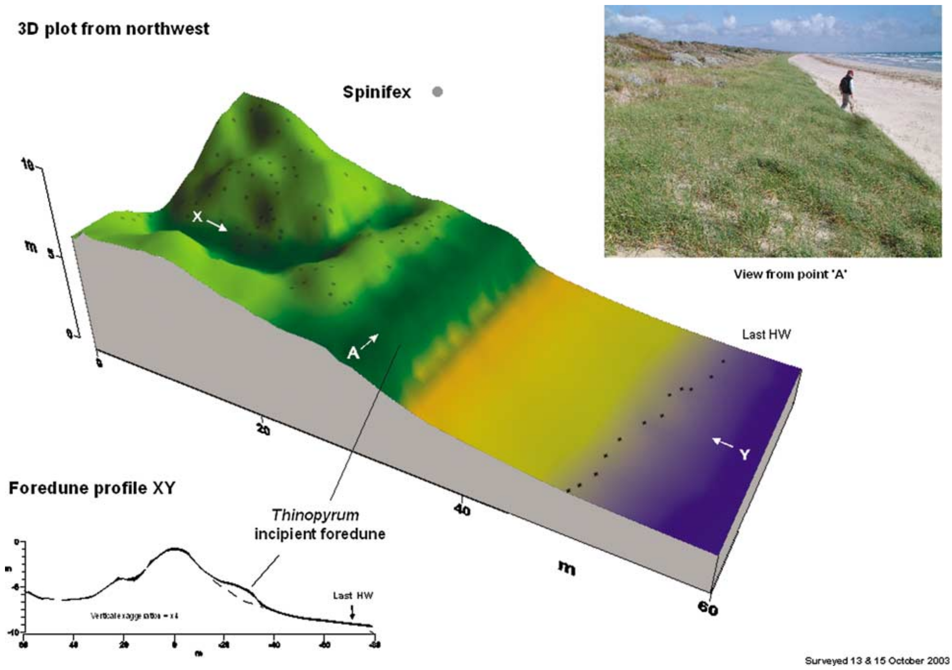

FIGURE 7. 'The Granites'—*Thinopyrum* occurs in a narrow band seaward of the former *Spinifex* foredune.

'28 Mile Crossing'

'28 Mile Crossing' is one of several 4-wheel-drive tracks that enable access to the beach along the southern Coorong. The '28 Mile Crossing' study site is located approximately 100 m southeast of the beach access of the '28 Mile Crossing' 4-wheel-drive track. The site was chosen to examine the morphology of incipient *Thinopyrum* foredunes on a section of eroding shore. The former *Spinifex* foredune comprises a series of remnant knobs (Type 3–4 foredune; Hesp 1988), interspersed with lobes of sand associated with *Thinopyrum* (see Figure 8). These lobes constitute sections of incipient foredune, which extend 3–4 m from the face of the eroding foredune. They have a 'ramp' morphology (after Hesp 2002). Unvegetated sections of scarped foredune separate these lobes. An extensive deflation surface lies inland of the foredune, with transverse dunes occurring downwind. The strandline was 15–20 m in front of the foredune on the day of the survey.

Thinopyrum forms a dense patch of vegetation across and extending away from the eroding face of the foredune and, secondly, a sparse cover over the lee slopes of the foredune and into the deflation surface (see Figure 8). *Spinifex* occupies the remnant knobs and overlaps with *Thinopyrum* in places. *Euphorbia paralias* occurs across the crests of the knobs and across the rear of the foredune. The presence of various mature backdune shrubs and sedges (*Stackhousia spathulata*, *Olearia axillaris*, *Isolepis nodosa* and *Ozothamnus turbinatus*, for example) suggests that the former *Spinifex* foredune has been stable for some time, albeit the face of the foredune is eroding.

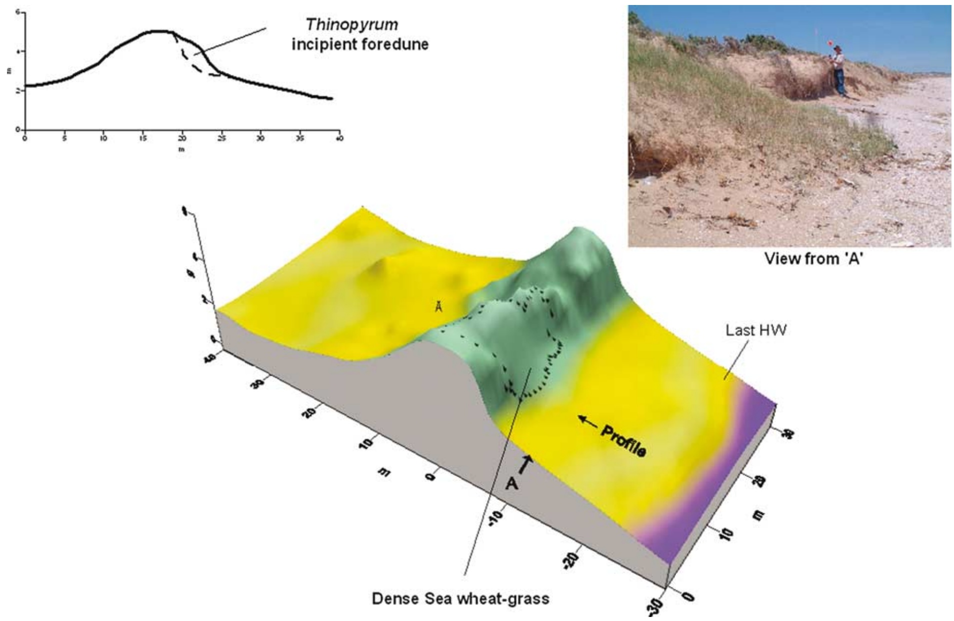

FIGURE 8. 3D representation of the '28 Mile Crossing' survey area. *Thinopyrum* has occupied hollows between remnant knobs of *Spinifex* and built incipient ramp foredunes 3–4 m seaward of the foredune scarp.

Incipient foredune formation in conjunction with *Thinopyrum*

Thinopyrum has formed a narrow, usually low, incipient foredune along the Younghusband Peninsula since the early 1980s. The terms 'foredune' and 'incipient foredune' require some clarification. Foredunes are 'shore-parallel dune ridges formed on the top of the backshore by aeolian deposition within vegetation' (Hesp 2002, p. 145). 'Incipient foredunes are new, or developing, foredunes within pioneer plant communities' (Hesp 2002, p. 145). The sites described contain type 2a and 2b incipient foredunes (after Hesp 1989), that is, they have formed on the backshore by growth of *Thinopyrum* rhizome growth into that section of the back-beach that lies between the toe of the foredune and the driftline. At the two sites described, *Thinopyrum* has formed a terrace against the former *Spinifex* foredune, usually at a slightly lower elevation. We do not know, at present, whether *Thinopyrum* is in the process of establishing a more substantial incipient foredune at '28 Mile Crossing', or whether the environment is preventing continuous alongshore colonisation.

Thinopyrum invasion has had a significant impact on the morphology of the pre-existing *Spinifex* foredune at both sites. It has caused the stoss face of the foredune to prograde and establish at lower elevations. *Thinopyrum* tends to occupy low-lying gaps in eroding foredunes and encourage deposition, resulting in a higher overall vegetation cover and more uniform topography. Hence, the overall impact of *Thinopyrum* is to encourage the formation of wider, more uniform and more continuous foredunes, at least in situations of low to moderate rates of accretion. We have seen higher (4–5 m) *Thinopyrum* foredunes at the Murray Mouth, where the rates of accretion may be significantly greater than observed at the sites reported here.

Thinopyrum grows vigorously on the stoss face of the foredune, and is clearly tolerant of more frequent sea-water inundation and soil salinity. Our surveys demonstrate that it also survives in backdune environments, albeit in a semi-moribund form. It is not, therefore, vulnerable to catastrophic removal during episodes of severe foredune scarping. Backdune plants of *Thinopyrum* are probably capable of rapid growth when erosion exposes them to higher rates of sedimentation and higher nutrient levels.

Spinifex has been displaced from the front face of the foredune along the Younghusband Peninsula. This will greatly reduce the distribution of *Spinifex* and associated indigenous species, but it may have significant ecological implications for other flora and fauna. It is inevitable, for example, that the habitat of shore birds such as the hooded plover will decline, as *Thinopyrum* colonises gaps in the foredune and blowouts, and occupies areas of the backbeach that would not normally be colonised by *Spinifex*.

The potential impact of *Ammophila* and *Thinopyrum* on blowout formation

Ammophila and *Thinopyrum* have produced new dune morphologies in the dune systems described. A massive foredune complex established at Mason Bay following *Ammophila* invasion. The landscape associated with *Desmoschoenus* has been buried beneath an evenly vegetated, continuous established foredune, 150–200 m wide and 10–12 m high. Large quantities of sand, which would otherwise have entered the dune system, are now trapped in this foredune complex. *Ammophila* has also invaded the hinterland of the dune system, with resulting loss of dune flora and transgressive dune mobility. *Thinopyrum* occupies a more limited range—it is primarily a species of the back beach. It has also established continuous incipient foredunes along most of the length of the Younghusband Peninsula, and by the mid-1980s occupied approximately 170 km of coast between the Murray Mouth and Kingston. In both cases irregular foredunes have been replaced by regular, continuous-alongshore foredunes. *Thinopyrum* and *Ammophila* have also had a major impact on the indigenous flora of the two study sites. *Thinopyrum* has displaced *Spinifex* from the stoss face of the foredune along the length of the Younghusband Peninsula. The range of *Spinifex* may be reduced over time, since it is likely that the crest and rear of the foredune will experience less sediment input, greater stability and (possibly) accelerated vegetation succession. *Ammophila* has had an overwhelmingly adverse impact on the indigenous dune flora of Mason Bay. The indigenous species associated with the pre-*Ammophila* foredune have been totally displaced.

Thinopyrum and *Ammophila* have produced new dune landscapes and new dune ecosystems. Here we will consider whether these grasses are likely to reduce the frequency or intensity of blowout development. This impact would have significant implications for the long-term development of Mason Bay and Younghusband Peninsula dune systems, by reducing the incidence of transgressive dune development. This would, in turn, impact on the diversity of habitats within the dune systems.

The processes that lead to blowout development are well documented. A blowout is a saucer-, cup- or trough-shaped depression or hollow formed by wind-forced erosion in a pre-existing deposit of sand. They may be initiated as a result of: wave erosion along the seaward face of the foredune; topographic acceleration of airflow over the dune crest; climate change; vegetation variation through space or change through time; water erosion; high velocity wind erosion, sand inundation and burial; and human activities (for a review of these processes see Hesp 2002).

There is some evidence that *Ammophila* and *Thinopyrum* respond differently to these processes compared with indigenous foredune species. Both species form uniform, continuous, Type I foredunes (or contribute to this character along the stoss face of pre-existing *Spinifex* foredunes). The potential for blowout development through topographic acceleration of airflow is, therefore, likely to be reduced. *Ammophila* and *Thinopyrum* occur on a range of coasts, including those with dry Mediterranean climates. *Ammophila* has a number of physiological and morphological adaptations that reduce the impact of drought stress. In a series of glasshouse experiments, Dixon *et al*. (2004) compared the tolerance of *Ammophila* and *Desmoschoenus* to drought conditions. *Desmoschoenus* showed signs of water stress after 8 days in glasshouse drought conditions, whereas *Ammophila* showed no signs of stress until day 18. At the completion of the drought trial, 5 per cent of *Desmoschoenus* and 80 per cent of the *Ammophila* recovered. These results accord with field observations and the results of earlier glasshouse experiments (Huiskes 1979). The relative tolerance of *Spinifex* and *Thinopyrum* and *Spinifex* and *Ammophila* to drought has not been ascertained.

Both *Ammophila* and *Thinopyrum* species are rhizomatous grasses capable of trapping and binding sand. Their leaves are capable of 'lodging' and so are able to withstand strong winds and maintain a uniform vegetation cover. Established foredunes associated with both species are vulnerable to scarping by storm wave swash; however, gaps or low points are likely to be rapidly repaired by post-storm growth. Our observations at '28 Mile Crossing' on the Younghusband Peninsula indicate that *Thinopyrum* is able to establish cover and form incipient foredunes on an eroding coastline. Burial may pose a significant threat to *Thinopyrum*; however, like *Ammophila*, it is possibly tolerant of darkness and may be able to emerge when buried. The incipient foredunes of both species are scarped during episodes of storm wave activity and storm surge. We suspect that in both cases incipient foredunes are rapidly repaired by, first, mass failure of the upper sections of the scarp and then rapid elongation of lateral rhizomes. The toe of foredunes of both species must be in constant flux, even on prograding coasts, given their proximity to the sea. Finally, *Thinopyrum* is known to be exceptionally tolerant of salt during episodes of elevated sea level associated with storms. *Ammophila* is not tolerant of salt in the root zone, but avoids the problem by building relatively high, massive foredunes.

Conclusions

In conclusion, it has been demonstrated that two exotic dune grasses, namely *Thinopyrum junceiforme* and *Ammophila arenaria*, have been introduced into dune environments in Australia and New Zealand, respectively, where they have:

(1) replaced irregular, sparsely vegetated, established foredunes with continuous incipient foredunes;
(2) encouraged accretion and progradation;
(3) increased the extent and evenness of vegetation cover;
(4) rapidly displaced native species; and
(5) altered dune habitat for indigenous fauna and flora.

These impacts have occurred over the last few decades. We have raised the question of the long-term impact of these species on barrier and dune system development. Are these species likely to reduce the incidence or extent of blowout development? If so, could a reduction in transgressive dune development affect the natural development of coastal barriers along coasts occupied by *Ammophila* and *Thinopyrum*? These processes are an essential part of the geomorphic and ecologic character of temperate sandy coasts. Both study sites are located in national parks which have been designated to conserve natural values.

A substantial programme of research is required to resolve this matter. Such a programme would need to compare the relative response of indigenous and exotic species to the environmental stresses identified above, both in isolation and in combination. We already know that *Ammophila* is more tolerant of burial (Sykes & Wilson 1990) and more tolerant of drought (Dixon *et al*. 2004) than *Desmoschoenus*. Relatively little is known about the response of *Thinopyrum* to environmental stress on temperate coasts, in part because this species has attracted virtually no attention in the short period it has been in Australia.

There is clearly a need for a management response to this issue. In New Zealand the Department of Conservation (DoC) has commenced a programme of *Ammophila* eradication in Fiordland and Rakiura National Parks (Stewart Island) in southern New Zealand. The DoC has employed helicopters, all-terrain vehicles and back packs to apply selective herbicides in these parks. Much smaller operations, targeting *Ammophila*, are occurring elsewhere in New Zealand. The Stewart Island operations commenced in 1987 and are likely to run for at least another 15 years. The question remains as to whether the DoC, local authorities or private landowners will undertake *Ammophila* eradication in significant conservation areas outside national parks. At least one NGO, the Yellow-eyed Penguin Trust, based in Dunedin, has initiated marram-control operations on private land to improve penguin habitat and restore indigenous vegetation. In contrast, there has been little extensive control of *Ammophila* in Australia, apart from work by the Department of Primary Industry, Water and the Environment (DIPWE) in southwest Tasmania. No control of *Thinopyrum* has yet occurred in Australia. This may be due to the recent focus on invasive species of backdune and established foredunes such as Bitou Bush (*Chrysanthemoides monilifera*), but this inaction probably also reflects low levels of awareness of the impact of introduced foredune species. The recent release of the Tasmanian Beach Weed Strategy (Rudman 2003) and initiation of an investigation of the impact of South African Pyp Grass (*Ehrharta villosa*) in Coorong National Park by the Department of Environment and Heritage indicate a developing awareness of exotic dune weeds.

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