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Vegetation recovery following sand mining on coastal dunes at Kaitorete Spit, Canterbury, New Zealand

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A section of the extensive sand dunes at Kaitorete Spit, Canterbury, New Zealand, has been mined for sand over a period of 40 years. Unmined dunes are dominated by dense stands of the otherwise now restricted indigenous sand binder *Desmoschoenus spiralis*, making them an area of great conservation value. Plant communities on mined surfaces of various age and on unmined dunes were examined by using classification and ordination. Classification clearly distinguished communities of unmined and mined dunes respectively. The principal ordination gradients represent the typical landward dune sequence and the mined/unmined differences. Although there are sites on unmined dunes that carry vegetation of the mined group, there is no evidence that mined sites have recovered communities typical of the unmined dunes. The conclusion is that there is no sign of recovery of the original dune communities despite partial colonisation by *Desmoschoenus*. Two explanations are offered. Adventive *Ammophila arenaria* has invaded the older mined dunes, displacing *Desmoschoenus* or excluding it from re-invading, while the remaining mined area has developed a sparse sand-plain vegetation, the result of lateral sand movement. Implications for conservation management are discussed.

INTRODUCTION

Opencast mining typically causes such massive damage to landscapes and biological features (Down & Stocks, 1977) that considerable restoration work needs to be undertaken to establish vegetation which is generally unrelated to that originally present (Johnson & Bradshaw, 1979). In certain situations, especially where substrate remains, there is a reasonable expectation that the original plant communities will at least show some natural recovery despite the damage. One such situ- ation is the mining of sand from coastal dune systems (Brooks, 1976; Lewis, 1976). Certainly, mining severely damages the original dune structure, but the processes that build dunes are likely to remain: a supply of sand, wind to move it, and sand-binding plants. Even if full recovery takes a long time, it might be expected that trends towards recovery would be detectable.

One sand-dune system that has been affected by mining is that at Kaitorete Spit, Canterbury, New Zealand. A section of these dunes has been mined since 1952 for its coarse-grained, angular, well-sorted sand. The dunes are important for conservation values, being one of the few remaining systems in New Zealand where the indigenous sand-binding sedge, pingao *Desmoschoenus spiralis*, still dominates. This species has declined considerably, initially through destruction of the indigenous dune cover by burning and grazing that accompanied the arrival of Europeans in New Zealand 150 years ago. Most dune systems were subsequently stabilised by extensive planting of the introduced sand binder marram *Ammophila arenaria*, a species that has further displaced much of the remaining *Desmoschoenus* where the two

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come into competition. Kaitorete Spit therefore rates as one of New Zealand's most botanically valuable dune systems. As well as the high proportion of communities dominated by indigenous species, there are endemic invertebrates and plants (*Carmichaelia appressa*, an unnamed species of *Asperula*, and possibly others), otherwise localised plants (e.g. *Austrofestuca littoralis*), and important archaeological sites; the dune system is also peculiar in being of a dry coarse sand instead of the more usual fine sand. It is desirable therefore that the mined section, although relatively small, recovers as much as possible its valuable botanical features. Some attempts have been made to assist recovery, but have either failed completely (replanting of *Desmoschoenus spiralis* cuttings) or are of uncertain success (spreading of *Desmoschoenus spiralis* seed following mining), because mining and conservation interests dispute the effectiveness of the methods employed. Such claims are a feature of emotionally charged conservation debates. Certainly there is no difference between areas where restoration has been claimed to have been carried out and where it has not.

Little has been published on the ecology of New Zealand sand dunes and their species. Early studies are particularly rare (Cockayne, 1911, 1928; Pegg, 1914; Logan & Holloway, 1934), although Esler (1969, 1970, 1974, 1975) produced detailed descriptions of some North Island dune systems. Recent interest has been greater, especially in the South Island (Johnson, 1982; Simpson & Mason, 1984; Smith *et al.*, 1985; Sykes & Wilson, 1987, 1988, 1989), many studies being detailed examinations of plant/environment interactions. Although there have been a number of conservation reports (e.g. Palmer, 1980) and theses (e.g. Peace, 1975; Holland, 1981; Courtney, 1983) on botanical aspects of the Kaitorete Spit dunes, little has been published in the scientific literature, the exceptions being the brief description of Burrows (1969) and inclusion of this area in a larger study of vegetation/environment relations in dunes by Sykes and Wilson (1988). The effects of mining have not been specifically addressed.

The aims of this study were twofold: to determine exactly how sand mining has affected the plant communities and to know whether there has been complete or partial recovery of the original communities after mining. If recovery has taken place, the processes by which this occurs are of great importance, and if not, the reasons for non-recovery become significant. The study has been aided by a known history of mining operations, at least in relative terms, as mining has taken place in a systematic west to east direction over a period of 40 years. Even where areas have been remined this is known.

Nomenclature follows Webb *et al.* (1988) and Connor and Edgar (1987) and references therein.

STUDY SITE

Kaitorete Spit is a sand/gravel barrier complex that separates brackish Lake Ellesmere from the Pacific Ocean (Fig. 1). The complex is only about 5,000–7,000 years old, and the product of rapid growth, as it is now 28 km long and up to 3·2 km wide at the eastern end (Kirk, 1969; Armon, 1974). Continuous sand dunes occur on the seaward side at an average width of 220 m. An older, inactive, discontinuous series of sand dunes occurs a further 100 m inland, but is not included in the study. The eastern half of the spit's dunes has a stable to slowly accreting seaward margin, while the western half is eroding under wave attack, and a number of parabolic dune blowouts have occurred. The area examined in this study is on the eastern half and has a stable dune margin. Inland of the dunes is dry grassland dominated by introduced species and especially the grass *Stipa nodosa*. The whole dune system is subjected to frequent winds from both the south (moist, cool, especially in winter) and northwest (dry, warm, mostly in summer). Mean annual rainfall at Lincoln University, some 20 km to the north, is 590 mm. This, coupled with the coarse base material, makes the area very drought-prone.

Sand-mining has taken place in a confined area of the central section of the dunes and to the east of Kaitorete Scientific Reserve, beginning on a small scale in 1952. Records were started in 1964 with the granting of the first licence, and at that time some 6,000 m^3 were removed per annum. Removal of sand peaked in 1974 when 33,000 m^3 were extracted (Palmer, 1980). Restrictions on amounts and areas available considerably reduced the extraction of sand in the 1980s. The total length of dunes mined by 1990 was approximately 1,300 m. Sand has been mostly removed from the central section, but at the peak extended from close to the front dune almost to the grass flats. The effects of sand-mining on dune structure are demonstrated by six dune profiles of the areas sampled (Fig. 2). Of the two unmined sections, A

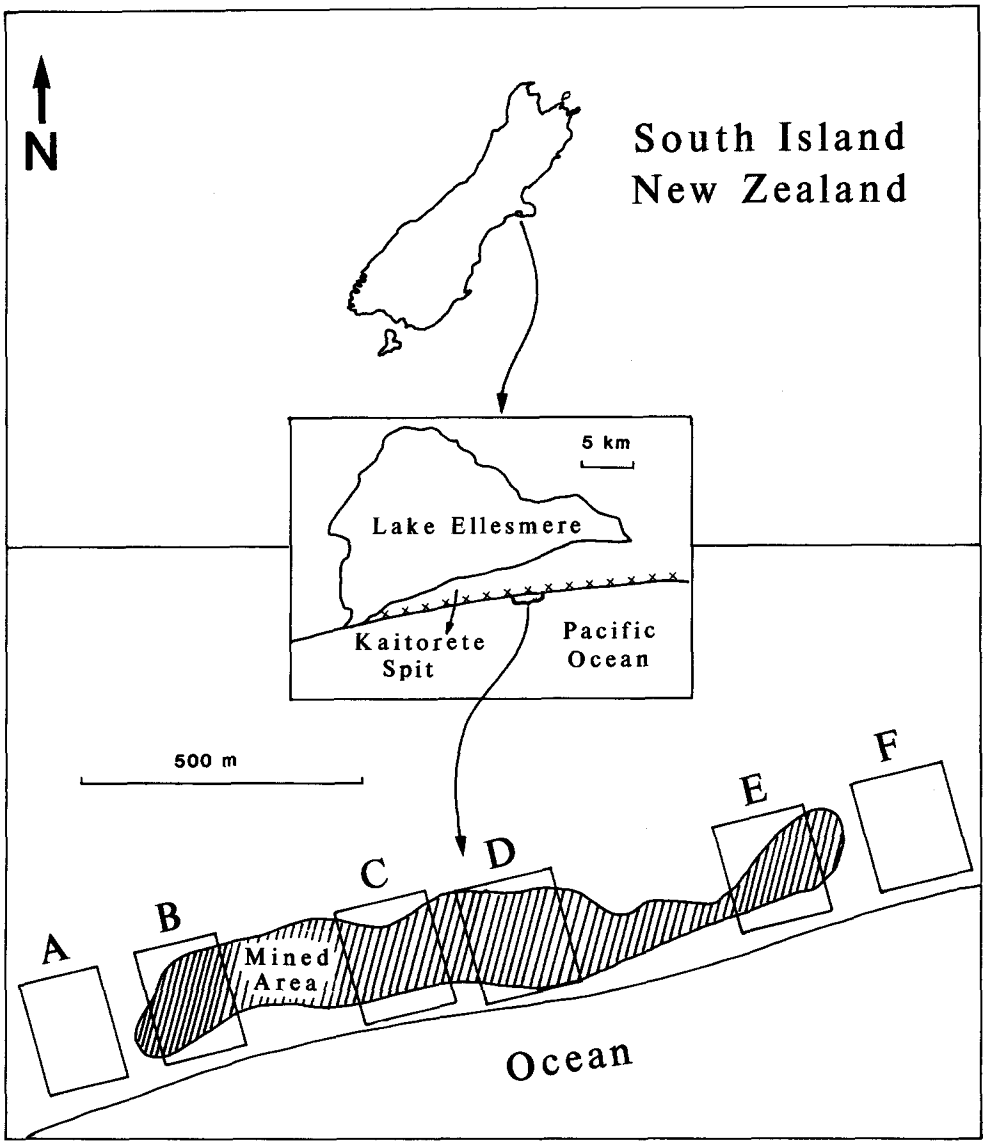


Fig. 1. Location map of the Kaitorete Spit dunes showing the position of the six sample areas.

has a single, and F a double ridge system. Section B was mined in the 1950s–1960s, but not to a great depth, while in the most recently mined section E (late 1980s) mining has been restricted to only a narrow part of the dune sequence. The most extensively mined dunes are in the central sections C and D, where almost the entire dune sequence was removed during the 1970s, often including the whole front dune, and to below mean sea level.

METHODS

Each of the six sections (A to F) covers a 200 × 220 m area with the longer axis perpendicular to the shore. The wide dunes at section B necessitated increasing this to 240 m. Each section was divided into 20 × 20 m squares, making a 10 × 11 sampling shape. Within each square a 5 × 5 m quadrat was randomly placed and species rooted frequency measured in the 25 1 × 1 m sub-quadrats at this site.

Sites and species were classified by Cluster Analysis. The association measure was Canberra Metric and the sorting strategy Flexible with beta set at –0·25 to create groups of comparatively even size (Clifford & Stephenson, 1975). Gradients in the data were examined by Detrended Correspondence Analysis (Hill & Gauch, 1980). It was necessary to exclude two species — *Carex pumila* and *Austrofestuca littoralis* — because of their excessive scores on the first ordination axis. This resulted in the removal of one site. Analyses were performed using the PATN software package (Belbin, 1989).

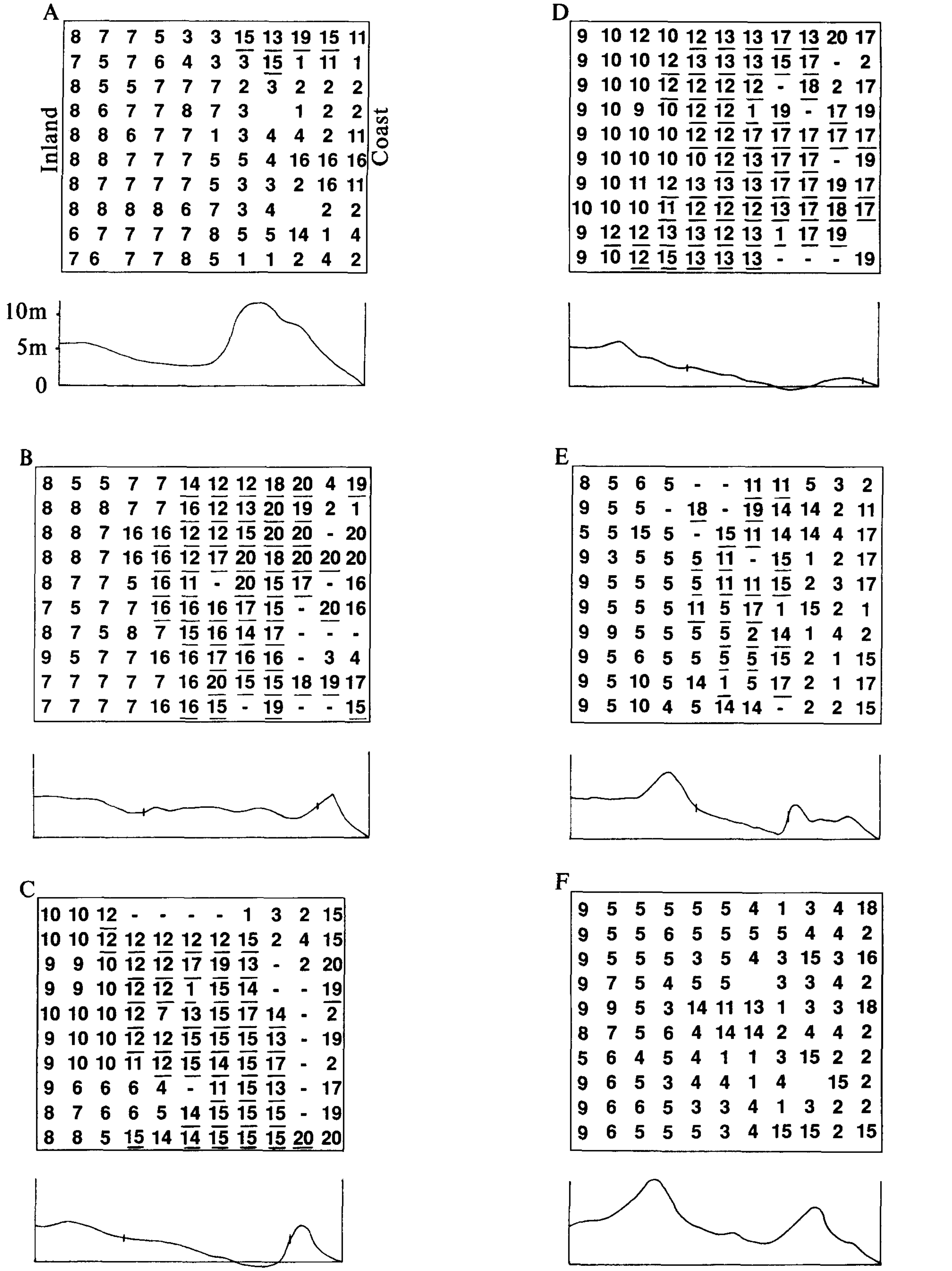


Fig. 2. Community maps of the six sample areas, A–F. The numbers refer to the 20 communities described (1–10 = mostly unmined, 11–20 = mostly mined). Underlining indicates sites that have been mined; dash indicates mined with no vegetation; blank is unmined with no vegetation. Dune profiles are included for the central part of each area, with the marked points indicating the extent of mining.

RESULTS

Community descriptions

The twenty communities discriminated by Cluster Analysis are described below. The term frequency is used as a within-community characteristic, while sample site frequency is termed abundance. Interpretation is aided by Table 1, which summarises frequency and mean site abundance of the major species within the communities, and Fig, 2, which consists of the community maps of the six sections. Table 2 gives the number of unmined and mined sites within each community.

Communities characteristic of unmined dunes (U1–U10)

U1: Moderately vegetated Desmoschoenus spiralis *(25 sites).* Dominated by *Desmoschoenus spiralis,* but at a lower abundance than any of the other unmined communities, and tending to occur mostly on open areas on the steep back face of the foredune. Characteristic species: *Desmoschoenus spiralis, Lagurus ovatus, Hypochoeris radicata* and *Calystegia soldanella.*

U2: Dense Desmoschoenus spiralis *on front dune (41 sites).* The typical unmined front dune community. Characteristic species: *Desmoschoenus spiralis, Lagurus ovatus, Hypochoeris radicata* and *Calystegia soldanella.*

Table 1. Frequency and abundance within the 20 communities

	Community																			
Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
No. of sites	25	41	30	31	78	20	55	31	36	35	18	40	24	21	44	24	34	8	16	16
Acaena agnipila		+		9–1	4–1	8–1	7–2	9–4	*F–5*	5–2		+				3–1				
Trifolium arvense					+	+	8–3	9–7	6–2	3–1	+	+		+		5–1				
Zoysia pungens					2–+	L	9–6	*F–8*	3–1	L			+			L				
Rytidosperma clavatum							+	5–2	9–5	+										
Stipa nodosa					+	+	+	7–3	9–6	+										
Aira caryophyllea					+	+	L	5–1	+							+				
Silene gallica			+		+	+	2–1	3–+	4–1											
Trifolium glomeratum								3–1	5–1		+									
Bromus diandrus	L	L	7–1	6–2	9–5	9–5	7–2		4–2	8–4	L	8–3	+	+	+		+			
Rumex acetosella		L	8–2	8–2	9–4	9–3	*F–7*	*F–8*	9–8	9–4	6–3	3–1		9–2	+					
Desmoschoenus spiralis	*F–5*	*F–8*	*F–8*	*F–8*	*F–6*	9–4	9–4	+	2–1	+	3–1	8–2	*F–2*	*F–3*	9–3	8–3	9–3	*F–1*	*F–4*	+
Hypochoeris radicata	*F–2*	*F–5*	*F–3*	9–5	9–2	7–2	9–5	*F–6*	9–3	9–3	4–1			*F–2*	9–1	*F–4*				
Lagurus ovatus	*F–4*	*F–6*	*F–8*	*F–8*	*F–8*	*F–8*	*F–9*	*F–9*	9–8	9–6	7–3	7–3	+	9–2	5–1	*F–5*	4–1			+
Calystegia soldanella	7–2	9–5	9–4	9–4	5–1		9–4	3–1	+	+	6–2		+	+	3–1	9–3	7–1			
Ammophila arenaria	+	L					+			L	3–1	5–1	L	3–1	5–2	*F–7*	5–1	6–2		*F–6*
Raoulia australis	4–1	L			1–+	+	5–1	9–6	6–2	+	+	6–2	*F–2*	7–3	5–2	+	+			
Erodium cicutarium	L					+	+		+	L	+	9–4	6–2	+	+	L	+			
Carmichaelia appressa					1–1	5–2	L	L	L	L										
Muehlenbeckia complexa	L			L	L	*F–7*	L	+	+	L					L					
Melicytus alpinus					L	L			+											
Holcus lanatus		+		+			+		L	L	+	+			+					
Poa cita						5–1	+	.	9–2	5–1		L	+		+					
Pteridium esculentum				L	L	L	L	+	4–3	*F–8*	L	L								
Carex breviculmis								L												
Pseudognaphalium luteoalbum	+	3–+		+	+	+	+					3–+		+	+	+				
Anagallis arvensis											+	L								
Foeniculum vulgare												L								
Lolium perenne						+	L			+	+	+								
Cirsium arvense										L		L			+					
Carex pumila											L				L					
Elymus rectisetus									L	L										

Only the 31 most abundant species are included. For each species the first number is frequency within the community (*F* = 100%, 9 = 90–99%, 8 = 80–89%, etc.) and the second is mean site abundance (expressed similarly as frequency in the 25 subquadrats). L indicates locally abundant, and + present but rare.

Table 2. Number of unmined and mined sites within each community

Community	Unmined	Mined
1	21	4
2	40	1
3	30	—
4	31	—
5	72	6
6	20	—
7	55	—
8	31	—
9	36	—
10	35	—
1–10	371	11
11	7	11
12	1	39
13	1	23
14	13	8
15	12	32
16	13	11
17	8	26
18	2	6
19	5	11
20	5	11
11–20	67	178
Bare	5	38

U3: Dense Desmoschoenus spiralis *in central part of dunes (30 sites).* Occurs only in the zone between the front dune and back dune, or on the single dune crest where present. Characteristic species: as for community U2 plus *Rumex acetosella* and *Bromus diandrus.*

U4: Dense Desmoschoenus spiralis *with* Acaena agnipila *(31 sites).* As for community U3, plus *Acaena agnipila*, although this species is never abundant.

U5: Dense Desmoschoenus spiralis *on back dunes (78 sites).* Characteristic community of the gently sloping faces of back dunes, except where these are of low stature, mined, or covered in *Pteridium esculentum.* Characteristic species: *Desmoschoenus spiralis, Lagurus ovatus, Hypochoeris radicata, Rumex acetosella* and *Bromus diandrus.*

U6: Muehlenbeckia complexa *on back face of back dune (20 sites).* A distinct community of low-growing woody species mixed amongst community U5. Characteristic species: shrubs — *Muehlenbeckia complexa, Carmichaelia appressa*; herbs — *Desmoschoenus spiralis, Lagurus ovatus, Bromus diandrus, Rumex acetosella, Hypochoeris radicata, Acaena agnipila* and *Poa cita.*

U7: Desmoschoenus spiralis/Zoysia pungens *deflation dunes (55 sites).* A community of low hummocky deflation dunes at the westernmost two sections where back dune is absent. Characteristic species: *Desmoschoenus spiralis, Rumex acetosella, Hypochoeris radicata, Lagurus ovatus, Calystegia soldanella, Zoysia pungens* and *Trifolium arvense.* This is one of the richest communities.

U8: Zoysia pungens *sand flats (31 sites).* Similar to community U7, but on flatter surfaces at the westernmost two sections. Characteristic species: *Lagurus ovatus, Hypochoeris radicata, Rumex acetosella. Zoysia pungens, Raoulia australis, Trifolium arvense, Stipa nodosa* and *Acaena agnipila.* The small sedge *Carex breviculmis* is locally abundant in a few sites and the sub-shrub *Pimelea urvilleana* is occasionally present.

U9: Grass flats (36 sites). Behind the dunes are extensive grass flats that extend beyond the sampling area. Characteristic species: *Stipa nodosa, Rytidosperma clavatum, Lagurus ovatus, Poa cita, Acaena agnipila, Trifolium arvense, Trifolium glomeratum, Raoulia australis, Hypochoeris radicata.* This is the richest of the communities.

U10: Pteridium esculentum *(35 sites).* Dense stands of *Pteridium esculentum* occur on a discrete area of the back dunes of the two central sections, the otherwise typical dune species all being less common. Characteristic species: *Pteridium esculentum, Lagurus ovatus, Hypochoeris radicata, Rumex acetosella* and *Bromus diandrus.*

Communities characteristic of mined dunes (M11–M20)

M11: Weedy sites (18 sites). Sparsely vegetated and poorly defined with low species faithfulness and abundance, but a large complement of species. Scattered (a) on recently mined sites with little sand remaining, (b) as a weedy strand, (c) as isolated sites on roads and parking areas. Characteristic species: *Rumex acetosella, Lagurus ovatus* and *Calystegia soldanella.*

M12. Recently mined sites with sand (40 sites). Recently mined areas of low sand activity nearer the back of the mined dunes and rather poorly vegetated except by *Erodium cicutarium.* Characteristic species: *Erodium cicutarium, Bromus diandrus* and, with low abundance, *Desmoschoenus spiralis, Lagurus ovatus* and *Raoulia australis.*

M13: Sparsely vegetated pavement (24 sites). Pavement occurs where wind deflation leaves a stony surface, this process favouring the cushion species *Raoulia australis.* Characteristic species: *Raoulia australis, Erodium cicutarium* and *Desmoschoenus spiralis* (low cover).

M14: Sparsely vegetated pavement/dune with Rumex acetosella *(21 sites).* With a different composition to community M13, this occurs more often on unmined areas. Characteristic species: *Desmoschoenus spiralis, Hypochoeris radicata, Lagurus ovatus, Rumex acetosella* and *Raoulia australis.* Notable associated rarer species include *Austrofestuca littoralis, Asperula* sp. and *Scleranthus biflorus.*

M15: New low dunes on mined areas of intermediate age (44 sites). New, low, hummocky dunes have formed in the seaward half of the mined sections where sand is most active. Characteristic species: *Desmoschoenus spiralis, Hypochoeris radicata, Raoulia australis, Lagurus ovatus* and *Ammophila arenaria* (all low cover). A small number of sites form a narrow unmined strand dominated by *Carex pumila.*

M16: New dunes on older mined areas (24 sites). Mostly in areas where dense *Ammophila arenaria* is displacing *Desmoschoenus spiralis* on the oldest mined dunes. Also includes unmined front dune where *Ammophila arenaria* has spread up the front face from its establishment point at the strand. Characteristic species: *Ammophila arenaria* (dense), *Desmoschoenus spiralis, Lagurus ovatus, Hypochoeris radicata* and *Calystegia soldanella.*

M17: Areas mined on to foredune front (34 sites). Occurs where mining has both directly and indirectly (through over-steepening) destroyed the front dune, resulting in new active dunes with a sparse cover of *Desmoschoenus spiralis.* Characteristic species: *Desmoschoenus spiralis, Calystegia soldanella* and *Ammophila arenaria* (all low cover).

M18: Extremely sparse Desmoschoenus spiralis *(8 sites).* Almost bare, actively moving sand near the front dune on mined areas carries *Desmoschoenus spiralis* as isolated small plants, not yet building dunes. *Ammophila arenaria* sometimes occurs similarly. Characteristic species: *Desmoschoenus spiralis* and *Ammophila arenaria* (low cover).

M19: Pure Desmoschoenus spiralis *on foredune (16 sites).* Mostly occurring on mined front dunes, but also in active blowouts, with a moderate cover of *Desmoschoenus spiralis*, but with no associated species. Characteristic species: *Desmoschoenus spiralis.*

M20: Dense Ammophila arenaria *(16 sites).* Virtually all sites occur at the oldest mined area. There are few associated species that are never abundant. Characteristic species: *Ammophila arenaria.*

Bare sand (43 sites). Extensive bare areas are present where sand movement is too great to allow establishment, and on over-steepened dune faces, especially the eroding rear face of the foredune. They are generally the result of sand-mining.

Summary of communities

Communities U1 to U10 form the natural unmined vegetation, although the part of the dune pavement community M14 is also unmined. *Desmoschoenus spiralis* dominates the dunes from the front of the front dune to the back of the back dune. On the front face of the front dune it typically forms community U2 with U3 in the central section. The back dune, where present, has U5 mixed in with the shrub-dominated U6. Where the back dune is absent the shrubby vegetation occurs on the back face of the single dune and there are extensive hummocky deflation dunes and sand flats (U7, U8) further inland. Beyond the dunes are grass flats (U9). The back dunes dominated by *Pteridium esculentum* (U10) are an important variant.

The mined dunes of communities M11 to M20 have a sparser vegetation. *Desmoschoenus spiralis* is often present, varying from tiny isolated clumps (M18) to relatively dense (M19), but never as dense as in the unmined communities. *Ammophila arenaria* is important, especially in M16 and M20, where it usually dominates as a dense stand. Associated species in these communities are variable and unpredictable, and there are a number of weedy species that seldom occur on unmined sites, the most notable being *Erodium cicutarium.* Where wind deflation occurs a *Raoulia australis* stone pavement (M14, M15) is established.

The separation of the mined and unmined groups is very clear and highly significant ($\chi^2 = 451$, $p < 0{\cdot}0001$). The greatest number of exceptions are of sites in the typically mined group (M) that occur on unmined dunes. Many of these are on the strand (M11), natural pavement (M14), active front faces of the front dunes (M17), or areas invaded by marram (M16). Mined sites that carry vegetation of typically unmined (U) communities are less common. Bare sites are clearly mostly related to mining.

Distribution of the communities

At the unmined Section A (Fig. 2), 90% of the sites carry vegetation classified as part of the unmined group of communities (U1–U10). Here there is only a single, but wide, dune ridge in the central part of the dune system. All the *Desmoschoenus spiralis*-dominated communities are well-represented (U1–U5), with some *Muehlenbeckia complexa* (U6) on the backslope. Behind this are the deflation dunes and sand flats characterised by *Zoysia pungens* (U7, U8) and not the grass flats of the central and eastern sections. Sites carrying vegetation classified as part of the mined group (M) include some weedy strand areas (M11), a large patch of dense *Ammophila arenaria* on the front dune face (M16), and a few sites in the east that have been destabilised by adjacent sand mining (M15).

At Area B, sand-mining has removed most of the front and central sections of the dunes. Of the *Desmoschoenus spiralis*-dominated unmined communities, only the common U5 is at all well-represented. Most notable of the mined communities are M16 and M20, both characterised by dense *Ammophila arenaria*, this also occupying unmined foredune remnants and some of the unmined backdunes as well. Behind the foredune remnants are extensive bare areas where sand is extremely mobile. The grouping of sites of the typically recently mined community M12 at the eastern end represents an area that was remined in the 1980s. Beyond the mined area, the deflation dune and sand flat communities (U7, U8) typical of Section A are again well-represented.

The mining at Section C has been far more extensive. Sites representing typically unmined communities are present only on foredune remnants (U2), small unmined 'islands' such as that in the east (U2–U4), and backdunes (U5, U6). *Pteridium esculentum* (U10) dominates most of the backdunes and spreads onto the grass flats (U9) beyond, although the western end is beyond the range of this species and has sand flats (U8). The mined area is dominated by sparse vegetation, especially of community M15, which is characteristic of mined areas of intermediate age, most sites of this community occurring here, Many of these sites contain *Ammophila arenaria*. Also well-represented is community M12, which dominates a large, deep hollow in the east, this being an area that was remined in the 1980s. On some of the older mined areas, erosion of sand has resulted in *Raoulia australis*-dominated dune pavement (M16).

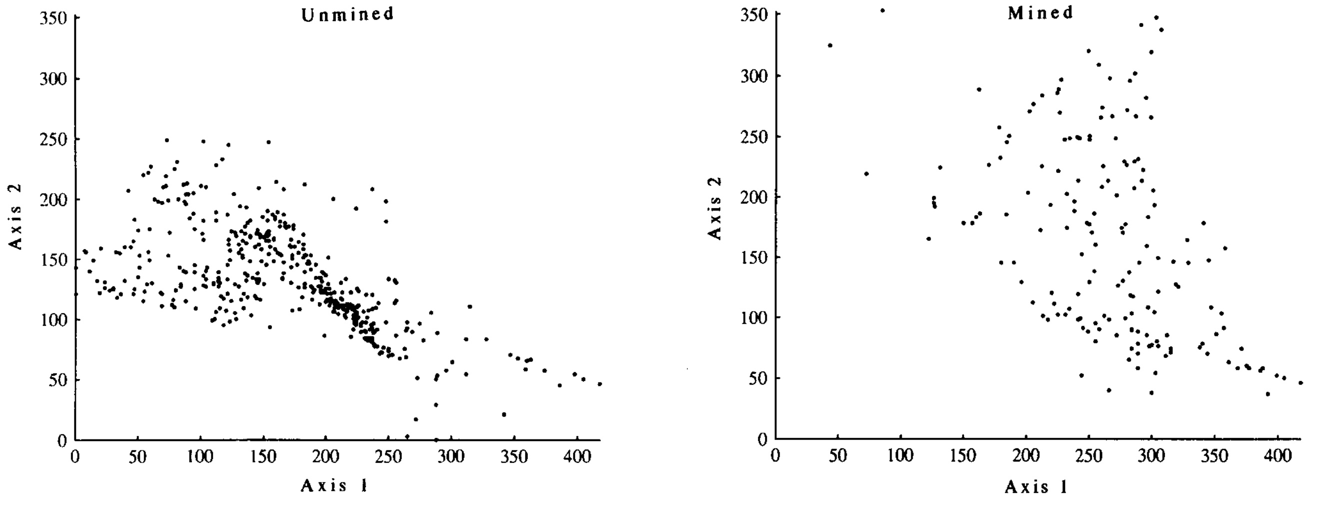
Foredune damage has been a feature of the mining at Section D. This has resulted from oversteepening of the backslope which has been followed by blowouts, to leave large active areas between small, isolated foredune turrets. The distinctive community M17, with its presence of *Calystegia soldanella*, now occupies most of the former foredune area along with many bare areas of moving sand. The central part has community M12, this being characteristic of recently mined sites where sand is accumulating, and community M13, which is pavement where sand is eroding. Behind, the unmined area is dominated by *Pteridium esculentum* (U10), with grass flats (U9) beyond.

Mining at Section E is restricted to a narrow part between the foredune and backdune. The foredune is made up of many communities including active foredunes otherwise characteristic of mined areas (M17), and both moderate (U1) and dense (U2) *Desmoschoenus spiralis*. There are two areas of community M14, sparsely vegetated dune/pavement, both on unmined dunes. In the west a small area has been left unmined to protect a population of the rare *Asperula* sp., while an area in the east has *Austrofestuca littoralis*. Much of the mined area is bare or has weeds (M11) or establishing dunes (M15). A number of mined sites have the otherwise typically unmined community U5 — these have been invaded by many *Desmoschoenus spiralis* seedlings and associated species common in unmined areas on sand of low activity. More typical community U5 occurs behind the mined area, although in the west there is some *Pteridium esculentum* (U10). Grass flats behind are mostly of community U9.

At Area E, unmined communities dominate, except near the foredune front where some active areas have community M15. Unlike Area A, there are two distinct dune ridges and no sand flats. Dense *Desmoschoenus spiralis* occurs throughout, with communities U2–U5 all being well-represented variants. In the west the backslope of the backdune has abundant woody vegetation, especially of *Muehlenbeckia complexa* (U6), while beyond are grass flats (U9).

Ordination

The first two axes of the DCA site ordination are presented using separate diagrams for each of two sets of site attributes. Separate diagrams were used to avoid clutter, as there were many sampling sites. Figure 3 divides the sites into mined versus unmined. There is, in general, a good separation of the sites both on axis 1 and especially axis 2. The many unmined sites on the lower left are densely clumped whereas the mined sites on the upper right are more scattered, those with the highest values on axis 2 being vegetation dominated by non-dune weeds and *Erodium cicutarium* (Fig. 4). There is, however, considerable overlap of mined and unmined sites at the lower right.



(a) (b)

Fig. 3. Site ordination divided into (a) unmined and (b) mined sites.

These are dominated by *Ammophila arenaria* and occur on the unmined foredune where this species has displaced *Desmoschoenus spiralis*, and on the oldest mined areas.

Figure 5 separates the sites by distance from the sea, each diagram representing a 40 m step. The trend is from coastal (right) to inland (left) on axis 1, and from bottom to top on axis 2, with increasing distance inland. The trend is more pronounced, however, on axis 1. Unmined sites show the trend very clearly while it is also present, but less well-defined, in the mined areas. Mined sites, as shown in Fig. 1, are mostly in the central sections, leaving the extremes the mostly clearly defined groupings.

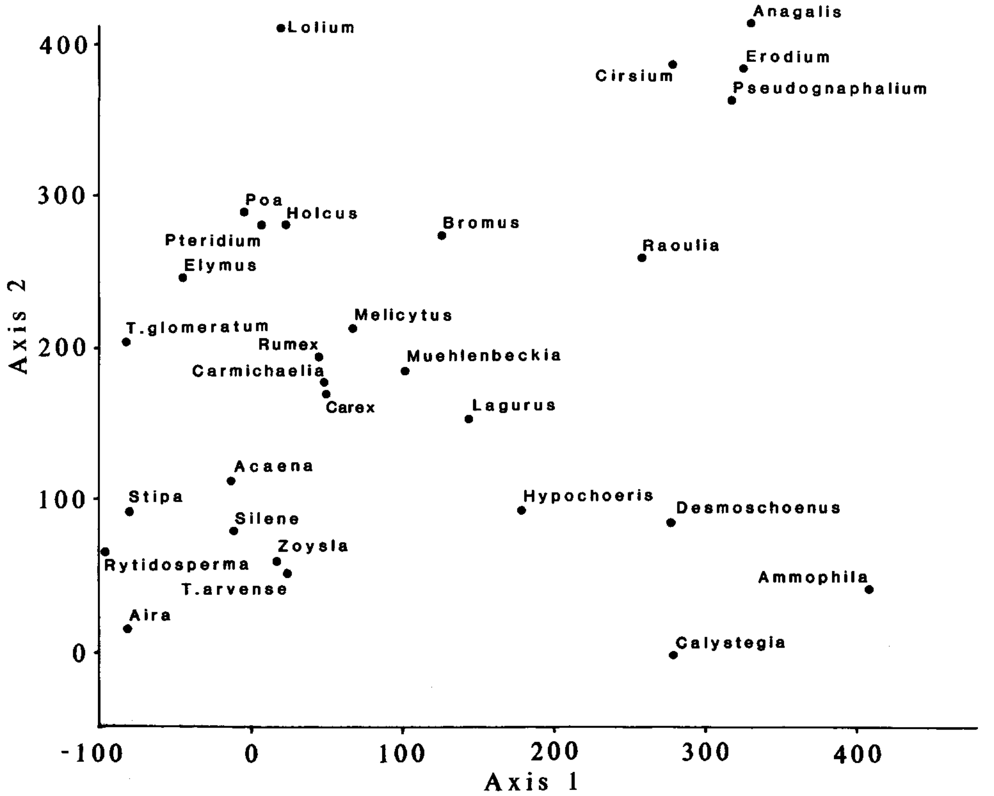


Fig. 4. Species ordination showing only the most important species (Table 1). *Foeniculum vulgare* and *Elymus rectisetus* are not shown as they had large values on axis 2.

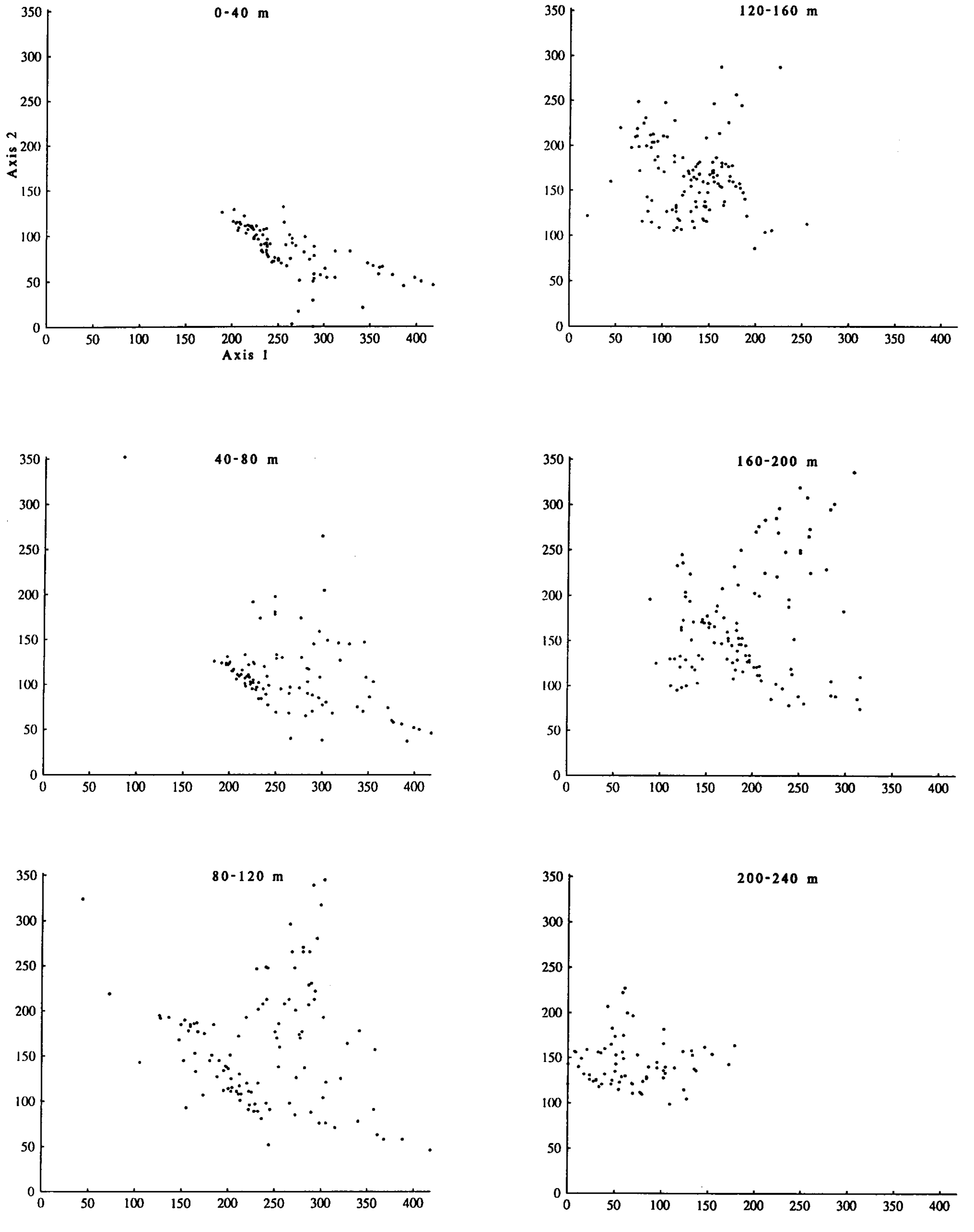


Fig. 5. Site ordination divided according to distance from the shoreline. Each diagram represents a step of 40 m.

The ordination clearly shows two important trends within the vegetation. The typical sea-to-land gradient is most obvious on axis 1, while axis 2 more represents the difference between unmined and mined vegetation. Axis 2 might also be interpreted as representing a stability gradient, this being very much the product of mining, but with a coast to inland component as well.

DISCUSSION

Sand-mining has caused major changes to both the physical structure and the plant communities of the Kaitorete dunes. The central parts of the dunes have been hollowed out to varying depths, and those areas mined in the 1960s and 1970s have suffered the greatest, with sand having been removed from virtually the entire dune system. Furthermore, the effects of mining have caused instability on some adjacent areas by over-steepening of faces, and through mining sand from below mean sea level.

The results clearly demonstrate that the major effect of mining on the plant communities is the establishment of a suite of communities that are less common on unmined dunes, including those that are characterised by ephemeral weeds, establishment areas of *Desmoschoenus spiralis*, recently developed *Raoulia australis* pavement and stands of *Ammophila arenaria*. Where these communities do occur on unmined dunes, they mostly tend to be on disturbed sites of active dunes including the strand at the base of the foredune. The major exception is the stable unmined dune pavement that clusters as one of the mined communities.

Mining has occurred over a period of some 40 years. If the plant communities are recovering, then it is expected that there would be mined sites that carry communities otherwise characteristic of unmined areas, especially on the older mined dunes. The results clearly demonstrate that this has not taken place. There is indeed no indication that mined areas are developing vegetation similar to that on unmined dunes. Such failure was noted by Woodhouse (1982) on the east coast of North America. Although *Desmoschoenus spiralis* has colonised mined areas it has formed novel, sparse communities. The failure of the dunes to recover their original communities can be attributed to two factors. The first is the invasion of much of the older mined area by *Ammophila arenaria*. This species has effectively halted any potential recovery by the development of a dense sward that competitively excludes *Desmoschoenus spiralis*. The second is the development of a continuous sand plain that runs parallel to the beach front, through the mined area. Within this sand plain lateral winds move sand through the mined dunes to form a sparsely vegetated hummocky low dune system dominated by *Desmoschoenus spiralis* along with some erosion pavement. Such sand-plain vegetation is characteristic of some dune systems in other parts of New Zealand, such as the Manawatu (Esler, 1969).

Ammophila arenaria is clearly having an important impact upon the dunes. On unmined areas this grass establishes probably mostly from rhizome fragments along the strand and spreads slowly up the front of the foredune by vegetative growth (Gemmell *et al.*, 1953). Its establishment in this zone demonstrates a distinct preference for areas of maximum sand activity. It is this preference for active sites that has caused it to become so dominant in parts of the mined dunes. In such areas, mining has cut into the stands of *Ammophila* that had previously colonised the front face of the foredune, thus supplying the active areas behind with an abundance of stem fragments. In such areas initial establishment following mining involves a large number of *Desmoschoenus spiralis* seedlings and a smaller number of *Ammophila* clumps from stem fragments (community M12, for instance). However, the ratio changes rapidly as (1) the *Ammophila* grows and spreads at a much faster rate, (2) the *Desmoschoenus* is heavily grazed by rabbits and hares, and (3) *Desmoschoenus* disappears when the two species come into competition, resulting eventually in community M20. The result is a dense *Ammophila* stand with only little *Desmoschoenus* remaining. From the back of the mined area, *Ammophila* slowly spreads vegetatively on to the dunes behind as well, in the same way that it invades unmined foredunes.

The more recently mined areas have not been invaded by *Ammophila arenaria*. Here the initial establishment of *Desmoschoenus spiralis* proceeds in two possible directions. Where sand accumulation occurs low dune hummocks of *Desmoschoenus* establish, but where erosion takes place, a stone pavement dominated by *Raoulia australis* develops. There is no real sign, however, of a tendency for *Desmoschoenus* to build higher dunes, probably because the sand supply is limited. There is little prospect for such sand becoming available.

Mining has introduced a number of other weeds to the area. These are presently uncommon, but some, including *Lupinus arboreus* and *Cytisus scoparius*, have the ability to spread and become problems. All these species occur close to vehicle tracks and their presence can be attributed to introduction by vehicles.

The back dunes of the central mined area have a dense covering of *Pteridium esculentum* fern instead of the *Desmoschoenus spiralis* and *Muehlen-*

beckia complexa typical of other areas. The success of *Pteridium* cannot be attributed to mining, but may be the result of fires that have spread onto the dunes from the grassland. Indeed, to the east, *Pteridium* covers the entire dune system in an area that was previously a military firing range and has a history of burning. *Desmoschoenus spiralis* seems unable to compete with *Pteridium*, but it is not known whether the fern is increasing its range.

The non-recovery of plant communities and the invasion by *Ammophila arenaria* have important implications for both mining and the management of the dune botanical resources. It is clear that sand mining creates conditions in which community recovery is unlikely. Restorative planting and replacement of a layer of sand seem to be having no effect. These plantings of pot-grown material have been more successful than the cuttings used earlier, but there is so far no evidence that survival is better than in areas left unplanted. Although some of the communities that establish are dominated by native plants, they are not the same as those removed during mining. The mining, however, is due to cease soon, although much of the central part of Section F is planned for sand extraction. This pattern is in contrast to the situation in Queensland, Australia (Brooks, 1976; Bradshaw & Chadwick, 1980), where restorative planting on mined dunes has been successful. However, there most of the sand has been returned to the system following removal of rare minerals, unlike the situation at Kaitorete where virtually all the sand is removed and virtually none returned.

If left unchecked, it seems that *Ammophila arenaria* will spread over the entire mined area and onto adjacent dunes as well. In the absence of mining, this species is restricted to along the strand, and has only a slow, largely manageable spread up the foredune. In only a small number of locations has it reached a situation where its management requires extensive and expensive treatment. If allowed to spread throughout the mined area, it will become a vast management problem. The oldest mined dunes have already reached that stage, but the remaining areas where *Ammophila arenaria* is either sparse or absent have the potential to be saved from the invasion of this species. To preserve the valuable botanical features of the Kaitorete Spit dunes, it is important that sand-mining should cease, and *Ammophila arenaria* spread be controlled.

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