Stabilising Sand Dunes By Revegetation: The Role Of Introduced Nitrogen-Fixing Plants

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SUMMARY - The stabilisation of sand dunes is dependent on having a continuous vegetation cover which minimises sand mobilisation. The vigour of the vegetation cover is often limited by the severe nitrogen deficiency of coastal sands. As intermediates in a three-stage artificial vegetation succession from a pioneer to a climax community on the dunes, nitrogen-fixing species provide valuable biologically-fixed nitrogen to the ecosystem. These plants can also increase cover and provide sheltered microsites for other species. Until the late 1980s *Lupinus arboreus* Sims was used extensively in this role in New Zealand. Destruction of *L. arboreus* populations by disease stimulated the search for replacement species. A series of trials on the west coast of the North Island has identified a number of nitrogen-fixing species that have potential in this role. They include *Chamaecytisus palmensis*, *Dorycnium hirsutum*, *D. pentaphyllum*, *D. rectum*, *Hedysarum coronarium*, *Lathyrus latifolius*, *Lotus corniculatus*, *L. pedunculatus*, *L. tenuis*, *Medicago arborea* and *Teline stenopetala*.

1. INTRODUCTION

1.1 The Role of Dune Vegetation

The degradation of the natural vegetation cover on sand dunes occurs as a result of human activities or physical events. One of the management strategies for sand dune conservation that has proved successful has been the application of a three stage artificial vegetation succession, carried out in accordance with scientific principles. In this paper, the role of nitrogen-fixing plants in this succession is described and species with potential to fulfil that role are identified.

The main nutritional factor limiting plant growth on coastal dunes is the chronically low level of nitrogen compounds in the sand which is a consequence of the virtual absence of organic matter. Nitrogen can be supplied in the form of fertiliser, but this leaches out rapidly in drainage water and has only a short-term effect. Use of nitrogen-fixing plants can provide a long-term solution, partly because their growth and development is independent of soil nitrogen supply, but mainly because they fix atmospheric nitrogen into organic compounds which act as a nitrogen reservoir. The slow process of decomposition of plant material is the main pathway by which the fixed nitrogen becomes available to other organisms and plants in the ecosystem.

The sand dune environment is characterised by an unstable substrate, high diurnal temperature fluctuations, drought, sand blasting and strong salt-laden winds. The combination of these factors limits the number of species that can survive on the dunes and makes the maintenance of plant cover difficult. Loss of vegetation cover very quickly leads to sand erosion and destabilisation of the dunes, and can result in inundation of adjacent land.

Human activity on coastal dunes in the past 150 years has interfered with the natural dune vegetation cover and increased the extent of sand mobilisation. Clearing of land by burning, livestock grazing, introduction of pests such as rabbits and snails, planting of inappropriate species, use of sand dunes as recreational areas, subdivision of the coastal strip for residential purposes and inappropriate siting of building structures have all contributed to erosion problems (Cockayne, 1911; Dahm, 1994).

Public attention was called to the serious nature of these problems during the latter part of the last century (eg. Thomson, 1870; Stewart, 1873). The Sand Drift Act of 1903 (revised in 1908) stimulated a thorough survey of the country to quantify the issue. The area of land made up of sand dunes and drifting sand was estimated to be 313,000 acres (127,000 ha). A comprehensive study undertaken by the scientist Leonard Cockayne included the analysis of physical characteristics as well as recommendations for stabilisation of the dunes by revegetation. A three-stage process was suggested which would render the dunes both harmless and profitable (Cockayne, 1911).

Cockayne's recommendations were only put into practice on a small scale until the Public Works Department undertook a planting programme for the stabilisation of 3,800 ha of coastal sand between 1931 and 1951 (Wendelken, 1974). The New Zealand Forest Service then assumed responsibility for coastal dune management and continued the planting programme, concentrating on three regions on the west coast of the North Island which had the most extensive problems - Ninety Mile Beach, Auckland and Manawatu (Wendelken, 1974).

1.2 Artificial Vegetation Succession

The first stage in the revegetation sequence was the establishment of sand binding plants. Marram grass (*Ammophila arenaria*), an exotic sand binding species, was widely used for this purpose because it grew vigorously and was easily propagated. Native species of sand binders have been used, particularly *Spinifex sericeus* (kowhangatara, silver sand grass) on the foredune and, to a lesser extent, *Desmoschoenus spiralis* (pingao) (Wendelken, 1974). All of these plants trap sand and are able to grow and thrive even when inundated. Their extensive rhizomes and root systems impede sand movement and lead to the gradual modification of dune shape and form.

Vigorous growth of sand binding plants is enhanced by the addition of nitrogen fertiliser, and applications were routinely made to the marram grass in order to maximise vegetation cover before the establishment of the nitrogen-fixing legume *Lupinus arboreus* Sims (yellow tree lupin) in the second stage of the planting sequence (Restall, 1964). *L. arboreus* seed was sown with the second fertiliser topdressing in autumn, 6 - 12 months after the marram grass was planted. Individual *L. arboreus* plants grew vigorously for about six years, completing the vegetation cover and fixing up to 160 kg N/ha/year (Gadgil , 1971).

The third stage of the artificial vegetation succession was the establishment of the climax community. On the large expanses of the west coast dunes, economic considerations led to the extensive planting of exotic forest. *Pinus radiata* was the preferred species because of its rapid growth rate, ability to withstand salt-laden winds and marketable timber (Wendelken, 1974). It is now recognised that in many localities where there is a strong local interest in the restoration of natural character, native tree and shrub species are the most appropriate plants to form the climax community.

P. radiata was planted inland of a coastal strip (up to 400 m wide) as soon as the marram and lupin had formed a continuous, dense vegetation cover (4 - 5 years after initial marram planting). Existing vegetation was crushed at the time of planting, but the young trees often had to be released from vigorous *L. arboreus* regrowth (Restall, 1964). A belt of untended trees was used to protect the inland tree crop from salt-laden winds and sand blasting. Fenton (1949) suggested that this belt should be approximately 400 m wide, with a 2 - 3 km wide strip of productive *P. radiata* forest planted inland.

Experimental work demonstrated clearly that *L. arboreus* could not be established on exposed sites without the sand-binding grass and that the trees could not grow without the vegetation cover and fixed nitrogen provided by the lupin (Berg and Smithies, 1973; Jackson *et al.*, 1983). The three stage vegetation succession was considered to be highly successful from the view point of dune stabilisation. Extensive sand movement on the coastal strip was prevented and the remaining dunes were made economically productive. Areas inland from the forest could be used for farming, horticulture, housing or further forestry without threat of sand inundation.

1.3 The Demise of *Lupinus arboreus*

In 1988, staff at Woodhill Forest (northwest of Auckland) noted a serious decline in *L. arboreus* populations in the forest and on the sand dunes (Dick, 1994). A nationwide survey in early 1989 showed that the decline was widespread and subsequent work identified the fungal blight *Colletotrichum gloeosporioides* as the causal agent (Dick, 1994). The disease has continued to affect *L. arboreus* seedlings establishing from the extensive seed bank in the sand and has meant that this species can no longer be used at most sites to provide shelter for the climax community or contribute nitrogen to the ecosystem.

Attempts to identify local or overseas *L. arboreus* populations with substantial levels of resistance to the disease were unsuccessful (Dick, 1994). Annual lupin species are also vulnerable to the fungus and overseas work appears to have concentrated on controlling the disease in those annual species that are commercially cultivated (eg. Shea, 1996). The fungal blight left New Zealand coastal and forest managers with two options for maintaining a vegetation cover on the dunes: either applying nitrogen as a fertiliser; or planting alternative nitrogen-fixing species to supply the nitrogen.

2. METHODOLOGY FOR THE SCREENING OF REPLACEMENTS FOR *LUPINUS ARBOREUS*

2.1 Spaced Plant Trials

A series of trials was begun in 1991 to screen 26 species as possible replacements for *L. arboreus* on the dunes. All the trials described here were spaced plant trials, whereby seedlings were grown on under glasshouse conditions and after a period of hardening off, were planted in the trials at set spacings. All plants were inoculated with the appropriate strain of *Rhizobium* prior to planting out, to maximise the likelihood that the plant-bacteria symbiosis essential for nitrogen-fixation would develop. The results presented are from trial sites located on the North Island west coast, from Ninety Mile Beach in the north to Santoft Beach in the south.

2.2 Species Selection Criteria

Several criteria were used to select nitrogen-fixing species for the first screening trials established in 1991/92 (trial series A). Of greatest importance was the ability to grow and to fix nitrogen in the dune environment. This precluded the use of native nitrogen-fixing plants (eg. *Coriaria arborea*, tutu; *Sophora* spp., kowhai) which tend to be intolerant of coastal conditions. Persistence by means of sexual or vegetative reproduction was also important, providing that the rate of spread would not cause weed problems. The species chosen included both herbaceous and woody perennials. The choice of species for a second trial series established in 1993 (trial series B) was made with reference to available results from the earlier trials. Species used in both sets of trials are listed in Table 1.

Table 1: Nitrogen-Fixing Species Tested in Trials

Species	Trial Series A						Trial Series B		
	1	2	3	4	5	6	1	3	4
Acacia saligna w[2]	+[1]	+	+	-	-	+	+	+	+
Acacia sophorae w	+	+	+	-	-	+	+	+	+
Astragalus cicer h	-	-	-	+	+	+	+	+	+
Casuarina glauca w	-	-	-	-	-	+	-	-	-
Chamaecytisus palmensis w	+	+	+	+	+	+	+	+	+
Dorycnium hirsutum w	-	-	-	+	+	+	+	+	+
Dorycnium pentaphyllum w	-	-	-	-	-	+	+	+	+
Dorycnium rectum w	-	-	-	-	-	+	+	+	+
Hedysarum coronarium h	-	-	-	+	+	+	+	+	+
Hippophae rhamnoides w	-	-	-	-	-	+	-	-	-
Lathyrus japonicus h	-	-	-	+	+	-	-	-	-
Lathyrus latifolius h	+	+	+	+	+	+	+	+	+
Lathyrus tuberosus h	-	-	-	+	+	-	-	-	-
Lespedeza cuneata h	+	+	-	-	-	-	+	+	+
Lotus corniculatus h	+	+	-	-	-	+	+	+	+
Lotus pedunculatus h	+	+	+	-	-	-	+	+	+
Lotus tenuis h	-	-	-	+	+	+	+	+	+
Lupinus arboreus w	-	-	-	+	+	-	-	-	-
Lupinus nootkatensis h	+	+	+	-	-	-	+	+	+
Medicago arborea w	-	-	-	-	-	+	+	+	+
Robinia pseudoacacia w	-	-	-	-	-	+	-	-	-
Sutherlandia frutescens w	+	+	+	-	-	+	+	+	+
Teline stenopetala w	+	+	+	-	-	-	+	+	+
Trifolium ambiguum h	+	+	+	-	-	-	+	+	+
Vicia gigantea h	-	-	-	-	-	+	-	-	-
Vicia sepium h	-	-	-	+	+	-	-	-	-

[1] + species planted in trial; - species not planted in trial
[2] w - woody species; h - herbaceous species

2.3 Experimental Design

Trials A1 - A5 were established in spring, 1991 and Trial A6 was installed in autumn, 1992. Single species plots were replicated either three or four times. Trials A1 at Ninety Mile Beach and A2 at Kawhia compared the same 11 species, and nine of these species were planted in Trial A3 at Harakeke. Plants were spaced at 0.5 m x 0.5 m intervals in square plots in Trials A1 - A3, with 36 plants per plot in Trials A1 and A2, and 20 plants per plot in Trial A3.

Trials A4 - A6 were all located at Santoft Beach. Ten species were planted in Trials A4 and A5, and 17 in Trial A6. In Trials A4 and A5, the plots were square with eight plants per plot, planted at 0.3 m x 0.3 m spacings. Trial A6 was planted in rows, with ten plants at 0.5 m intervals per row. All trials were sited in marram stands behind the foredune. Trials A1 - A3 and A6 were fenced to exclude rabbits.

The second series of trials, with 18 species, was established in autumn, 1993. Trial B1 was located at Ninety Mile Beach, B3 at Muriwai Beach and B4 at Santoft Beach. Trial B2 is not reported here. Trials were situated behind the foredune and each was protected with rabbit-proof fencing. A randomised complete block design with six blocks was used. Each plot was a single row consisting of 15 plants of one species. Spacing was 30 cm between plants within a row and 1 m between rows.

Full details of trial establishment, including climatic data from each of the trial sites, can be found in Douglas *et al.*, 1994.

2.4 Measurement of Trials

All trials were assessed annually in spring. Results presented here are a summary of data collected after 3.0 years for the A1 - A5 trials (in 1994), and after 2.5 years for the A6 (in 1994) and trial series B (in 1995).

In Trials A1 - A6, the percentage of plants surviving was determined unless it was difficult to distinguish individuals. In this case the extent of contribution to plot cover by the nitrogen-fixer plants was estimated. In trial series B, percentage occupancy of the original planting positions was determined. This allowed for the fact that although two of the original plants in the row had been harvested for biomass estimates in previous years, neighbouring plants had often grown to cover the gaps. In all trials, the results of these measurements from replicate plots were averaged.

Maximum plant spread was also measured differently in the two trial series. In trial series A, the spread of individual plants (where distinguishable) was determined by measuring the width of the plant at its widest part. Plant spread in trial series B was calculated by measuring maximum plant width perpendicular to the row, at the original 15 planting positions in each row. This procedure addressed the problem of identifying individuals. The data for plant spread were averaged for each plot and the mean spread for each species then calculated.

In trials A1-A3, A6, B1, B3 and B4 the relative rate of activity of the nitrogen-fixing enzyme, nitrogenase, was measured using the acetylene reduction technique (Hardy and Knight, 1967). Limitations of this procedure (Silvester, 1983) meant that comparisons of nitrogenase activity could only be made between plants assayed at the same time, which limited comparisons to those between plants within the same trial. Two root systems of each species were analysed wherever possible, but in some instances only one plant could be spared for destructive analysis. There were a number of species in each trial which had insufficient biomass for any analysis to be undertaken.

3. RESULTS

3.1 Plant Survival and Growth in Trial Series A

Five species were present after three years in the Ninety Mile Beach trial (A1). Survival rates of *Acacia saligna*, *Chamaecytisus palmensis* and *Teline stenopetala* were all less than 12% and maximum plant spread was less than 1 m for these species. Plot coverage achieved by *A. sophorae* and *Lotus pedunculatus* was variable, but did not exceed 60%. Spread of these species was not measured.

At the Kawhia site (A2), six species remained, with *A. saligna* and *A. sophorae* providing almost total plot cover. *L. pedunculatus* plants covered about one quarter of the plots. Only one plant each of *C. palmensis* and *Lathyrus latifolius* had survived, but in both cases the plants had spread 1.8 m. *Trifolium ambiguum* had a low survival rate and limited plant spread.

Eight species persisted in Trial A3 at Harakeke, with *Lupinus nootkatensis* being the only failure. *A. saligna* had the highest survival rate, while *C. palmensis* and *Teline stenopetala* provided the greatest plot coverage. Plants of the latter two species had the greatest maximum spread (over 2 m), while *A. sophorae* and *Lathyrus latifolius* plants spread more than 1 m.

Four species planted in Trial A4 at Santoft Beach survived for three years. *Astragalus cicer* had a higher survival rate than the other species (*Lathyrus japonicus*, *L. tuberosus* and *Lupinus arboreus*), but rates did not exceed 20% in any species. *L. arboreus* plants had the greatest spread (55 cm).

In Trial A5 at Santoft Beach, five species were still present after three years. *A. cicer*, *Lathyrus latifolius* and *L. tuberosus* had the highest survival rates (21 - 25%). *Dorycnium hirsutum* and *Lupinus arboreus* were the other two species present. Plants of both *Lathyrus* spp. had spread more than 1 m.

Of 14 species remaining in Trial A6 at Santoft Beach, seven had survival percentages of 50% or more. These were *Acacia saligna*, *A. sophorae*, *Astragalus cicer*, *Casuarina glauca*, *Lathyrus latifolius*, *Lotus tenuis* and *Medicago arborea*. Failed species were *Hippophae rhamnoides*, *Sutherlandia frutescens* and *Vicia gigantea*. Plants of six species had a maximum spread of more than 1 m, with *Acacia sophorae* plants achieving 1.9 m. *C. glauca* had spread the least (20 cm).

3.2 Plant Survival and Growth in Trial Series B

Six species failed to survive the first two and a half years at the Ninety Mile Beach site (B1). These were *Astragalus cicer*, *Lespedeza cuneata*, *Lupinus nootkatensis*, *S. frutescens*, *Teline stenopetala* and *Trifolium ambiguum*. *Acacia sophorae* and *D. hirsutum* had position occupancy rates greater than 50% while *D. pentaphyllum* had the lowest occupancy rate. The average spread of *A. sophorae* plants was greater than that of any other species (4.7 m), while plants of *Chamaecytisus palmensis* and *M. arborea* had spread on average more than 1 m.

At the more sheltered Muriwai Beach site (B3), only *Lupinus nootkatensis* and *S. frutescens* failed to survive. Occupancy rates exceeding 50% were recorded for 12 species, and *D. hirsutum*, *Lathyrus latifolius* and *Lotus corniculatus* achieved 100% occupancy. *Astragalus cicer*, *Lespedeza cuneata*, *M. arborea* and *Trifolium ambiguum* had very low occupancy rates and the lowest plant spread. *D. rectum* and *Teline stenopetala* plants spread more than 2 m on average. Seven of the remaining species had spread more than 1 m.

In Trial B4 at Santoft Beach, sixteen species persisted, only *Lespedeza cuneata* and *Lupinus nootkatensis* having failed. Occupancy rates of greater than 50% were recorded for 12 species. *Acacia sophorae*, *D. hirsutum*, *Lathyrus latifolius* and *Lotus pedunculatus* all occupied 90% or more of the original positions. *A. sophorae* and *D. hirsutum* plants had spread more than 1 m while other species had spread 20 - 99 cm.

3.3 Relative Rates of Nitrogenase Activity

Table 2 shows within trial rankings of species according to the relative level of nitrogenase activity detected in root systems. All species analysed in trial series B had detectable levels of nitrogenase activity, although values were very low in some instances. Nitrogenase activity was not detectable in some of the species present in trial series A.

None of the species planted in two or more trials ranked highest throughout. In six of the seven trials *A. sophorae* was among the three highest ranked species. *Lathyrus latifolius* had the highest rate of activity in two of the series B trials, but very low rates in the A6 trial. *Astragalus cicer* had a low ranking in all trials, as did *D. hirsutum* in trial series B.

4. DISCUSSION

These interim results from the screening trials confirm that some of the species tested are able to grow and fix nitrogen in the sand dune environment, and thus may be useful as replacements for *Lupinus arboreus*. The ability to provide good coverage of the sand is critical for potential replacement species. Besides limiting sand movement, vegetation cover offers a variety of protected microsites suitable for other species, including those planted in the

Table 2: Species Ranking with Respect to Nitrogenase Activity[1]

Trial Series A		
A1 Ninety Mile Beach	**A2 Kawhia**	**A3 Harakeke**
L. pedunculatus	*A. sophorae*	*T. stenopetala*
A. saligna[2]	*A. saligna*	*C. palmensis*
A. sophorae[2]	*L. pedunculatus*[2]	*A. sophorae*
C. palmensis[2]	*T. ambiguum*[2]	*A. saligna*
		T. ambiguum[2]
	A6 Santoft Beach	
	A. sophorae	
	C. palmensis	
	R. pseudoacacia	
	A. saligna	
	L. tenuis	
	D. rectum	
	D. hirsutum	
	M. arborea	
	L. corniculatus	
	A. cicer	
	L. latifolius	
	C. glauca[2]	
Trial Series B		
B1 Ninety Mile Beach	**B3 Muriwai Beach**	**B4 Santoft Beach**
L. latifolius	*H. coronarium*	*L. latifolius*
A. sophorae	*A. saligna*	*A. sophorae*
L. pedunculatus	*A. sophorae*	*T. stenopetala*
D. pentaphyllum	*L. corniculatus*	*A. saligna*
L. tenuis	*L. latifolius*	*D. pentaphyllum*
H. coronarium	*C. palmensis*	*L. corniculatus*
D. rectum	*L. pedunculatus*	*M. arborea*
L. corniculatus	*D. rectum*	*L. pedunculatus*
D. hirsutum	*D. pentaphyllum*	*C. palmensis*
A. saligna	*T. stenopetala*	*D. rectum*
	L. tenuis	*L. tenuis*
	D. hirsutum	*D. hirsutum*
	A. cicer	*A. cicer*

[1] Species are arranged so that those with the greatest nitrogenase activity for each trial are at the top of the list.
[2] No nitrogenase activity detected.

third stage of the artificial vegetation succession. The extent of vegetation cover provided by a species in the trials reported here was a function of the survival rate of plants and the extent of individual plant spread. Species which demonstrated the ability to provide extensive cover in at least one of the trial sites were *Acacia saligna*, *A. sophorae*, *Chamaecytisus palmensis*, *Dorycnium hirsutum*, *D. pentaphyllum*, *D. rectum*, *Hedysarum coronarium*, *Lathyrus latifolius*, *Lotus corniculatus*, *L. pedunculatus*, *L. tenuis*, *Medicago arborea* and *Teline stenopetala*.

Nitrogenase activity was observed in all of the species that were able to provide vegetation cover. Indeed, it is unlikely that plants would have persisted and grown unless they were able to utilise atmospheric nitrogen. Although the amount of nitrogen fixed by each species has not been quantified, it is clear that these species were self-sufficient in nitrogen. Benefits of this fixation accrue to other plants in the ecosystem as organic matter with a high nitrogen content from above and below ground tissues is decomposed. As more nitrogen becomes available, a greater level of plant growth can be sustained, which in turn increases the rate of accumulation of organic matter. The ecosystem will eventually diversify and become self sustaining as nitrogen is recycled. The *Lupinus arboreus* plants originally used in the second stage of the artificial succession were able to fix sufficient nitrogen to support the growth of the *Pinus radiata* trees until thinning (Gadgil, 1971), when a new crop of *L. arboreus* seedlings became established. It is highly desirable that replacement species have a similar capacity. The results of these trials thus far do not indicate which of the more successful species can achieve the required fixation rates.

The results did show that species survival and growth varied between sites. In Trials A1 - A3 and trial series B, which were replicated at different sites, species persistence was higher at the more southern sites than at Ninety Mile Beach. At this site *Lespedeza cuneata*, *Lupinus nootkatensis*, *Sutherlandia frutescens* and *Trifolium ambiguum* failed in trials of both series. The percentage occupancy averaged across all species in the trial series B was lowest at this site, although the average plant spread was greater than at Santoft Beach. The only species to fail consistently across a range of sites was *Lupinus nootkatensis*.

Of the thirteen species which had the ability to produce vegetation cover and to fix nitrogen, eight were woody and five were herbaceous. It is not possible to determine from the results described here whether one growth form has an advantage over the other. In some trials, the greatest plant cover was achieved by woody species (especially the *Acacia* species), but in a number of trials plants of *Lathyrus latifolius* and *Lotus* spp., which were herbaceous, also provided high levels of cover. Woody species had higher rates of nitrogenase activity in trials A2, A3 and A6 than herbaceous species, but in the remaining trials the highest ranking species were herbaceous (Table 2).

In Trials A4 - A6 at Santoft Beach, species survival and plant spread were lowest in the two unfenced trials. The fencing of trials provides a degree of protection from grazing, but it would not be justifiable on an operational scale. Species that did survive in Trials A4 and A5 may have more potential as replacement species for *Lupinus arboreus*, which is also unpalatable to grazing animals.

Before the suitability of any nitrogen-fixing species for operational use is confirmed, it will be necessary to characterise its long-term growth, reproduction and ability to establish from seed. Maintenance of vegetation cover in remote or extensive coastal dune areas requires nitrogen-fixing species with enough regenerative capacity to overcome the destructive effects of storm events, pests and human recreational activity. However, the type of vigour required is also characteristic of species that can pose a threat as weeds. The consideration of the weed potential of the species used in these trials is important as all the species tested are exotic species. In addition, seed of many species of legume tend to remain viable in the soil for very long periods of time, which can exacerbate a weed problem. *Acacia saligna* and *A. sophorae* have already been removed from several trials because of concerns that their growth habit and reproductive capacity have the potential to create a weed problem. It should be noted that *Lupinus arboreus* has been regarded as a weed in some situations. Species choice must strike an acceptable balance between the vigour required of second stage plants and excessive growth that threatens other parts of the ecosystem.

The variety of form and vigour already expressed by nitrogen-fixing plants in the screening trials suggests that eventual matching of nitrogen-fixing species to specific sand dune types, locations and sand stabilisation requirements will be possible. Costs relating to weed control or the releasing of plants used in the third stage of the revegetation succession are almost certain to be less than those associated with repeated fertiliser application over large areas, or with the consequences of neglected gaps in the vegetation cover which are the source of mobile sand.

A further problem which has yet to be solved relates to the difficulty of establishing plants from seed sown directly on the sand dunes. The trials described in this paper were all planted with glasshouse-raised seedlings. Optimisation of techniques for successful seedling establishment forms a major part of the ongoing research programme which seeks to identify a suite of nitrogen-fixing species capable of enhancing the vegetation cover of sand dune ecosystems.

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6. REFERENCES

Berg, P. J. and Smithies C. W. (1973). "*Subsurface Sowing of Yellow Lupin (*Lupinus arboreus*) for Economical and Rapid Sand Dune Stabilization at Woodhill Forest*", New Zealand Journal of Forestry, 18 (2):285-293.

Cockayne, L. (1911). "*Report on the Sand Dunes of New Zealand, Their Geology, Botany and Reclamation*", Department of Lands, Wellington, New Zealand, 76 pp.

Dahm, J. (1994). "*Environment Waikato's Beach Care Programme*", Proceedings of the 1994 New Zealand Institute of Landscape Architects Conference, Whakatane, 1994, pp39-54.

Dick, M. A. (1994). "*Blight of* Lupinus arboreus *in New Zealand*", New Zealand Journal of Forestry Science, 24 (1): 51-68.

Douglas, G. B., Gadgil, R. L., Skinner, M. F., Bulloch, B. T., Sandberg, A. M., Foote, A. G. and Lowe, A. T. (1994). "*Nitrogen-Fixing Replacements for Tree Lupin (*Lupinus arboreus *Sims) on North Island Coastal Dunes*", Proceedings of the 1994 New Zealand Conference on Sustainable Land Management, Lincoln University, New Zealand, pp216-222.

Fenton, G. R. (1949). "*Sand Dune Reclamation in New Zealand*", Empire Forestry Review, 28:137-142.

Gadgil, R. L. (1971). "*The Nutritional Role of* Lupinus arboreus *in Coastal Sand Dune Forestry: 3. Nitrogen Distribution in the Ecosystem Before Tree Planting*", Plant and Soil, 35 (1):113-126.

Hardy, R. W. F. and Knight, E. Jr. (1967). "*ATP-Dependent Reduction of Azide and HCN by N_2-Fixing Enzymes of* Azotobacter vinelandii *and* Clostridium pasteurianum", Biochimica et Biophysica Acta, 139:69-90.

Jackson, D. S., Gifford, H. H. and Graham, J. D. (1983). "*Lupin, Fertiliser, and Thinning Effects on Early Productivity of* Pinus radiata *Growing on Deep Pinaki Sands*", New Zealand Journal of Forestry Science, 13 (2):159-182.

Restall, A. A. (1964). "*Sand Dune Reclamation on Woodhill Forest*", The New Zealand Journal of Forestry, 9:154-161.

Shea, G. (1996). "*Lupin Anthracnose Strikes*", Newsletter of the Plant Protection Society of Western Australia 8 (4): 1-2.

Silvester, W. B. (1983). "*Analysis of Nitrogen Fixation*", In: Gordon, J. C. and Wheeler, C. T. (ed's) Biological Nitrogen Fixation in Forest Ecosystems: Foundations and Applications, pp173-212.

Stewart, J. (1873). "*On the Reclamation of Sand Wastes on the Coast, and the Prevention of Their Inland Advance*", Transactions and Proceedings of the New Zealand Institute, 6:42-45.

Thomson, P. (1870). "*On the Sand Hills, or Dunes, in the Neighbourhood of Dunedin*", Transactions and Proceedings of the New Zealand Institute, 5:105-106

Wendelken, W. J. (1974). "*New Zealand Experience in Stabilization and Afforestation of Coastal Sands*", International Journal of Biometeorology, 18:145-158.