Transgressive dune development following deliberate de-vegetation for dune restoration in The Netherlands and New...

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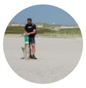

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Targeted ground-based application of herbicide to isolated Ammophila plants, northern dunes, Doughboy Bay, February 2004. The blue patches on the sand in the foreground show where herbicide has been applied.


Mechanical excavation of foredune and blowouts, The Netherlands.

Transgressive dune development following deliberate de-vegetation for dune restoration in The Netherlands and New Zealand

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Abstract/Résumé

Coastal dune management in The Netherlands and New Zealand seeks to restore dune mobility by removing vegetation. Different methods are used to remove vegetation – mechanical excavation in the Netherlands and chemical means in New Zealand. This paper compares a herbicide-based restoration project at Doughboy Bay, New Zealand to mechanical-based projects in The Netherlands. Several parallels can be drawn between the New Zealand case and dune management in the Netherlands. Namely 1), both mechanical and herbicide methods are effective at removing *Ammophila*; 2), a single intervention is insufficient to maintain long-term sand mobility, whichever the treatment method; and 3), long-term self-sustaining aeolian activity appears to be dependent on allowing significant exchange of sand between beach and dune environments.

Introduction

Historiquement, la gestion des dunes en Nouvelle-Zélande et aux Pays-Bas avait pour but la lutte contre l'érosion, soit pour des usages forestiers et agricoles, soit pour la protection contre les inondations. Au cours des quelques décennies passées récentes, une attention particulière a été portée sur les dunes mobiles et leur biodiversité. De nombreuses espèces peuvent survivre dans les sols dunaires, mais certaines sont inféodées à la mobilité du système. Ces psammophytes spécialisés sont menacées par le choix de stabiliser les dunes. C'est pourquoi, tant en Nouvelle-Zélande qu'aux Pays-Bas, des gestionnaires de dunes ont expérimenté différents systèmes de remobilisation en vue de restaurer la dynamique éolienne et la biodiversité des dunes. Aux Pays-Bas, c'est le plus souvent l'enlèvement de la couverture végétale au bulldozer qui est mise en œuvre. En Nouvelle-Zélande, la couverture végétale est plutôt détruite par des herbicides. Dans cet article, nous décrivons les effets géomorphologiques et écologiques de l'une de ces expérimentations à Doughboy Bay en Nouvelle-Zélande et nous la comparons avec une opération de restauration menée aux Pays-Bas. L'opération de Doughboy Bay, commencée en 1999, permet un regard exceptionnel sur l'effet de la dévégétalisation sur la dynamique dunaire durant une période de 14 ans.

Site d'étude

La baie de Doughboy, étroite et allongée en profondeur, est située sur la côte ouest de l'île de Stewart, au sud de la Nouvelle-Zélande. La géomorphologie et l'écologie des dunes barrières de cette baie ont été fortement transformées par Ammophila arenaria. *L'invasion par* Ammophila *dans les années 1960 a induit une augmentation du recouvrement végétal, une perte d'espèces dunaires locales, et la progradation d'une série d'avant-dunes. Le projet de restauration de la baie de Doughboy a commencé en février 1999 avec l'épandage d'herbicide sélectif par hélicoptère. Trois traitements aériens ont été effectués. Des recrus à partir des rhizomes d'*Ammophila*, et issus de la banque de graines du sol ont été pulvérisés annuellement au sol depuis 2001.*

Méthode

Des photos aériennes géoréférencées de 2000 à 2013 ont été utilisées pour étudier et comparer les surfaces nues et végétalisées du site tout au long de l'opération de suppression de Ammophila. *Six transects perpendiculaires à la côte ont été implantés en 1999, avant le premier traitement herbicide, afin d'enregistrer les changements de morphologie. L'évolution des communautés végétales a été mesurée sur des quadrats de 12,4 x 2,6 m.*

Résultats

Il a fallu trois ans pour réduire à zéro la densité de Ammophila, *alors on a pu observer la formation de dunes transgressives. Le processus fut favorisé par l'introduction volontaire de* Ficinia spiralis *(Pingao, Cypéracée endémique des dunes de NZ). Les plantations ont été effectuées en 2002, 2003 et 2004, selon un dispositif triangulaire, par groupes de de 5-7 plants séparés de 30 mètres. L'accumulation de sable autour de ces plants a provoqué la formation de nebkhas perchées sur les formes antérieures. Ces nebkhas ont accéléré la sédimentation, mais aussi l'érosion (entre les nebkhas). En même temps que l'éradication de* Ammophila, *le recouvrement et la diversité végétale ont fortement diminué, cependant une grande partie de ces espèces n'étaient pas caractéristiques des dunes mobiles. La composition de la couverture végétale est maintenant proche de celle des systèmes dunaires du sud de la Nouvelle-Zélande sur lesquels* Ammophila *n'a jamais été introduit. La distribution de ces espèces est cependant différente de celle des systèmes naturels. Avec le temps, les processus de dispersion et de colonisation végétale vont certainement accroître la naturalité de cette distribution.*

Discussion et conclusion

Nous avons montré l'impact de l'élimination de Ammophila *sur le site des dunes de la baie de Doughboy : développement de dunes mobiles et changement de composition des groupements végétaux. Ces modifications ont nécessité des applications répétées d'herbicides. Une grande partie de ces dunes est maintenant mobile. Le paysage actuel comprend toutefois encore une forte proportion de formes héritées, en effet les formes transgressives sont perchées au-dessus des dunes préexistantes. Si le but de la restauration de ces dunes était de recréer les systèmes antérieurs à l'introduction de* Ammophila, *alors l'objectif n'est pas encore atteint. Cependant, à ce stade, les travaux ont permis d'établir des habitats de dunes mobiles et de réimplanter les espèces pionnières indigènes. De nombreux parallèles peuvent être établis entre cette expérience de Nouvelle-Zélande et celle des des Pays-Bas. Les méthodes mécaniques et chimiques sont toutes deux efficaces pour supprimer* Ammophila. *Quelle que soit la méthode employée, des interventions annuelles sont nécessaires pendant une longue période (décennies) afin d'éviter la reprise de* Ammophila. *A la différence des méthodes mécaniques, les nouveaux traitements herbicides sont relativement faciles après la première phase de dépérissement. L'effet des herbicides est plus graduel, alors que les interventions mécaniques permettent une remobilisation immédiate du sable. Dans les deux cas, le maintien d'un bon degré de mobilité naturelle semble dépendant du niveau d'échange sédimentaire possible entre plages et dunes.*

Key-words/Mots clés

New Zealand, *Ammophila* eradiction, chemical methods.

Nouvelle-Zélande, éradiction d'Ammophila, méthodes chimiques.

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Introduction

Transgressive coastal dunefields were once widespread in The Netherlands and New Zealand. In the Netherlands parabolic dunefields extend up to 4.5 km inland (Arens et al., 2013a) and in New Zealand, parabolic dunes reached almost 20 km inland in the Manawatu Region (Clement et al., 2010). The largest dunefields in New Zealand are now mostly stabilised (Hilton, 2006), but significant mobile dunefields remain in the far north and far south of New Zealand. Transgressive dunefields in the Netherlands are largely vegetated and stable. In both countries there is recognition by authorities of the need to maintain and develop habitat for dune-related flora and fauna.

Historically management of coastal dunes in the Netherlands has been concerned with erosion control (Klijn, 1990). Dune-systems were stabilised, usually through the deliberate planting of dune vegetation, so as to halt the natural geomorphic processes of aeolian sand transport and dune migration. Large stable foredunes have been encouraged in order to protect the low-lying hinterland from flooding. Natural dune dynamics, including blowout development and parabolic dune migration, have been tolerated only when they are not a threat to coastal safety (Van Boxel et al., 1997). A similar stabilization of coastal dunes has occurred in New Zealand. Here dune vegetation, primarily *Ammophila arenaria* (marram grass) was planted in order to stabilise mobile dune landscapes for pastoral and forestry purposes (Hilton, 2006). Remote dune systems were subsequently stabilised as a result of the natural dispersal of *Ammophila*. Large stable foredunes were also encouraged for flood protection. *Ammophila* is also the dominant species on mobile (yellow) dune-systems in the Netherlands.

Over the last few decades there has been increasing awareness of the importance of young and mobile dunes and associated biodiversity. Many species are able to survive in dune soil, inland from the foredune, but a few are dependent on a dynamic dune landscape. These obligate and semi-obligate psammophytes are now threated as dune-systems have been managed to promote stability. Further, dune mobility creates diverse landscapes capable of supporting a range of plant communities whereas stable dunes do not. Consequently, dune managers in The Netherlands have experimented with a range of disturbance regimes since the 1990's with the goal of restoring aeolian dynamics in order to restore dune biodiversity (Arens et al., 2013b).

To date more than 15 restoration projects have been completed in The Netherlands (**figure 1**; Arens et al., 2013b). These projects can be divided into two categories. The first seek to restore dune mobility behind the foredune through either the reactivation of blowouts and parabolic dunes (e.g., Arens et al., 2004), or by removing and adapting artificial landscapes (canals, golf course, and sand dykes) to replicate a "natural" dune landscape (e.g., Arens and Geelen, 2006). The latter involve destabilization of foredunes (Van Boxel et al., 1997). In both forms of restoration, mobility is usually induced by the removal of dune vegetation by bulldozers. These projects range in scale from re-activation of individual blowouts or parabolic dunes (e.g. Van Boxel. et al., 1997; Arens et al., 2004) to large landscape scale projects (e.g., Van Limburg site – 35 ha; Arens and Geelen, 2006).

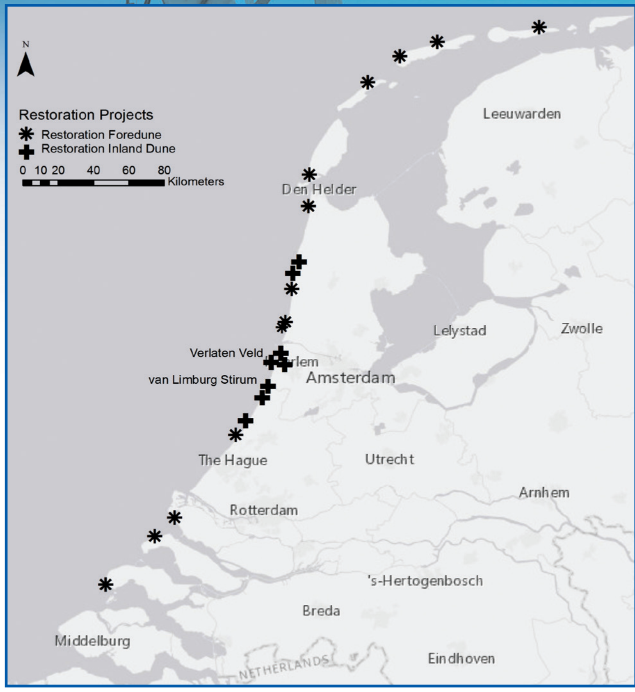

figure 1: Restoration projects, aiming at aeolian processes, in the Netherlands. Projects labelled are referred in the text (Adapted from Arens et al., 2013).

The success of the Netherland restoration projects has been mixed. Many interventions have led to an initial increase in dune dynamics following devegetation; but re-colonisation from rhizomes and seedling results in re-stabilisation (Arens et al., 2013a; Arens et al., 2013b). Restoration efforts in foredunes have been more successful than inner dune restoration projects in reinstating aeolian processes, at least in the medium term (>10 yrs).

Dune restoration projects have also been implemented in New Zealand. As with the Netherlands these projects also seek to re-establish a more natural dune dynamic for the conservation of native dune species. Here the non-native *Ammophila* is removed from dune-systems through the large-scale application of herbicide. In doing so it is hoped that the development of transgressive dunes that are topographically diverse and which provide habitat for increasingly rare dune species will be initiated.

In this paper we document and compare the geomorphic and ecological effects of one of these projects at Doughboy Bay, Stewart Island, New Zealand, with dune-restoration projects implemented in the Netherlands. Restoration at Doughboy Bay commenced in 1999. Hence, the case provides a rare insight into the development of dune dynamics and dune flora over a 14 year period following devegetation.

I- Study Site

Doughboy Bay is a funnel-shaped, swell-aligned, embayment situated on the west coast of Stewart Island, New Zealand (-47° lat, 167° long). The climate in Stewart Island is temperate with no strong seasonal contrasts. The prevailing and dominant winds are from the northwest, although all westerly winds are likely to be funnelled so that the incident winds at the shore are more or less from the west **(figure 2)**. Winds are strong with wind speeds exceeding 20 knots common. Beach morphology is generally intermediate, between reflective and dissipative types.

Three distinct barriers and associated dune-systems, altogether comprising 40 ha, are located at the head of this bay - the northern dunes, the central dunes, and the southern dunes **(figure 2)**. Sections of the northern and southern barriers are relatively sheltered from the prevailing onshore winds although exposure reaches maximum levels towards the centre of the bay. Thus, the distal end of the southern dune barrier is relatively exposed to westerly (onshore) winds. This paper focuses on the changes to the morphology and ecology of the northern and southern barriers following *Ammophila* removal. The central dunes are located at the apex and most exposed section of the bay. Here dune morphology consisted of parabolic and transgressive dunes. Post-*Ammophila* changes to the central dune system are not examined in the present study.

The geomorphology and ecology of the northern and southern dune barriers prior to restoration was strongly influenced by *Ammophila*. Prior to the invasion of *Ammophila*, the dunes at Doughboy Bay were probably similar in morphology and ecology to the modern barriers of South Westland and south Fiordland (described by Johnson, 1998). The native dune binder, *Ficinia* spiralis (pingao), would have dominated the exposed face of the foredune, with a range of other native plants growing across the more sheltered inland section of the barrier. Vegetation cover would have been relatively sparse and patchy. In the 1960's a storm eroded a significant width of the dunes resulting in a well-defined erosion scarp still apparent today (Hilton et al., 2009). *Ammophila* was present at the time of the storm, but it may not have been the dominant sand-binder. Post-storm progradation, however, occurred in conjunction with *Ammophila*, not *Ficinia*. This shift in species dominance resulted in an increase in vegetation cover and associated alterations to foredune morphology. The morphology of these barriers prior to *Ammophila* control consisted of a progadational series of foredune ridges. The cover of *Ficinia* would have been too sparse to prevent the formation of secondary dunes (blowouts, parabolic dunes, shadow dunes). When the restoration programme commenced, *Ammophila* was the dominant dune species, forming an almost continuous canopy.

The restoration project at Doughboy Bay commenced in February 1999 when the Department of Conservation initiated a dune restoration programme on Stewart Island. In practical terms this involved the eradication of *Ammophila*. A helicopter equipped

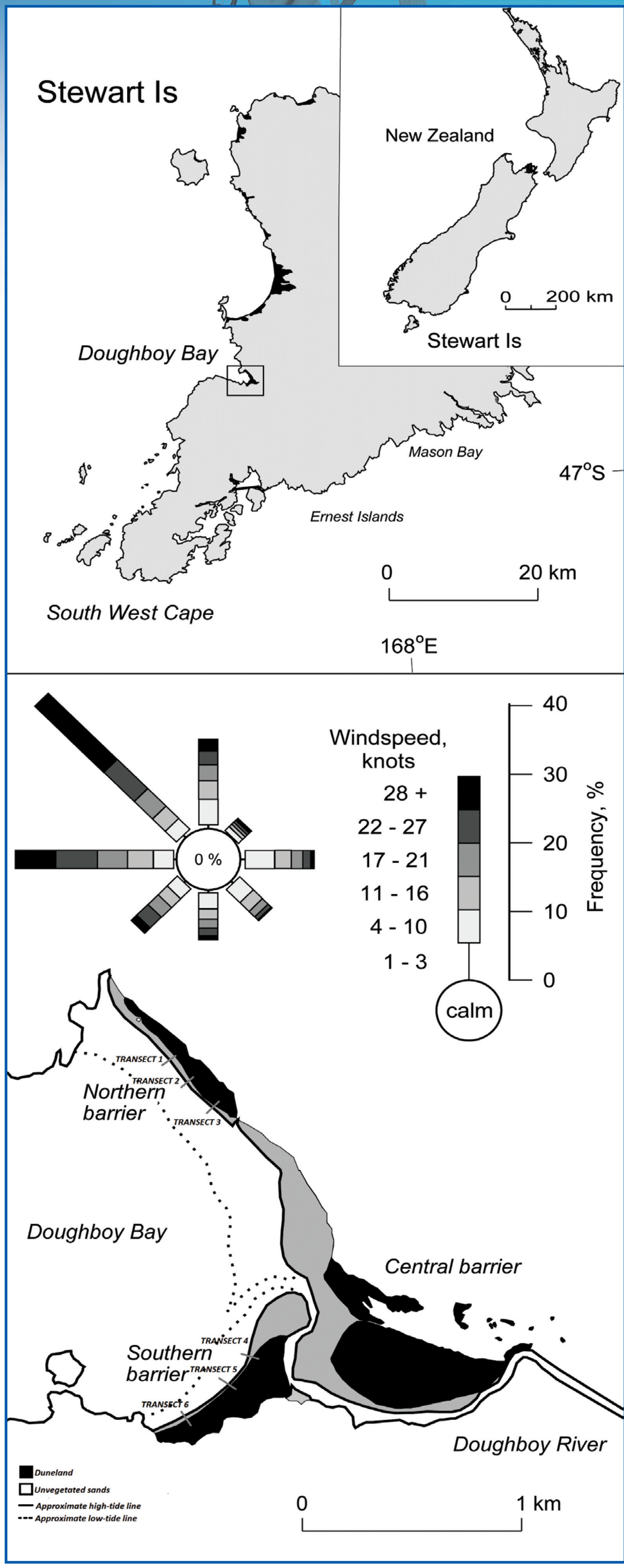

figure 2: Location of the northern and southern barriers, Doughboy Bay, Stewart Island (Rakiura). The windrose is derived from data gathered at Southwest Cape, 20 km south of the study site, from 1992 to 2003.

with a spray boom was used to apply a systemic, grass-selective herbicide (haloxyfop-R) with uptake oil, to the southern dunes. Complete necrosis of leaf material was observed 4 months later; however, numerous shoots established from surviving rhizome by late spring (November 1999). The helicopter was used to spray re-growth in the southern dunes in February

2000 and the northern and central dunes for the first time in February 2001, after which DOC employed a pump unit mounted on an Argo amphibious vehicle. Subsequent re-growth, from rhizome and an in-situ seed bank, has been sprayed using the Argo or with knapsacks annually since 2000. Operations remain ongoing due to the presence of a long-term persistent *Ammophila* seed bank (Konlechner and Hilton, 2010). Growth from marine-stranded *Ammophila* rhizome, in 2005 and 2008, has also been a problem. *Ammophila* was washed into the sea during storm events and rhizome deposited around the entire 2.1 km margin of Doughboy Bay by wave action, above the line of spring high tides (Hilton and Konlechner, 2011). On both occasions stranded rhizome produced vigorous growth within 12 months.

II- Method

We used digital geo-referenced aerial photos recorded between 2000 and 2013 to study and compare the area of bare or vegetated surfaces and identify and map erosional features. Six cross-shore transects were established in 1999, prior to the first application of herbicide, to record changes in barrier morphology and sediment volume transfers following *Ammophila* removal. These transects were located through the northern and southern dune-systems, three on each of the barriers (TRANSECT1 is the northernmost; TRANSECT6 the most southern). A number of transects were established alongshore, since we expected some alongshore variation in barrier development with alongshore variations in exposure to westerly (onshore) winds **(figure 2)**. The topography along each transect was first surveyed prior to the initial application of herbicide, then annually until 2009, then again in 2014. Surveys until 2003 were conducted using a dumpy level. All subsequent surveys were conducted using a Leica laser total station. Changes to vegetation communities following *Ammophila* removal were measured using twelve 4 x 2.6 m quadrats. Six quadrats were established in each of the northern and southern dunes, with two quadrats situated on each transect. The number of native and non-species within quadrats was counted annually from February 1999 to 2004, and then again in 2014. The percentage cover of all species was also estimated annually from December 1999.

III- Results

A- Dune activation

The removal of *Ammophila* was expected to increase the area of bare sand and to initiate mobile dune formation. Over time, barrier morphology was expected to evolve, from a prograded bayhead barrier to a barrier dominated by transgressive dune forms. Indeed, a zone of active sand transport developed across the northern and southern dunes following the commencement of herbicide operations and *Ammophila* decay **(figure 3)**. The development of this zone is not uniform alongshore. The northern end of the northern barrier and the southern end of the southern barrier are relatively sheltered from onshore winds, by headlands, with the result that a section of the foredune-ridge barrier has persisted even though *Ammophila* has been removed. However, most of the surface of the northern and southern barriers is now active and associated with a sparse or patchy cover of indigenous vegetation. The predominant dune forms are nabkha, 3-5m high, forming persistent shadow dunes, 20-30 m in length. The long-axis of these dunes is oriented more or less towards the west, in contrast to the shore aligned foredune ridges formed by *Ammophila* **(figure 4)**.

The development of this zone of active sand transport was initially gradual. There was little geomorphic change in either the northern and southern barriers until 3 years after the initial application of herbicide. Minor blowouts, a meter or so wide, formed at intervals along the seaward edge of the foredune following the first application of herbicide. These increased in size and frequency towards the more exposed centre of the bay, but they did not develop into major blowouts. The vigorous regrowth of *Ammophila* from rhizomes maintained a dense vegetation cover limiting sand movement (Hilton et al., 2009). Regrowth was particularly vigorous on the stoss face of the seaward-most foredune ridge. This regrowth likely contributed to increased stability by interrupting sediment transfer from the beach. Further, vegetation cover initially remained high even when *Ammophila* was removed. The total stability of the barrier surface, associated with *Ammophila*, had allowed other species, opportunistic native and non-native species, to form a dense ground cover beneath the *Ammophila*. This cover gradually declined following *Ammophila* removal.

Once *Ammophila* was removed, mobilization of the dune surface occurred rapidly **(figure 5)**. Some sedimentation was initiated at the seaward-most foredune ridge. Blowouts per se did not develop. Instead there was general erosion of the stoss face and associated deposition downwind. Simultaneously the crests of the inland foredune ridges were eroded and sand deposited in the swales. Collectively these two processes, erosion of the stoss face of the foredune and activation of the barrier surface, produced significant downwind drift of sand. This activity varied alongshore, as expected, but by 2002 most of the surface of the southern dune barrier was devegetated and geomorphically active **(figure 3; figure 5)**. At this time vegetation cover was sparse.

Sand mobility was at a maximum 4-8 years and 3-5 years following initial control in the northern and southern dunes, respectively. While the total dimensions of the zone of active sand transport has continued to expand since 2005, the area of total bare sand has declined as indigenous dune plants have begun to recolonize the dune system or were planted. It should be noted, however, that vegetation cover over most of the dune surface remains relatively sparse and patchy.

B- Native plant species re-colonization

This re-colonization of the barriers by native species was accelerated by the deliberate re-introduction of the native sand-binding sedge, *Ficinia* spiralis.

figure 3: Aerial photographs of the northern (2002-2013) and southern dune (2000-2013) systems in Doughboy Bay.

Ammophila had replaced this species by 1999 and sampling by the second author found that the remaining seedbank of *Ficinia* was sparse with low viability. In 2002, 2003 and 2004, *Ficinia* was deliberately planted to re-establish a local population of this species. Juvenile plants were planted in patches of 5-7 plants, 20-30 m apart, in a triangular pattern. Most of these plants survived and flourished.

This planting strategy has had implications for the ongoing evolution of these barriers. First, the survival and subsequent growth of these plants led to a decrease in total sand cover and increased stability. Second, sand accumulation around these plants has led to the development of high nabkha perched on top of the pre-existing foredune ridge barrier. Persistent shadow dunes have formed in the lee of these nabka.

Northern dunes, Doughboy Bay, January 2011 – 10 years following the initial application of herbicide. Ammophila was the dominant plant species forming an almost continuous canopy prior to commencement of the restoration project.

figure 4: View looking north taken from the centre of the southern dunes in a) 1999 (prior to Ammophila *removal); and b) from a similar location in 2013. Comparison of such images illustrates the shift from a densely vegetated, stable, sequence of shore-aligned foredune ridges, formed seaward of an erosion scarp (a) to a sparsely vegetated sand-sheet and nabkha system aligned with the prevailing wind (b) following* Ammophila *removal.*

Towards the centre of the bay exposure to moderate strong onshore winds has resulted in significant erosion as winds are funnelled and accelerated between nabkha. This has had the effect of increasing the rate of sedimentation between the nabkha and lowering the intervening sections of barrier. These depressions have provided corridors for accelerated sediment transport from the beach to the barrier hinterland. It has also led to the over-steepening and erosion of the nabkha **(figure 6)**. It is likely that the nabkha toward

figure 5: Ground photos capturing the change in plant cover from 1999 (pre-control) to 2002 (all Ammophila removed, partial mobility) to 2003 (Ficinia planted, general sand mobility).

the more exposed distal end of the southern barrier will continue to erode and eventually collapse. Thus, the supra-tidal barrier should decline in area and trend towards its pre-marram footprint (Hilton et al., 2009).

The 15-year time series of profiles surveyed across the permanent transects records the change in barrier morphology following *Ammophila* grass necrosis **(figure 7)**. Along all transects, except for TRANSECT1, there has been a trend of erosion and lowering of the most seaward foredune ridge. The seaward foredune on TRANSECT1, which is relatively sheltered by a headland, shows relatively little topographic change except for a shift in the position of the foredune crest. Here also an incipient foredune formed between 2006 and 2009, indicating a positive sediment budget on this portion of the coast. Along all other transects the coastline has retreated. Slip faces have developed and migrated inland along the southern dune transects consistent with an inland migration of sand under onshore winds. Sediment transport in the northern dunes is predominantly alongshore (from west to east) resulting in enhanced sand accumulation at the southeastern end of this barrier. Importantly there has been no lowering of the landward portions of the barrier. Although *Ammophila* necrosis led to the development of mobile dune forms, this enhanced sedimentation and the resulting nabkha are largely superimposed on the *Ammophila*-developed barrier.

Ecologically, removal of *Ammophila* has resulted in a shift from a non-native dominated plant community to one dominated by native dune species **(figure 8)**. Vegetation cover has declined as sand mobility has increased, particularly in the southern dunes where exposure to wind is highest. Species richness also declined as increasing sand movement selected for species tolerant of high levels of burial **(figure 8)**. Many of the native plant species now present are found only on mobile dune systems (e.g. *Ficinia* spiralis, *Poa billardierei*). Many of these are nationally rare and threatened. Plant community composition is now similar to comparable habitats in nearby dune systems where *Ammophila* has never been present. The distribution and density of plants across the surface of the dunes, however, remains very different from more "natural" dune-systems. In part, this is an artefact of the planting pattern of *Ficinia* and the time it takes for plants to colonise de-vegetated surfaces. It remains to be seen whether, in time, the distribution of species such as *Ficinia* will approach a more natural distribution.

IV- Discussion

Comparison with dune restoration in The Netherlands

We have documented the development of mobile dune forms and shifts in plant communities following widespread *Ammophila* necrosis at Doughboy Bay. These changes have been achieved by repeated (annual) applications of herbicide. Most of the surface of the Doughboy barrier is now mobile and transgressive elements (nabkha, shadow dunes) have developed. The contemporary landscape, however, shows a high degree of landform inheritance; since these transgressive elements are now (in large part) perched on the surface of the former barrier.

Vegetation cover and plant species richness declined following *Ammophila* necrosis, since many of the species present prior to restoration depended on *Ammophila* grass for shelter. The remaining species are mostly native dune-specific species tolerant of much higher levels of post-*Ammophila* sedimentation. If the

figure 6: Following the removal of Ammophila *nabkha developed in association with the native sand-binding sedge* Ficinia*, planted in scattered clumps in 2002. They had developed to a height of 4-5m by 2012. At this time the "pimpled" topography of the barrier generated localised accelerated flows between adjacent nebkha and the more exposed specimens began to erode.*

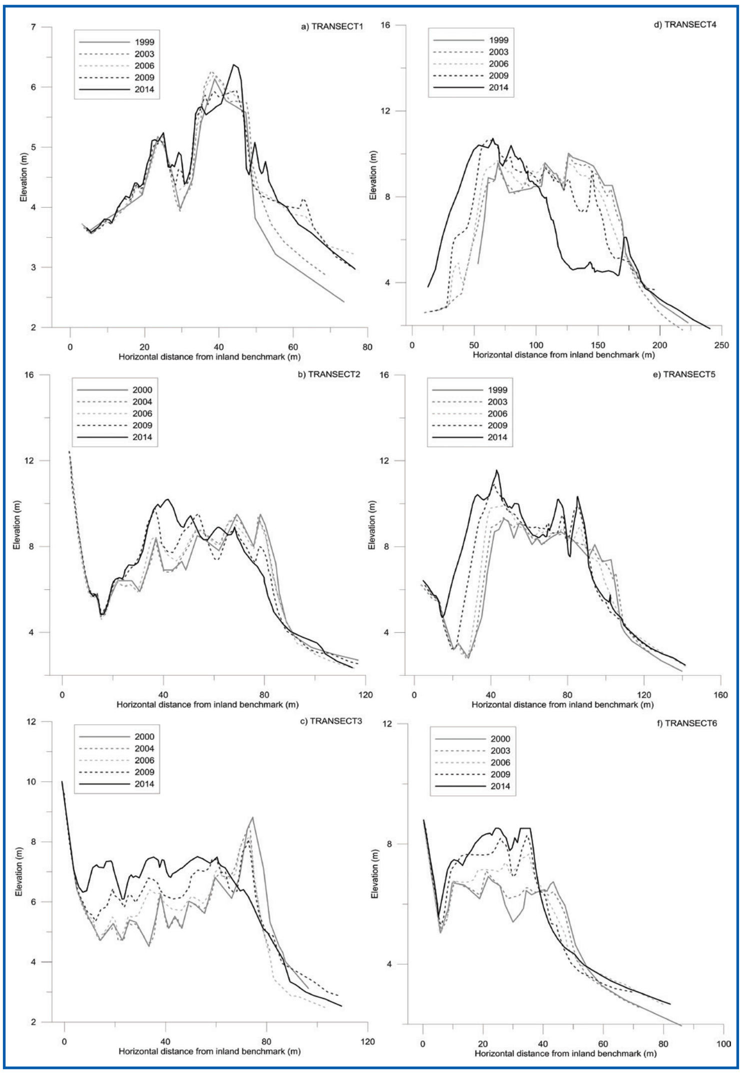

figure 7: Time series of profile surveys across the northern (transects 1-3) and southern (4-6) barriers.

goal of restoration at Doughboy Bay was to re-establish pre-*Ammophila* landforms, then this goal has not yet been achieved. However, restoration work to date has established and maintained mobile dune habitat and re-established the primary colonising species.

Here we compare the Doughboy case to similar restoration projects in The Netherlands. Restoration projects in The Netherlands involve removal of native dune vegetation (primarily *Ammophila*) which has been managed to promote stabilization. In contrast, the Doughboy case has involved the removal of the same non-native sand-colonising species. Management agencies in both New Zealand and The Netherlands have attempted to re-establish dune mobility, or the potential for natural dune mobility, and associated biodiversity. In the Doughboy case the project was driven by a need to provide habitat for rare and threatened dune-species.

Different methods have been used to devegetate the dunes. In The Netherlands dune managers have used excavators and bulldozers to mechanically excavate the dunes to achieve target morphologies almost instantaneously. In the New Zealand case it may take some years to achieve the desired morphology. Indeed, it is possible that the desired morphologies may not develop for many years, or decades, given the physical transformations required.

Herbicide has proved to be a very effective method of eradicating *Ammophila* from sand dunes; but only after repeated applications of herbicide to counter regrowth (Hilton and Konlechner, 2010). Similar regrowth from rhizomes and roots has hampered restoration efforts in the Netherlands (Arens et al., 2013a and b). Vegetative growth from surviving plants around the edges of the restoration projects and the growth of seedlings also contributed to re-colonisation of the de-vegetated areas. Managers in New Zealand have the advantage of removing *Ammophila* from entire dune fields, contained within embayments, with reduced likelihood of reinvasion. Regeneration from rhizomes remains ongoing until the bud-bank is exhausted (approximately 3 years). Once exhausted the re-invasion rate is unlikely to be as high as that experienced in The Netherlands because of the isolation of the restored site from the remaining populations of *Ammophila*.

In The Netherlands, dune de-vegetation by excavators is achieved very rapidly, over a matter of hours, days or weeks. Sedimentation and dune mobility is achieved almost instantaneously. In the van Limburg Stirum project, for example, aeolian processes enlarged the bare sand surface immediately after the dunes were excavated and re-contoured (Arens and Geelen, 2006). In contrast, complete removal of *Ammophila* by herbicide at Doughboy Bay, was not achieved in the first three years. Widespread sedimentation

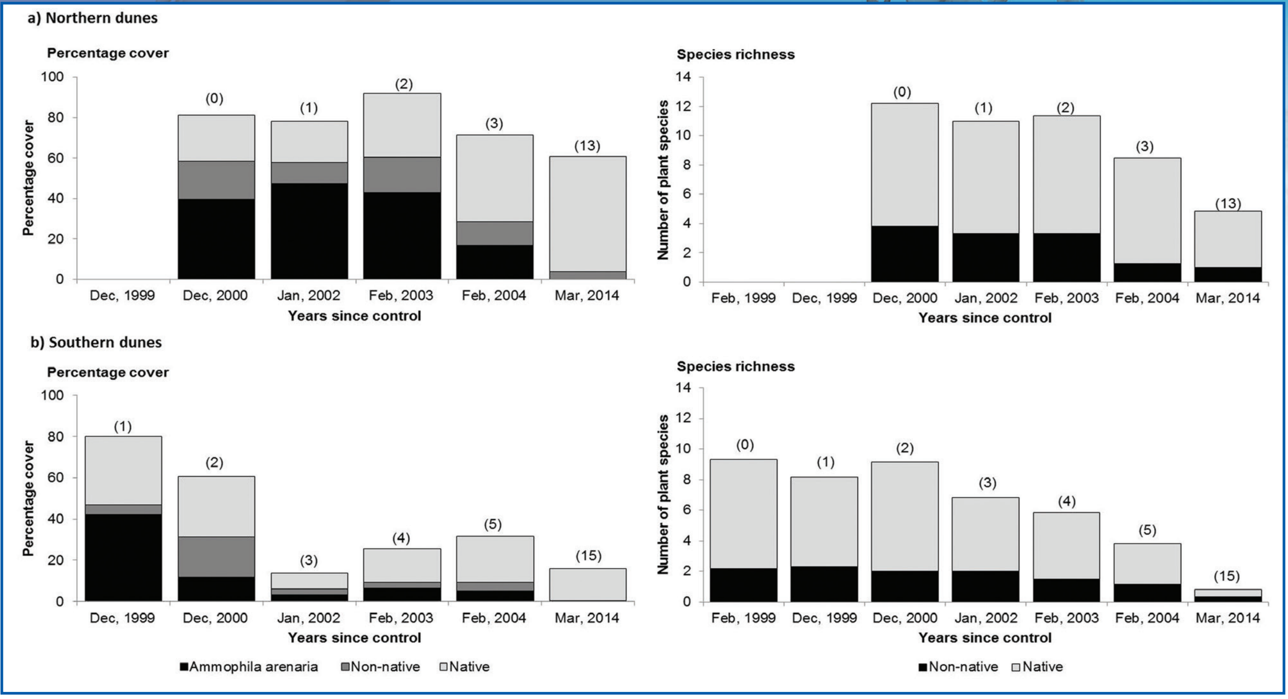

figure 8: The change in species richness (mean number of species in survey quadrats) and plant cover, southern and northern dunes, Doughboy Bay. The number of years elapsed since the initial application of herbicide is shown in parentheses.

did not occur at Doughboy Bay until *Ammophila* was effectively eradicated (that is, nil re-growth). Despite the delay, mobility and dune development is ongoing at Doughboy Bay and can be expected to continue, so long as the management agency continues a programme of annual eradication of seedlings and plants developed from stranded rhizome. Annual management of regrowth is essential because of the continued germination of seedlings (13 years after the *Ammophila* canopy had been removed from the barrier). Konlechner and Hilton (2010) hypothesised that the processes of foredune accretion and progradation at Doughboy Bay would lead to the formation of a deeply-buried persistent *Ammophila* seed-bank. This seed-bank has been exposed as sand has eroded, resulting in widespread germination on the eroding surfaces of the seaward-dunes. Some hundreds to thousands of seedlings are still emerging each summer. Experience from other dune-systems in New Zealand shows that, without ongoing management, seed germination would allow *Ammophila* to rapidly recolonize the Doughboy dunes (Hilton et al., 2005).

The method of de-vegetation, whether mechanical or herbicide-based, is probably not critical to the success of a dune restoration programme. The method is probably less important than the commitment to ongoing (annual) management of vegetation regrowth, specifically colonisation by *Ammophila*. It might be concluded that the use of herbicide at Doughboy Bay is not the most efficient method of *Ammophila* eradication, particularly given the relatively small size of the treatment area. However, the isolation of Doughboy Bay would have made it very difficult to establish a mechanical operation. The Department of Conservation flies all materials and personnel to the site by helicopter. The field operations are carefully programmed and executed, and involve annual herbicide application (involving at least 40 'person-days' each year for most of the last 15 years) and outcome monitoring by independent consultants (Hilton and Konlechner, 2010). Persistence and careful management of operations using GPS, and spatial data analysis using GIS, are key attributes of this programme.

Dune restoration projects would ideally result in self-sustaining aeolian activity, ensuring permanent possibilities for dune-vegetation related to or dependent on dune mobility. The Netherlands has made significant progress in assessing the potential to mobilise dunes within stabilised parabolic dune fields. Clearly one intervention will result in devegetation and mobilisation, but cannot ensure ongoing mobility because of recolonisation by sand-binding species (e.g., Arens and Geelen, 2006; Arens et al., 2013a and 2013b). In the case of Doughboy Bay the high exposure of the site ensured a high level of post-marram sedimentation. Re-establishing the physical link between the beach and barrier dunes has also been advantageous – the profile data suggests that significant quantities of sand has been transported between beach and dune environments. The sand drift evident in figure 3 from 2002 in the Southern dunes and 2005 in the Northern has, in part, been the result of sand transported onshore, and not simply erosion of the foredune. In comparison, the Verlaten Veld site in The Netherlands is well inland and relatively sheltered and lacks a beach-dune connection.

The use of herbicide has the distinct advantage of reducing the target species to zero density, while allowing natural colonisation of the devegetated barrier by dune-related plant and animal species and/or the deliberate reintroduction of species. The development of the southern and northern Doughboy Bay barriers has clearly been influenced by the planting of clumps of *Ficinia* plants. The decision to plant this native sand-binder was made early in the restoration programme, but without consideration of the influence of nabkha development on the evolving barrier morphology. These plantings have been very successful, in terms of restoring a key indigenous species (and generating large quantities of seed), but also in retarding the erosion of the barrier following *Ammophila* removal. Nabkha in the relatively exposed sections of the barriers are actually likely to erode, having grown rapidly in an environment of surplus sand, high nutrient supply and rapid *Ficinia* growth after *Ammophila* decay. Those in the more sheltered sections of the barrier are more likely to persist, and with each year of flowering seed is being contributed to the seed bank. They are also providing shelter for other early successional species.

In hindsight it may have been preferable to plant *Ficinia* extensively, as single specimens, rather than in clumps. The clumped pattern resulted in the development of very large nabkha and the erosion of intervening surfaces. Whether this environment will provide habitat for a wider range of dune-related flora is uncertain. The current landscape is one of very rapid deposition (nabkha) or erosion (intervening areas); which may not provide opportunities for the grasses, sedges and herbs usually associated with active dune systems. This may follow the establishment of a semi-continuous foredune associated with *Ficinia*, and the establishment of a more sheltered inland section of the barrier.

Conclusion

In this paper we have documented changes to a prograded foredune barrier over 13 years following *Ammophila* necrosis. It took three years to reduce *Ammophila* to zero density, thereafter transgressive dune forms started to develop. This process was greatly influenced by the introduction of clumps of the native sand-binder, resulting in the formation of nabkha perched on top of the former barrier. These nabkha have contributed to accelerated rates of sedimentation, erosion and deposition. Plant cover and species diversity declined significantly following *Ammophila* eradication, although most of these species are not usually found in active dune environments. Plant community composition is now similar to dunes-systems in Southern New Zealand where *Ammophila* has never established. Species distribution, however, is different to that usually seen in natural dune systems. It is expected that over time, processes of plant dispersal and colonisation will result in an increasingly "natural" distribution of plant species.

Several parallels can be drawn between the New Zealand case and dune management in the Netherlands. Both mechanical and herbicide methods are effective at removing *Ammophila*. Whichever method is employed, annual treatments for prolonged periods (decades) are required to prevent re-invasion by *Ammophila* and maintain long-term sand mobility. The mechanical method practiced in The Netherlands is effective at removing vegetation but does not lend itself to annual treatments required to manage regrowth. In contrast herbicide can be reapplied relatively easily and with precision after the initial *Ammophila* canopy has collapsed. The herbicide method results in a relatively gradual change to the dune landscape whereas mechanical interventions result in immediate increases in sand mobility. In both cases long-term self-sustaining aeolian activity, appears to be dependent on allowing significant exchange of sand between beach and dune environments.

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