The Rakiura Dune Restoration Programme (1999-2021)

Lessons Learned from 21 Years of Operations, Monitoring & Research

Mike Hilton & Teresa Konlechner

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Department of Conservation Rangers grid searching and spraying marram grass seedlings in the 'Great Stonefield', Central Dunes, Mason Bay, 8 November 2012

Back Cover image:
Southern Dunes, Doughboy Bay, October 2017

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Foreword

Professor Dame Juliet A. Gerrard DNZM HonFRSC FRSNZ

One of the nicest parts of my role as Prime Minister's Chief Science Advisor is being approached to engage with a huge range of projects carried out by researchers in Aotearoa and do a deep dive into some amazing research efforts that I otherwise would not have heard about. This volume on the restoration of the dunes of Rakiura is one of those efforts, and I'm delighted to have been asked to contribute this foreword.

So often in my role when I'm asked to find evidence to inform policy, the data turn out to be rather more sparse than is helpful to guide action, or to understand whether previous policies that have been put in place are working. This is especially true in the environmental sphere, where it takes such a long time for the impact of interventions to be manifest with measurable change. It is also rare to find projects which have secured long term funding to support monitoring to measure that change. So it was a treat to dip into this account of a 21 year study covering not only research, but also monitoring efforts, on the world's most southern dune systems.

According to StatsNZ, as of 2008, Aotearoa's active sand dunes had decreased 80.5 percent from their predicted pre-human extent. This is of concern since we know that such dunes are home to flagship species for biodiversity such as Latrodectus katipo, an endangered species of native spider. Dunes nationally have been threatened by human modification – such as sand mining, stock grazing, infrastructure development, urbanisation and the introduction of a wide range of exotic plant, shrub and tree species. Marram grass – an introduced and invasive dune species – threatens pīngao and spinifex – both important native species known to bind the sand in these dynamic systems, and both traditionally used by Māori for weaving.

The New Zealand Coastal Policy Statement (2010) has clear policy objectives for restoring, protecting, and maintaining coastal dune systems. Objective 1 of the statement seeks to "safeguard the integrity, form, functioning and resilience of the coastal environment and sustain its ecosystems, including marine and intertidal areas, estuaries, dunes and land". Beneath this are various policies relevant to sand dunes. Policy 13 recognises that dunes reflect a landscape form with natural character worth preserving, and rehabilitating (Policy 14). Finally, Policy 19 restricts walking access in dunes to preserve sensitive habitats and Policy 26 recognises dunes as natural defences against coastal hazards.

Marram grass, the seeds of which can remain viable for decades, has now invaded the majority of natural dune areas in Aotearoa, displacing native plants and altering natural character, providing a barrier for dune restoration. Efforts to implement our policy objectives and restore these important habitats therefore need to be sustained over very many years, and it is inspiring to see that the restoration programme described in this book has stayed the distance. I hope this volume serves as an inspiration to others around Aotearoa to apply similar approaches and tenacity to restore our dune landscapes and congratulate the authors on their remarkable mahi.

Professor Dame Juliet A. Gerrard DNZM HonFRSC FRSNZ
Prime Minister's Chief Science Advisor
Kaitohutohu Mātanga Pūtaiao Matua ulpe Pirimia
July 2021

Foreword

Lou Sanson, Director-General, Department of Conservation

I am thrilled that Mike Hilton and Teresa Konlechner have written a book on the lessons learned from 21 years of the Rakiura Dune Restoration Programme. The work undertaken by DOC has benefitted greatly from research collaboration with Mike and Teresa's work at the University of Otago. This book is a valuable resource and provides DOC and others with a comprehensive record and a way forward for further restoration of these rare and endangered dune ecosystems.

The Rakiura Dune Restoration Programme is also very dear to my heart, beginning in the 1990s when I was Southland Conservator for DOC. Together with Conservancy Scientists, botanists and local managers, DOC began an approach to eradicating marram via aerial spraying operation in Doughboy Bay in 1999. Since then, the restoration effort has continued to increase with the community, DOC and the University of Otago working together to achieve amazing results. It is one of DOC's proudest achievements.

I look forward to the day when all the amazing coastal dune ecosystems across Rakiura are restored and lessons learned from this programme can be further implemented throughout Aotearoa.

Lou Sanson
Director-General
Department of Conservation Te Papa Atawhai
Aoteaora New Zealand
July 2021

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Introduction

1.1 Background

This book was prepared to celebrate 21 years of dune restoration on Rakiura (Stewart Island) by the Department of Conservation and former government agencies. The focus is the period since aerial spray operations commenced at Doughboy Bay in February 1999; however, the foundation for this work was laid in the early 1980s, during a period of ground control of marram grass (*Ammophila arenaria*) on Whenua Hou (Codfish Island), and beaches on the northeast coast of Rakiura. The Rakiura Dune Restoration Programme has since evolved to encompass almost all the major dune systems on Rakiura, making it the largest and longest-running coastal dune restoration programme in the world.

Active dune systems are one of New Zealand's most damaged and endangered ecosystems. The area and naturalness of dune systems declined rapidly during the latter half of the 20th century as a result of human activity; including agriculture, forestry, urbanisation, infrastructure development and waste disposal (Hilton *et al*. 2000; Hilton, 2006). Those dune systems that retain high conservation values are now threatened by marram grass, tree lupin (*Lupinus arboreus*) and associated weed species, particularly in central and southern New Zealand. All remaining dune systems of high conservation value are subject to invasion from these or other weed species and require active conservation management – including our most isolated dune systems in southern New Zealand.

The natural character of 'active' dune systems is not well understood. These landscapes are characterised by sand movement and a sparse and changing vegetation cover; and to many people they appear degraded landscapes. They are distinct from older, (late-Holocene) dune landscapes, that have relatively well-developed soils. These former dune landscapes are now largely farmed, but they were probably forested prior to the arrival of people in New Zealand. In contrast, active dunes comprise mobile dunes, or recently mobile dunes, and show poor or no soil development over wide areas. Sand transport occurs periodically, whenever wind speed passes the threshold for sand transport, usually around 30 kph. A wide range of dune forms can develop; depending on the balance between the amount of sand and rate of sand transport (which is related to the wind regime and local climate); the underlying topography; and the type and extent of vegetation. In southern New Zealand such dune systems survive in Fiordland and Rakiura National Parks, on remote coasts, and so are seldom seen and are generally underappreciated.

Active dune systems contain more than just sand dunes. The largest New Zealand dune systems usually contain a diversity of environments and associated habitats – including ephemeral and permanent wetlands, lakes, coastal turf, stony and rocky deflation surfaces, as well as sand dunes. Large transgressive dune systems, such as Mason Bay, the focus of this monograph, comprise a complex of dune landforms, which range from stable and densely vegetated, to very active, with a sparse vegetation cover - with a great deal of variety in between. The geomorphic dynamism of active dunes means that particular habitats evolve, expand, contract, or disappear, as the dune system evolves – hence the qualifier 'active'. Some parts of a large dune system may be trending towards stability, other parts instability, while areas may be in transitional between these states. Landforms, habitats and the distribution of species, are in a near constant state of change. Today's wetland may be next year's dune, and vice versa.

The flora of New Zealand's active dune systems is rich and distinctive. Unfortunately, many members of this flora are in decline across New Zealand, either directly displaced by exotic weeds, or indirectly following management to promote dune stabilisation; or as a result of habitat loss. Certain plant species are only found in active dune systems. In New Zealand, these include a small number of species that occur in most dune systems (e.g. pīkao/pīngao (*Ficinia spiralis*); species endemic to regions and individual dune systems (e.g. *Craspedia kaitorete, Spinifex sericeus*); and species that are now restricted to just a few dune systems (e.g. *Gunnera hamiltonnii*). Species such as *Gunnera* may once have been more widespread, but always very localised, while other species may have been regionally widespread, but now occur in just a few dune systems (e.g. *Euphorbia glauca*). Other species are associated with particular New Zealand regions; species of the *Pimelea* genus, for example. Most obligate dune species, species only found in dunes, are adapted to some degree of sand burial and are resistant to abrasion and adapted to desiccation.

Active dune systems also contain an important native fauna; including threatened species of gecko and skink, invertebrates and shore birds. Coastal dunes are important haul-out sites for the New Zealand Sea Lion (*Phocarctos hookeri*) in Southland and Otago (e.g. Surat Bay) and the lack of unmodified dune habitat may be limiting their recovery. The New Zealand Fairy Tern (*Sternula nereis*); the New Zealand Dotterel (*Charadrius obscurus*); and Banded Dotterel (*Charadrius bicinctus*) - species now 'critically endangered' and 'endangered'- rely on back-beach and active dune habitat to nest or flock at high tide. The mainland dune systems have lost the rich burrowing avifauna, including a range of petrels, which have succumbed to mammalian predators.

Only a small number of New Zealand active dune systems, or recently active dune systems, retain high natural biodiversity (Figure 1). These ecosystems contain a disproportionate number of threatened species and a few sites hold a high proportion of these species. The inventories of Partridge (1992) and Johnson (1992) found that only 64, of the over 600 dune systems surveyed, retained significant conservation values and the situation has deteriorated since this work. Most dune-specific flora are 'nationally threatened and at risk' (de Lange *et al*., 2018). Hilton (2000) reported that the area of active dunes declined over 70% during the 20^{th} century and probably only 5% of dune systems retain some dynamic character. Holdaway *et al*. (2012) in a review of New Zealand's 45 naturally uncommon ecosystems lists six ecosystems that are associated with active dunes, including three that are 'critically endangered' and three that are 'endangered'. Time is fast running out to conserve what remains of this important coastal ecosystem and landscape.

1.2 The coastal sand dunes of Rakiura National Park

The dune systems of Rakiura are particularly important to the conservation of New Zealand's dune biodiversity; partly because of the size and diversity of dune environments and partly because marram grass and tree lupin were introduced relatively recently. Most species have survived the last 70 years of marram invasion, albeit their distribution and abundance has been impacted. Seven of the 64 New Zealand dunes systems of high conservation value, identified in the 1992 inventories, are located on Rakiura (Figure 2). Consequently, the Rakiura Dune Restoration Programme affords an opportunity to safeguard the plant and animal species and communities, as well as landscapes and landforms, associated with the dune systems of New Zealand's third largest island; and conserve the type of dune system ecology associated with southern New Zealand.

Rakiura is the third largest island (1,746 km^2) in the New Zealand archipelago. It is situated in the 'Roaring Forties' westerly wind belt at latitude 47° S, 167° E; so it experiences frequent gale onshore winds and moderate rainfall. Eighty percent of Rakiura is conservation estate administered by the Department of Conservation. Compared with most other New Zealand dune systems those on Rakiura face relatively few pressures. The island is free of rabbits and hares (which browse pīkao) and mustelids. The only settlement (Oban) is on the sheltered east coast of the island. Grazing domestic animals, mainly sheep, were removed from the Island Hill farm in Mason Bay in 1987; however, red deer (*Cervus elaphus*), whitetail deer (*Odocoileus virginianus*), the Australian brush-tail possum (*Trichosurus ulpecula*), rats (mainly *Ratus ratus*) and feral cats (*Felis catus*) commonly visit and feed in the dunes and predate nesting dotterels in the hinterland. The main weed species of concern are marram grass, tree lupin and gorse (*Ulex europaeus*). Wilding conifers, particularly *Pinus radiata*, widespread in recently stabilised dunes throughout New Zealand, are not present in the Rakiura dune systems.

Rakiura has a 'mid-latitude oceanic' (*Cfb*) climate (Köppen-Geiger climate classification system). Temperatures are mild to cool year-round, with average high temperatures ranging from 17.2 °C (63.0 °F) in January, the warmest month, to 9.9 °C (49.8 °F) in July. The strong oceanic influence, including relatively warm water carried to the island from the remnants of the East Australian Current, results in relatively small temperature variations. The seasonal temperature variation (the difference between the warmest and coldest months) is about 7 °C (13 °F). Precipitation averages 1,490 mm per year, at Oban, on the east coast of the island, with higher levels along the west coast and across the ranges, evenly distributed across the year. The island is in the direct path of mid-latitude cyclones (low-pressure systems, or depressions), which generally move from the southwest to the northeast, or west to east.

The west coast of Rakiura is very windy. We ran an anemometer on the foredune at Mason Bay from June 2011 to September 2016; 14m above the high tide line and 50m inland.

Days with calm to minimal wind were rare during this period. The anemometer recorded calm weather (=<1ms^{-1}) just 1% of the period. Winds over 8ms^{-1} (or 30kph, when 'aeolian' or wind-blown sand transport is likely) occurred 33% of the record and winds over 20ms^{-1} occurred 3% of the record. Maximum mean hourly wind speeds exceeded 40ms^{-1} (150kph), on occasion, and individual gusts exceeded 50ms^{-1} (190kph). Massive volumes of sand are transported in salting clouds of sand at Mason Bay whenever westerly winds exceed 20ms^{-1}; 76kph). Sand goggles (and eye wash) are an essential part of the aeolian geomorphologist's equipment when working in such conditions.

Rakiura contains 13 major sand dune systems and a number of smaller sites. Of these seven are transgressive systems (Mason Bay, Smoky, East Ruggedy, West Ruggedy, Little Hellfire, Big Hellfire and Doughboy Bay), that contain mobile dunes, ranging in size from Mason Bay (694ha) to Big Hellfire (6.5ha). A series of smaller dune systems, mostly less than 1 ha in area, usually comprising a single stable and narrow foredune, occur along the east coast at a number of sites, including Murray Beach, Maori Beach, The Neck (9.1ha) and Sealer's Bay on Whenua Hou (Codfish Island). These systems are usually backed by much older and now forested dunes. Many sandy beaches, with small adjoining dunes, are scattered down the east coast and adjacent to larger dune systems ('Little Doughboy' and 'Little Smoky', for example). These have low ecological values but are nevertheless important as sites that contain marram infestations that have the potential to fuel reinvasion of the larger dune systems.

The biodiversity of Rakiura dune systems is exceptional – and compared with most other high-value dune systems in New Zealand, they are relatively large, intact and unmodified. They contain plant and animal species which are now geographically restricted or lost from other regions of New Zealand. Mason Bay, the largest of the Rakiura dune systems, comprises 55% of the area of the remaining South Island dune systems of high conservation value. This dune system contains 31 plant species classified as nationally threatened. The population of pīkao, a taonga to Māori, is probably the largest in New Zealand (and the largest not subject to lagamorph (rabbit and hare) browse). Pīkao is the only native primary foredune species present on Rakiura, since *Spinifex sericeus* does not occur in the southern South Island. The New Zealand dotterel, southern subs-species, flock in the hinterland of the Mason Bay dunes, where they once nested. Gastroliths indicate that the New Zealand Sea Lion occupied the dunes at least 1km inland and we have observed young sea-lions attempting to cross the foredune between Martins and Duck Creek. A deceased female, born in the Port Pegasus colony on the east coast of Rakiura, was found on the plateau of the foredune in August 2019. Restoring a lower foredune at sites such as Mason Bay may assist this species in the future.

The Rakiura dunes are also distinctive for being (almost) the world's most southern dune systems (at latitude 47°S). The south coast of Enderby Island (Lat 50.5°S) contains a solitary dune system (~8 ha). The combination of frequent and strong onshore winds across the west coast of Rakiura produces high rates of onshore sand transport, resulting in the formation of distinctive dune landscapes as dunes migrate over ridgelines and ranges that are generally oriented north-south. The 'Big Hellfire' dune system, essentially a single 'tongue' of sand that climbs the coastal ridge, attains an elevation of 200m just 900m from the high tide line. Parabolic dunes occur widely, in a range of forms, from isolated long-walled dunes to imbricate

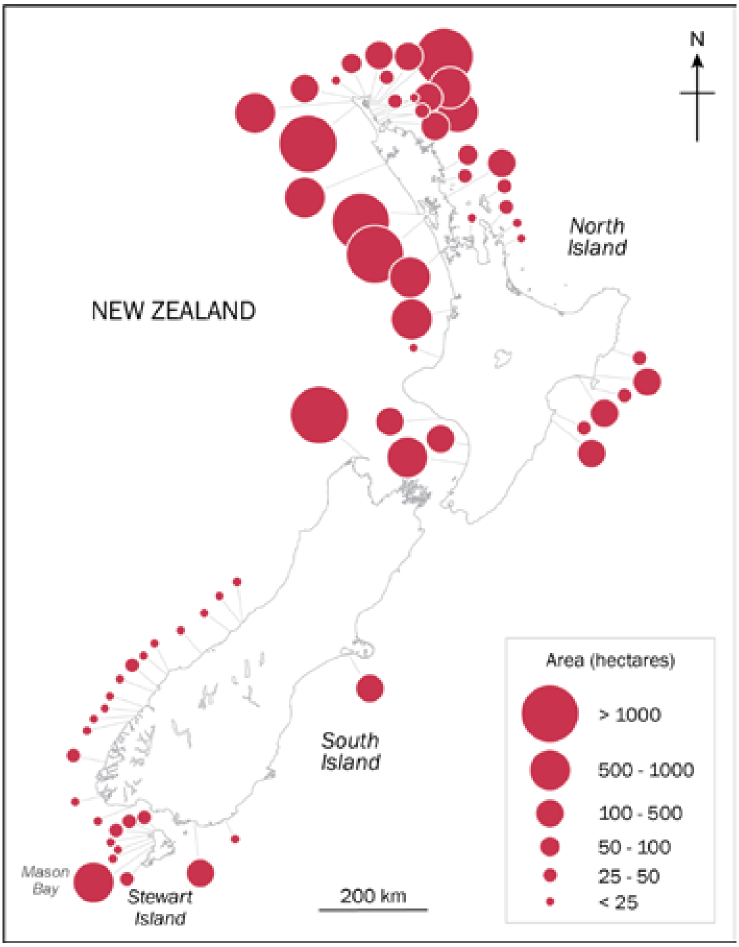

Figure 1: Dunes systems recognised as having high conservation and biodiversity values (based on Johnson, 1992: Partridge, 1992; Hilton *et al*. 2000; and subsequent work by the authors). All of these systems contain weed species, including marram grass, so the size of the circles is not necessarily related to their absolute conservation value.

(overlapping) clusters of dunes, depending on variations in sand supply and the terrain of the hinterland. Small-scale aeolian features, a few centimetres to metres in length, including shadow dunes formed in the lee of patches of vegetation, are also distinctive. The interaction of high rates of sand flux, moderate to high rainfall, sparse native vegetation, and exposed rock and topography, create a range of bedforms of aeolian and fluvial (and mixed) origin, which are of high scientific interest and curiosity.

The Mason Bay dune system contains a mosaic of environments, landform elements and landscapes, and associated plant communities (Figure 3). The nature of these communities depends, in large part, on patterns of sand accumulation (accretion) and erosion and the balance between these processes. The rate of sand accumulation determines which species can establish in different parts of the sand system. Small, prostrate, herbs might tolerate a few millimetres or

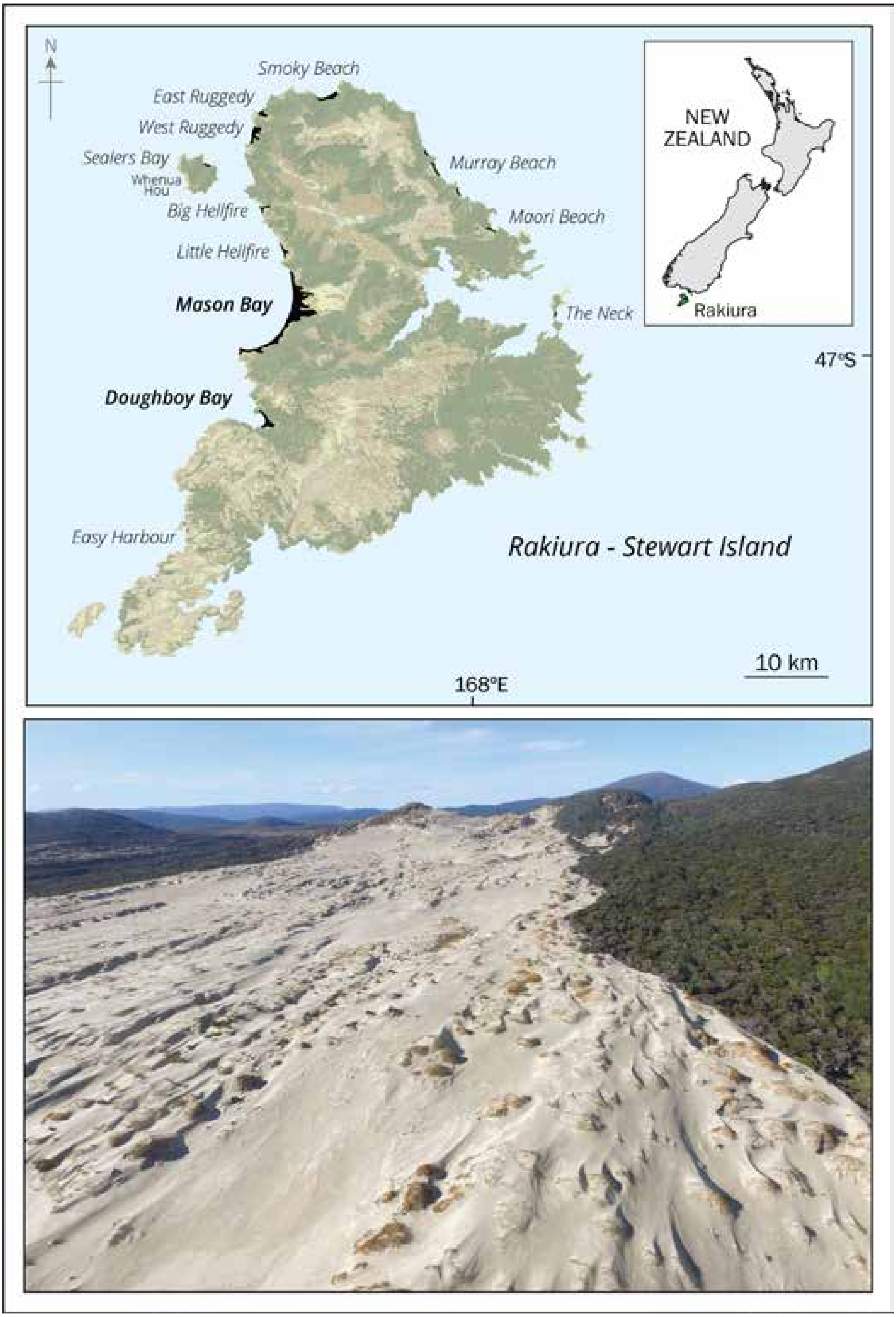

Figure 2: The location of the major dune systems (shaded black) on Rakiura and a view of a section of the central dunes in Mason Bay, looking across the island to Mt Rakeahua.

centimetres of sand deposition and accretion each year; whereas pīkao might tolerate tens of centimetres or more. Marram grass can tolerate over a metre of accretion per year, at sites with high rates of sand input; which explains how it can rapidly displace native species.

The pattern of plant communities that occupy the dune system change as patterns of sediment deposition and erosion change. This relationship is illustrated by the recent expansion of the stonefields in the central dunes of Mason Bay. These are deflation surfaces that contain a mixture of sand and gravel and a scatter of pīkao and low-lying plant species. The gravel originates from former coastal terraces, now eroded in the Central Dunes, which are still present in the northern section of Mason Bay. These deflation surfaces are areas where the balance is tipped towards erosion, or at least deposition of sand is zero or nearly so, either because sand is not entering these areas, creating a sand deficit, or they are too exposed to wind to allow sand to settle during sand transport events. The development of the marram foredune in the Central Dunes of Mason Bay, since the mid-1950s, trapped sand that would otherwise be transported into and circulated within the dune system. The pre-marram parabolic dunes in the hinterland have continued to migrate inland, leaving deflation surfaces in their wake. The largest deflation surface, locally known as the 'Great Stonefield', has formed and enlarged over the last 50 years as a result of this process (Buckley *et al*. 2016; Konlechner *et al*. 2016). There has, consequently, been a substantial increase in habitat for native plant species that favour open and stony deflation surfaces, including *Colobanthus muelleri*, and the cushion plant *Raoulia* sp. aff. *hookeri* which, on Rakiura, is only found at Mason Bay. The stonefield on the windward flanks of Big Sandhill is an example of the second type of deflation surface, where accelerated wind flow across this hill prevents the deposition of most sand.

Parabolic dunes, which have a parabolic plan form (Figure 4), are the most common dune form on the west coast of Rakiura, although at most sites their morphology is distorted as they migrate across the coastal hills. Classic parabolic forms comprise stable (trailing arms), erosional (deflation surface and erosional 'throat') and depositional elements (the depositional lobe) landform elements. These elements arise from the geomorphic processes that form and maintain the parabolic dune form, and each is distinguished by quite different rates of sand erosion and burial. Parabolic dunes evolve from blowouts or breaks in the foredune or a body of sand in the hinterland. These blowouts form gullies that elongate and widen as sand is eroded and deposited downwind and on the sides of the enlarging parabolic-shaped depression. Erosion of sand usually extends (down) to the water table (or a resistant layer of soil or rock) within the deflation surface of the dune. This eroded sand is largely deposited downwind of the deflation surface, to form the depositional lobe. Other landscapes and landforms develop as parabolic dunes migrate across a raised hinterland (climbing parabolic dunes) and occupy gullies and valleys (typical of the parabolic dunes of the northern dunes of Mason Bay); or climb over each other (imbricate parabolic dunes). Such imbricate or superimposed parabolic dunes occur north of Cavalier Creek in Mason Bay. Which form of parabolic dune develops depends largely on the direction and rate of sand supply and the topography over which the dune migrates.

Distinctive plant communities are associated with each of these landform elements – with sharp boundaries between communities over small distances, often a few metres or less, depending on variations in sand deposition, exposure to wind and soil moisture. In general, we can distinguish a flora associated with the three main elements of the long-walled parabolic dunes in Mason Bay. The sides of the parabolic dune (the so-called 'trailing arms') are stable once formed and receive low rates of sand deposition. The deflation surfaces are exposed to high wind speeds, and high rates of sand transport, but low rates of sand deposition. In contrast the depositional lobes are areas of rapid sand accumulation as well as high levels of sand abrasion. Consequently, these three environments provide very different habitats for native plants. The trailing arms usually have a high diversity of herbs, grasses and sedges; whereas, the depositional lobe may be colonised solely by pīkao. Pīkao, usually non-thrifty, and the deflation-surface species mentioned above, colonise the deflation surfaces. Over time the deflation surfaces may become more or less saturated, as water drains into them from landward, or sand enters them from the west. Wetlands, rich in species, under a canopy of *Leptocarpus similis* (jointed wire rush), are common in the former. Hence, the pattern of landforms and plant communities is intertwined.

Mason Bay is the stronghold for 31 native plant species that are listed as 'nationally threatened and at risk' (de Lange *et al*. 2018). It contains extensive areas of the native sand tussock (*Poa billardierei*) and pīkao, probably more than is found nationwide in the case of sand tussock. The population of pīkao is exceptional – the only comparable population occurs at Kaitorete Spit, Canterbury, and that population is significantly affected by rabbits and tree

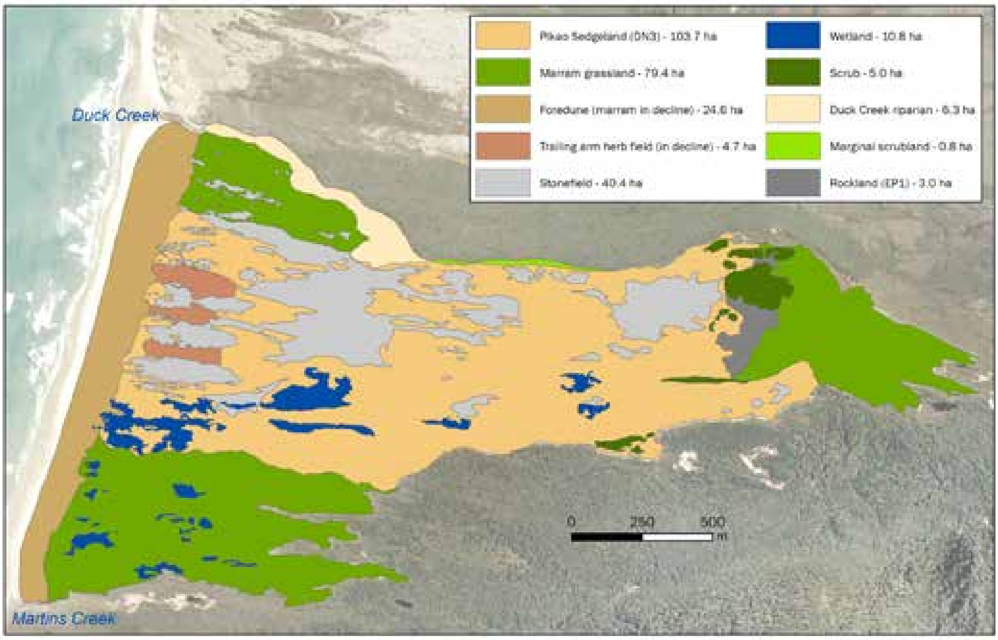

Figure 3: Landscape elements of the Central Dunes of Mason Bay (2017): foredune; long-walled parabolic dunes; the Great Stonefield; imbricate parabolic dunes and the sandy plateau; the upper stonefield; exposed rock and vegetation around Big Sandhill; and multiple nabkha and related dunes. Wetlands occupy the former deflation surfaces of parabolic dunes along the southern margin of the dune system and a riparian plant community borders Duck Creek. Pīkao is associated with most dunal sections of the landscape, but it is particularly abundant across the central section of the system.

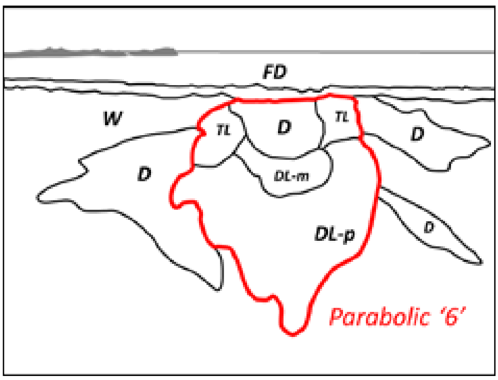

Figure 4: Geomorphic elements of 'parabolic 6' in the central dunes of Mason Bay after marram grass had been largely removed (photographed by UAV in June 2020). Elements: *FD* – eroding foredune; *D* = deflation surface; *DL-m* – eroding former (marram) depositional lobe; *DL-p* – accreting new (pīkao) depositional lobe; *TA* – trailing arm; and *W* – *Leptocarpus similis* wetlands formed in former deflation surfaces. Parabolic dunes 6 and 5 (to the north, right hand side of scene) share a trailing arm. Photo 18th June 2020.

lupin. The southern subspecies of the New Zealand Dotterel is particularly associated with Mason Bay. This bird is classified as 'Threatened: Nationally Critical' by the Department of Conservation and numbers have been declining in recent years (estimated to be 167 individual birds in 2018). Dotterel nested in the dune system in the early 1900s (Guthrie-Smith, 1914) and two nests were recently recorded in the central dunes, but they currently nest in the subalpine zone in the central ranges of Rakiura where cat predation is the main threat to nesting success. The Dotterel, along with the Banded Dotterel, flock in the deflation surfaces of the Great Stonefield, which has evolved quite recently – since 1958 – partly as a consequence of marram grass invasion (Konlechner *et al*., 2016).

In summary, the active dune systems of Rakiura comprise a mosaic of environments

Figure 5: The ‘seepage’ plant community (dashed yellow lines) comprising (a) *Triglochin striata*; (b) *Lilaeopsis novae-zelandiae*; and (c) *Isolepis cernua* (and related species) occur in a narrow zone at the apex of deflation surfaces within mobile parabolic dunes, and are closely associated with stable wetland communities (UAV image August 2017; plant photos courtesy Campbell McCusker).

and associated plant communities. The first impression may be of an eroding and degraded landscape, however, there is a recognisable arrangement of landforms and landscape elements resulting from the balance between sand depositional and sand erosion. There is a rich diversity of plants and plant communities – albeit a number of species are inconspicuous, best viewed with a hand lens – and the total biomass is low compared with other ecosystems. Pīkao and native sand tussock are widespread, and the dunes systems of Smoky Beach and Mason Bay are national strongholds for these species. Other species and plant communities are highly localised and closely associated with particular dune forms and rates of sand erosion and deposition, including the ‘seepage’ communities; a small assemblage of plants associated with damp areas in parabolic dunes (Figure 5). This exceptional biodiversity is dependent on a dynamic dune system, comprised of mobile dunes, to provide habitat and to free the native species from competition from (most) exotic plant species. The notable exception is marram grass, which has the ability to thrive in conditions of high rates of sand transport, stabilise dunes, and degrade or extirpate native plant habitat.

1.3 Tangata whenua

Māori utilised the resources of the west coast beaches and dune systems of Rakiura. Multiple archaeological sites have been discovered, photographed and recorded in the course of dune restoration operations and monitoring at Mason Bay since 2000, and during earlier archaeological work at The Gutter, at the southern end of Mason Bay. The increasing number of site reports led the Department of Conservation to commission an archaeological survey in 2015, resulting in 41 new site records (Jacomb *et al.* 2015). These comprise midden (some of them indicating prolonged occupation or frequent visits); ovens (intact and deflated); and stone tool manufacture sites. The initial analysis of the survey data concluded the archaeological landscape is of considerable significance, in that it is one of very few places that has not been extensively modified through European occupation.

A high proportion of archaeological sites are located on the world's shorelines and recent research has documented the vulnerability of these sites to coastal processes and climate change. At some sites it might be argued that marram grass and associated stable dunes be retained to protect the underlying archaeological landscape; however, the impact of marram grass on dune system dynamics and the underlying archaeological landscape is complex. Such landscapes on many temperate coasts have already been degraded as a result of marram grass invasion and the risk of degradation of the archaeological landscape does not cease after marram invasion (Hilton *et al.* 2018). Full invasion may result in site burial under stable dunes, but the risk of degradation of sites is high during the invasion process. In southern New Zealand, marram invasion has often resulted in the formation of stable foredunes, often associated with coastal progradation. Archaeological sites located close to the shoreline can be subject to either burial or erosion, or both, as marram changes the pattern of sand erosion and accumulation in the foredune zone. Further, the spatial relationship between cultural sites and the shoreline may be lost as the coast progrades (builds seawards) as marram traps sand and colonises the back beach. The impact of marram invasion can extend throughout the hinterland dune system as a result of (i) dune mobility triggered by marram grass invasion; and (ii) the development of a negative sand budget, which prevents or reduces beach sand entering the wider dune system, so that sections of the hinterland are in sand deficit, resulting in the erosion of archaeological sites.

The dynamic nature of the Mason Bay dune system poses a particular challenge to the interpretation and conservation of the archaeological landscape. Transgressive dunes advancing through this landscape may first expose, and then erode and scatter, artefacts and occupation sites. The exposure of an oven in the eroding throat of a parabolic dune, north of Duck Creek, is a good, albeit unfortunate, example. The oven was first observed, intact, in January 2010 (Figure 6a). By June 2010, just 6 months later, the oven had been eroded and the component stones and charcoal scattered downslope (Figure 6b). Other ovens have remained relatively intact where they occur on stable stony deflation surfaces. Clearly DOC and mana whenua must anticipate occasional discoveries of this type and such protocols exist for the discovery of Ko Iwi and reburial consistent with tikanga Māori. Timely reporting will help ensure that particularly important sites can be revisited by iwi and archaeologists while they are intact, and this has occurred from time to time since the commencement of dune restoration at Mason Bay in 2000.

The widespread presence and activity of Māori in the Mason Bay dunes is indicated by midden, artefacts and ovens in the contemporary active dunes. In northern New Zealand the

Figure 6: (a) An intact oven exposed by sand erosion in the throat of a parabolic dune north of Duck Creek (January 2010); and (b) deflated after 6 months (June 2010).

occupation of dune systems by Māori is associated with vegetation disturbance and phases of transgressive dune development (Coster, 1995; McGlone & Wilmshurst 1999). However, Māori occupation of the Mason Bay dunes was likely to have involved relatively few people and less frequent seasonal visits (Jacomb *et al*. 2015). Which is not to discount the possibility that the combination of drought and fire might have led to the localised disruption of the vegetation cover. The scatter of ovens on the stony deflation surfaces below Big Sandpass suggests the landscape was more wooded in the past and that some activity and occupation was geographically focused. The presence of long-dead trunks of mutton-bird scrub at places in the northern and central dunes in association with paleosols suggests a period of substrate stability and recent (ongoing) erosion. However, such paleosols are widespread in transgressive dune systems and may be equally explained as the result of spatio-temporal variations in dune development related to natural variations in climate and dune system development. That is, we can reasonably expect natural patterns of erosion and deposition associated with mobile dunes to periodically expose old soils and *in situ* vegetation. At present, all we can say is that pre-European Māori were once an important part of the dune landscape at Mason Bay.

2

Marram Grass

Marram grass and tree lupin are the main threats to most of the remaining dune systems of high conservation value on Rakiura and throughout New Zealand. Both species were introduced deliberately to stabilise and vegetate active dune systems and facilitate *Pinus radiata* afforestation along the west coast of the North Island of New Zealand. Marram has spread to almost all New Zealand dune systems, including our most remote beaches and dunes, largely by marine dispersal of rhizome. It has established in ALL dune systems in southern New Zealand, and it is often the dominant plant cover in central and southern New Zealand, except where dune systems are actively managed – namely in Fiordland and Rakiura National Parks (Hilton, 2000; Hilton, 2006). Geographic isolation has only slowed, rather than prevented, the spread of this species in southern New Zealand, where it is probably growing in optimum climatic and geomorphic conditions. We now know that no dune system in central and southern New Zealand is sufficiently isolated from coastal surface currents to avoid marram grass invasion by marine dispersal of rhizome (Konlechner, 2008). Dune systems of high conservation value must, therefore, be actively managed to conserve these values and regularly monitored to detect new invasions before secondary dispersal of rhizome or flowering occurs.

Marram grass is recognised as one of the most effective exotic plant invaders in New Zealand (Owens *et al*. 1996; Owens, 1997). Marram grass displaces native species and degrades dune ecosystem in two ways. First, by changing patterns and rates of sand transport and sand accretion and erosion, resulting in either or both the erosion and burial of native species. Secondly, by suppressing natural dune dynamism which, over times, leads to landscape stability and the development of a dense vegetation cover. Such landscapes provide habitat for opportunistic native and exotic species that rapidly displace any surviving native species. Marram was, after all, imported to stabilise active dune systems as the first step in the afforestation of the dune systems of the west coast of the North Island (McKelvey, 1999; Beattie, 2011).

Much of what we know about the biology and ecology of marram grass in New Zealand is due to work on Stewart Island and in southern New Zealand by University of Otago staff and postgraduate students. The dune systems of Rakiura National Park have provided an exceptional opportunity to study the processes and consequences of marram grass invasion, in large part because these processes are still underway; a consequence of the late introduction of the species to Rakiura. This work has occurred in parallel with the Rakiura Dune Restoration Programme and was either directly or indirectly supported by the Programme. It has examined how marram grass disperses in the sea and strands on beaches (Henshaw, 2004; Peddie, 2004; Konlechner & Hilton, 2009); controls on marram grass growth from rhizome (Konlechner *et al*. 2016); factors that restrict marram establishment on beaches (Konlechner *et al*. 2016); marram grass seed production (Lim, 2011), spatial and temporal patterns of seed production (Hilton *et al*. 2019); dispersal of seed inland by wind (Pope, 2005; McLachlan, 2014); controls on seed germination and seedling growth (ref); the development of seed banks (Konlechner & Hilton, 2010; Hilton *et al*. 2019); the dispersal of tree lupin seed by whitetail deer (Robinson, 2010); the decline of particular species as a result of marram invasion (e.g. Euphorbia glauca, Weggery, 2005); and the decline of plant communities as a result of marram invasion (Duncan, 2000). This work has also examined how marram grass responds to possible control methods (solarisation; salinity; crushing; herbicides); and how best to monitor and report the effects and effectiveness of these methods of control (for example, using foredune 'texture' to assess restoration efficacy, Konlechner *et al*. 2015).

2.1 Marram grass dispersal and invasion

Our interest in processes of marram grass dispersal were sparked by observations of marram growth from stranded rhizome on the beach at Sealers Bay on Whenua Hou, 4km west of Rakiura in 2005 (Figure 7). At the time marram was absent from Whenua Hou, present but

Figure 7: Marram grass culms developing from stranded rhizome a little above the reach of spring high tide, Sealers Bay, Codfish Island (Whenua Hou) (November 2005).

managed on Rakiura, and abundant around much of the South Island coastline. At Sealers Bay we noted marram rhizome 'growing' only a few metres above the level of spring high tide, and it was clear that the green shoots had developed from nodes on the rhizome. Similar growth was observed at Doughboy Bay, close to stranded fishing floats that had originated in Fiordland and from the West Coast of the South Island, as well as a road 'stop' sign marked 'Grey District Council'. At that point we hypothesized that marram rhizome, washed into the sea during an episode of foredune erosion, might drift south and cross Foveaux Strait, to be eventually stranded on Rakiura. It seemed a plausible idea given all Rakiura beaches contained marram grass, yet the only confirmed plantings of marram in the foredune zone took place at Kilbride, at the southern end of Mason Bay, probably in the 1930s.

Marram dispersal by drifting rhizome in the sea explains the rapid colonisation of beaches and the formation of very linear marram foredunes. We observed multiple stranding events where rhizome was deposited during storm events in a line, or zone, above the usual reach of spring high tides. In the Doughboy Bay case rhizome was eroded from a section of dune above the Doughboy River during a storm in the winter of 2007; which was subsequently deposited around the bay by a combination of nearshore currents and waves (Figure 8). The resulting strandings of rhizome produced a zone of vigorous marram growth, remarkably continuous within the bay, between the toe of the existing foredune and the line of spring high tides (Figure 9). In this way a new foredune (initially a low 'incipient' foredune) can develop from a single stranding event.

Figure 8: A zone of vigorous marram grass (left of the figure) developing from stranded rhizome, Doughboy Bay (September 2008). The rhizome was eroded below the sunlit scarp in the distance and carried into the bay by the Doughboy River, then dispersed by currents and redeposited by waves.

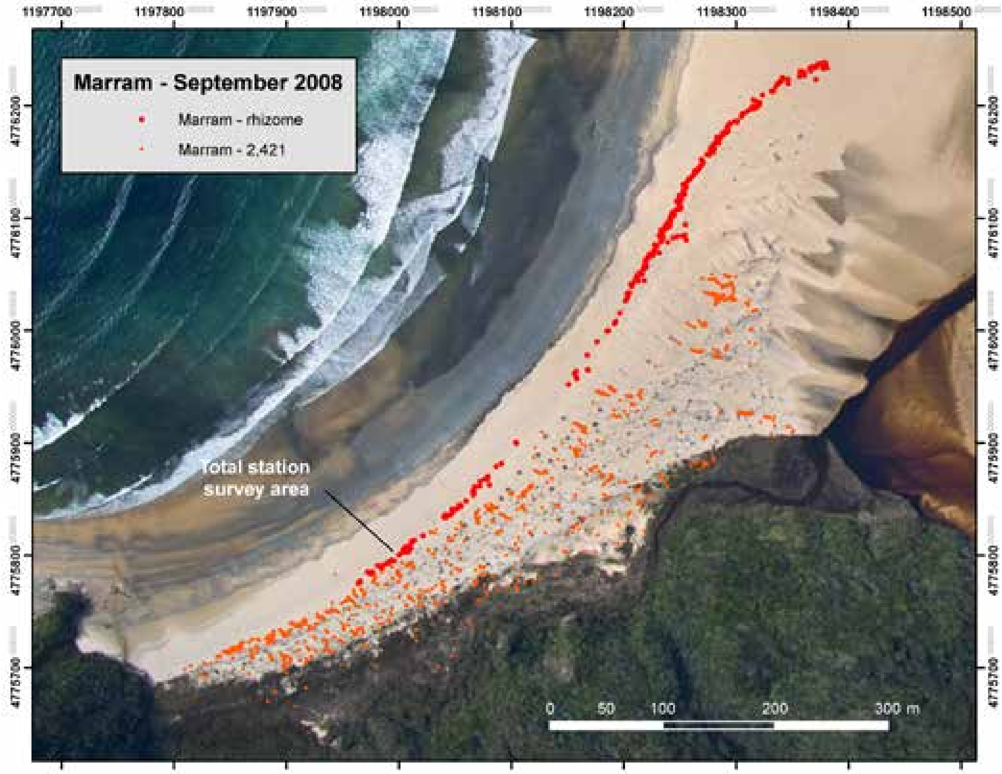

Figure 9: Marram grass regrowth from stranded rhizome (red dots) and seed (orange dots), southern dunes, Doughboy Bay (surveyed 22 September 2008).

Subsequent work in sea water tanks established that marram is able to regenerate (produce shoots from nodes) after 70 days in seawater (Konlechner & Hilton, 2009). Tolerance to seawater immersion is seasonal – rhizome is able to remain viable for longer during winter months in cooler water. Rhizome remained buoyant for up to 161 days in sea water, much longer than rhizome retained viability. Once stranded, the sprouting ability of marram grass rhizome is high (80-95%), with some variability related to source population, season, fragment length and type (vertical or horizontal) (Konlechner *et al*. 2016). Clearly there is the potential for rhizome to drift hundreds of kilometres between the source population and stranding location, with the implication that no beach in New Zealand, no matter how remote, is sufficiently isolated to avoid marram invasion. Which explains why almost every patch of sand on Rakiura, hundreds of locations in total, now contains marram grass. It also indicates that dune restoration programmes involving marram grass eradication must anticipate an indefinite period of beach and foredune surveillance after the removal of the target population.

2.2 Terrestrial dispersal and growth

Once established from rhizome, marram thrives in the upper beach environment, or the sandy margins of stream mouths; where growth is rapid under conditions of high and ongoing sand and nutrient supply. The resulting plant and dune growth may result in the plant rising above the reach of spring high tides and storm surge, or they may be washed away by subsequent storm events or during spring high tides. In this respect the type of beach on which the rhizome is stranded is very important. Rhizome stranded on a narrow beach, in front of an existing high and uniform marram foredune, has little chance of survival, although it might find a niche at the mouth of a stream that cuts through such a foredune. In comparison, marram rhizome may be stranded well inland within relatively low, and irregular pīkao foredunes, within depressions between individual pīkao dunes. The initial invasion of the Mason Bay dune systems, where the foredune zone comprised a series of pīkao nabkha (hummocky dunes formed around individual colonies of pīkao) was probably very rapid and quite extensive and may have taken place in a single storm. Marram rhizome was likely deposited tens of metres inland and well above the usual reach of spring high tides and hundreds of metres along the banks of streams during a storm event.

Invasion of the hinterland dunes, from wind-blown seed, may rapidly follow colonisation of the foredune zone. Marram plants that survive stranding and subsequent storms may flower in their second to third year. Flowering is most prolific on the stoss (windward) face of the foredune (Hilton *et al.* 2019), where seed is produced on long flower stems that stand above the marram canopy. When released the seed is readily dispersed downwind during high onshore winds, a process that is assisted by topographic acceleration and onshore steering of wind flow as onshore winds cross the beach and encounter the foredune (Hesp *et al.* 2017). Experiments at Mason Bay established that wind may transport seed 20-30 m as it falls from flower stems (Pope, 2005; McLachlan, 2014). In sparsely vegetated transgressive dune systems, the hinterland of Mason Bay, for example, individual seeds may be transported hundreds of metres and possibly kilometres during gales winds, particularly when released within, or just upwind of, deflation surfaces. Invasion of the hinterland of dune systems, over metres or kilometres, occurs after seeds are deposited by wind, often in the lee of a stone or plant, germinate and mature. Thereafter the fate of the plant is determined by the supply of sand. Partial burial stimulates vertical and horizontal rhizome development as well as providing nutrients. Conversely, plant vigour declines as burial declines and plants may become moribund when sand deposition ceases completely. Such plants can persist for many years, although flowering is curtailed.

2.3 Seed production, germinability and seed banks

In southern New Zealand marram grass produces large quantities of seed in late summer. Lim (2011) estimated seed production of 2,200 – 7,700 seeds m-2 in foredune and 17,400 – 17,800 seeds m-2 on hinterland nabkha at Mason Bay (Figure 10a & b). Seed germinability was estimated at 82 – 94 % for fresh seed; which is comparable to estimates in The Netherlands (Van der Putten, 1990). Burial treatments established that seed is sensitive to light and unlikely to germinate and emerge from depths in excess of 5cm; which in part accounts for the formation of large seed banks.

2.4 Marram grass seed banks

Persistent, long-lived, seed banks of marram grass may develop in foredunes and hinterland dunes in southern New Zealand. Seed is incorporated in the foredune (or nabkha) annually as

Figure 10: Marram grass seed production is high in (a) foredune (P6 profile line, March 2007) and (b) hinterland nabkha dune environments (1.6km inland), Mason Bay.

seed falls on the dune surface and is buried by wind-blown sand. The emergence of marram grass seedlings on eroding foredunes in Doughboy Bay, 3-5 years after the cessation of flowering (due to the commencement of aerial control operations in 1998), provided the first indication that marram grass forms seed banks (Figure 11). Long-lived seedbanks of this species have not been reported in its native European range (see Huiskes, 1979); so these observations were both surprizing and a source of concern. Extractions of viable seed from strata of known age in southern New Zealand foredunes established that, unfortunately, marram grass seed remains viable for at least 21 years in ideal conditions (Hilton *et al*. 2019). Such conditions include seed deposition in rapidly accreting foredunes and nabkha. It follows that restoration programs involving marram grass eradication should anticipate and plan for regeneration from seed banks, either from germinating in situ seed or seed dispersed downwind of an eroding dune. The Doughboy Bay work indicates that seedlings may take some years to emerge following the initial applications of herbicide (over years 1-3), during which the potential for regrowth from buds on in situ marram rhizome declines and ceases (years 2-4). Erosion of the dune surface cannot then occur until the marram grass culms have died and decomposed and/or blown away, which may extend into year 6 of a program, depending on local circumstances. Only then is the substrate exposed to erosion by wind and germination of buried seed may occur (Woodley & Hilton, 2003). These figures are estimates based on our experience of dune restoration and

Figure 11: Seedlings emerged from the seedbank in the 'Northern Dunes' in Doughboy Bay following marram grass necrosis, decomposition and erosion of the surface of the dunes (May 2006). The vertical structures are decaying remnants of marram (vertical) rhizome.

marram eradication at Doughboy Bay and Mason Bay, and will vary depending on the exposure of the site to onshore winds, the effectiveness of the marram eradication operations and other factors.

2.5 Germination success

Germination success is closely related to geomorphic context. We have relatively little information about rates or spatio-temporal patterns of marram grass recruitment in different dune environments within large transgressive dune systems – but we know that not all seed eroded from the foredune following flowering or from a seedbank will germinate. Seedlings are found on nearly all dune surfaces, except where rates of sand transport are very high or where dunes are eroding. For example, marram grass was widespread within the Central Dunes of Mason Bay when control operations commenced in 2000, as either dense areas of marram grass, isolated plants or nabkha. Three dune environments were relatively free of marram grass: (i) the eroding landward margins of the Great Stonefield (an erosional surface); (ii) the eroding throats of parabolic dunes (erosional surfaces); and (iii) the central plateau in the central section of the Central Dunes (where rates of sand deposition are high; the surface has a sparse vegetation cover and the area is exposed to very high winds). It is likely that marram seed passes through the latter landscape, given the relatively smooth surface and sparse vegetation. Seedlings have continued to emerge in all other dune environments, as a result of ether in situ germination from the seed bank, or seed transported downwind from untreated populations, but both are expected to decline with time.

Seedlings have not yet been observed downwind of the eroding Mason Bay foredune, even though the foredune is known to contain large numbers of viable seed. Approximately half the cross-sectional area of the foredune has eroded since spray operations commenced in late 2010; with erosion accelerating between 2015 and 2020 (Figures 12 & 13). It's likely that these high rates of erosion of the foredune, and downwind deposition, do not provide surfaces sufficiently stable for seeds to anchor, germinate and mature. This may change as rates of sedimentation decline, with the progressive lowering of the crest of the foredune. Moreover, the quantity and viability of seed in the upper 6m of the former foredune has been assessed, but the viability of marram grass seed in the lower 6-8m of the foredune is unknown. Seeds in these lower strata are probably in excess of 20 years old and may not be viable.

2.6 Rates and impacts of marram grass invasion

Marram has the capacity to invade active dune systems very rapidly, with the rate and pattern of invasion closely related to the geomorphology of the site. In general, the rate of invasion will be higher in more exposed (to onshore winds), sparsely vegetated, and dynamic dune systems. We know little about the early years of marram grass invasion in Mason Bay. Marram was planted at Kilbride, at the southern end of the bay some time prior to the 1940s. It probably dispersed north by rhizome sometime in the early 1950s, sometime after a substantial colony of marram had established in the Kilbride foredune. A single storm event might yield many thousands of fragments from such a foredune and it is conceivable a single storm event resulted in the erosion, dispersal and stranding of large amounts of rhizome in the northern half of Mason Bay.

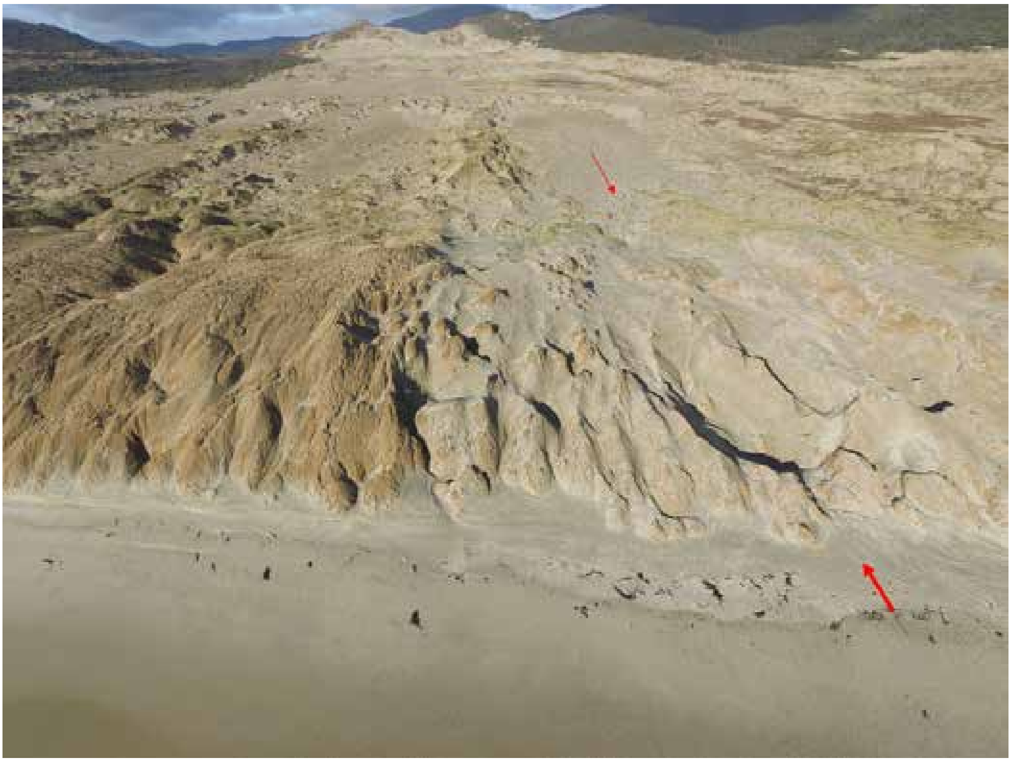

Figure 12: Oblique aerial view across the eroding foredune into Parabolic 6 (September 2016). The foredune is known to contain seed, but the high rates of sedimentation on the stoss face (erosion) and lee slopes (deposition) of the foredune may have inhibited marram recruitment. The survey line used to monitor the changing form of the foredune is indicated by the red arrows.

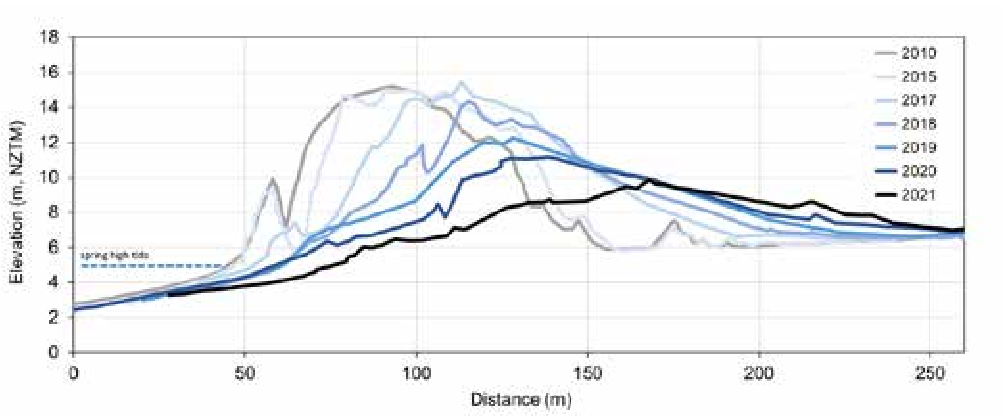

Figure 13: The foredune adjacent to Parabolic 6 has progressively eroded on the seaward side since it was first sprayed in 2010 (Hankey, 2021). To date most of the sand released has accumulated in the lee of the foredune or within the deflation surface of the adjacent parabolic dune.

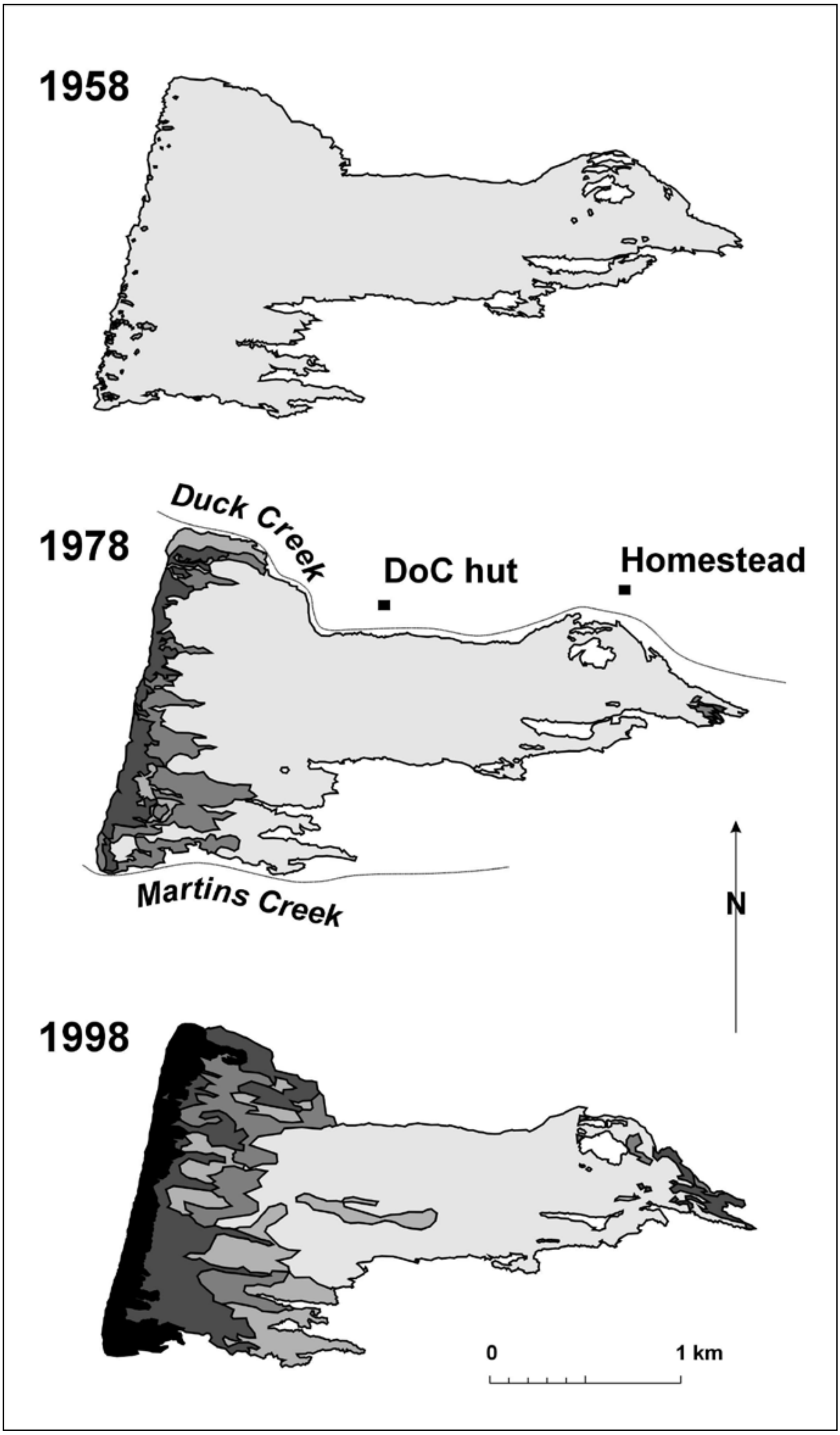

Figure 14: Distribution of marram grass in the Central Dunes, Mason Bay, 1958, 1978 and 1998. The grey tones grade from 5% cover (light grey) to 100% (black) marram grass cover.

It is difficult to be certain without better historic data. The first aerial photograph was flown in 1958; and by then the area of dense marram grass (classified as greater than 50% cover) in the Central Dunes of Mason Bay (between Duck Creek and Martins Creek) covered about 1.4ha (Figure 14); though it is likely marram grass was already widely established in the Central Dunes at lower densities. The area of dense marram increased to 74.9ha in 1998, an increase of 5,204% over a 40-year period (Jul 1998). Jul *et al*. (1999) estimated that marram grass would invade all potential marram habitat in the central dunes by (between) 2023 and 2043, were management not to occur. Fortunately, marram grass control operations commenced in 2000 before the species could expand through most of the hinterland of the dune system; although the area just north of Martins Creek (comprising 53ha) and north of Duck Creek was already moderate to dense marram at this time.

Marram has had a major impact on the landscapes of southern New Zealand coastlines. Marram invasion (or planting) was followed by the development of large and stable foredunes, often where no such foredune existed prior to marram grass (Hilton *et al*. 2019). Accretion of sand around marram grass, once stranded above the usual reach of tides, is very rapid (Hilton & Konlechner, 2011) and the subsequent transformation of the foredune zone may take just a few decades. Cockayne (1911) described the dunes behind Mason Bay beach, between Duck Creek and Martins Creek, as “low hummocks”, 2-3m high. Cockayne’s account is consistent with photographs of the back-beach taken by Edgar Williams in 1945, at Duck Creek, which show scattered nabkha formed with pīkao. A large Type 1 foredune (long, uniform foredunes, with no or minor blowouts along the seaward (stoss) face of the foredune; after Hesp, 1988) developed along this shoreline in the early 1950s. By 1958 (the first aerial photograph), multiple marram nabkha had formed between Martins and Duck Creeks within 400m of the high tide line (Figure 15). By 1978 these shadow dunes had coalesced, to form a continuous, albeit, irregular foredune. Thereafter, the morphology of the foredune became more uniform as accretion (vertical growth) continued and the foredune became more uniform alongshore (Hilton *et al*. 2006; Hart *et al*. 2012; Konlechner *et al*. 2016a). The foredune also became wider as the shoreline prograded (moved seawards). Between 1958 and 2003 the toe of the foredune (indicated by the edge of the stoss vegetation) advanced 75m, on average, across the former beach (Figure 16), and accreted by up to 12 m (Hart *et al*. 2012; Kelly, 2012; Garden, 2012). Progradation ceased in 2003, suggesting the accommodation space for this foredune was by then fully occupied (Konlechner *et al*. 2013) – further progradation was prevented by wave-forced erosion during spring high tides. The foredune maintained its overall dimensions, while continuing to accrete (Petersen *et al*. 2012; Hesp *et al*. 2017), until marram grass eradication operations (aerial) commenced over a section of foredune (P6) in December 2010.

The corollary of foredune development has been hinterland dune erosion. Foredune development since 1958 has fundamentally changed the natural character of the hinterland dunes at Mason Bay. The new foredune has prevented sand entering the hinterland of the dune system since the early 1990s. Between 1958 and 1999 approximately 9.84 x 105 m3 of sand accumulated in the foredune between Martins Creek and Duck Creek. The foredune did not prograde (advance seaward) significantly after 1999, but it did continue to accrete. Between 1999 and 2010 (when marram grass eradication operations commenced in the foredune zone)

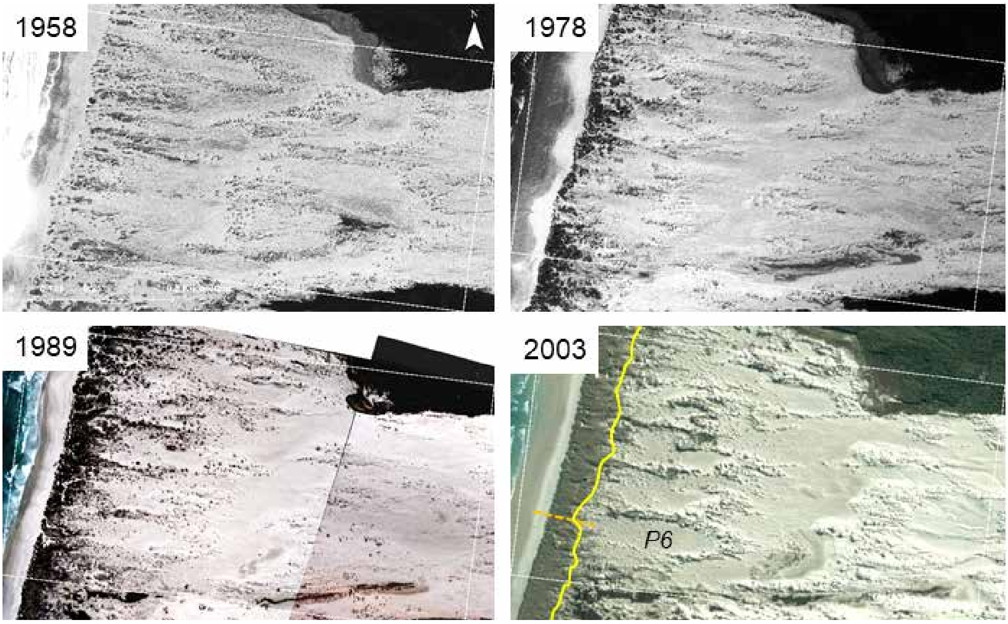

Figure 15: Marram grass invasion, foredune progradation and accretion, and associated parabolic dune development, 1958 – 2003, Central Dunes, Mason Bay. Multiple marram grass nabkha were already present in a zone within 250m of the shoreline in 1958. The 1958 shoreline (edge of foredune vegetation) is superimposed on the 2003 aerial photograph. The orange dashed line indicates the location of the survey line in Figure 13.

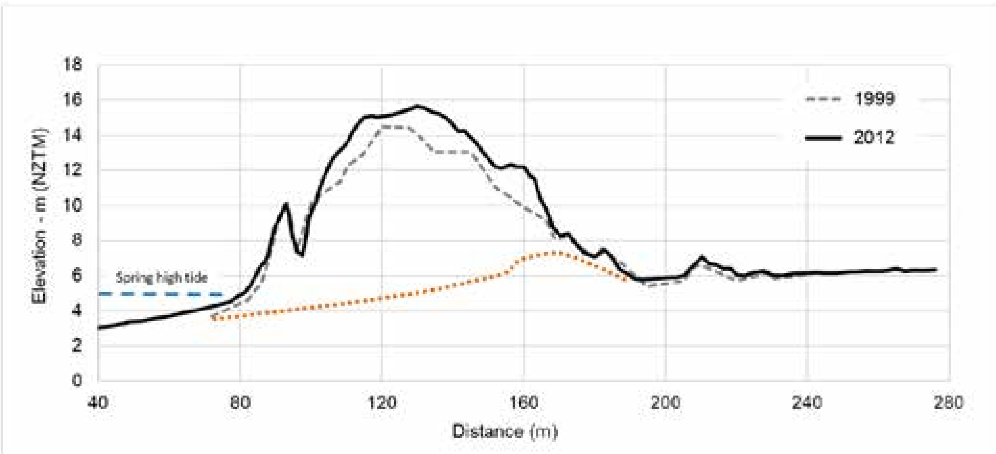

Figure 16: Surveyed cross sections (P6 Profile, Figure 12) in 1999 and 2012, when the foredune attained its maximum dimensions and seaward position. The likely location of the pre-marram profile (dashed brown line) is based on our understanding of vegetation cover and shoreline location in 1958.

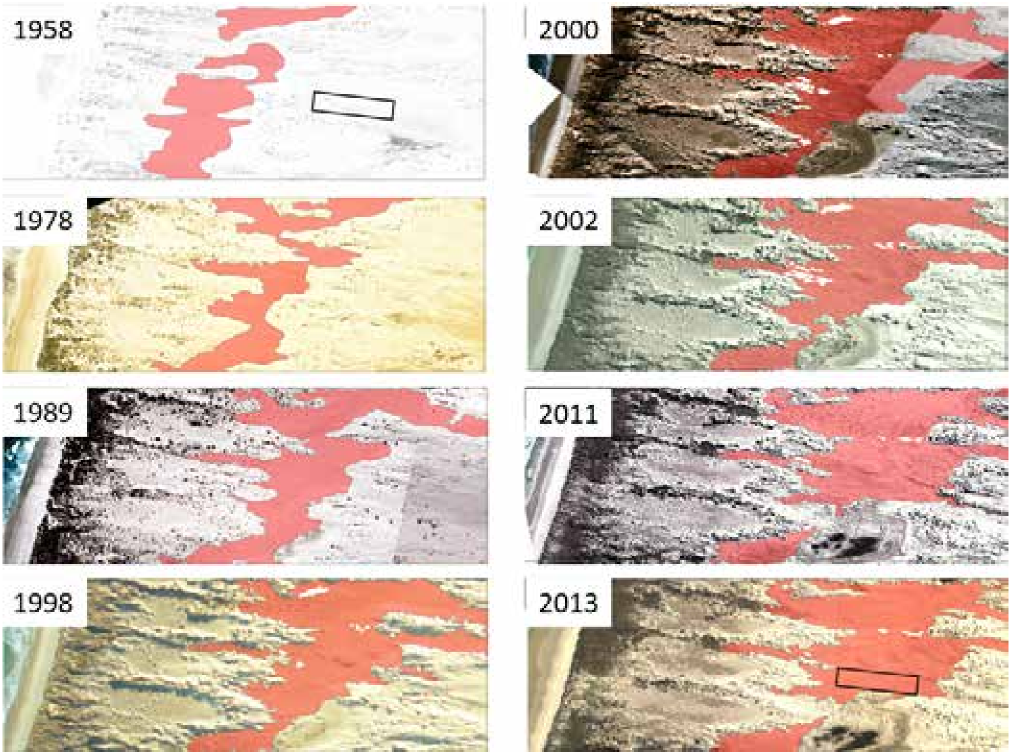

Figure 17: Habitat change associated with parabolic dune development in the central dunes (1978 to 2013). The area of deflation surface has significantly expanded since the establishment of the marram foredune in ca. 1978. Habitat in the sample rectangle (displayed in the 1958 and 2013 panels) has transitioned from completely dunal to completely stonefield (deflation surface) over this period (Table 1).

the elevation of the foredune plateau increased by up to 2.0m, primarily across the plateau and rear slopes of the foredune. This process was driven by winds transporting sand from the beach, across the stoss face of the foredune, to the foredune crest and plateau (Petersen *et al*. 2012; Hesp *et al*. 2017).

It follows that the sand trapped in the foredune never reached the hinterland of the wider dune system, which has resulted in a negative sand budget across the hinterland of the dune system. This process is seen in the expansion of what is locally known as the 'Great Stonefield' – a stony surface landward of the long-walled parabolic dunes. This stonefield did not exist in 1958 – it formed and expanded as the modern marram grass foredune developed and sand transport from the beach to the hinterland dunes declined and then ceased (Figure 17, Table 1). At the same time the dunes along the eastern margins of the stonefield eroded, causing the stonefield to progressively widen. The few historic photographs of the central dunes of Masons Bay illustrate the conversion of a relatively sparsely vegetated, dynamic, dune system, to a stable grassland over the same period (Figure 18).

In summary, marram grass disperses freely between dune systems; establishes in a wide range of beach conditions above the usual reach of spring tides; matures rapidly; produces large quantities of seed; seed is readily dispersed downwind by high-energy onshore winds

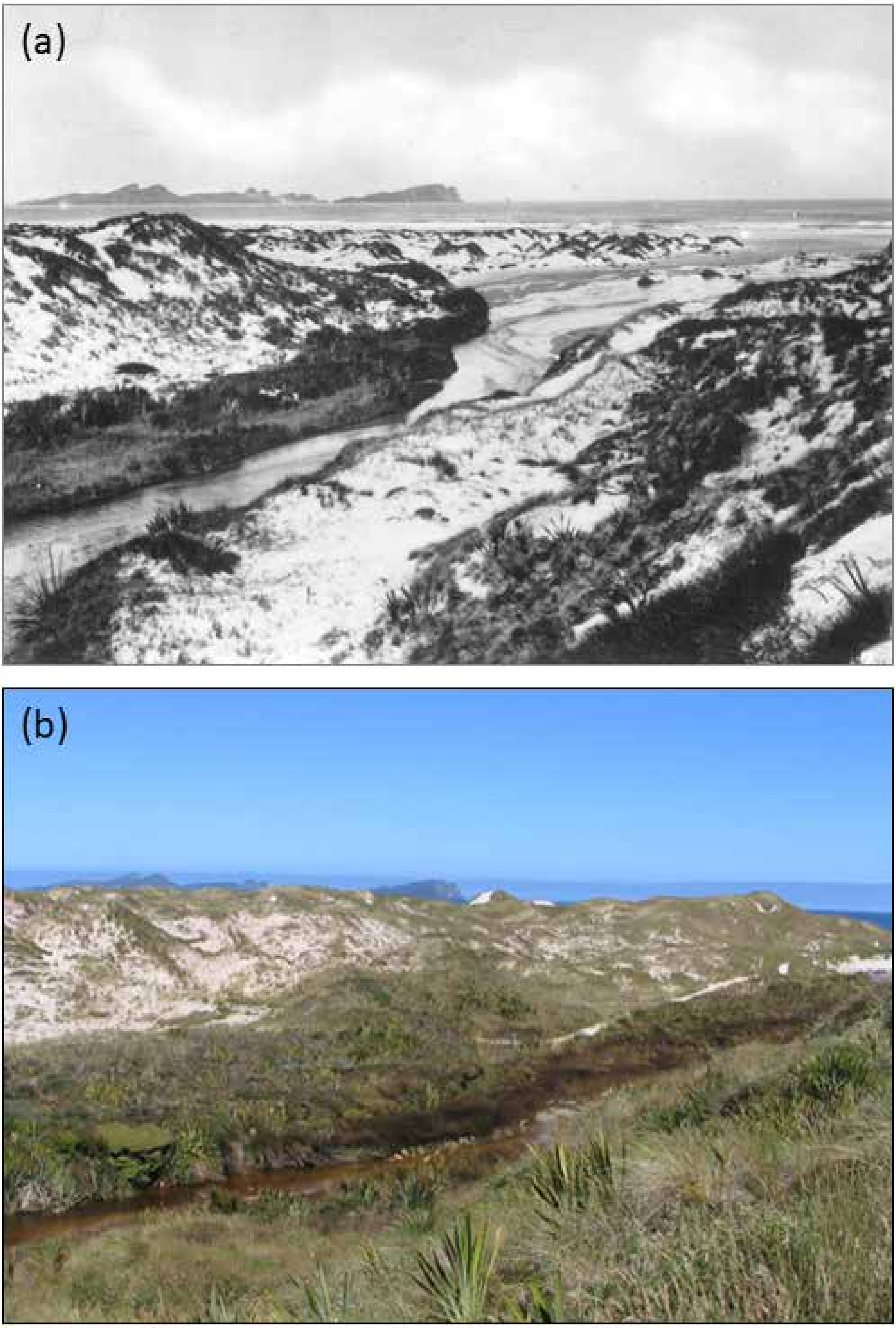

Figure 18: The first synoptic view of the foredune environment south of Duck Creek, Mason Bay (a) (G.M. Turner, 1935: Hocken Library); and (b) the current marram landscape (2005). The Earnest Islands, at the southern end of Mason Bay, are on the horizon.

(or incorporated in dunes as they accrete to form persistent seed banks); rapidly forms large and stable foredunes after a period of accelerated erosion; and fundamentally changes patterns of sand erosion, transportation and deposition in the hinterland of large dune systems, to the eventual detriment of native species. No dune system in southern New Zealand has been (or is) sufficiently isolated from coastal surface currents to avoid marram grass invasion by marine dispersal of rhizome (Konlechner, 2008). The transformation from a biodiverse natural dune landscape to a marram grassland of negligible conservation value occurs over decades. Dune systems of high conservation value must, therefore, be actively managed to conserve these values and regularly monitored to detect new invasions before secondary dispersal of rhizome or flowering occurs.

Year	Stonefield (%)
1958	0.0
1978	0.0
1989	49.2
1998	83.5
2000	90.6
2002	95.9
2011	100.0
2013+	100.0

Table 1: The transition of a section of the Mason Bay dune system, now downwind of Parabolic 5, from duneland to stonefield (deflation surface), 1958 – 2013. It is uncertain whether the current stonefield, including this area will become increasingly dunal as the former marram-associated parabolic dunes erode. The rate of erosion of these landforms appears to have slowed as pīkao replaces marram.

2.7 Synergies with tree lupin (*Lupinus arboreus*)

Tree lupin poses an additional threat to the natural character of the Mason Bay and Rakiura dunes. Lupin seed was deliberately introduced to the dunes in the Duck Creek area and the Northern Dunes of Mason Bay and now occurs throughout much of the dune system (Figure 19). The strategy for eradicating this species contains three elements: (i) delineate containment lines; (ii) destroy any plants outside of these lines during annual surveys; and (iii) eradicate marram grass to re-establish natural (high) levels of sand flux and so reduce the habitat for tree lupin, gorse and other exotic weeds. The Department has endeavoured to contain the spread of tree lupin while maintaining a programme of eradication in the central dunes. The former is difficult, since whitetail deer browse on lupin and disperse viable seed (Robinson, 2010).

There are clear synergies between marram grass and tree lupin. Marram benefits from the fixation of available nitrogen by tree lupin, a member of the legume family, while marram establishes environments – by reducing the rate of sand movement – that facilitate tree lupin spread by wind-blown seed dispersal. Marram also produces stable substrates that provide for lupin maturation. The Programme will indirectly assist in the management of non-target weed species. Farming was practiced at Mason Bay from the late 1800s until 1987, which led to the deliberate introductio n of pasture grasses and accidental introduction of some weeds associated with farming, including gorse (*Ulex europeus*). These are species of stable substrates and will continue to decline as restoration re-establishes a more dynamic landscape and higher

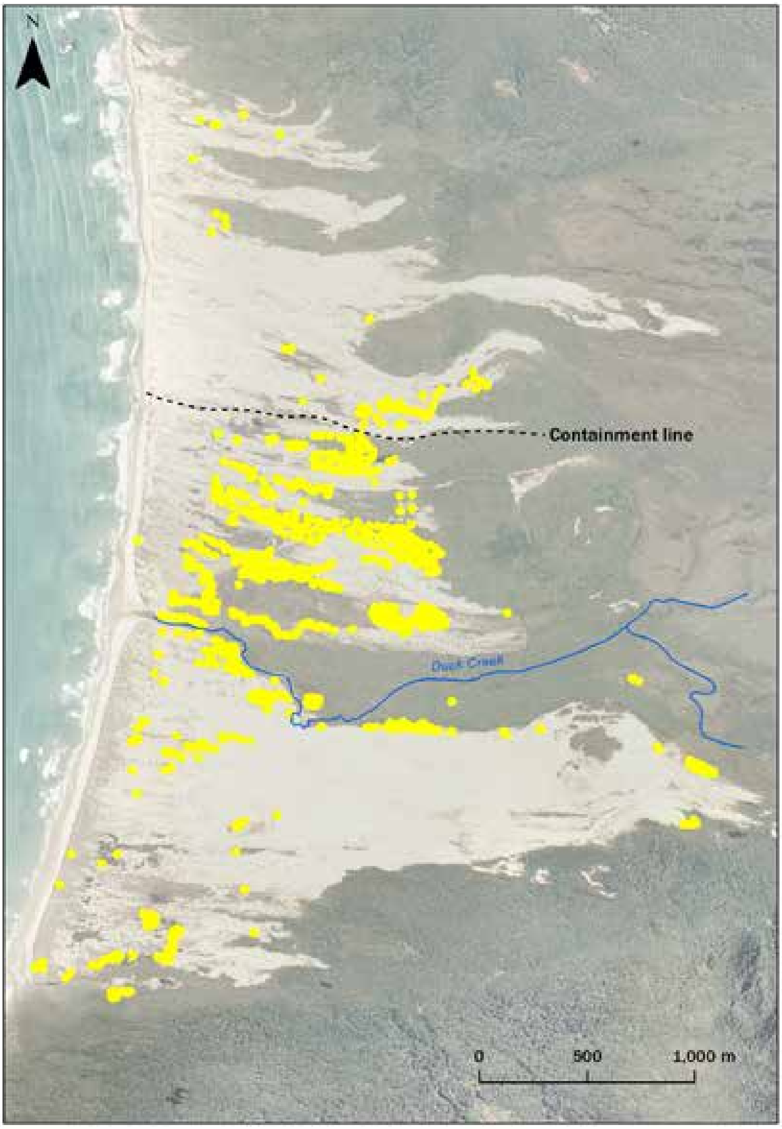

Figure 19: Recorded tree lupin sites north of Martins Creek, Mason Bay (to August 2019). The Department endeavours to remove any lupin north of the containment line and south of Duck Creek using herbicide and mechanical methods.

rates of sand transport. Hikers, hunters and (paradoxically) those Department and University staff associated with the Programme, are now the most likely vectors for the introduction of new plant species. However, it is anticipated that the restored dune systems will be relatively resilient and resistant to incursions by new species, and regeneration of existing weed species, as the system becomes more dynamic and dune mobility reduces exotic species habitat. New incursions will also be relatively obvious and more easily managed in a more natural, sparsely vegetated, landscape.

3

History and Methods of Marram Eradication

The (then) Southland Conservancy of the Department of Conservation pioneered large scale aerial eradication of marram grass using herbicide, commencing with the Doughboy Bay operations in 1999. This was the first use of helicopters to manage large areas (hectares) of marram. Other methods have been employed elsewhere, to manage small infestations, but none are useful over large areas or in isolated locations. For example, mechanical excavators and hand-weeding are used to control marram in the dunes of northern California. Notches have been cut through marram foredunes in Wales and in The Netherlands to create areas of instability and habitat that favours plants associated with a dynamic dune landscape. But these operations are relatively small scale compared to those on Rakiura, which at Mason Bay now cover 407ha. The methods employed on Rakiura have evolved and been refined, partly through good planning, partly through trial and error. Throughout the last 21 years there has been a commitment to research the biology of marram grass and adapt operations as new information becomes available.

Marram grass control operations commenced on Codfish Island (Whenua Hou), at Sealers Bay (Figure 2) in the early 1980s by the (now disestablished) Lands and Survey Department. At that time there was concern the rhizome and root mass of marram grass was hindering the nesting of the South Georgian Diving Petrel (*Pelecanoides georgicus*) at Sealers Bay. Whenua Hou contains the only New Zealand population of this species (which may be a new species). As with many petrels this species nests in burrows, but at this site these burrows are largely excavated in the face of the foredune and are, therefore, prone to inundation during storm surge events. Burrow excavation may also have been hindered by the root and rhizome system of marram grass. The initial method of marram control involved the use of 'Valpa Powder', applied as a powder and as a spray. Most of the work was subsequently carried out by staff of Fiordland National Park using the boat 'Renown'.

Early marram control on Rakiura was driven by individual rangers during a period when there was no strategy for marram control on Rakiura and little national recognition of New Zealand's dune biodiversity. After 1987 Department of Conservation staff, from the (then)

Southland Conservancy, began trials to assess the efficacy of different herbicides (including grass-selective sprays) to improve the effectiveness of marram control for use in Fiordland and at Fortrose Spit. Operations commenced on the northern beaches of Rakiura (East Ruggedy, West Ruggedy and Smoky Beach) around the same time (probably 1988). These operations were small scale compared to the current Programme, involving one or two rangers with spray knapsacks. They were, however, invaluable contributions to the long-term goal of eradicating marram grass from Rakiura, since they prevented the invasion and loss of the northern Rakiura dune systems in the two decades prior to the commencement of the current Rakiura Dune Restoration Programme in 1999.

This Programme developed from the first operations at Doughboy Bay on the 8th February 1999, with the application of the herbicide 'Gallant', across a section of the southern dunes using a Robinson-22 helicopter (Figure 20). The catalyst for this operation was work by the then Conservancy Scientist (Dr Carol West) and Technical Support Officer – weeds (Mr Brian Rance), who were concerned for the survival of *Gunnera hamiltonii* at Dougboy Bay, specifically 'Dough-girl' the last surviving (wild) female of the species.

These operations signalled the start of a new era of systematic and science-based dune restoration on Stewart Island. It launched a major commitment by the Department of Conservation to eliminate all marram and tree lupin from Rakiura National Park (then Rakiura Forest Park). It also signalled a substantial investment in understanding the ecology and geomorphology of the dune systems of Rakiura, and new approaches to the systematic monitoring of the effects

Figure 20: The first aerial operations in the southern dunes of Doughboy Bay (8th February 1999).

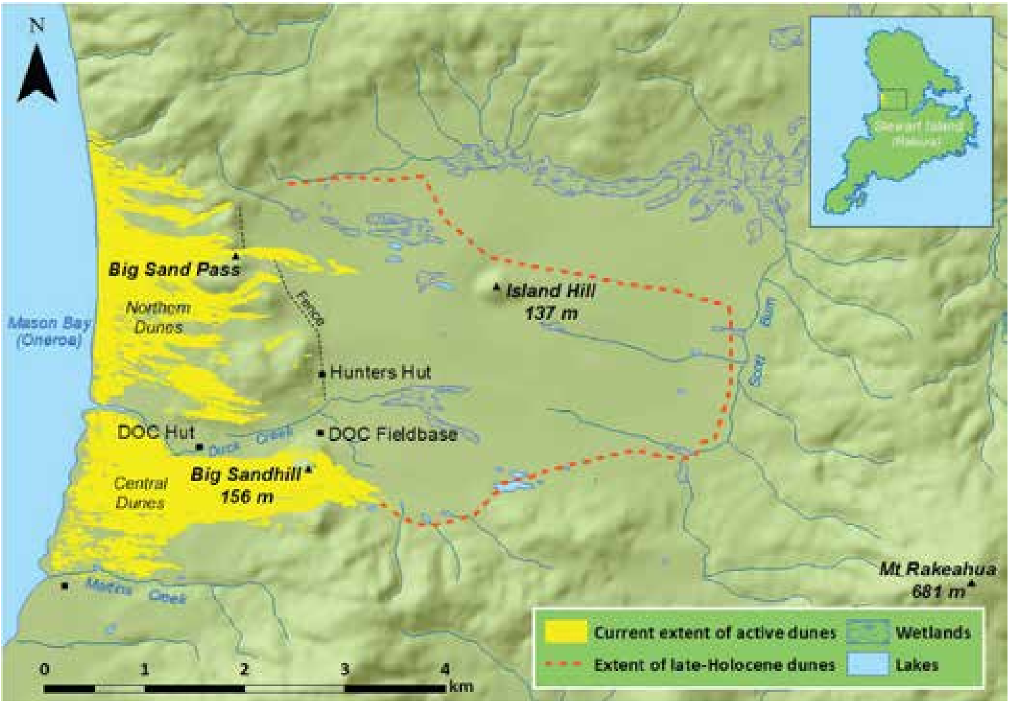

Figure 21: The active dunes of the northern section of Mason Bay, north of Martins Creek, extend up to 3.5km inland. Older, stabilised and vegetated, dunes extend a further 4-5km inland.

Figure 22: Progressive expansion of marram eradication operations between 2000 and 2020, Central Dunes and Northern Dunes, Mason Bay. See Figure 19 for the most recent coverage (spray season 2020/21). The black shading represents ground operations targeting marram grass and tree lupin and the dark grey indicates helicopter operations.

and effectiveness of the spray operations. The University of Otago was contracted, prior to the commencement of the Doughboy Bay operations, to establish baseline conditions and monitor these operations. A system of permanent transects and quadrats were established in 1997 and 1998 to record the response of the flora and dune landforms to marram de-vegetation and pīkao reintroduction. At that time the only experience of marram grass eradication was from the small-scale knapsack work on the northern beaches. Operations extended to the northern dune system in 2000 and the central dunes in 2002.

The Department was faced with a difficult choice when marram control operations commenced at Mason Bay in 2000 in the Central Dunes (Figure 21). The first operations occurred in an area of 35ha of sparsely vegetated dunes adjacent to Duck Creek and near the current tramping hut (Figure 22). This work resulted from a decision by the then Area Manager – Southern Islands, who advocated for the commencement of marram control operations at Mason Bay. The decision was made to target isolated patches of marram in a section of the central dunes where the native vegetation cover had been least affected by marram (Figure 23). An ecology-based argument might have been made for operations to commence at the coast, across the foredune or parabolic dunes. Until recently these dunes contained a flourishing population of (flowering) marram grass which released seed into the hinterland of the dune system. This process has, until recently, frustrated efforts to clear marram from the main body of the dune system. However, funding at that time was insufficient to support extensive (aerial) operations at both Doughboy Bay and Mason Bay.

When operations commenced at Mason Bay areas of continuous and dense marram were primarily within 800m of the shoreline – including the foredune and the trailing arms and depositional lobes of the adjacent parabolic dunes. It was present in large numbers, as scattered individuals and small nabkha, across the Great Stonefield, landward of the parabolic dunes, and formed larger nabkha further inland in the central dunes (Jul *et al.* 1999). These nabkha were concentrated on the inland (eastern) edge of the Great Stonefield, and in sections of the dunes between Big Sandhill and the stonefield (Figure 23). The central section of the Central Dunes – an elevated dunal area that experiences very high rates of sand deposition and/or sand flux – contained relatively low numbers of marram plants. We hypothesize that marram grass seed transported by wind probably passes through this area, because the sandy substrate is not conducive to anchoring and recruitment.

All areas of the Mason Bay dune system contained marram grass in 2000, but the characteristics of some environments resulted in somewhat slower rates of invasion. The relatively slow rate of marram invasion in the northern dunes of Mason Bay, for example, is related to the geomorphic context of these dunes. The 'northern dunes' extend 2.7km north of Duck Creek. Marram grass operations commenced in these dunes during the spray season of 2005/06. The decision to focus on certain areas of these dunes was also based on the pattern of marram grass at the time, with again the decision made to start where marram grass invasion was less advanced. However, unlike the central dunes, the area prioritised for treatment was defined by populations of dense marram to the north and south. This pattern was due to the presence of 'sand cliffs' along 1500m of shoreline, almost half the length of shoreline bordering the northern dunes, which has slowed marram seed dispersal inland. A large section of the

Above – Figure 23: Aerial oblique across the dunal hinterland of the Central Dunes towards Big Sandhill and Mt Rakeahua. At the commencement of the Programme marram grass in this area was associated with multiple nabkha (arrowed examples) formed from wind-blown seed (photo 26th January 2001). The first marram eradication operations commenced along the northern (left hand side of this scene) margins of the central dune system.
Below – Figure 24: An aerial oblique view across the sand/gravel cliffs and associated stonefields towards Big Sandpass, Northern Dunes, Mason Bay (August 2018). Marram grass seedlings emerge across this area in very low numbers because of the absence of an established foredune and windward seed source.

Figure 25: Aerial oblique view across the southern boundary of the northern dunes. Marram grass is the dominant cover south of this line (to the right of the line) and pīkao and native sand tussock is dominant north of the line (January 2011).

northern dunes is perched on top of a distinctive lithology, which comprises alternating layers of a weakly-consolidated sand facies and thin layers of angular gravels. This lithology is exposed at the coast in cliffs that increase in height from south to north (Figure 24).

This section of the Mason Bay dunes is not fronted by a foredune and the coastal margin has never held an extensive population of flowering marram grass. Consequently, there have been low rates of seed supply to the hinterland of the dune system and rates of marram invasion have been relatively low. The southern boundary of current marram grass operations in the northern dunes corresponds to the southern limit of the sand cliff lithology (Figure 25). Further south marram has formed a complex foredune and the hinterland contains large quantities of marram and lupin.

The history of expansion of marram grass operations in Mason Bay reflects the initial decisions to work across sections of the northern and central dunes where marram grass was present in relatively low densities (Figure 23). These 'low density' areas still contained large numbers of individual marram plants at the commencement of the Programme in Mason Bay, as well as areas of dense marram associated with nabkha. For example, volunteers pulled 4,712 seedlings in an area of 105ha over a 4-day period, in November 2006, in the central dunes (Figure 26). A further 1,105 mature plants were recorded in the area but were too big to pull and were left to be sprayed. Further, it took 5 years, from 2000 to 2005, to eradicate marram grass associated with some of the larger nabkha along the eastern margin of the Great Stonefield (lower right in Figure 23). Marram may have been widespread in the central dunes at that time; however, it was relatively straightforward to reduce the population of marram grass to near zero-density, and restore ecosystem function, compared to the very dense and continuous

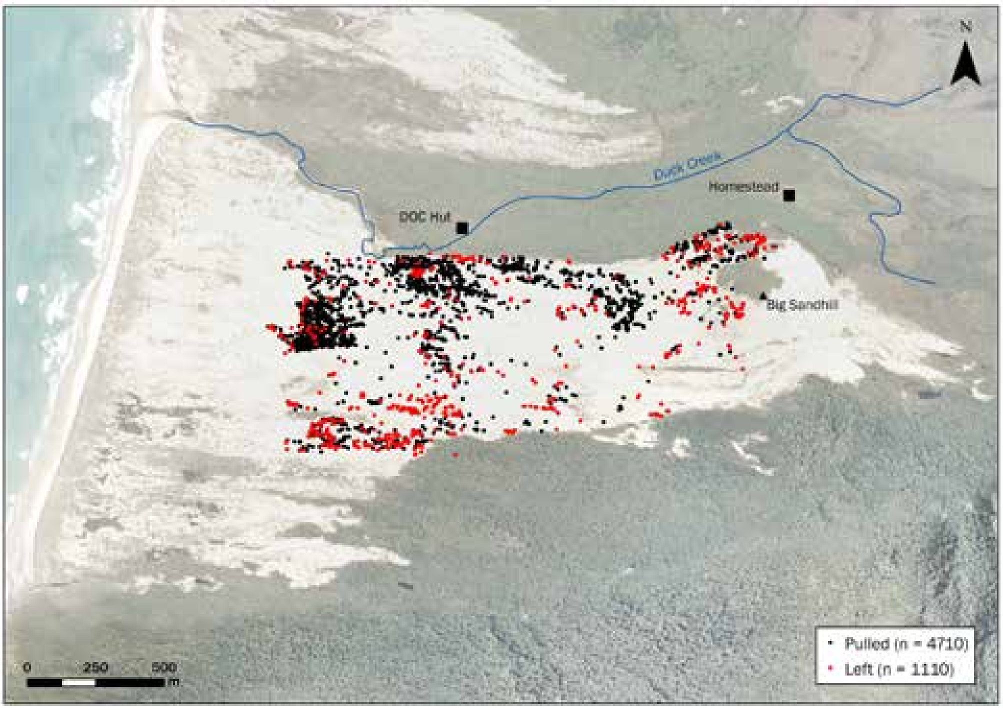

Figure 26: During a 4-day period in November 2006 volunteers located 5,820 seedlings in a 105ha section of the central dunes of Mason Bay; a demonstration of the propagule pressure of this species as seed is blown inland from mature populations.

populations of marram across the foredune and adjacent parabolic dunes. Had funding (and current knowledge) been available there are obvious advantages in treating all sections of the dune system simultaneously to avoid the problem of seed dispersal downwind from coastal marram. It has been frustrating to repeat ground operations over the Great Stonefield, over a period of 15 years, in the knowledge fresh seed would be blown into this area each autumn. In smaller dune systems a strategy of eradicating marram across shore-normal strips of land, rather than shore-parallel zones, where each strip is treated annually, could be considered.

The area of dune system and marram treated at Mason Bay has increased from 35ha in 2000 to 407ha (by the end of the 2020/21 spray season) (Figures 27 & 28). The area of marram control expanded to approximately 100ha in the second spray season (2001/02), and remained at this level until 2003, when heli-spray operations commenced in the Northern Dunes. Monitoring showed these helicopter operations were only partially successful and they ceased in 2006 when ground operations commenced in the northern dunes (Figure 22). These early heli-ops were closely monitored between 2003 and 2006, with multiple permanent quadrats used to record operational efficacy. Full or partial marram die-back occurred after each aerial application, however, the area treated was too large to ensure a sustained rate and coverage of herbicide application and plant recovery was recorded in many quadrats. Subsequent heli-ops have targeted much smaller areas (10-20ha) during each operation and employed strategies to maximise herbicide uptake; including overlap between flight lines, avoidance of adverse

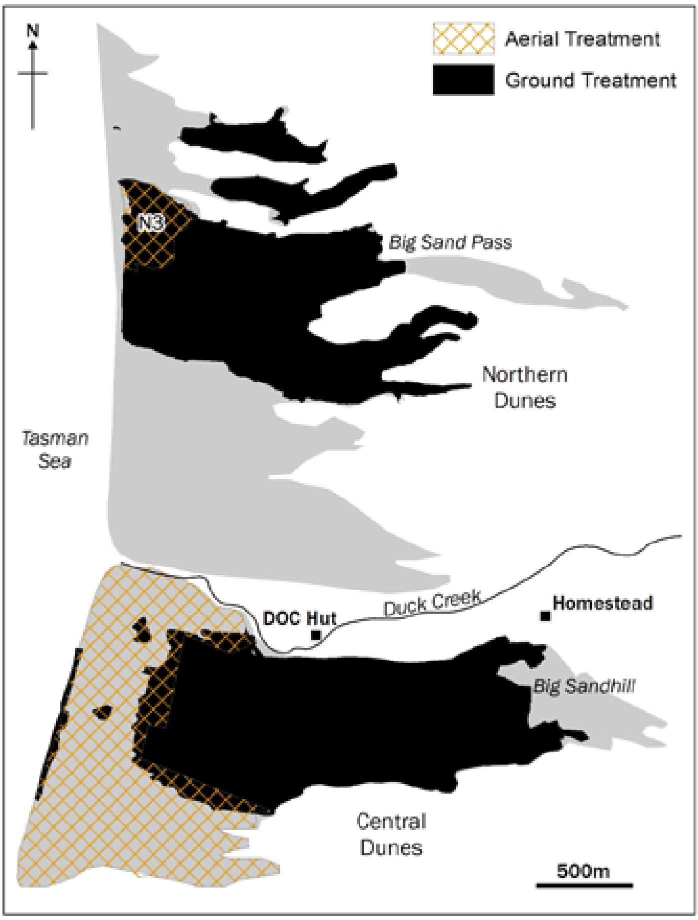

Figure 27: Cumulative marram grass eradication operations (2000 –2021). Tree lupin management covers the entire area of the Central Dunes (except the section east of Big Sandhill) and the southern half of the Northern Dunes.

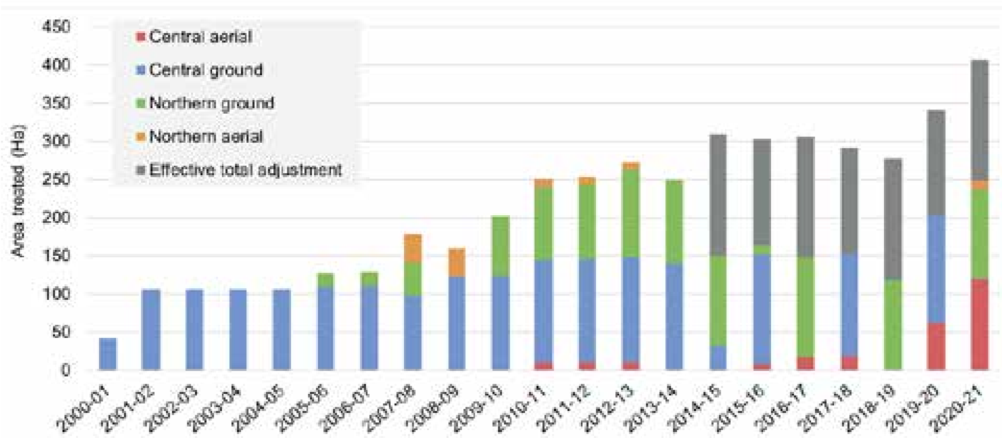

Figure 28: History of marram grass control by area in the Central and Northern Dunes, Mason Bay. Ground operations have alternated between the two dune systems since 2014, so the average annual area of marram control in each dune system (grey tone) has been added to the actual operational area to indicate the total area of management after 2014. The 2003-2006 heli-spray operations in the northern dunes are not included in this histogram.

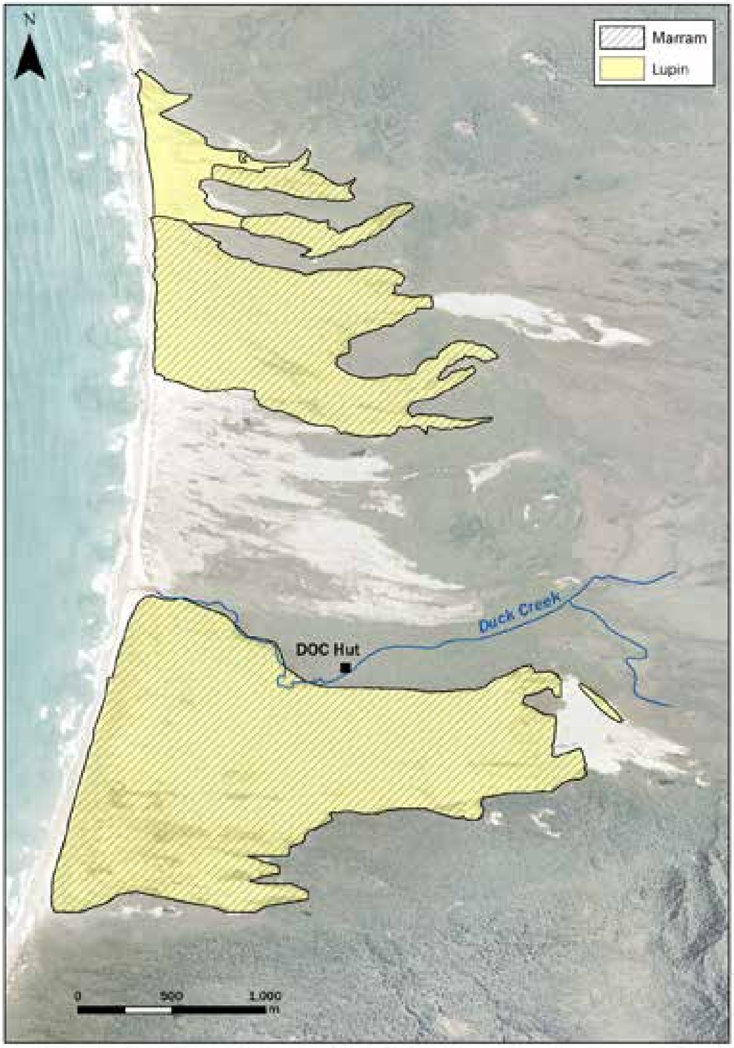

Figure 29: The current extent of annual or biennial marram grass and tree lupin operations (all methods) in the northern and central dunes, Mason Bay, 2000 – 2020.

weather, and low altitude application (pers. com. Ranger Phred Dobbins). The selection of experienced pilots has been an important factor in the recent efficacy of these operations.

Annual ground operations in the Northern Dunes expanded between 2005/06 and 2014, with a comparatively small increase since 2014, as operations extended into the northern-most management units (Figure 22). The area treated in the central dunes also increased, as operations extended into the long-walled parabolic dunes (behind the foredune), and aerial operations commenced over the foredune during the 2010/11 spray season. Recent aerial operations in the northern dunes have focused on management unit 'N3' (Figure 27), which is difficult to access using the ARGO and which originally contained a large and dense infestation of marram grass. The penultimate phase of expansion occurred in 2014 when DRAG resolved to conduct ground operations in the northern and central dunes in alternate years. This decision followed reduction of marram grass to very low densities in the two treatment areas; and monitoring that indicated the risk of plants maturing and flowering between biennial treatments, before they could be sprayed, was close to nil. This decision allowed resources to be committed to additional management units, resulting in an increase in the effective area of management (from 250ha to approximately 341ha). A significant increase in funding in 2019 allowed the expansion of heli-spray operations across the southern (Martins Creek) section of the Central Dunes in 2020/21 – the most recent expansion of operations.

These area estimates do not include tree lupin operations, which have expanded and become more systematic since 2000. In recent years 155ha of the northern and 261ha of the central dunes were grid searched for lupin (Figure 29); including 104ha outside the marram grass treatment areas. The total area of dune restoration at Mason Bay, involving marram grass and/or lupin management is, therefore, 416ha (or 68% of the total Mason Bay dune system north of Martins Creek (607ha)).

Expansion of the Programme has in part been achieved through the use of helicopters. Heli-spray operations allow the efficient treatment of large areas of dense marram. For example, an operation on the 5th March 2020 covered 31.76ha in approximately 3 hours and involved just one DOC ranger. However, helicopter operations are not a fail-safe option. It has proven difficult to achieve general necrosis of back-dune marram grass, which tends to be non-thrifty, when sprayed from a helicopter. Experience gained to date suggests an area should be sprayed three times, in consecutive years; flight lines must allow for at least 50% overlap; and flight speed and other parameters should be consistent and documented. It is likely that areas with steep terrain (with slopes in excess of 20 degrees) will need to be sprayed twice during each operation. Regardless of the heli-spray method employed it is still necessary to cover the area with ground operations, including the ARGO, for some years following the completion of aerial operations.

3.1 The response of marram grass to herbicide

Marram grass has been controlled by repeated excavation in California using excavators and spades (Pickart, 2013); solarisation (covering plants with a material that prevents photosynthesis); and by burning. None of these methods is viable in the relatively large and isolated dune systems of the west coast of Stewart Island. Herbicide is the only viable method, applied by knapsack, pump/gun carried on an ARGO all-terrain vehicle, or by a helicopter equipped with a spray boom. Both Gallant™ and Hurricane® (100g/litre haloxyfop-P-methyl) have been used by the Department. Haloxyfop-P-methyl is a grass-specific systemic herbicide. It is absorbed by the foliage and roots, and hydrolysed to haloxyfop-P, which is translocated to meristematic tissues where it inhibits growth. It is commonly used to control perennial and annual grasses in food and fodder crops for human and animal consumption. Hurricane has been used exclusively since aerial trials in the Mason Bay foredune in December 2010. These trials included Roundup Transorb™ (300L/Ha), which was ineffective, two concentrations of Gallant Ultra™ (200 & 400L/Ha); and one of Hurricane™ (400L/Ha). The response of marram grass to these treatments was assessed by counting culms and rhizome buds over the following three years in a network of 80 permanent quadrats. Hurricane is currently used in helicopter operations (at the rate of 15 L Hurricane™ plus 4 L of a surfactant (Synoil™) to 400 L water per ha of marram) and Gallant Ultra™ in knapsacks (60ml Gallant + 60ml Uptake™ + 5ml blue dye to 10 L of water). The helicopter pilot uses GPS technology to achieve a 50% overlap, flying in opposing directions, using gorse nozzles on a 10m spray boom.

The Environmental Risk Management Authority reviewed and approved a new herbicide (Crest 520) containing haloxyfop-P in 2009 (ERMA 2009). The assessment identified a low acute risk to the aquatic environment, with some uncertainty relating to a lack of chronic aquatic organism data; but that appropriate use would reduce the level of these risks to negligible. The toxicology of haloxyfop-P has been reviewed and approved for use by the European Food Safety Authority (2014).

A significant advantage of Hurricane™ is that the spray does not adversely affect native sedges, including pīkao, however, care must be taken to avoid native sand tussock or any other native grass of interest. The Mason Bay dunes probably contain the largest populations of native sand tussock in New Zealand, with a collection of other grasses of which *Deyeuxia billardierei* is specific to dunes. Aerial operations result in 'blanket' coverage of the ground surface beneath the helicopter; however, this method has only been used where sand tussock is known to be absent and where marram grass forms dense infestations in the foredune and adjacent parabolic dunes. The native grasses that do occur in these marram-dominated areas are common and widespread in the Mason Bay dune system.

Since the goal is to destabilise and essentially remove the current foredune between Duck Creek and Martins Creek, and the foredune north of Duck Creek, to restore a dynamic dune system, it is inevitable native grasses in all environments close to the shoreline will be displaced. However, the loss of native grasses in comparatively small sections of the wider dune system is not considered significant compared with the goal of restoring dune system function and dune ecology across Mason Bay. The main populations of sand tussock occur in hinterland areas of the central and northern dunes where spray has been carefully applied to discrete areas of marram grass using either an ARGO-mounted pump or knapsack. These methods allow careful targeting of marram grass which is now encountered as isolated plants. Misidentification does occur, on occasion, with small (<15cm) marram and sand tussock seedlings appearing similar in some growth conditions. However, the number of sand tussock plants sprayed is insignificant given the size of the local population and reproductive vigour of this species.

The response of marram grass to Hurricane™ is affected by a number of factors that can be controlled, including the concentration of the solution; the rate of application (amount of solution applied per hectare); the application method (e.g. droplet size); but response is also affected by the condition of the plant at the time of application (particularly antecedent stress factors such as drought); and environmental conditions on the day of spray (e.g. rainfall). Ideally, the herbicide would be applied towards the end of the growth season (February- March in southern New Zealand), when the area of foliage is at a maximum, but the plant is still actively growing; the antecedent growth conditions are positive (the plant is not stressed and the leaves fully open); spray is applied evenly across a population; and spray is applied in low wind and dry conditions. For a range of reasons, including the remote location of the site in the 'roaring forties', this is not always the case.

Two growth conditions limit the effectiveness of aerial spray operations. Very dense marram grass, typically found on the stoss face and plateau of the foredune at Mason Bay, but also present elsewhere, may prevent effective penetration of herbicide to all leaves in a culm. Secondly, marram grass growing on the stoss face of the foredune has proven particularly resilient. It is not clear whether this is simply the 'terrain effect' or a combination of this effect and plant density. The terrain effect causes a reduction in the application rate, since the herbicide falling beneath the helicopter is spread over a larger surface. In addition, the bud-bank beneath the stoss face may be significantly greater, resulting in more vigorous regeneration following initial necrosis. Resolving this problem awaits further work, however, targeting this regrowth with ARGO-based pumps has proved effective (Figure 30).

Each spray operation, regardless of the method or growth environment, should result in general leaf necrosis, expressed as yellow to brown foliage. We have found, however, that effects can take at least 6 months to appear. This has implications for monitoring operational effectiveness, which must be timed in early spring to assess leaf necrosis, and in mid to late summer to assess regeneration from the bud bank. Therefore, there is a relatively small period available to assess the effectiveness of the last spray season before the commencement of the next season's operations. In practice this problem (of delayed necrosis) is largely negated by ongoing monitoring and operational planning.

Figure 30: ARGO operations targeting marram grass regrowth on the stoss face of the foredune at Mason Bay (April 2015).

4

Monitoring Outcomes and Impacts

The Department of Conservation's commitment to monitoring and research is a distinctive attribute of the Rakiura Dune Restoration Programme. In many respects the two processes are inseparable; since routine monitoring has led to particular hypotheses and investment in targetted research; and some research involves many years of routine monitoring. Investigations of the seedbank of marram grass and of the impact of foredune erosion on downwind plant communities being good examples. Simply visiting a site on a regular basis, over 20 years, has led to discoveries or ideas that have shaped future monitoring and research priorities. Some monitoring has lasted just a few years, but we have gained valuable insights from monitoring activities that have spanned decades and we suggest it is wise to plan and establish any monitoring activity with the expectation it will continue in perpetuity – which is a challenge in a shifting dune environment. In part the advent of GPS-controlled UAV photogrammetry has reduced our dependence on pegs and other physical markers, but not entirely.

Monitoring by the University of Otago examines the efficacy of marram and tree lupin operations and reported landscape evolution resulting from these operations. The first objective has been achieved through monitoring permanent quadrats and transects and by undertaking post-operation surveys of marram numbers and locations. The latter has involved the strategic placement of survey lines, permanent quadrats and UAV flight lines to monitor changes in vegetation cover and topography. The exact methods have evolved through time as technologies have evolved and been tailored to the characteristics of each dune system.

Monitoring has been sustained since aerial operations commenced at Doughboy Bay in 1999. Programme, although now only every three years at Doughboy Bay. The continuity of this work has been critically important to the development of the dune research programme at the University of Otago, in that monitoring has provided insights into particular botanical, ecological or geomorphic processes which have been subsequently examined by staff or post-graduate students - recognition of the seed bank of marram, for example, stemmed from sustained monitoring of defined sites.

4.1 Doughboy Bay

The establishment of a network of permanent quadrats and survey lines provided a foundation for monitoring the environmental effects and effectiveness of marram grass operations at Doughboy Bay. Preparation of this network commenced in 1997, prior to the first aerial operations in February 1998 (Figure 31). Fieldwork in 1997 and 1998 provided baseline data against which to assess changes in vegetation cover and dune system morphology following the commencement of marram grass eradication operations.

Early research provided an understanding of how marram grass had modified the dune landscapes of Doughboy Bay and how they might evolve after marram grass eradication. Aerial photographs from the 1950s demonstrated that the three dune systems in Doughboy Bay had been substantially modified by marram grass; and that the landscapes associated with the prograded foredune ridge morphology of the southern and northern dunes were an artefact of marram grass invasion (Hilton *et al*. 2009). A landscape characterised by a sparse vegetation cover and sand movement (as blowouts and parabolic dunes) had been converted to one of dense vegetation cover and a series of regular foredunes. It followed that eradicating marram grass would trigger the reactivation of sand transport and a return to a more natural, dynamic landscape, characterised by transgressive dunes. We expect that the post-marram landscape will be much less vegetated and much less regular (topographically) than the densely vegetated foredune ridges that had evolved in conjunction with marram grass. Removing marram grass has initiated a return to transgressive dune forms, particularly parabolic dunes. Consequently, the overall dimensions of the northern and southern dune systems should decline, since marram grass invasion had forced seawards (progradation) and barrier elongation. Eradicating marram grass should reverse this process, resulting in smaller and more dynamic dune barriers.

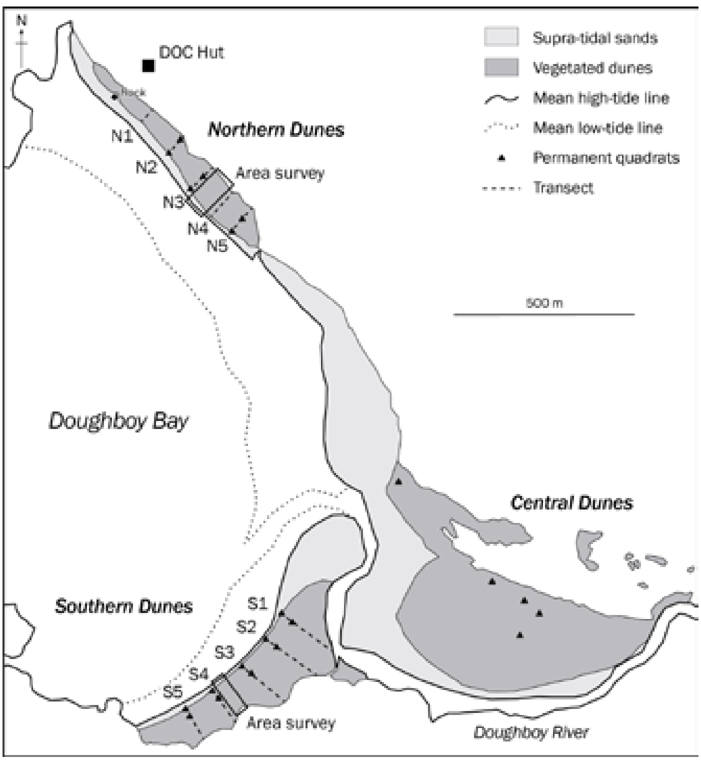

Figure 31: Shore-normal transects and permanent quadrats established in 1997 and 1998 to monitor the effects and effectiveness of the Doughboy Bay marram grass operations.

The results of routine monitoring at Doughboy Bay, undertaken annually between 1998 and 2009, and every second or third year since 2011, provided significant insights into aspects of the biology of marram grass. These included the potential for sustained and unexpected regeneration of marram grass from the seed bank and the 'bud bank'; the (slow) rate of substrate erosion and landscape change following marram grass eradication after total marram necrosis; and the rapid growth of pīkao nabkha from plantings. Two 'area' surveys in Doughboy Bay, one in each of the southern and northern dunes, proved particularly illuminating. This work commenced with the general goal of monitoring landscape and vegetation change following marram grass eradication. These rectangular-shaped areas, each 50x150m, extend across a section of the barrier (comprising a section of the inland 'pre-marram grass' landscape; the marram grass foredune ridges; and the intertidal beach). Work at each of these sites involved 6-8 hours of surveying using a Leica total station, with the goal of surveying 1000 – 1500 xyz points each visit. Points were coded to record the location of individual plants/species (and seedlings); relevant environmental features (including the edge of the vegetation line and the line of the last high tide); as well as points surveyed to capture the general topography. The margins of the 'scarp' population of G. hamiltonii were included in the northern dunes survey area, to monitor the proximity of the reactivated dune system to this species and report the risk of burial.

Data from these two 'area surveys' provided new insights into the rate of change of a prograded foredune barrier (the southern and northern dunes) following general marram grass necrosis. As reported above we observed a number of processes related to marram grass that delayed dune system erosion and development by 4-5 years after the first application of herbicide. For example, the area data provided the first unequivocal evidence that marram grass forms persistent seed banks in accreting foredunes (Hilton *et al*. 2019). This understanding developed as we observed and surveyed (annually), to approximately 1cm accuracy, individual seedlings (Figure 32). These seedlings were sprayed during the following summer spray season by the Department of Conservation, but a new cohort was surveyed 12 months later. This data also captured patterns of secondary seed dispersal, resulting from the erosion and downwind dispersal of a section of the seed bank, and the emergence (and decline) of gorse seedlings. These area surveys, in conjunction with anemometer deployments and topographic analysis, demonstrated that sand transport through the 'northern dunes' is primarily shore-parallel, west to east; such that the risk of burial of the *Gunnera* 'population' at this site, following marram grass eradication, is low.

4.2 Mason Bay

Monitoring of environmental change and operational outcomes at Mason Bay also commenced prior to operations and has developed in parallel with Department operations as the Programme evolved. Monitoring has focused on the efficacy of particular operations; the response of marram grass to particular herbicides and application methods; and the rates and patterns of landscape change in different environments. Three examples of this work are examined below.

The first involved the installation of a large number of marked quadrats in 2000 in the northern and central dunes to determine the effectiveness of marram grass eradication

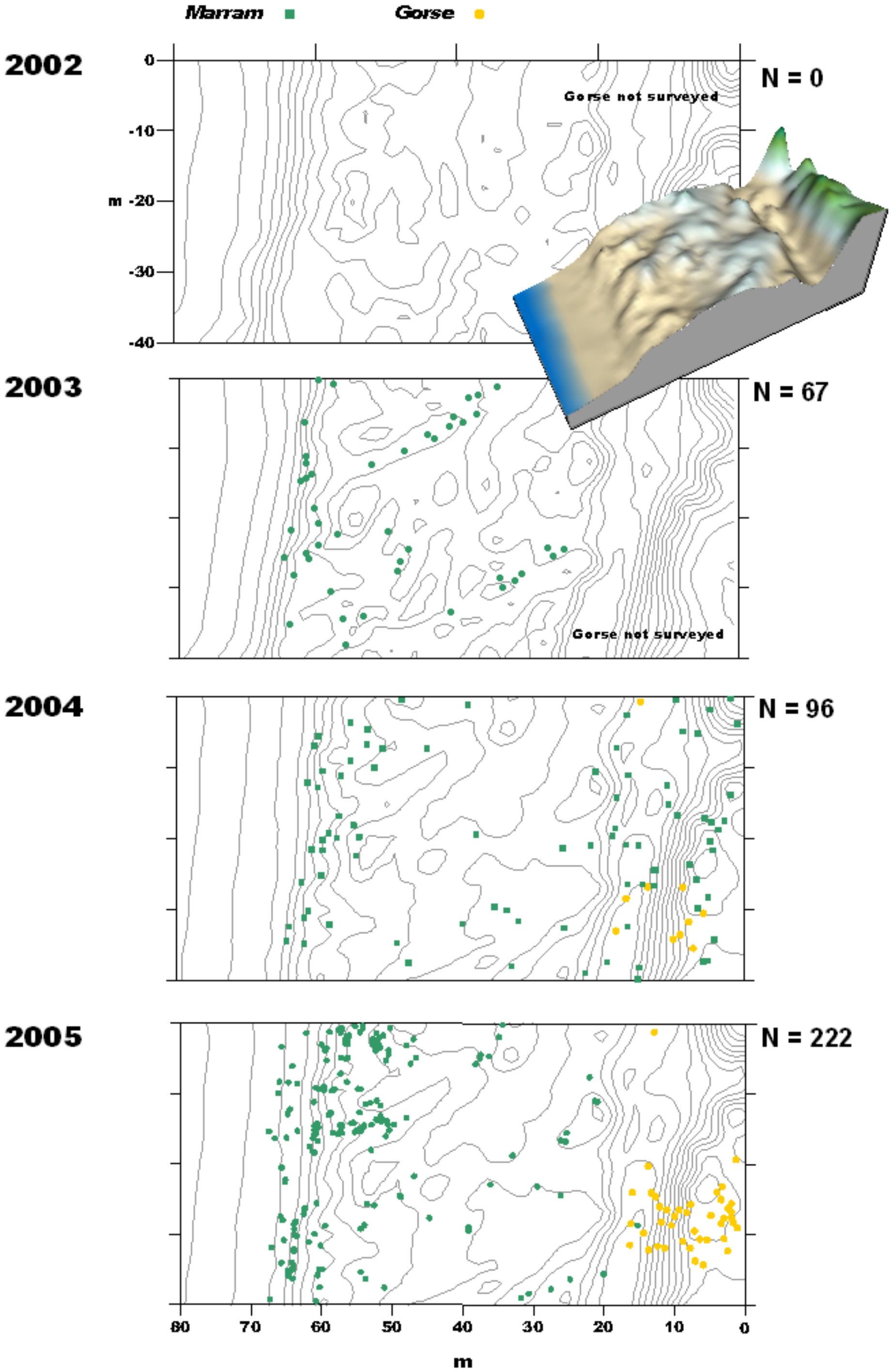

Figure 32: Marram grass seedlings first emerged in the area survey in the Southern Dunes in 2003, four years after marram grass was first sprayed, and following erosion of the surface by wind. The persistent seed bank continued to fuel regeneration as seed was exposed following further erosion. Gorse seedlings emerged in 2004, but these have struggled to cope with increasing rates of sand transport.

operations, including ground and aerial operations. These quadrats were initially marked by white PVC tube and later by fibreglass poles labelled with etched cattle ear-tags. They were visited annually, usually in August and September, and species diversity and cover recorded. The number of marram grass culms in each plot was counted and the proportion of green, yellow-green (stressed) and brown foliage recorded. The cover and condition of native species was also recorded. The quadrats in the northern dunes were maintained between 2003 and 2008, in part to determine the effectiveness of a large scale heli-spray trial, which covered a large area of the northern dunes between 2004 and 2006. These operations were discontinued when the data gathered indicated that herbicide coverage in successive years was not sufficient to result in complete marram grass necrosis. A proportion of foliage experienced necrosis after the first application, but the rate of application of herbicide in the second year was not sufficient to result in total necrosis. Since 2010 helicopter operations have largely focused on smaller areas in the foredune environment in the Central Dunes and flown to achieve at least 50% overlap in herbicide coverage.

A second network of quadrats and transects were established in four 2-Ha sections of the foredune in 2010 to assess the efficacy of four herbicides – Roundup™ (300l/Ha); Gallant Ultra™ (200 and 400 L/Ha); and Hurricane™ (400L/Ha). A fifth, adjacent area, a pseudo-control, which received no treatment, was also monitored (Figure 33). Work entailed annual surveys of marram grass vigour between 2010 and 2015; morphological survey along transects to record spatial and temporal patterns of erosion and deposition; and excavation and survey

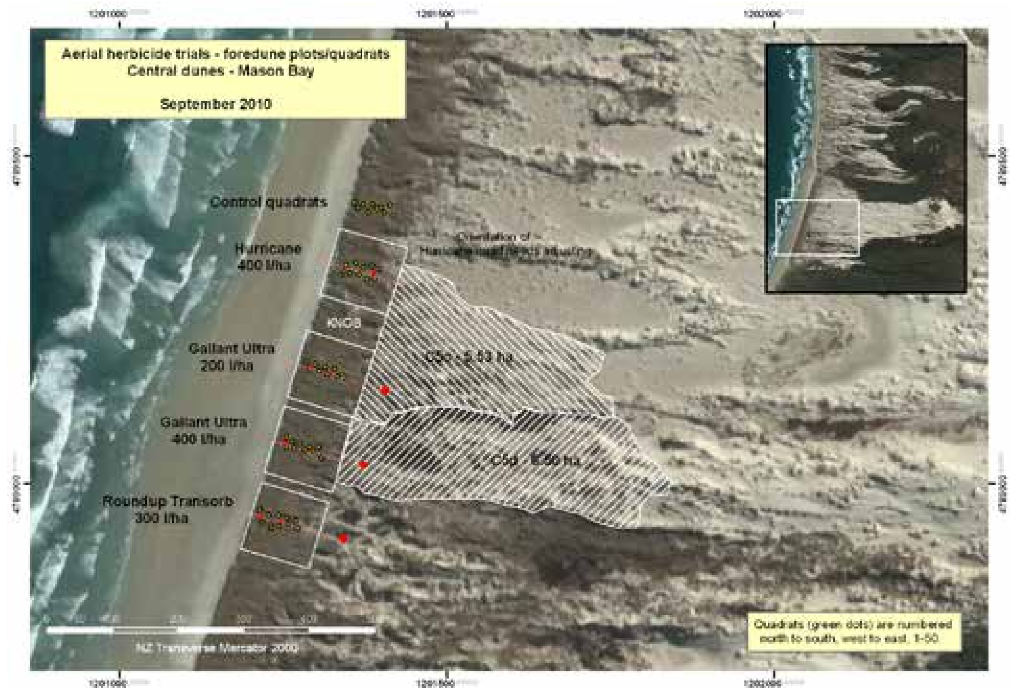

Figure 33: Foredune herbicide trial plots, survey transects and bud-assessment plots (2010). P6 profile is through the centre of the Hurricane 400l/Ha treatment area.

Figure 34: Marram grass bud survey, Mason Bay foredune (December 2011).

of the marram grass bud-bank (Figure 34). This work confirmed Hurricane™ as the preferred herbicide. It also revealed the high potential for regeneration of marram grass from the rhizome bud-bank. The excavations and bud counts established that 1 cubic metre of sand on the plateau of the Mason Bay foredune might contain in excess of 1,100 dormant buds. Vigorous and extensive regeneration of marram grass from these buds can be expected for at least three years following the initial application of herbicide, as vertical rhizomes and tillers emerge from buds attached to rhizome. Emergence occurs from buds within 1m of the surface.

The pattern and diversity of flora and fauna of the Mason Bay dune system is closely associated with geomorphic processes of landscape development, which is in turn is related to the distribution of primary plant colonisers (pīkao and marram grass). The morphology and stability of the current foredune north of Martins Creek is entirely an artefact of marram colonisation.

Environmental monitoring at Mason Bay has focused on the consequences of removing marram from the massive foredune between Duck Creek and Martin's Creek. We expected the foredune and adjacent parabolic dunes, landforms that developed in conjunction with marram grass, would be replaced by a less regular landscape of pīkao-related nabkha. We were unsure whether operations in this coastal zone would result in sand accumulation in the Great Stonefield, with a concomitant transition from a stony deflation surface, with a sparse vegetation cover, to a dune topography. This area comprised rolling pīkao dunes prior to the arrival of marram grass and the deflation surface of the Stonefield developed as a result of marram grass invasion and foredune formation. However, any change in vegetation cover might adversely impact the population of New Zealand Dotterel that flock in the stonefield and is therefore a question of interest; albeit, whatever native cover evolves, will be significantly less dense than the inevitable marram grass cover in the absence of dune restoration.

Monitoring in recent years has included a focus on the geomorphic and botanical development of the deflation surfaces to help resolve this question. Our approach has involved regular UAV survey of a section of stonefield downwind of Parabolic 6 (which is

Figure 35: UAV survey and plant monitoring plots, Central Dunes, Mason Bay (UAV images 11 November 2018).

itself downwind of the most rapidly eroding section of foredune) and the establishment and monitoring of six clusters of quadrats in the deflation basins of parabolic dunes 4-6 (Figure 35). Annual surveys using total stations or RTK-GPS show that the rate of foredune erosion is increasing, but it appears that most of the sand released from the foredune is being trapped by native species in the deflation surfaces of the parabolic dunes (Figure 13). At the same time, pīkao has recolonised sections of the former marram grass-dominated parabolic dunes, including the depositional lobes (Figures 4 & 36), where marram grass has been eradicated. The depositional lobes of these parabolic dunes have partially eroded, however, much of the sand released as a result of marram control has been captured by pīkao growing downwind (Figures 4 & 13). Hankey (2021) estimates that just 2% of the sand eroded from the foredune between 2015 and 2020 has left the P6 foredune-parabolic dune system.

The Great Stonefield does not appear to have become more dunal (and less 'stoney') as a consequence of foredune and parabolic dune erosion over the last decade. The surface of the stonefield may not favour the accumulation of sand, either because there is too little sand entering this part of the dune system, or because sand does not accumulate. The stonefield is at least partly a fluvial landscape, with recent drone imagery indicating there are numerous ephemeral surface flow channels which are active during heavy rainfall events. The surface of the stonefield slopes landward and is exposed to relatively high wind speeds beyond the lee effect of the parabolic dunes. That is, sand transported into the stonefield, from the parabolic

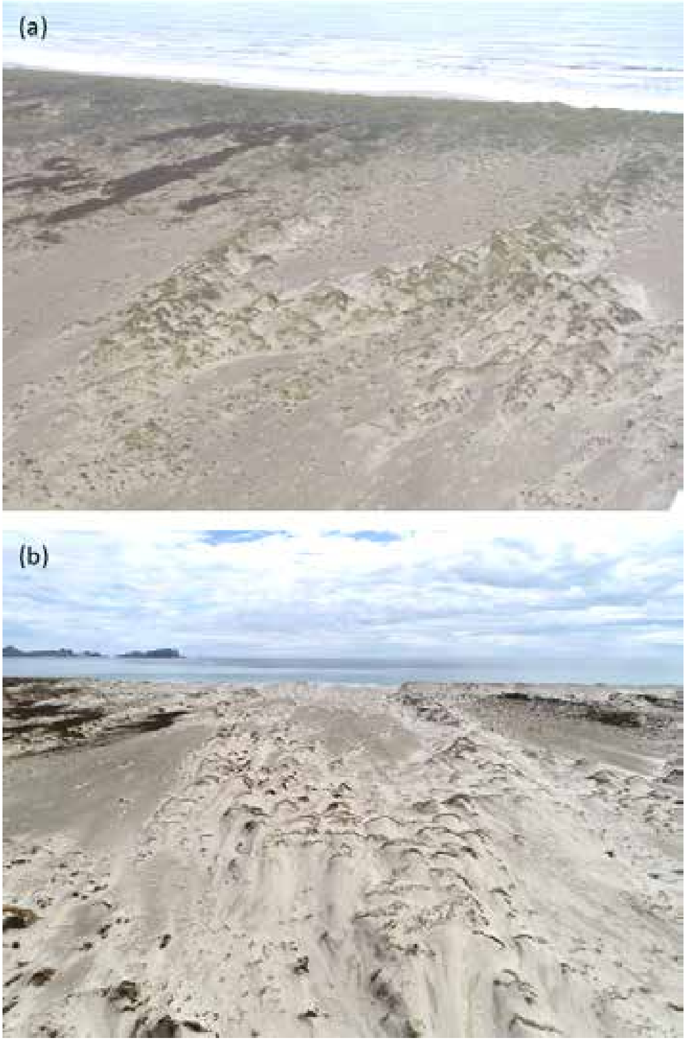

Figure 36: Prior to the commencement of the Dune Restoration Programme the trailing arms and depositional lobe of 'Parabolic 6' was dominated by marram grass, although some pīkao persisted in the deflation surface (a) (Photo: March 2007). Pīkao is now thriving across the depositional lobe and in the lee of the foredune (b) (October 2021), nourished by sand and nutrients released from the former marram dunes.

dunes, may pass through the stonefield. In addition, a significant quantity of sand is blown back into the parabolic dunes by winds from the northeast, which may also prevent or slow the development of pīkao nabkha on the stonefield.

UAV surveys of the Great Stonefield, foredune morphology and the morphology and vegetation cover of the parabolic dunes, are likely to be ongoing for some years while these questions are resolved. At present the evidence points to the current parabolic dune landscape being replaced by relatively low, undulating pīkao dunes, formed from sand blown from the eroding foredune; a landward shift in shoreline position as the foredune erodes; and relatively little change to the character of the Great Stonefield, at least over the medium term (decades).

5

Reasons for Success

5.1 Measuring success

The success of the Rakiura Dune Restoration Programme will ultimately be celebrated when marram grass is eradicated from Rakiura; a dynamic dune landscapes (characterised by active, transgressive dune forms) is re-established in areas previously dominated by marram; and the pre-marram diversity of habitats and native species is restored. Over the medium term (decades) this should comprise the progressive decline of marram grass cover (to zero) across all Rakiura dune systems; the eradication of all regeneration; and the eventual depletion of the marram seed and bud bank.

In the short term, years, success is not equivalent to 'eradication', rather the re-establishment of ecosystem and dune system function. Eradication will be achieved if operations are sustained and operational coverage is systematically managed to identify and deal with regrowth and recolonization as it occurs. In this respect the eradication of marram grass (and tree lupin) is no different from programs to eradicate rodents on offshore islands, where spatial coverage is achieved using GPS technologies. The key difference between pest animal and marram eradication operations is the potential regeneration of marram from the seed and bud bank; the extent of marram; and the partial and progressive treatment of the marram population.

The Department of Conservation has already, over the last three decades, restored or conserved ecosystem function over most Rakiura dune systems – including Doughboy Bay; Easy Harbour; large areas of the Northern and Central Dunes in Mason Bay; Sealers Bay on Whenua hou; the remaining dune systems of the north and west coast of Rakiura (Little Hellfire, Big Hellfire, West Ruggedy, East Ruggedy and Smoky Beaches); and Murray and Maori Beaches on the east coast of Rakiura. The Programme has not yet extended to The Neck and several other small beaches on the east coast of Rakiura.

The area over which pīkao is the primary colonizing species is a useful indicator of the success of dune restoration, since it is an indicator of landscape dynamism and habitat diversity (Figure 37). Pīkao has also been extensively displaced by marram grass. At Mason Bay pīkao is absent or in low densities in large sections of the dune system – including the foredune north of Martins Creek; the coastal parabolic dunes; and the hinterland north of Martins Creek. These are areas where marram was well established at the commencement of the Programme in 2000.

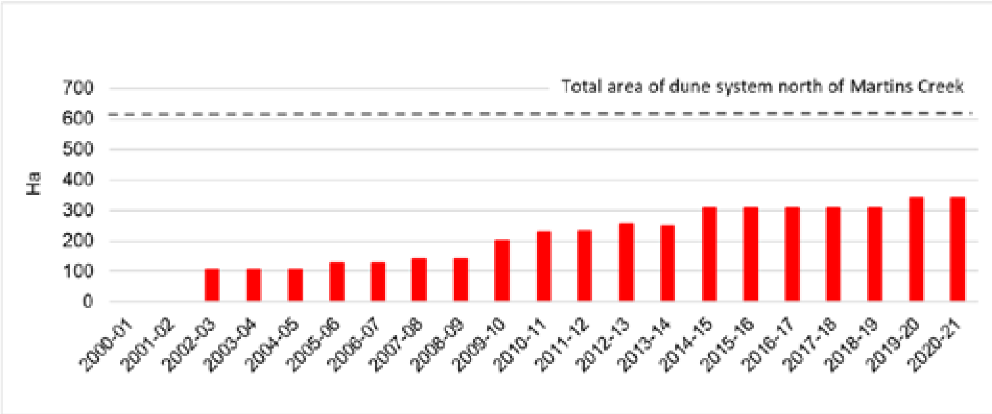

Figure 37: The area of restored pīkao habitat, Mason Bay, 2000-2021. The dashed line indicates the total area of the dune system north of Martins Creek.

The area of restored pīkao habitat, areas where marram grass has been eradicated, or reduced to scattered seedlings, and pīkao has reestablished, increased from 0 in 2000, to 106ha in 2003, to 341ha in 2019.

The experience gained by the Department at Doughboy Bay, from 1998-2000, was critical to the decision to expand operations to the much larger Mason Bay dune system. At this site the Department has successfully transformed stable, marram-dominated, dune systems to dune systems characterised by sand movement with extensive populations of pīkao and native sand tussock (Figures 38, 39 & 40). During the 1980s and 1990s Doughboy Bay was considered by botanists to be too difficult to restore, however, the combination of agricultural heli- and ground-spray technologies and grass-specific herbicides has allowed the selective removal of marram grass and the reintroduction of pīkao. Just one pīkao plant was present in the 7ha section of the southern dunes associated with marram grass in 1997, although moribund individuals were still present on the old pre-marram section of the barrier. Following the demise of the marram cover pīkao was planted in the southern and northern dune systems, however, native sand tussock re-established naturally (in the northern dunes) from remaining plants (and possibly a seed bank).

The success of the Rakiura Dune Restoration Programme, whether measured as the decline in area of the target species at particular sites, or the recovery of native species, can be attributed to several factors, which are discussed in the following sections. These include the strategic approach adopted by the Department; sustained funding and annual field operations; innovations in chemical selection and application; commitment to monitoring; and the establishment of a sustained research relationship with the University of Otago; ongoing review and adaptive management of goals and operations via a technical advisory group; and (not least) the commitment of Department rangers and volunteers to the Programme. This commitment has been critical during two phases of the Programme – the low-level knapsack work during the 1980s and 1990s – which was timely in preventing the spread of marram in the northern dunes systems of Rakiura – and the current form of the Programme which commenced with the Doughboy operations in 1999.

Figure 38: Aerial oblique views of the southern dunes, Doughboy Bay (February 1998 and October 2017).

Figure 39: Comparison of a section of the southern dunes, Doughboy Bay (February 1998 and January 2011).

Figure 40: Comparison of 1999 and 2011 images of a section of the northern dunes, Doughboy Bay. The vegetation cover in the 2011 comprises native sand tussock (Poa billardierii); pīkao; knobby club rush (Ficinia nodosa) and flax (Phormium tenax). No marram is present in the 2011 image.

5.2 Funding

Consistent funding of the Programme, with annual investment in dune restoration, from 1998 to the present, has been critical to the success of the Programme. Any restoration programme that targets marram grass and tree lupin must be sustained for years to decades until the risk of regeneration is nil. Both species flower annually, so the goal is to prevent flowering and subsequent seed production, then prevent maturation from the seed bank and, in the case of marram, bud bank. Annual treatments are necessary for lupin, but in some conditions, when a program is well advanced, marram can be managed on a biennial basis. In the Mason Bay case the decision was made in 2014 for ground operations to alternate between the Northern and Central Dunes, to allow the area treated to be expanded. The risk of a plant maturing, flowering and dispersing seed, between biennial treatments, was then considered acceptably low. This approach can only succeed if DOC operations are near perfect in locating and destroying maturing plants of lupin and marram before they flower.

The level of funding is equally important. The ideal level of funding will vary from site to site, depending on the geomorphology and nature of weed infestation, particularly the size of the infestation. The historic level of funding on Rakiura enabled the Programme to grow to a certain scale, measured in hectares under management, but not to completion. The level of funding for operations at Doughboy Bay, and for most of the other dune systems on Rakiura, has been sustained and has been adequate to deal with the regeneration of marram grass from the persistent seed bank. Funding for operations at Mason Bay, in comparison, has not allowed the Programme to be completed in a timely fashion. Full funding, which would allow total coverage of the marram and lupin population each year would be ideal, so that the Programme can reach a surveillance phase more rapidly, allowing funds to be redirected to other conservation projects.

The operational budget for Mason Bay has been increased from time to time, which has allowed the Programme to expand (Figures 22 & 28), but these increases were not sufficient to sustain growth of the programme between 2010 and 2020. The problem was one of 'cumulative area'. Each new management area treated was added to the sum of the existing treated areas. At some point, and this occurred in 2010 with the Mason Bay site, funding was not sufficient to allow further expansion. This led to a frustrating condition in the Central Dunes at Mason Bay, where fresh seed from the untreated foredune was continuing to enter management units in the hinterland of the system. It has been necessary to continue with annual, then biennial, treatment in the central dunes, downwind of the foredune, long after the hinterland seed bank and rhizome bank have been exhausted because of ongoing marram invasion.

Funding of the Programme has recently increased. The Government announced an extra $181.6 million for Department of Conservation operations (over 4-years) and the Rakiura Dune Restoration Programme was granted an additional $105k/year. This extra funding should permit the Programme to extend operations to cover the Central Dunes; between Big Sandhill and the coast, and between Duck Creek and the existing southern boundary; and possibly the entire area of the Central Dunes. It should also allow the extension of operations throughout N1a and N2a in the Northern Dunes. At that point, the focus could shift to the area north of Duck Creek, and the southern dunes of Mason Bay (including the Cavalier Dunes). Much depends on the efficiency of current DOC operations in the short to medium term and whether the marram seed bank prolongs intensive operations in the Central and Northern Dunes.

In most dune restoration programmes that target invasive species it is likely to be cost-effective to treat the total area of a dune system from the outset, for the reasons discussed above. The initial cost of such a strategy is high, however, the total cost is lower over the duration of the Programme. It is feasible to model the Programme cost of the Mason Bay operation, for example, based on the initial area and density of marram; the response of marram in different growth environments to herbicide; and the efficacy of different control methods (aerial, ARGO, knapsack, hand-pulling). In an ideal funding environment the Department of Conservation would have had the resources to treat all marram grass in the central dunes of the Mason Bay dune system in the first year of the Programme – the year 2000 in the case of Mason Bay. Such a programme would achieve its objectives when the reproductive potential of marram is exhausted. Given our current understanding, the investment would have exceeded $270k annually for years 1-3; then $220k/year for years 4-10; dropping to $45k/a for years 10-20; then $15k/a for years 20-30 – a total expenditure of $2.95M. The level of investment required to treat a large area of dune system is high, but approximately half the cost of the current 'incremental' approach over the duration of the Programme. The above analysis is for arguments sake and based on a range of assumptions. Programmes might be completed more rapidly where marram has not formed a seed bank, or where post-marram dune dynamics are unfavourable for recruitment from the seed bank.

The management unit approach to operations, combined with systematic monitoring of each unit under management, can enable effective financial modelling of operational scenarios. The management units are based on ecological and geomorphic subdivisions of the dune system – which contain distinct populations of the target species. We know these populations respond differently to herbicide, and to different rates and methods of application of herbicide. At Mason Bay the response of marram grass to management has been systematically monitored using management units, distinct geomorphic subdivisions of the dune system, which has allowed rational evaluation of operational scenarios prior to each spray season. Monitoring has also revealed the rate of regeneration resulting from the dispersal of seed from the erosion of local dunes; from the erosion of upwind dunes; and from populations of untreated marram. Logically, smaller management units provide for finer-scale financial modelling, but in the case of Mason Bay the sizes of management units was decided with regard to (i) the nature of the marram population; and (ii) the area that can be sprayed using a ground-based method over a reasonable period. For example, most of the management units in the central dunes can be sprayed by a 4-person knapsack team over a period of 1-2 hours, which allows time for regular breaks and sustained work over a typical working day.

The level of funding for the Rakiura Dune Restoration Programme has been suboptimal if the goal is to eradicate marram grass and tree lupin in a timely manner, such that the work can be completed (to the point where work is ongoing surveillance) and funding can be diverted to other projects as soon as possible. Funds for the Programme have been allocated on a regional basis, despite the national conservation significance of the Rakiura dune systems, and the particular importance of the Mason Bay dune system. Fortunately, funding for the Mason Bay part of the Programme was significantly increased in the 2019/20 financial year as a result of an increase to Vote Conservation in the 2018 budget and may (eventually) benefit from funds distributed from the International Visitor Levy, introduced in 2019. The challenge for the Department is to ensure dune restoration at Mason Bay and other key sites is adequately funded over the short to medium term to expedite rapid restoration so that funds can be diverted to other programs once the surveillance phase is reached.

5.3 Sustained monitoring of environmental outcomes

The success of the Rakiura Dune Restoration Programme has been based, in part, on monitoring of the effectiveness of the operations and the environmental consequences of these operations. The early marram grass eradication work, on Whenua hou (Codfish Island) and the northern beaches of Rakiura, was critically important in safeguarding the northern dune systems, but we know little about the extent of marram grass present in the 1980s, or the effectiveness of the operations. In contrast, the Department invested in baseline monitoring prior to the commencement of the Doughboy Bay operations (Hilton *et al*. 1998) and this work has since continued and evolved. These contracts (with the University of Otago) have funded baseline monitoring of environmental change, resulting in an exceptional time-series of observations; including 20 years of topographic change and vegetation data at Doughboy Bay.

Monitoring strategies and methods have evolved as technology and academic practice have advanced. For example, early survey work relied on dumpy levels – simple optical survey instruments - to derive cross-sectional profiles of the landscape. Current survey practice utilises a much wider range of instruments, including RTK-GPS and UAV photogrammetry, to survey areas of a landscape. These methods provide a 3-dimensional record of areas of interest; including ultra-high resolution images (oblique and vertical); orthophotographs (images stitched together and georeferenced); digital terrain models (representations of the topography of an area); and auto-classification of plant communities (maps of vegetation classes). The morphology and vegetation cover of a section of the landscape (1-10 Ha in area) can be surveyed, to sub-decimetre accuracy, over a few hours. How these technologies have been utilised to monitor the Programme is discussed below in relation to work at Doughboy Bay and Mason Bay. Monitoring and research have also been conducted at Sealers Bay Beach on Codfish Island (Whenua hou) and at Smoky Beach, but systematic monitoring has focused on Mason Bay and Doughboy Bay.

The ongoing collaboration between the Department of Conservation and the University of Otago has indirectly supported research by staff and postgraduate students to address particular ecological and management questions relevant to the success of the Programme. Funding has so far supported 32 University of Otago postgraduate students (doctoral, masters, honours); many of who were motivated to work on dune-related research questions after volunteering to support routine monitoring during their undergraduate years. Our understanding of the formation of persistent seed banks, for example, arose from the work of academics and postgraduate students at the University of Otago over several years (Hilton *et al*. 2019). Moreover, the continuity of monitoring has greatly informed our understanding of the natural dynamics of the dune landscapes, as well as the consequences of the progressive removal of marram grass cover. Maintaining and resurveying permanent quadrats and survey profile lines was critical to understanding how and how rapidly dunes associated with marram grass decay; where sand eroded from such dunes accumulates, as well as the consequences for downwind plant communities.

5.4 The management of spatial data

The generation and management of spatial data has been essential to the ongoing success of the Programme. This data includes operational GPS data (location of ground and aerial spray operations; species treated); monitoring data (the location of missed or mis-treated plants); the location of sites of significance (threatened species or particular plant communities); and the location of sites to be checked annually (tree lupin sites, where flowering has occurred, for example). The approach to spatial data has evolved, from sketches in a daily diary, that indicate the approximate range of operations and herbicide applied (Figure 41), to representations of

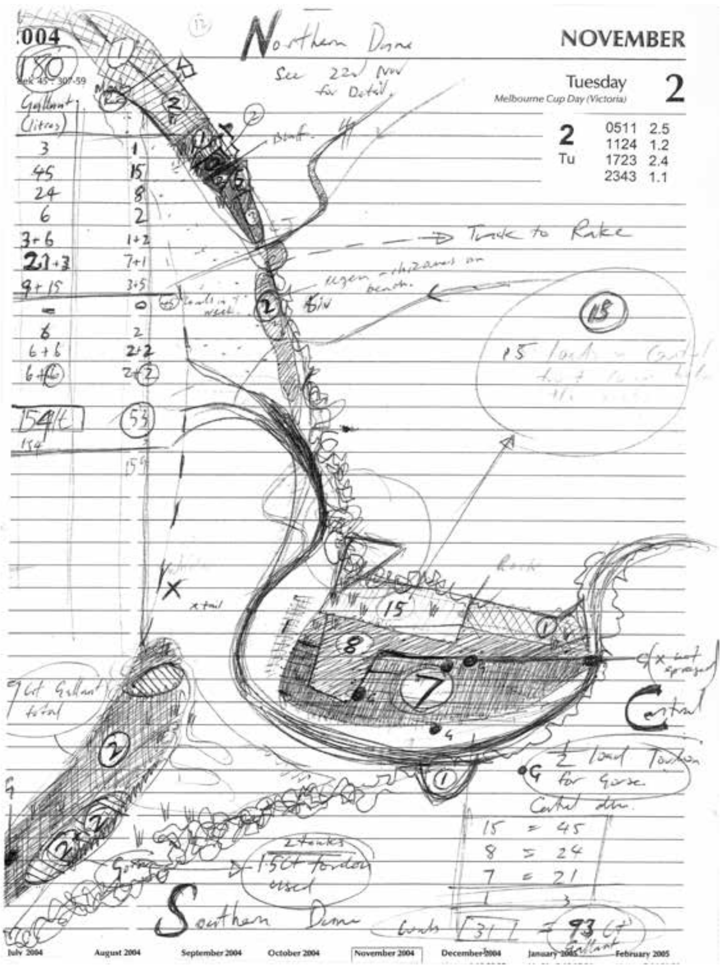

Figure 41: A detailed diary sketch summarising the coverage and herbicide used during a 10-day marram eradication trip to Doughboy Bay (November 2004).

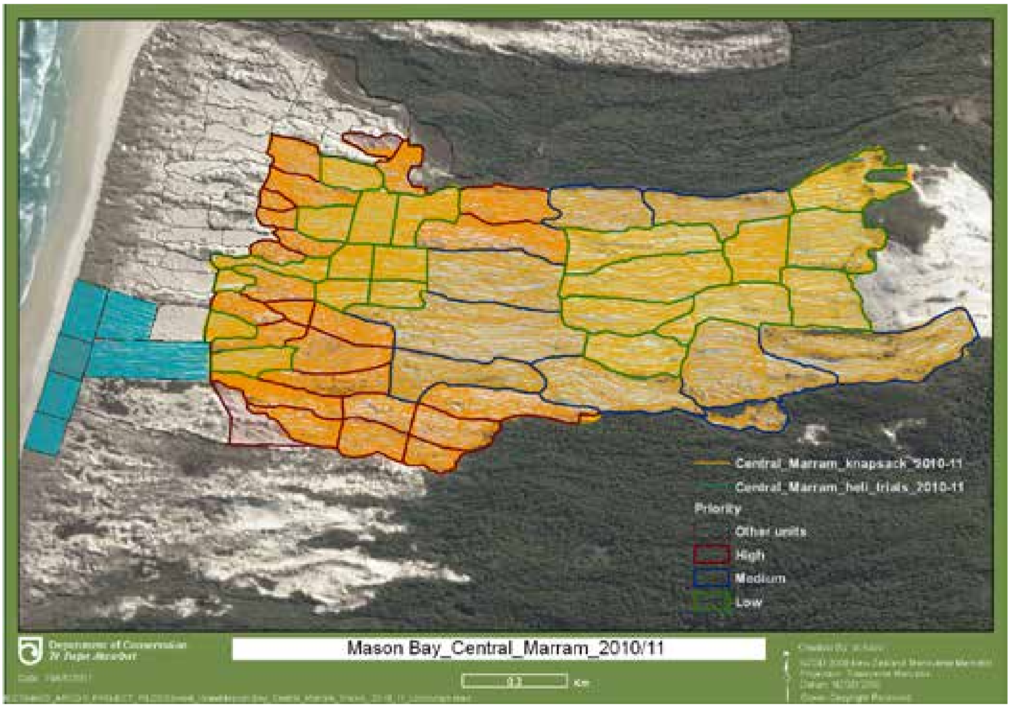

Figure 42: A GIS of spray tracks (knapsacks) in the central dunes, Mason Bay, over the 2010/11 spray season. Each line represents the track of one ranger searching for surviving marram grass, nearly always present as a seedling. The blue lines represent helicopter spray lines.

these data in a GIS (Geographic Information System) (Figure 42) within virtual management units. These units have allowed precise mapping of each operation, by day, by trip and during each spray season; estimation of the intensity of coverage; and calculation of the efficiency of the method employed (knapsack, vehicle-mounted pump, or helicopter). GPS-based systems allowed target species and target areas to be surveyed precisely prior to operations; sites of particular conservation value to be avoided; the extent of operations to be communicated graphically to managers and planners; and areas with persistent marram grass regeneration to be identified and prioritised.

Early research examined methods of mapping vegetation classes, including marram grass (Jul, 1998; Sibbmark, 2000; Duncan, 2001; Henderson & Hilton, 1998; Berry, 2005), with a focus on Mason Bay, but including a synoptic study of Rakiura dune systems (Hilton, 2001). This work was motivated by a need to determine the rate of spread of marram grass and develop classes of marram density to support the development of operational strategies (Main, 2008). Related work explored the dilemma of classification and boundaries, which are often 'fuzzy' and unstable in space and time. The large dune systems of Rakiura comprise a mosaic of landforms, plants and plant communities, which are partly inherited from past geomorphologies and ecologies, and partly evolving, as habitats evolve. Some boundaries are distinct - the edges of deflation surfaces, in most cases. Other boundaries are distinctly 'fuzzy' - particularly marram density classes in many dunal settings (Berry, 2005).

In general, interpretations of landscape and vegetation complexity have been based on geomorphic process and landforms, which is the primary driver of dune ecology through closely related variations in landform development, sedimentation and hydrology. Rates and spatial patterns of sedimentation (sand erosion, transport and deposition) result in distinct patterns of sand deposition and burial, the major determinate of plant community composition (Maun, 2009).

Accurate mapping of vegetation and landform boundaries has been frustrated, at times, by the unavailability of aerial and satellite imagery. The first aerial photographs of Mason Bay were taken in 1958, when marram grass had already established in the foredune zone. Most analyses of vegetation cover and landform development have relied on 1958, 1977, 1989, 1998 and 2007 imagery to classify vegetation, map landforms and landform dynamics, and examine shoreline change (Kelly, 2012; Garden, 2012; Hart *et al*. 2012; Konlechner *et al*. 2016). In most cases a few synoptic images of the dune system have been more useful than multiple low-level images that could not be geo-rectified. UAV photogrammetry is time consuming to establish, where ground control points are surveyed using RTK-GPS, but successful flights yield high quality aerial images over areas of interest that can also be used to derive digital surface models (Figure 43). Maloney et al. (2018) based part of their analysis of the efficacy of this method on data gathered at Mason Bay; and McConachie (2015) demonstrated the potential for automated classification of vegetation classes using ultra-high (Trimble UX5) UAV imagery. Automated classification of dune texture has been trialled to assess the success of restoration, based on comparisons of vegetation cover (texture) between non-treated, treated (Doughboy Bay) and pristine (Smoky Beach) dune systems (Figure 44) (Konlechner *et al*. 2015).

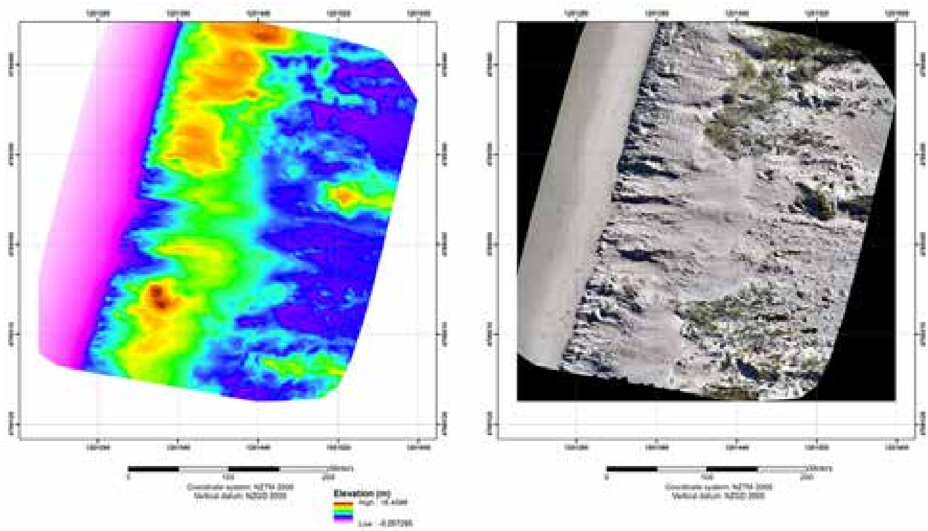

Figure 43: UAV-derived digital elevation model and orthophotograph of a section of the Mason Bay foredune (adjacent to Parabolic 6) based on images obtained in April 2019, showing erosion of the stoss face following sustained marram grass operations and deposition of sand in the lee of the foredune. Sections of the foredune are eroding at different rates because they have had different treatment histories. The section showing the greatest change (see cross-section in Figure 13) was first treated in 2010. The northern third of the foredune in this scene was first treated by helicopter in 2016.

Figure 44: Classified satellite images where sand is yellow and vegetation black. These series of classified images document the increase in bare sand following marram eradication across the Southern Dunes of Doughboy Bay after 1999 and the subsequent increase in native plant cover (2003-2013) from Konlechner et al. (2015). Such methods can provide an objective measure of restoration success.

5.5 Monitoring innovation

Working on the west coast of Rakiura has imposed some limitations on the field methods employed. All fieldwork requires beach landings in either 5- or 10-seater aircraft, imposing equipment loads of 200-500kg, as well as size limits, respectively, for a 4-person fieldtrip. Inevitably fieldwork has involved multiple objectives and a balance between survey instruments and equipment required for research or monitoring purposes. Experiments involving observations of wind flow and aeolian sedimentation are particularly demanding. The availability of a generator at the Department field base has been critical to maintaining logger, UAV and computer batteries. Surprizingly, given the latitude (47oS Lat.), and exposure of the west coast of Rakiura to the prevailing westerly winds, the weather has seldom disrupted flight plans. Since 1997 flights have been delayed only twice by high winds and once by fog. Overall, the isolation has increased the cost of research and monitoring, but hardly constrained activities. In large part this is testament to the skill, flexibility and support of the pilots of the airline servicing Stewart Island (Stewart Island Flights).

The University of Otago have, from the outset of the Rakiura Dune Restoration Programme, committed to gathering high resolution landform and botanical data to inform operational strategies and address key research questions. The survey methods employed have evolved since morphological monitoring commenced in 1997, as new technologies have been introduced. In this regard the technological support of the School of Surveying at the University has been fundamental. The adoption of UAV / RPAS (Remote Piloted Aerial Systems, or ‘drones’) survey technologies followed the first fixed-wing RPAS survey of a section of Mason Bay dunes by Dr Pascale Sirguey in 2015 (Figure 45). The first area survey at Doughboy Bay in the northern dunes used a total station, but many of the shore-normal transects, orientated perpendicular to the shoreline to capture barrier development, were surveyed with a dumpy level until 2002. Since then transect and area data has been collected using either an RTK-GPS (with a base station set up over a LINZ benchmark (Mason Bay); or a mark established using PPK-GPS (Smoky Beach and Doughboy Bay); or total station (laser-based survey instrument). Since 2015 these methods have been partly replaced by RPAS ('remotely-piloted aerial vehicle') (or 'drone') technologies which provide both an ortho-photo and digital surface model (Moloney et al. 2018). Consequently, there has been a significant increase in the quantity and value of data gathered as we've moved from (mostly) 2D profile to 3D datasets.

The increase in data gathered during fieldwork is staggering. A series of dumpy level surveys, shore-normal profiles at Doughboy Bay, for example, might yield a few hundred XY points, involving 3-4 days of fieldwork and processing. A quadcopter UAV, when used in conjunction with ground control points (GCPs), surveyed with RTK-GPS, might yield 20 x 106 XYZ data points, as well as the associated orthophoto. Over an area of (say) 4ha, this method involves (i) laying out GCPs (1-hour); (ii) surveying the GCPs with RTK-GPS (2 hours); (iii) one or two 20-minute UAV flights; (iv) packing-up (1-hour) and; (v) 4-6 hours (largely automated) post-processing using Pix4D™ or similar software. More advanced analysis, a

Figure 45: RPAS (or UAV (drone)) technologies are now used to derive orthophotographs and digital elevation models. The first RPAS survey was completed by the staff of the School of Surveying in April 2015 (a) - here launching the Trimble UX5 RPAS from the Mason Bay foredune. Subsequent aerial surveys have used a Phantom 4-Pro UAV quadcopter. PhD candidate Nguyen Minh Duc (b) is using a hand-held Garmin 62S GPS and an RTK-GPS to establish ground control points prior to a UAV survey (November 2018).

supervised vegetation classification using ARC-GIS, might take several days (McConachie, 2015). Calculating volumetric changes between surveys (cut/fill) using ARC-GIS is a relatively straightforward process and is a useful tool to monitor landscape development and derive sediment budgets. In practice, UAV technologies compliment rather than replace GPS and total station methods, since it is necessary to take a range of instruments into the field as insurance against adverse flying conditions. Rakiura is situated within the 'Roaring-40s' and calm days (<10knots) may not occur in a typical 10-day monitoring trip.

In ideal circumstances, all survey data would be reduced to a common vertical datum and coordinate system by relating observations to a high-order Land Information New Zealand datum. In practice there is only one such datum accessible in Mason Bay (Big Sandhill, A002(9)) and none in Doughboy Bay. Our practice has been to derive datums using GPS in PPK mode (at Smoky Beach and Doughboy Bay) and relate survey work to these derived marks. Additional marks have been established in the northern and central dunes at Mason Bay to facilitate monitoring of the extent and health of particular species (for example, G. hamiltonii); foredune development; and a terrestrial scanning lidar survey of a parabolic dune (Parabolic 6). RTK-GPS has been indispensable in these operations. It has also allowed us to maintain virtual transects at Doughboy Bay over the last decade when dune movement and less frequent visits made it very difficult to maintain physical marks on the transect line. Had we known, in 1997, that we would still be involved in the Dune Restoration Programme in 2021, we might have established a very different arrangement of survey marks. The lesson here is to imagine a programme of survey or monitoring work continuing indefinitely at the commencement of such a programme.

5.6 Integrating eradication operations and monitoring

Monitoring has focused on the effectiveness and efficacy of ongoing marram grass eradication operations. Methods of describing operational coverage have evolved since the early operations, from sketches in diaries during each spray operation, to the current GIS-based database. Since the spray season of 2004/05 each ranger involved in a ground-based herbicide operation has carried a Garmin GPS receiver. The GPS tracks showing the spatial extent of work for each day are downloaded to a field laptop and assessed for coverage and reported at the end of each spray season. Operations are organised on a day to day basis around 'management units'. These are subdivisions of the landscape, 2-5ha in area, that are delineated in each GPS unit carried by each member of the spray team. This technology allows rangers to operate over specific areas and spray to an explicit boundary in a large and complex dune landscape.

A selection of management units in the northern and central dunes are surveyed annually by the University team to assess the effectiveness of the previous spray season's operations. Nine management units in the northern dunes and 11 units in the central dunes were initially searched annually and are now searched in alternate years (consistent with the biennial north/central operations). The same grid search method is employed using the same shape files loaded on to hand-held GPS units. Teams of 3-4 persons, walking at 5-7m spacing, search for seedlings or plants that might have been missed during the previous years' operations or have since germinated. Missed plants are rare. A total of 102 plants, all of them seedlings, were found

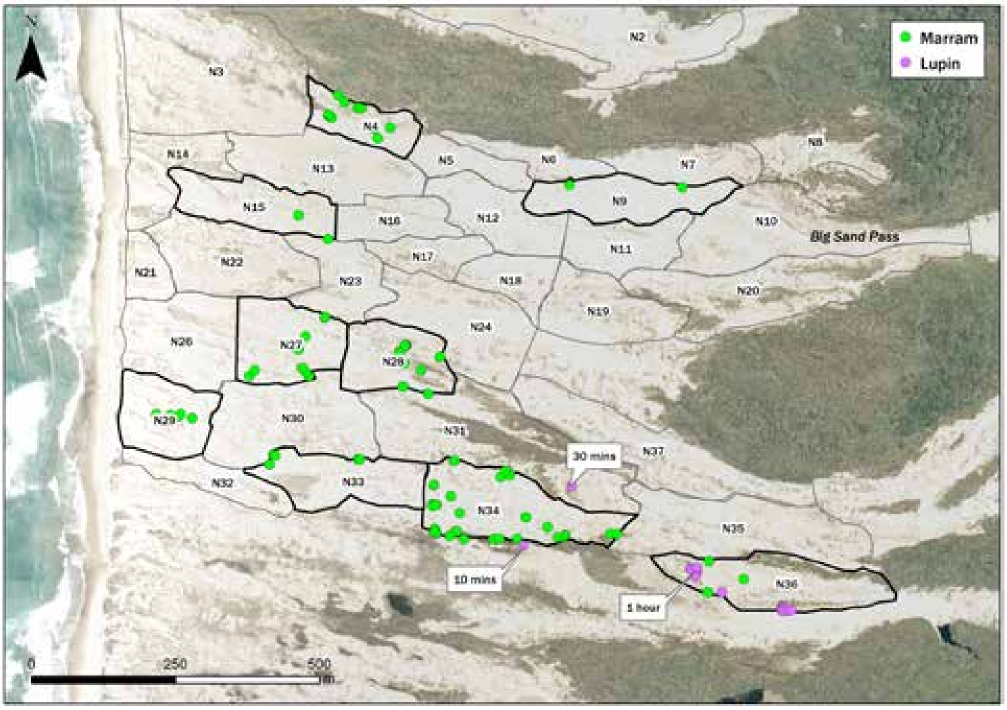

Figure 46: Location of seedlings in selected management units (heavy outline), Northern Dunes, August 2019.

across nine management units in the Northern Dunes during fieldwork over three days in August 2019 (Figure 46). A total of 20.7ha was searched, giving a density of approximately 5 seedlings / ha. In fact, many of the seedlings were found to be clumped, and presumably germinated downwind of an eroded seedbank. All seedlings are pulled by the monitoring team after their location is recorded. Flowers are removed from any mature marram plants encountered.

Over time the number of seedlings in each management unit will decline to zero, since the reproductive potential of the seedbank must be finite. From to time we can expect a seed bank to be exposed following dune erosion, resulting in downwind regeneration. In general, the number of seedlings in most of the management units in the northern dunes have declined (N36, for example; Figure 47); however, relatively large numbers of marram grass seedlings were recorded in 2014, somewhat disrupting this trend. Two management units, N4 and N34, adjacent to partially treated marram grass, accounted for 65% of the total seedlings located in August 2019. Clearly, treating upwind and adjacent populations of marram grass is critical to reducing and preventing regeneration from wind-dispersed seed (Figure 48). Regeneration of marram in the Central Dunes has also been high in management units located immediately downwind of untreated sections of the foredune and parabolic dunes. It is expected this level of regeneration will decline rapidly now that marram grass growing on the foredune and adjacent parabolic dunes is being managed and flowering has ceased.

The use of virtual management units, that generally correspond to dune and deflation surface boundaries, has permitted the systematic management of both operations and monitoring,

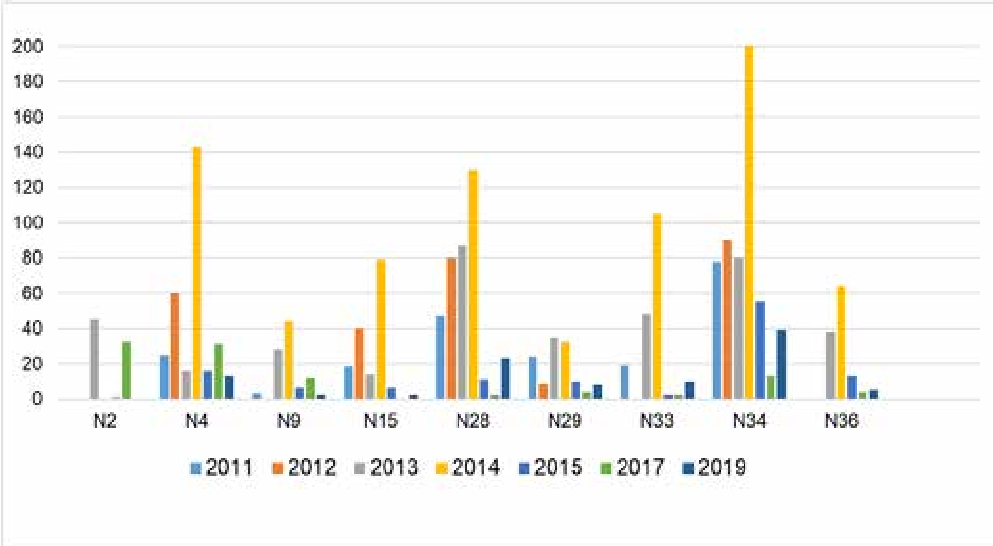

Figure 47: The number of seedlings recorded in selected management units in the Northern Dunes, 2011 – 2019.

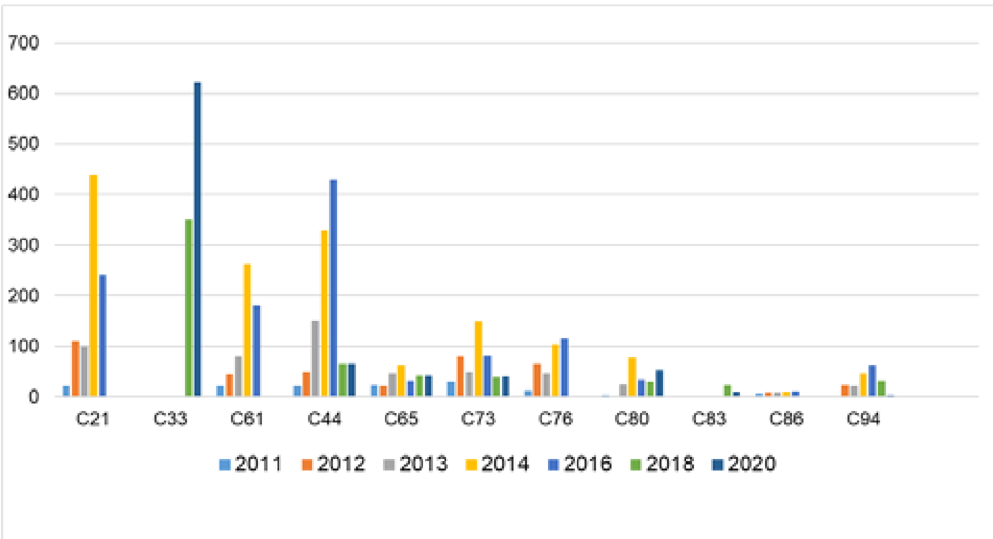

Figure 48: The number of seedlings recorded in selected management units in the Central Dunes, 2011 – 2019. Management units C21, C33, C61 and C44 are closer to the foredune.

within a complex landscape. Most management units contain one dune environment. The management units that cover the Great Stonefield, for example, are exclusively deflation surfaces with a stony surface. Other units are exclusively dunal, while some are a combination of one or more dune environments. These units allow strategic operational planning and business planning, in so much as they allow prioritisation or variations in control method to accommodate variations in marram occurrence or density. The first iteration of the current management units was established in 2009 by walking the margins of these landforms with a hand-held GPS unit, then converting the resulting tracks to shape files, which were uploaded to field GPS instruments. These larger units were subdivided in 2010 to achieve smaller units, each 2-4Ha in area, which could be completed in more human-related intervals (requiring 1-2 hours of work per unit) (Figure 49). A team of four rangers might complete a marram grid search of 6-8 management units in a day. Finally, management units are polygons that float above the dynamic dune landscape. It follows that these have to be re-established from time to time as particular landforms or landscapes evolve as dunes migrate downwind.

These management units can also be used to model the future progress of the marram grass eradication programme, since the response of marram grass to treatment in different growth and depositional environments is now well understood. We know, for example, that it takes 4-6 consecutive, annual, aerial applications of herbicide to suppress regeneration of marram grass

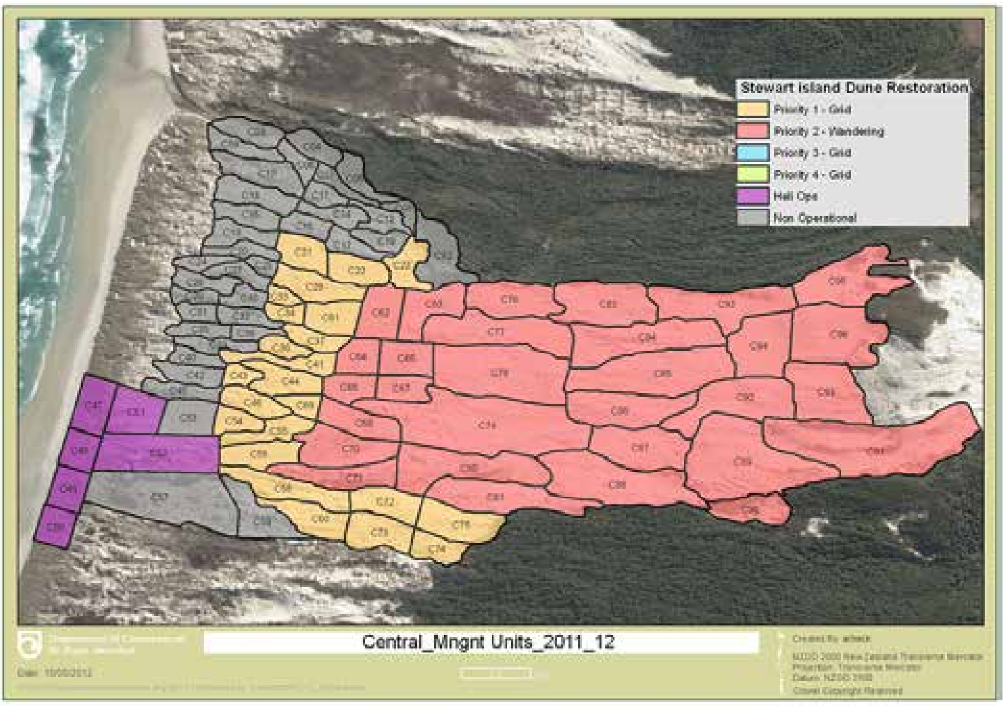

Figure 49: Management units in the Central Dunes, Mason Bay (established 2010). The Department of Conservation use the units to prioritise sections of the dune system for seasonal treatment - in this case spray season 2011/12 - as well as to ensure effective operational coverage each season. A selection of the same management units are surveyed each year by the University of Otago to help understand the biology of marram and assess the effectiveness of operations.

in the foredune environment at Mason Bay; followed by 3-4 years of ground operations to achieve eradication. On relatively sheltered coasts, Doughboy Bay, for example, the foredune seed bank may prolong (low-level) ground operations for periods in excess of 20 years. In the Doughboy Bay case the rate of post-marram dune erosion has been relatively low, which has allowed in situ germination of seeds that had remained viable in the persistent seed bank; or seed has anchored and germinated after being eroded and dispersed a short distance downwind. To date we have not observed regeneration from the seed bank at Mason Bay. We know the foredune contains large numbers of viable seed (Hilton *et al*. 2018) and that this seed must be exposed and dispersed downwind as the foredune erodes. However, it is likely that the rate of foredune erosion and rate of sand deposition in the lee of the foredune are hostile to marram recruitment from wind-dispersed seed. The seeds are exposed too rapidly to germinate in situ and rates of sand accretion are too high downwind (or the marram seed is unable to anchor in an environment of high wind speeds and sand flux). If we associate known regeneration and treatment scenarios with our understanding of the biology of marram grass in each management unit, as discussed above, it should be possible to model the cost and duration of the next phase of marram grass eradication at Mason Bay, or any other site (Main, 2008). This includes the remainder of the northern and central dunes and the Cavalier and Kilbride dunes.

5.7 Collaboration and innovation

The collaboration between the Department of Conservation and the University of Otago, which is ongoing, has contributed to the success of the Programme. This collaboration commenced with pre-treatment fieldwork in Doughboy Bay in 1997 (Hilton *et al*. 1998). The University has supported the Programme by permitting staff involvement (gratis); by investing in state of the art equipment; by providing financial support for student research; by supporting teaching field trips to Rakiura (which has led to follow-on postgraduate research); and by awarding research grants to staff to pursue research in Rakiura dune systems, much of it relevant to the overall goals of the Programme. Between 1997 and 2019 academics produced at least 11 reports for the Department (e.g. Jacomb *et al*. 2015); produced multiple field reports; published 25 peer-reviewed papers on the dune systems of Rakiura; presented more than 15 conference papers; and gained $173k in contestable University of Otago funds to facilitate research on Rakiura. A total of 33 postgraduate theses and dissertations, and 5 undergraduate reports, have been completed at the University of Otago on some aspect of the ecology or geomorphology of dune systems of Rakiura. This work has involved staff from the School of Geography, School of Surveying, Department of Botany, Department of Mathematics, School of Design, Department of Zoology and Department of Information Science, as well as visiting academics from Australia, the United States and Canada. The corollary of this association has been the opportunity for staff and students to conduct research in dune systems of international conservation significance and participate in the World's largest dune restoration programme. The current contract supports two 10-day fieldtrips to Mason Bay each year; occasional shorter visits to Rakiura (public meetings, staff training); fieldwork in Doughboy Bay every 2-3 years; at least one University/DOC meeting each year; and occasional visits to other dune systems.

A technical advisory group (DRAG), formed in 2010 by the then biodiversity manager, has made a major contribution to the Programme. Strategic management of the Rakiura Dune Restoration Programme is the responsibility of the biodiversity manager based in Rakiura National Park, supported by the Dune Restoration Advisory Group ('DRAG'), a technical advisory group. DRAG involves the annual review of operations and monitoring information, the sharing of ideas, and the review of proposals and innovations. The regular membership comprises Rakiura National Park biodiversity managers and rangers; technical support officers (TSO) from the regional office; and academics (and occasionally postgraduate students) from Otago University. But a range of Departmental staff have participated, depending on the agenda. TSO staff, with expertise in geographical information systems, were critical to the development of spatial data management systems from 2004 to 2006. Similarly, a TSO with heritage management expertise received a series of archaeological site reports from the University monitoring team and coordinated a major survey of the archaeological landscape at Mason Bay (Jacomb *et al*. 2015). Rangers from the Southland Conservancy, with expertise in particular technologies and spray operations, made a significant contribution to operational planning over several years. Meetings are usually held on Rakiura. Additional smaller meetings have been held at Mason Bay from time to time, including familiarisation visits by senior management and the Minister of Conservation and a programme review by staff of the Science and Research section of the Department of Conservation in 2016. These meetings have invariably involved discussions of potential innovations and efficiencies.

DRAG meetings have provided a forum for discussing particular problems and innovations, and for sharing the results of research, across all members of the restoration team. These include the use of GPS and GIS technologies to report operational coverage and synchronise monitoring; the development of management units to assist in the organisation of operations; methods of spray application (particularly aerial technologies); and assessments of herbicides. For example, the strategy of treating the northern and central management areas in alternate years arose from analysis of regeneration data and confirmed at a DRAG meeting in 2014. This particular innovation was forced by budget constraints, but it arose as an option because annual monitoring had established that flowering (and, hence, seed dispersal) was unlikely to occur before the completion of the biennial spray cycle. Improvements to the field base at Mason Bay; installation of a shower; restoration of the field base (the 'Homestead'); have significantly contributed to the productivity of Department staff during fieldwork. These may seem small comforts, but the work is laborious in extremes of cold and hot weather; distances walked with a 5-10kg knapsack may exceed 20km in a day; and sections of the dune system are steep and difficult to traverse. Chemicals must be safely handled in a range of conditions and sand-flies, flying sand and sunburn are frequent hazards. Working days are invariably long when spray conditions are favourable, with consequent fatigue and increased risk of health and safety problems occurring. Pressure to complete a task or cover a particular area has to be balanced against these hazards in an environment where the weather limits operations for at least a few days each trip. Despite these constraints the Department rangers, volunteers and casual staff, have maintained an annual effort at Doughboy Bay since 1998 and at Mason Bay since 2000, which in itself has been critical to the success of the Programme. Continuity of effort is the key to any weed-eradication initiative.

6

Constraints and Challenges

6.1 Operational conditions

The Department of Conservation currently schedules five 10-day fieldtrips to Mason Bay between November and February; one trip to Doughboy Bay; one trip to the northern dune systems (plus one extra trip ever second year to Smoky Beach); and shorter trips to the east coast dune systems. Helicopter spray operations at Mason Bay are usually scheduled around March or April, but these operations may be pushed back to May or June, if rangers have difficulty finding a period when a machine is available and weather conditions favourable for aerial spraying. The first trip to Mason Bay is usually concerned with containing the spread of tree-lupin in the northern dunes and treating tree lupin within the central dunes; by removing maturing plants before they flower. This first trip is also concerned with staff training and various operational matters. Training is necessary because usually only one or two of each 5-person team are tenured rangers with experience of operational procedures. Additional trips are arranged to ferry supplies and the ARGO, maintain equipment and arrange helicopter spraying. Occasional mechanical issues with the ARGO have delayed scheduled work from time to time, partly because of the age of the machines used, which is itself a result of budget constraints; and partly because of the impact on machinery of difficult terrain and the sandy environment.

Weed eradication operations at Mason Bay are vulnerable to weather conditions, which is to be expected on an island at latitude 47°S, downwind of the Great Southern Ocean. Spray operations must be conducted in low wind speed conditions and not during rain or when rain is forecast. The effect of inclement weather can be severe – spray operations during a recent trip were restricted to just one day (of ten) as a result of high winds and rain. Fortunately, field teams can focus on tree lupin during periods of adverse weather; albeit it is imperative lupin is removed from the management units before it flowers since this species forms a persistent seed bank and seed can be blown long distances. It is critical that all the treatment area for lupin (the central dunes and the northern section of the northern dunes) is searched for lupin each year; and important to avoid the inclination to just focus operations on known areas of lupin.

6.2 Staffing

Sustained annual operations have been critical to the success of the Programme. Arguably the most vulnerable element of the Programme is the availability of trained staff. Most field teams comprise one tenured ranger, with the remaining three or four team members volunteers or seasonal employees. Scheduled operations have been cancelled, or delayed, from time to time, as permanent staff have been diverted to other programmes; for example, to respond to episodic incursions of rats on Ulva Island. The Department attempts to maintain Ulva Island, a significant bird sanctuary within Rakiura National Park, rat-free; however, the island is within swimming distance of Norway rats (*Rattus norvegicus*), and the occasional incursions require an immediate response.

The Department of Conservation has been restructured several times since it was established in 1987. The last major restructuring, in September 2013, resulted in the loss of 100 positions nation-wide, and the redeployment of hundreds of staff to new roles and new locations. This restructuring, which has been partly reversed, resulted in the loss of experienced rangers from the Rakiura Dune Restoration Programme, within a structure that already relied on untrained volunteers and seasonal staff. The continuity of involvement of University of Otago staff has helped retain Programme knowledge, but academics do not safeguard technical operational knowledge. Over the last 20 years four biodiversity rangers have led the Programme, supported by a small number of field team leaders. It is important to the successful completion of the Programme that experienced DOC staff are retained and junior staff receive appropriate training.

7

Community Perceptions & Perspectives

The Rakiura Dune Restoration Programme has attracted relatively little public attention since it commenced at Doughboy Bay in 1998. However, the views of two stakeholder groups – international and New Zealand visitors to Rakiura National Park and, secondly, a small group of local people – are well known. The first group have been systematically surveyed at Mason Bay, a popular destination for visitors to Rakiura National Park. The Duck Creek hut is used by hikers on the northern and southern coastal circuit tracks and those flying or walking to Mason Bay from the Freshwater Hut. Chartered planes land daily on the beach, during the summer season, and a 4-hour walk connects Mason Bay to the water taxi service on the east coast of Rakiura (at Freshwater Hut). The majority of these visitors are supportive when introduced to the Programme. Surveys of visitors to Mason Bay found that 68% of respondents thought it was a good idea to remove marram grass, 28% had no view, and only 4% were against the work (Lyttle, 2013). Visitors have a high level of interest in the dunes – the "overwhelming intentions of people seemed to be that they wanted to do what was ecologically best for the dune systems, but they were not always sure what that entailed" (Lyttle, 2013, p.68). This uncertainty is not surprizing – the level of understanding of New Zealand's dune systems is understandably low. In the southern third of the North Island, and throughout most of the South Island of New Zealand, marram and tree lupin form the main vegetation cover in almost all dune systems; and comparatively few people visit or recognise the conservation values of the more natural dune systems, nearly all of which are in Rakiura or Fiordland National Parks in the South Island. Most New Zealanders have only ever known marram-covered dunes.

The second stakeholder group, a small number of Rakiura and Southland citizens, have actively opposed the Programme. A few were involved with planting marram at Mason Bay, including the last farmer at Mason Bay, or closely associated with the period of farming at Island Hill. Farming ceased in 1987 when the Department of Conservation was established and the farming lease was exchanged for land on the mainland. This opposition has been voiced through letters to members of parliament; letters to the editors of local newspapers; persistent official information requests to the Department of Conservation; at small non-public meetings with Department management; and at open public meetings convened by the Department. A wide range of issues have been raised, however, there appear to be four key concerns: (i) that the current extent of active dunes is the result of past overgrazing (by sheep) and browsing by introduced deer (whitetail and red deer) and the Australia brush-tail possum – therefore, dune management should favour revegetation (with marram grass); (ii) sand eroded from dunes following marram grass removal is inundating native forest on the margins of the active dune system; and (iii) the current large marram foredune should be protected because it is favouring native plant communities (particularly pīkao), by offering a level of protection or shelter and moderating rates of sand transport throughout the dune system; and (iv) modifying the morphology of the coastal dunes will expose the wider system to climate-crisis related eustatic sea-level rise and subsequent inundation. Other issues have been raised from time to time, including the suggestion that marram grass control has led to the loss of particular landscape features. A dune lake, known locally as 'Shag Lake', was the focus of initial attention when opposition surfaced in 2007 during a public meeting on Stewart Island to discuss the Programme.

Research by University of Otago staff and postgraduate students has provided a basis for responding to these issues with a high degree of confidence, yet there is a paucity of data to respond to all the questions raised with complete confidence. It is particularly difficult to report how the extent and composition of plant communities has changed through time, simply because that data has only recently been gathered. The Department has species lists prior to 2000, and some spatial data, but the Department, and its antecedent agencies, have never been resourced to establish comprehensive datasets of the dune flora of the west coast dune systems, in anticipation of some future need. The early botanical descriptions of Cockayne (1909b; p.18) and his peers, surveys and publications by Hugh Wilson (1987), Peter Johnson (1992) and other botanists, including the Department of Conservation's technical and scientific staff, have provided an overview of the flora of Mason Bay and detailed habitat and species studies have been conducted since 2000. Aerial photographs and chance images taken by hunters and trampers (Figure 50, for example) have also provided snapshots of the form and flora of the dunes at times. Some of the images taken by Edgar Williams are also valuable. In sum our understanding of the flora of Mason Bay is understandably incomplete, but the flora and landscapes observed are comparable to sites which have never had significant marram invasion (for example, Smoky Beach, Figure 51). Collectively this data indicates that the dynamic and native-dominated character of active sand dune systems on the west coast of Rakiura, their constitute habitats, and their associated flora, is dependent on dune migration. Such migration is critical to the evolution and maintenance of dune landscapes, dune environments and habitat for dune-related flora and fauna. Department of Conservation ecologists and University of Otago scientists consider exotic weed species, particularly marram grass and tree lupin, to be the major threat to Mason Bay and other Rakiura dune systems. This is because of its role in stabilising dunes, restricting sand movement (and hence nutrient supply), changing dune form, and competition with native dune species. Marram is the major threat to the extent of active dunes and to the diverse native flora including the many rare species that occur in these dunes.

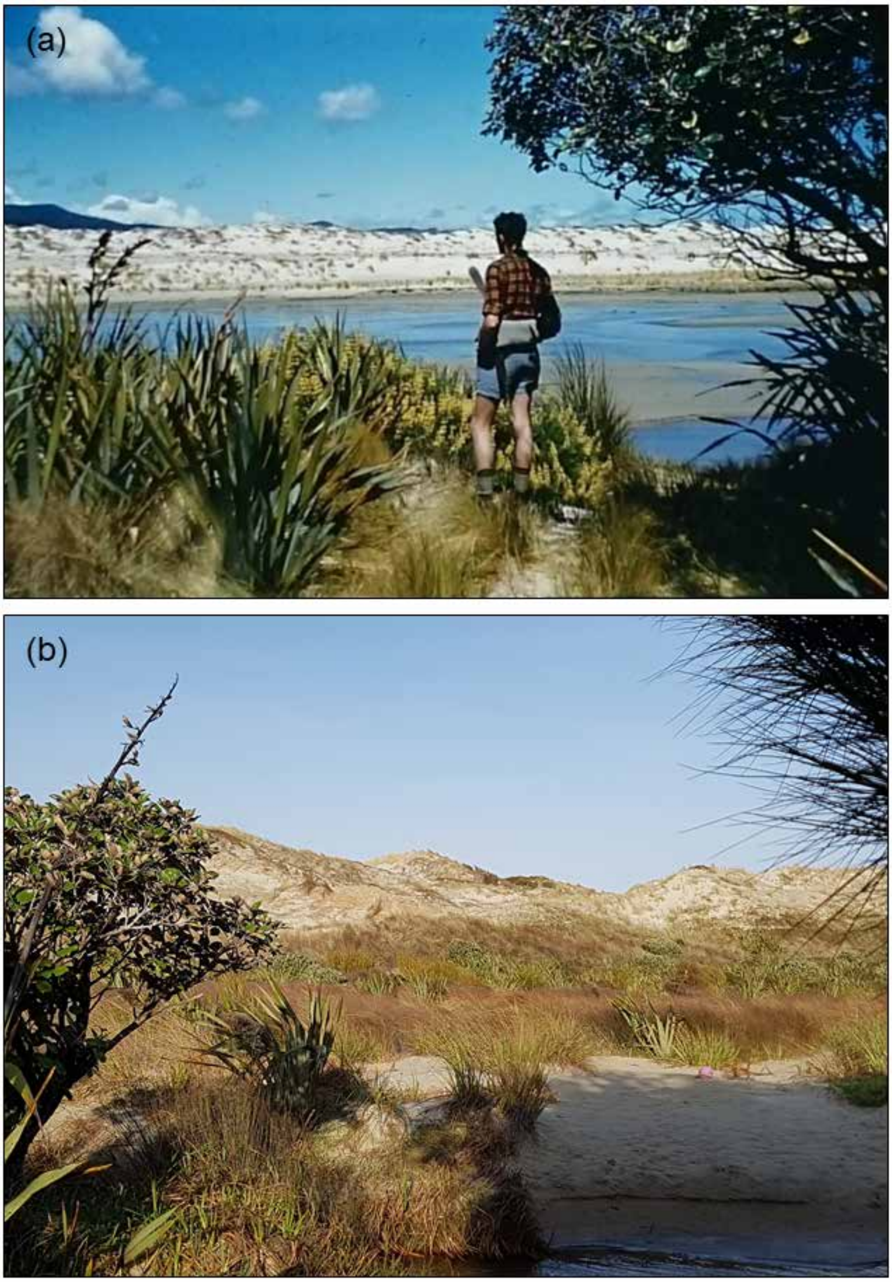

Figure 50. We have relatively few ground pictures of the Mason Bay dune system prior to the arrival of marram grass in Mason Bay. The above image was taken in 1956, looking south from a position where the current Department track meets Duck Creek, west of the tramping hut, and shows the central dunes before the widespread establishment of marram grass. At this time marram was already established in the foredune south of Duck Creek. Tree lupin, deliberately introduced to Mason Bay, is flowering behind the person in the image (Alexander Turnbull Library PA12-6461 (1956) John Lisle Kendrick). The same scene photographed in August 2020 shows that Duck Creek (foreground) is now confined to a narrow channel (foreground) and dunes that were relatively low and sparsely vegetated with native species are now much higher, and stable, with a relatively dense cover of marram grass.

Figure 51: Smoky Beach on the north coast of Rakiura (in 2015) and similar dune systems indicate the naturally sparse and/or patchy vegetation cover of Rakiura dune systems. Marram has never occupied a significant area of this dune system and it has not been affected by farming.

7.1 Natural or anthropogenic (human-related) dune migration?

The few opponents of the Programme have suggested that marram control has changed patterns of sand transport (rates and the direction of sand movement within the dune system); which has, in turn, resulted in accelerated dune migration and the inundation of podocarp forest on the margins of the dune system. We have some information on the historic nature of the dunes systems in Mason Bay and much more detailed information since the commencement of regular aerial photography from 1958. The first Lands and Survey Department maps indicate that the overall area of the Mason Bay dune system, north of Martins Creek, has not changed significantly since the late 1890s (Figure 52), or since Cockayne's (1909b) description of the dune system.

Farming commenced at Island Hill with the establishment of a pastoral lease of 5000 acres in 1879, on the stable and vegetated dunes, east of the current active dune system. The western boundary of the lease is marked today by the 'fence-line track' that runs north of the 'Homestead', one of the first dwellings on the property (Figure 21). The active dune system and areas of isolated sand, scrub and podocarp forest, lie to the west of this track, while the former Island Hill farm extends to the east. The lease comprises relict transgressive dunes – parabolic dunes – wetlands, lakes and the volcanic cone of Island Hill. This landscape is labelled 'ancient dunes' in 1898. The sand-based soils are poorly developed, and small pockets of bare sand persist at the apex of some of the parabolic dunes, suggesting this landscape was an active dune system within the last few hundred years; and was probably active prior to the arrival of

Europeans. The first map of the extent of active dunes in Mason Bay was published in 1898 by the Department of Lands – less than 20 years after farming commenced at Mason Bay. This map indicates that the (then) extent of active dunes, labelled ‘Sand Hills’, is similar to the current area of ‘active dunes’; or, in places, somewhat inland of the current boundary (Figure 21). The first topographic maps of the west coast of Stewart Island, based on the first synoptic aerial photographs (1958), show the dune system had a similar area over 60 years later. It seems implausible, therefore, that farming activities or grazing by deer or other introduced animals resulted in any general sand drift or expansion of the overall dimensions of the dune system. The active dune system was outside the pastoral lease and the primary sand binding plant species, pīkao, is not palatable to sheep or deer.

The margins of the active dune system comprise active and stable sections, with the former associated with advancing parabolic dunes. These advancing sections have been active for many decades and at least since the first aerial photographs (1958) of Mason Bay and well before the commencement of marram control in 2000. Since 1958 long sections of the dune margin have remained largely stable - former mobile dunes have stabilised and been recolonised by vegetation. In a few areas migrating dunes have crossed the 1958 boundary and continued

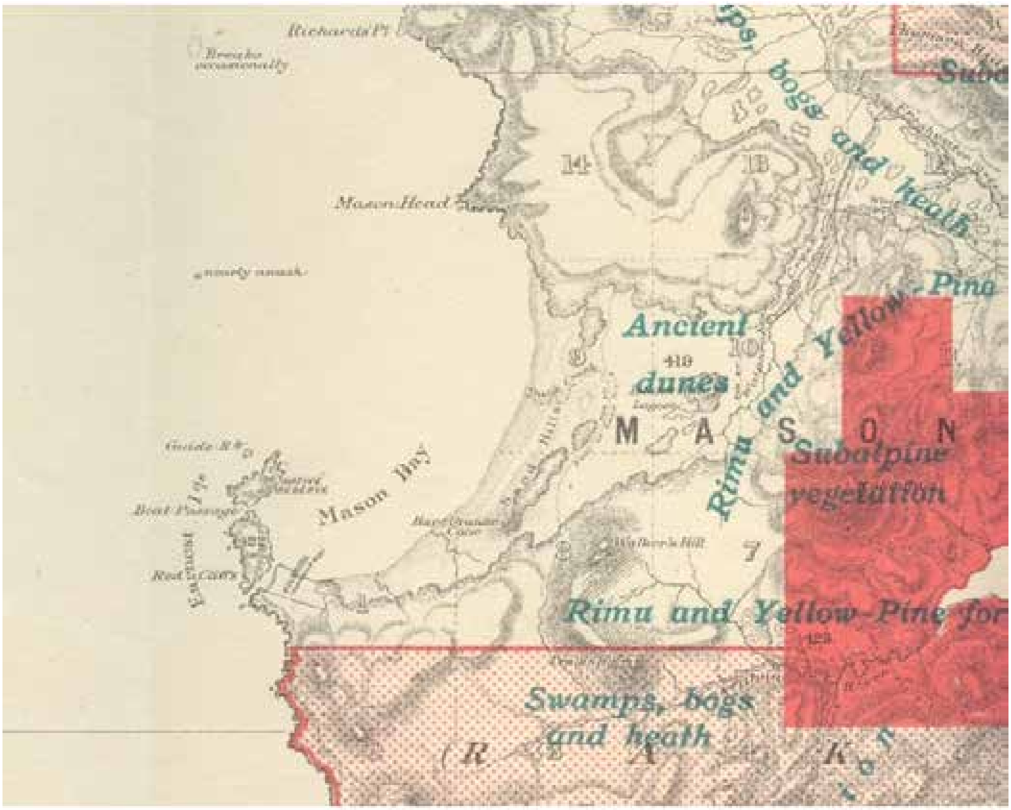

Figure 52: A section of the map compiled and drawn by W. Deverell, November 1898. The extent of the ‘sand hills’ in Mason Bay is very similar to the area of the contemporary active dune system. The stable dunes of the Island Hill flats are labelled ‘ancient dunes’. Lands and Survey Department. Alexander Turnbull Library.

to migrate inland. A GIS that compares the boundaries of the dune system in 1958, 1977 and 2007 show there are six sections where there has been recent (since 1958) advance of sand into the hinterland vegetation (Figure 53). Opponents of the Programme have suggested these areas of dune advance are the result of marram control, as sand is eroded from marram-associated dunes. However, with the exception of 'Area E' ground operations have only recently expanded to include dunes upwind of these sections of the dune system. It is reasonable to propose that some of the sand released from the foredune, following restoration, will be blown through the dune system to the margins of the system but, as discussed below, the evidence suggests almost all of this sand has been retained within native plant communities close to source.

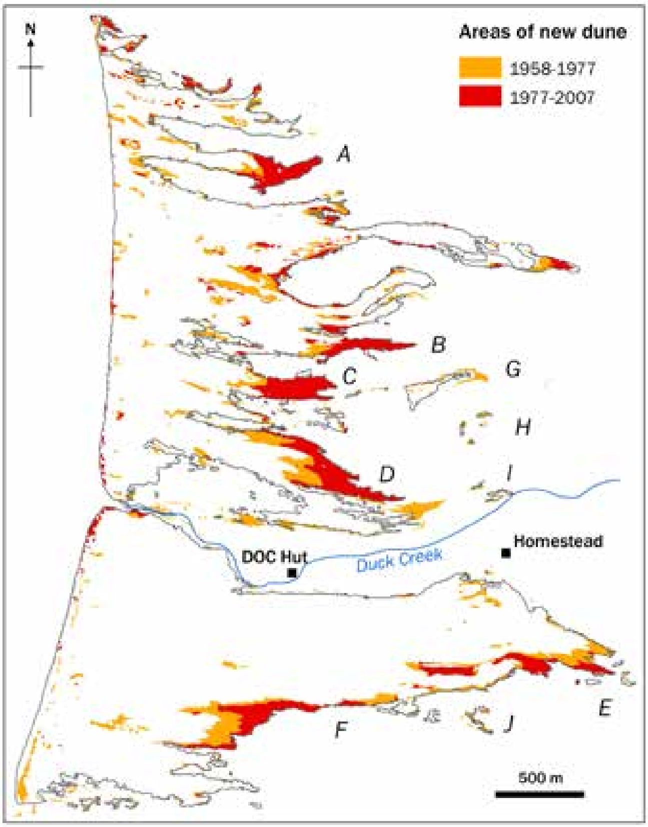

Figure 53: The recent (since 1958) evolution of the Mason Bay dune system north of Martins Creek is complex (Garden, 2012). At six locations (A-F) the dune system has advanced beyond the 1958 and 1977 boundaries. Sites C and D are now relatively stable as a result of marram plantings and invasion. In contrast, isolated patches of sand east of the modern boundary (G, H, I and J) indicate the loss of transgressive dune momentum and the recolonization of stable sand by vegetation. Most of the remaining margins of the modern dune system are stable.

The amount of sand released as a result of marram control since 2000 has been small; or, where significant volumes of sand has been released (in the lee of the foredune, for example), most has been trapped close to source. In most cases there is no geomorphic connection between marram control and dune migration at the margin of the dune system. For example, ground operations have not yet extended to the dunes upwind of sites C and D and the population of marram is thriving in these areas. It is not plausible that restoration has affected the adjacent margins, since wind flow and sedimentation is essentially normal (90o) to the shoreline. It is possible that marram control has released sand that has contributed to the migration of dunes at Site E, but the amount released as a result of restoration work between 2000 and 2015 across

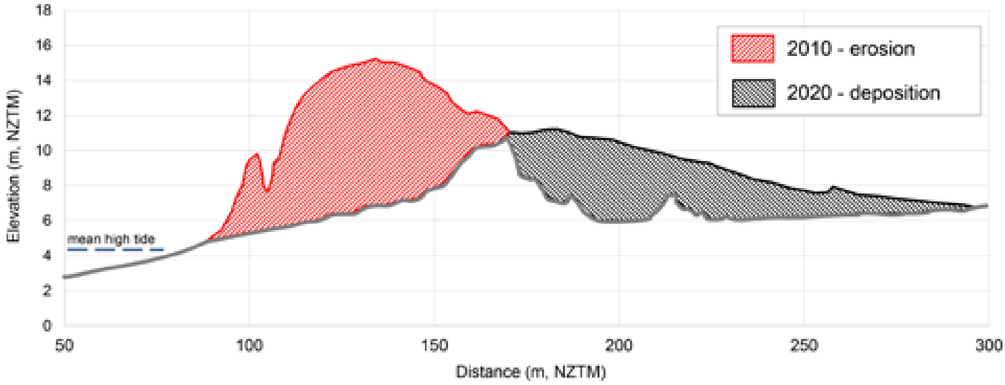

Figure 54: The front face of the foredune adjacent to Parabolic 6 has eroded since the commencement of the Programme in 2010, as represented by this comparison of 2010 and 2020 surveys. The cross-sectional area in red hatch represents the eroded section of the foredune, and the area in black hatch accretion (sand deposition).

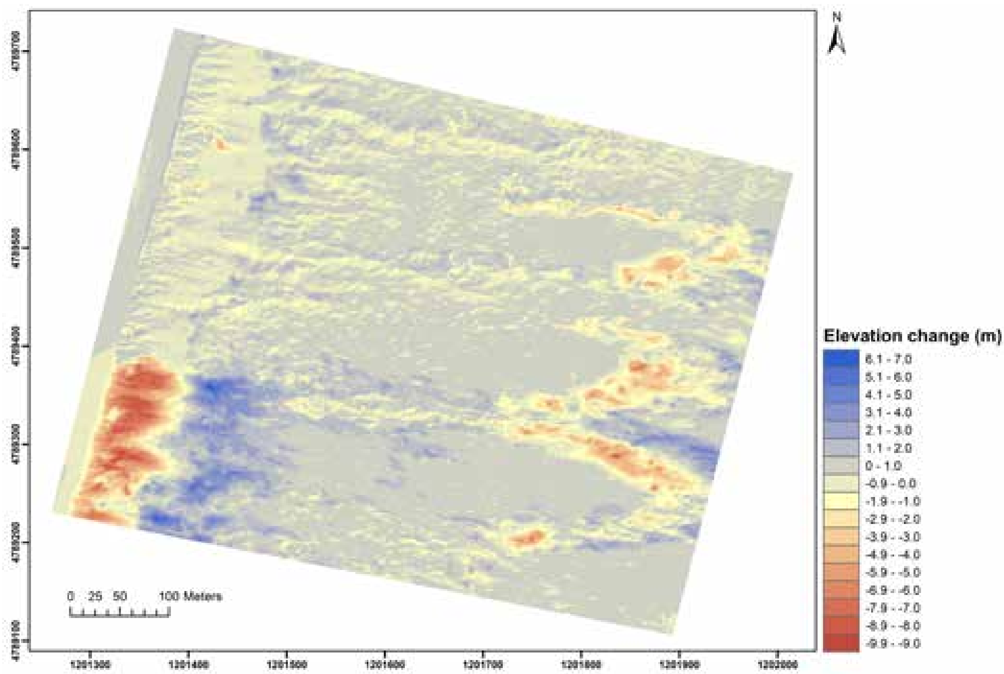

Figure 55: Net elevation change across the Mason Bay foredune and parabolic dunes 5 & 6 between April 2015 and June 2020. Most of the sand eroded from the foredune has accumulated close downwind, with much of the rest accumulating in the western half of the deflation surface of Parabolic 6 or the new depositional lobes (Hankey, 2021).

the central dunes appears to be insignificant compared to the total volume of this dune. Marram was widespread as nabkha in this area in 2000, but the dunes themselves occupied a small area and contained a relatively small volume of sand compared to the total dune system (Figure 23).

The foredune between Duck Creek and Martins Creek is now actively eroding, at different rates in different sections, after multiple applications of herbicide. The foredune has not been sprayed uniformly. UAV and total station monitoring and photogrammetry since 2015 has shown that most of the sand released from the foredune (approximately 65%), adjacent to Parabolic 6, has accumulated within 300m of the shore, and most of the remainder has accumulated within the deflation surfaces of the parabolic dune (Figures 54 & 55). Work is ongoing to determine a sand budget for the foredune/parabolic dune system, but we know that most of the sand released from the foredune has been retained within the pre-control parabolic dune landscape, including the depositional lobes of the parabolic dunes. These depositional lobes have migrated to the east (inland) and reformed in conjunction with pīkao, rather than eroded completely (Figure 4).

Some of the sand released from these lobes has blown through the Great Stonefield, which remains stony and there is no evidence of rapid nabkha development across the stonefield downwind of Parabolic 6 (Buckley, 2015). A small amount of sand originating from either the foredune or the depositional lobes of the parabolic dunes may have passed through the dune system and contributed to dune advance at Site E; but the quantities of sand involved are almost certainly negligible compared with the overall levels of sand movement in the wider dune system. Moreover, as described above, the depositional lobe at Site E was advancing into vegetation well before marram control was initiated.

The development of the Mason Bay dune system since 1958 – comprising the expansion, stabilization and revegetation of different sections of the dune system margin - results from a combination of factors; including the character of the pre-marram antecedent dune landscape; changes in dune development and sand movement following marram grass invasion; seasonal and cyclic variations in wind; and the chance (unpredictable) redirection of pathways of sand transport through the dune system. The combination and interaction of these factors is only partly understood, although research over the last two decades has helped explain some major and patterns. We know, for example, that the northern and southern margins of the central dunes are, respectively, relatively stable and relatively dynamic. This pattern reflects the importance of the northwest component of the local wind regime, which results in a slight north to south sand drift superimposed on the general westerly drift. The northern margin of the central dunes is relatively stable, which explains the presence of Gunnera hamiltonii, a species intolerant of high rates of sand accumulation, along this margin. In contrast, the southern margin of the central dunes comprises an active dune with a steep slip-face at the angle of repose of sand. Sand slips into the adjacent forest along this margin, although the rate of advance is low – less than 1m/year. Elsewhere in the Mason Bay dune system the northerly wind component is much less important than the interaction of onshore winds and topography. Wind is steered and accelerated as it flows over the hinterland of the northern dunes and enters gullies along the western face of the granite ridge that runs northwest to south east through the northern and central dunes. The movement of dunes through these valleys creates a few sites where rates of sand flux are exceptionally high ('Edge A', for example).

Opponents of dune restoration at Mason Bay have suggested that sand released as a result of the marram control programme is causing extensive and catastrophic devastation of hinterland podocarp forest. It has already been shown, above, that sites of dune advance are few and localised and predate the Programme. Moreover, the hinterland vegetation affected by dune advance is generally not podpcarp forest. At Site E, for example, the actively advancing dune is progressing along the same path as the last (penultimate) phase of dune advance. The dune is advancing downwind of the saddle to the south of Big Sandhill (located in Figure 56) across a relatively gentle slope (compared to Edge Site A) through a community of mānuka (Leptospermum scoparium) (Figure 57 & Figure 58). Mānuka extends several kilometres inland and is now a common vegetation cover across the former Island Hill farm. The widespread occurrence of mānuka over the former farm and adjacent areas indicates the last phase of dune expansion was relatively recent. Hence, we should not be surprized that the margins of the current active dune system are dynamic - this is the natural character of the dunes of Mason Bay. Cockayne (1909) captured this character in his early description of Mason Bay following visits in the early 1900s, prior to the introduction of marram.

The migrating dune at Site A is advancing into podocarp forest. The depositional lobe of the dune at Site A advanced 50m between 1958 and 1977; 360m between 1977 and 2007; and 150m between 2007 and 2013. The depositional lobe of this dune expanded 7.3ha between

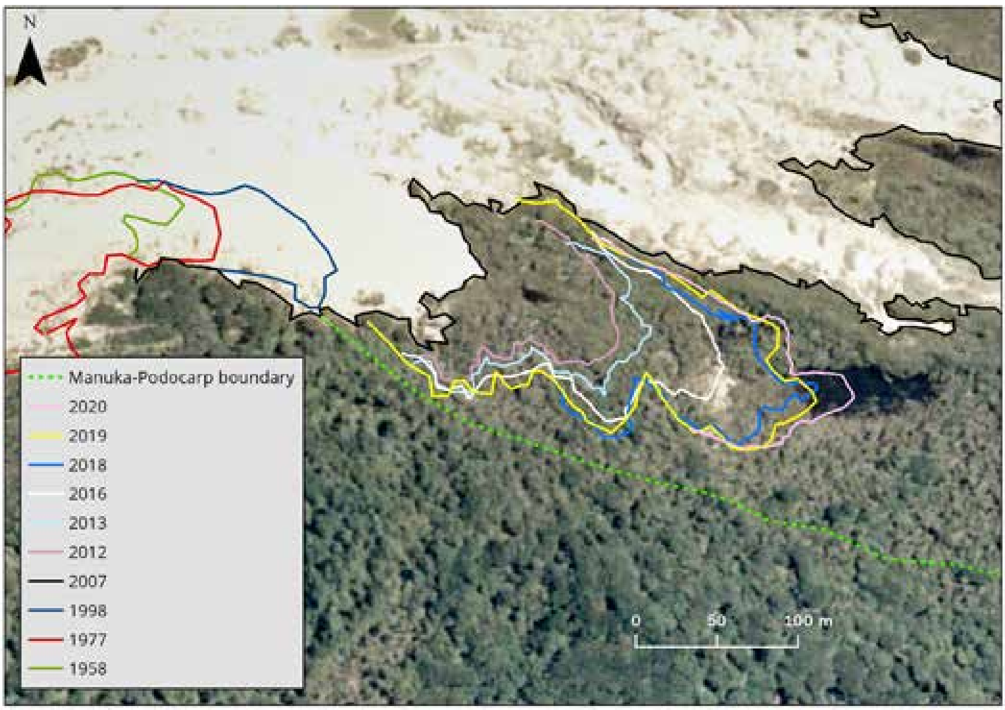

Figure 56: Edge 'E' shows a similar pattern of advance to Site A from 1958, but the rate of advance has not slowed as much in recent years because of the relatively gently sloping hinterland topography. The lobes to the north have stabilised following marram planting in the 1980s.

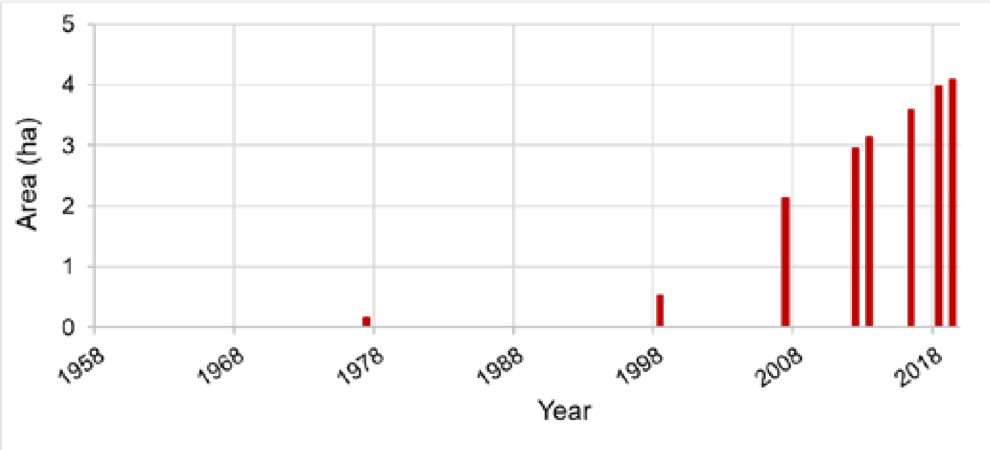

Figure 57: The dune at Site E expanded 4.1ha between 1958 and 2019, but it was actively migrating inland prior to the commencement of the Programme.

Figure 58: An oblique aerial image of the depositional lobe at Edge Site A viewed from the northeast (October 2017). The Earnest Islands, at the southern end of Mason Bay, are visible on the horizon.

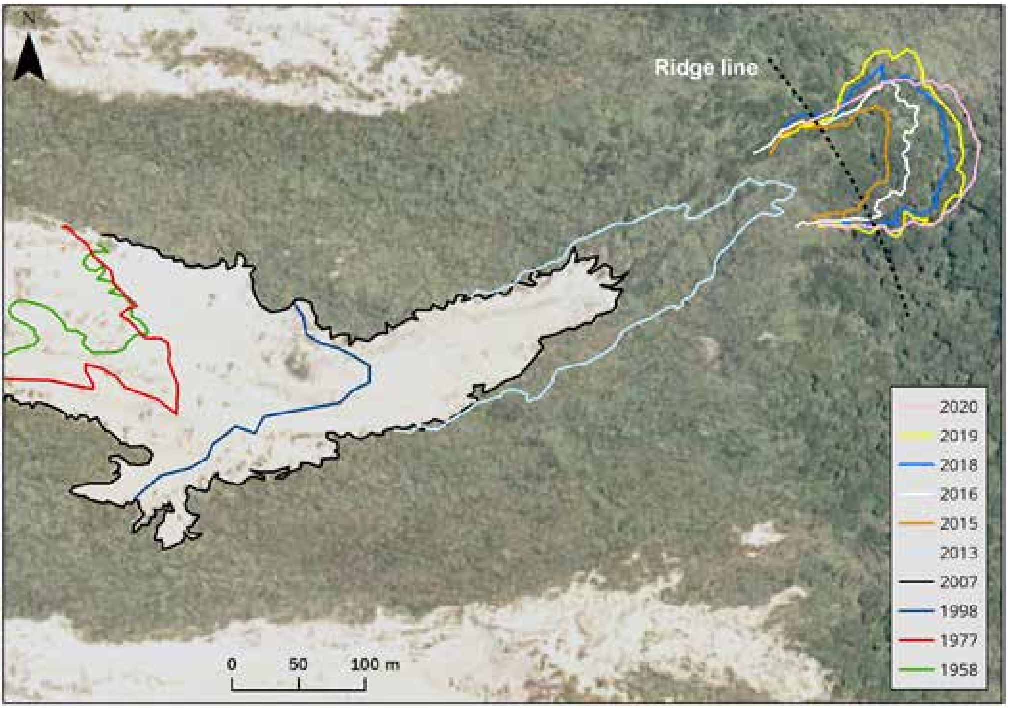

Figure 59: The depositional lobe at Site A advanced rapidly between 1977 and 2007, but it has since slowed as the lobe approached and has recently (2013) surmounted the ridgeline.

1959 and 2019 (Figures 58, 59 & 60). This is a large and very active 'confined' parabolic dune – sand is supplied to the depositional lobe from an upwind deflation basin approximately 9ha in area. Marram has never invaded a significant part of this basin, however, it is present in higher densities closer to the coast. The treatment of this marram, since 2008, has made no material difference to the progress of the dune, which migrated through a pre-existing gully vegetated primarily with Olearia species, and spilled into the rata-dominated forest on the lee side of the ridge. The rate of dune advance will slow now that the dune is past the crest of the ridge because of the topographic effect. Each linear metre of advance once the dune passes the ridgeline will require the deposition of very high volumes of sand (compared with the progress of the dune on the western side of the ridge, within the gully, when only a thin veneer of sand was needed to achieve dune advance). Similar landforms occur in the West Ruggedy and Big Hellfire dune systems and are part of the natural character of the Mason Bay dune system. At some time in the recent past sand must have overtopped the ridgeline at many places and spilled out over the Island Hill basin, presumably burying much of the forest on the lee of the ridgeline.

It has been suggested by opponents of the Programme that the loss of particular landscapes or landforms over the last decade can be attributed to marram control, including changes in the area of a small lake, locally named 'Shag Lake', in the Northern Dunes of Mason Bay. The term 'shag' is used in New Zealand for the more widely used label of 'cormorant'. This lake is a very young feature, formed between 1978 and 1998 when an active transgressive dune blocked an interdune gully and water was impounded (Figure 61). It has been a popular destination since

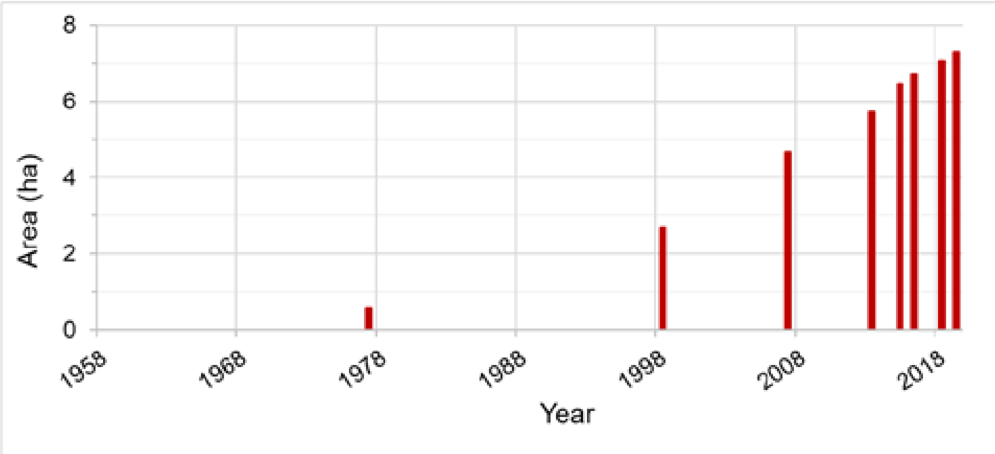

Figure 60: The dune at Site A expanded 7.3ha between 1958 and 2019, but the depositional lobe was actively migrating inland prior to the commencement of the Programme.

then because of the presence of a colony of Stewart Island Shags (*Leucocarbo chalconotus*) which built nests in drowned manuka standing in the lake. The same dune subsequently advanced into the catchment of the lake around 2005, after which the lake started to infill with sand, and the area of the lake declined from 0.31 to 0.20ha. At the same time the trees started to collapse as they decayed. Few trees now remaining standing. The development and decay of this lake is unsurprising since the formation of lakes and wetlands is a cyclic process in active dune systems and it would be unusual for small lakes to persist for decades or longer. Coincidentally a new lake formed a little north of Shag Lake as drainage was again impeded by a migrating dune.

7.2 The relationship between marram and native species

Throughout central and southern New Zealand marram-dominated dune systems have low or no significant native biodiversity (Partridge, 1992; Johnson, 1992). Perversely, opponents of the Programme have argued that marram enhances the habitat for native species. In fact, marram is incompatible with the conservation of the flora and fauna of the Rakiura dune systems, including Mason Bay. It may provide a microclimate for some native species over the short term – *Coprosma acerosa* and *Pimelea lyallii*, for example – however, the continued presence of marram grass results in the medium term (over years to decades) loss of active (migrating) dunes, which is essential to the maintenance of habitat quality and diversity and species survival. General marram invasion of the Mason Bay dune system would result in the rapid extirpation of the exceptional conservation, geomorphic and landscape values of this site.

Opponents have also argued that the current marram foredune supports pīkao growth by "moderating" rates of sand transport in the hinterland of the dune system. This argument might apply to a few specific locations, for short periods of time, but any benefit of allowing marram to flourish in the foredune environment (indeed, anywhere in the dune system) would be short lived. At the commencement of dune restoration work at Mason Bay marram was

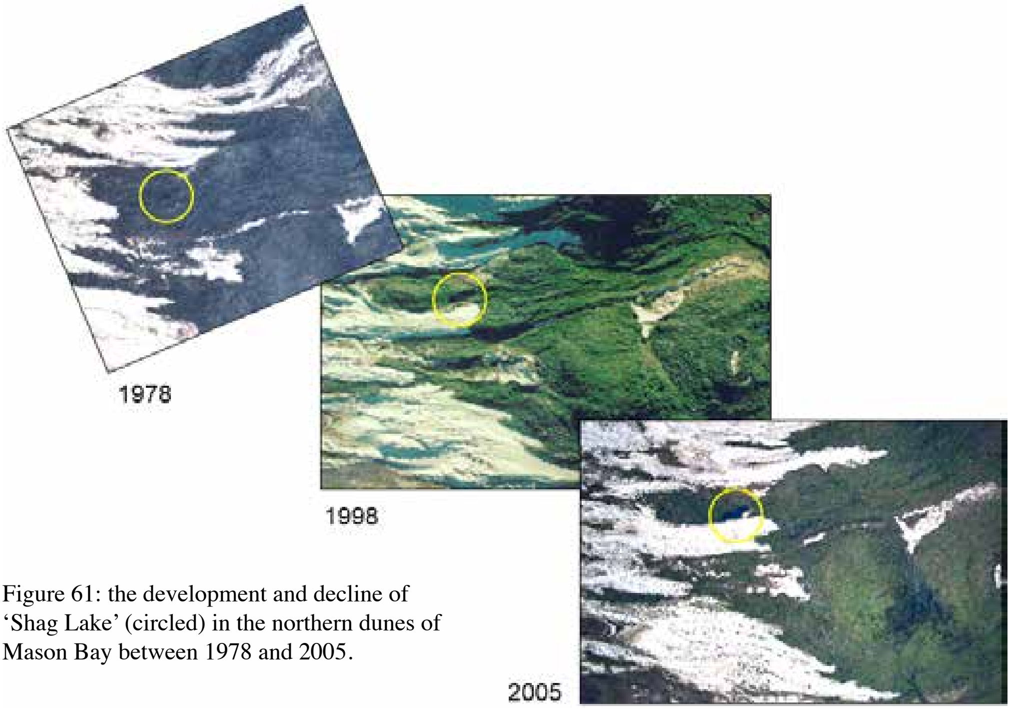

Figure 61: the development and decline of 'Shag Lake' (circled) in the northern dunes of Mason Bay between 1978 and 2005.

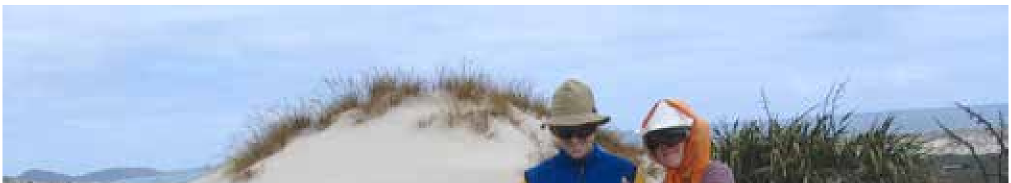

Figure 62: Volunteers searching for marram seedlings in the Central Dunes of Mason Bay (November 2006).

scattered throughout the central dunes as nabkha. Had control operations not commenced in 2000 marram would have rapidly spread by the dispersal of seed, since a typical nabkha produces over 17,000 m-2 seeds (Lim, 2011). Marram associated with each nabkha would also have spread vegetatively, and adjacent pīkao would be rapidly overgrown and displaced. Secondly, the foredune has, until recently, served as a source of marram seed that contributed to the widespread establishment of marram throughout the hinterland dune system. For example, 5,820 seedlings were hand pulled (or left to be sprayed) in the central dunes over a 4-day period (7-10th November) in 2006, within an area of 105ha (Figure 62). These seedlings would have matured and flowered during the summer of 2007/08, each producing a new generation of seedlings. The spread of marram from these sources would have been 'exponential' in character without management intervention.

Thirdly, the establishment of the modern foredune, after marram invasion, has prevented the transport of sand by wind into the dune system, which has in turn resulted in a negative sand budget across large areas of the dune system. This process has resulted in the expansion of stonefields in the period 1958 to 2010 and a reduction in pīkao habitat (Konlechner *et al.* 2016). Pīkao requires low to moderate rates of sand deposition (resulting from sand movement) in order to thrive. This condition is not consistent with a high, stable, marram foredune. Had the current restoration Programme not occurred the botany of the central dunes would now resemble the Martins Creek area, which was the first section of the central dunes to be invaded by marram. This area has a chaotic topography of irregular dunes; has a canopy dominated by marram (Figure 3); lacks a diversity of environments (including deflation surfaces, stony surfaces and seepages); and now contains only a scatter of pīkao (an indicator of native plant biodiversity). It shows how the Central and Northern Dunes would have evolved had the Programme not commenced in Mason Bay over the summer of 1999/2000.

7.3 The natural character of the Mason Bay dune system

The opponents of dune restoration at Mason Bay argue that the Department of Conservation's vision is misplaced – that the current extent and character of the active dune system is the result of past human-related disturbance of the dune system, specifically 'overgrazing' by introduced animals; domestic (sheep) and feral animals (deer, possums). They also link overgrazing to forest decline east of the active dune system and justify marram stabilisation to enable forest to "re-colonise" the active dunes to restore the "balance". According to this argument rates of sand transport are much higher, and the area of dunes is now larger (than they would otherwise be), as a result of overgrazing. Increased sand transport is, therefore, connected to dune migration and forest inundation. In the view of opponents, land (dune system) management should favour revegetation and lower rates of sedimentation. In their view marram grass, an efficient sand coloniser, is an appropriate species to achieve these outcomes.

The arguments for marram control are fundamentally the arguments for the conservation of nationally threatened native species and nationally threatened landscapes and landforms within a national park setting. The dynamic character of the Mason Bay dunes, which maintains natural dune ecological processes and functioning, is entirely consistent with the nature of the other west coast dunes of Rakiura; all of which are recognised nationally for their exceptional conservation values. Smoky Beach, for example, which has been ranked as one of the most pristine dune systems in New Zealand (Johnson, 1992), has a sparse vegetation cover of pīkao and associated native grasses, sedges and herbs (Figure 51). This dune system has never been grazed by domestic animals and contains species that are not palatable to deer. Marram grass is present and subject to annual management, but it has never occupied more than a small part of the dune system. Interestingly, opposition to the Programme has been entirely focused on Mason Bay and restoration work at Smoky and other Rakiura dune systems has not been mentioned. This is understandable, given the opponents have a strong link with past farming operations at Mason Bay.

For most of New Zealand's colonial history active dune systems were seen as degraded lands, a perspective related to New Zealand's economic reliance on agriculture and history of 'taming nature' (Beattie, 2011). There is still an underlying perception, exemplified by the opponents of the Programme, that sparsely vegetated, active dune systems, are degraded systems to be tamed and revegetated. New Zealand has a long history of converting active dune systems to forestry or farming (Hilton *et al*. 2000) and this process was seldom questioned. The introduction and planting of marram grass at Mason Bay, by generations of farmers, was entirely consistent with land management practices of the day. Marram was promoted by central government from the early 1900s and the 'Sand Drift Act 1908' enabled the government to force landowners to stabilise active dune systems. In the case of the Island Hill run migrating dunes posed a threat to farming operations at one location and the plantings of marram grass was an understandable response to an immediate problem. Rakiura National Park is now managed for the preservation of native flora and fauna, including the exceptional landscapes and biodiversity of the active dune systems, now some of the least disturbed and best conserved in New Zealand and globally. Marram poses the main threat to those values and is now being removed in what is the world's largest coastal dune restoration programme.

The natural character of active dunes systems and their biodiversity is still generally misunderstood. Advocacy and education programmes, run by local councils and central government departments, have raised awareness of the value of foredunes in coastal hazard management and the value of pīkao as a taonga to Maori. Communicating the quintessential dynamism of active dune landscapes, and the equally dynamic mosaic of habitats and plant communities, is a challenge. There is a low understanding of such systems and what we do know about them has only developed in recent years, in part through research at Mason Bay. Further, this understanding has not been well communicated to the general public.

7.4 Marram grass control and climate change

Finally, it has been suggested that restoring the Mason Bay foredune by removing marram grass will expose the adjacent dune system to inundation as a result of eustatic (global) sea-level rise. The proposition is that a lower foredune will allow inundation of the dune system. Some global climate change models predict an increase in the occurrence and strength of westerly winds over southern New Zealand. It would be reasonable to anticipate some landward shift in the shoreline, regardless of the type of foredune present; since future storm surge events will be superimposed on a higher base sea-level (Henshaw, 2004). In sum, the potential for erosion of

Figure 63: The last section of pīkao foredune in Mason Bay, located north of Duck Creek (April 2006) – since eroded – with a typically large marram grass foredune in the background. It contained 12 native species in addition to pīkao. The image is a stitch of two photographs.

the foredune might increase.

To date (July 2021) a little less than half of the seaward face – or 'stoss' face – of the foredune has eroded following marram eradication between Martins Creek and Duck Creek. Much of the sand eroded from the stoss face has accumulated just downwind of the new foredune crest. Much of the latter is bare sand, but pīkao has colonised the inland margins of this depositional feature, where rates of accretion are somewhat lower. It seems likely that a new foredune, of a hummocky nature, partly colonised by pīkao, will form around 80m landward of the eroding marram foredune. It is difficult to be sure of the elevation of this new landscape, however, the last surviving section of foredune associated with pīkao had an elevation of around 4m above spring high tide (Figure 63). Moreover, it is likely that the current deflation surface within Parabolic 6, and adjacent deflation surfaces, will evolve to form undulating dunes, as sand is trapped by regenerating pīkao. This new landscape will benefit from sand (and nutrients) blown from the beach, whereas the pre-restored marram foredune prevented significant quantities of sand from entering the hinterland of the dune system. In sum, the current marram foredune will be replaced by a much wider zone of undulating dunes that will rise well above current spring high tide level and projected levels. Which is not to suggest the future restored dune landscape will not continue to evolve under climate change conditions – episodes of inundation and shoreline adjustment are inevitable during severe storms. But these conditions will pose no threat to the wider dune system or the biodiversity of the system.

8

Conclusions & Lessons Learned

The Rakiura Dune Restoration Programme is the largest (by area and expenditure) weed management programme in New Zealand and the largest coastal dune restoration project globally. It has been discussed at international conferences, examined in over 30 academic thesis and dissertations, reported in multiple academic articles, and lauded as a ground-breaking restoration initiative. It is remarkable then, given the conservation significance of this work, that the Programme commenced and grew as a result of local decisions made in the (then) Southland Conservancy of the Department of Conservation. We congratulate the staff involved, mentioned in the acknowledgements of this report, and applaud their foresight and commitment. These are former staff of the disestablished Lands and Survey Department and the New Zealand Forest Service, and Department of Conservation staff, who worked on Codfish Island and the northern beaches of Rakiura in the 1980s and 1990s and prevented marram invasion in the dune systems of Smoky Beach, East and West Ruggedy and Sealers Bay. More recently, they are the Conservancy Science staff, regional and Rakiura National Park managers and rangers, who launched the current phase of the Programme at Doughboy Bay in the late 1990s.

The decision – actually multiple decisions - to commence marram and tree-lupin operations at Doughboy Bay and Mason Bay, and to expand operations to most dune systems in the current Rakiura National Park, was made at the regional (Southland) level. Has a system of prioritisation and funding since evolved to ensure that other key dune systems across New Zealand receive timely recognition and management? The Department of Conservation has instigated processes of ecosystem optimisation – the Ecosystem Optimisation Programme, for example - but to date funding decisions are regional; and a national strategy for the conservation of national dune biodiversity has not yet emerged. It is timely that the Department of Conservation identifies, at a national level, those dune systems of national conservation significance and adequately invest in their conservation. Restoration goals for key dune systems, including the Rakiura dune systems, should be incorporated in a revised New Zealand Biodiversity Strategy and revised New Zealand Coastal Policy Statement. Such recognition would contextualise local restoration programmes and ensure funding for restoration is forthcoming and sustained.

The current Rakiura Dune Restoration Programme is primarily focused on weed control – specifically the eradication of marram grass and tree lupin. Other weeds are widespread, but most if not all of these will decline as marram is eradicated and dune dynamism and processes of sand transport and dune migration are restored. The key restoration goal – of restoring dune dynamism to ensure habitats for individual native species and communities and to sustain dune landscapes and processes – has not been appreciated by all members of the community. An active, dynamic, dune system may appear a wasteland to some; and the idea of reducing the vegetation cover across a dune landscape may seem anathema to good land management practice. In part this stems from a limited understanding of the natural character of New Zealand's larger transgressive dune systems, which are naturally sparsely vegetated. However, the Doughboy Bay and Mason Bay operations have demonstrated the potential to not only eradicate marram grass from a site and restore dune dynamism, but also the potential for the native dune flora to rapidly recover following such operations. Fundamental ecological processes based on the transport of sand (and nutrients) and the movement of dunes, are being restored at these sites.

There was scant information on the biology and botany of this species to guide marram-control operations at the outset of the Programme. The international literature at that time provided few insights on the rate of marram maturation; rates of seed production; processes of seed dispersion; conditions for seedling recruitment; the formation of persistent seedbanks; and the response of the species to herbicide (to name just a few fundamental questions). Restoration at Doughboy Bay has taken longer than expected, primarily because of regeneration from the marram grass bud-bank and seed bank, which was not anticipated in 1999, based on the reported biology of marram grass in European settings. This knowledge, gained through persistent monitoring and targeted research at Doughboy Bay and Masons Bay, has shaped the Programme and influenced the expectations of Programme managers. The operations at Doughboy Bay, for example, are ongoing, largely as a consequence of marram regeneration from the persistent seed bank, but they should soon be reduced to annual visits of just a few days over the next few years.

The Programme has clearly benefited from the collaboration between the Department of Conservation and the University of Otago. This book is largely based on the results of many postgraduate theses and academic articles and knowledge gained and shared by Department staff. The University community has benefitted from the opportunity to conduct research on the geomorphology and ecology of the west coast Rakiura dune systems; approaches to monitoring and operational processes; as well as the biology of particular species. It has also provided the opportunity for hundreds of student volunteers and Department of Conservation rangers, seasonal workers and volunteers, to gain experience in the Programme. In turn the Department has benefitted from a significant level of expert science support that has informed and improved operational delivery (pers. Comm. Kevin Carter, Department of Conservation). We strongly recommend this partnership model to academics, life science professionals and Department of Conservation managers. The authors hope, and expect, that the next decades of the Programme will see closer collaboration with and involvement of tangata whenua and the community.

The success of the Programme across Rakiura is due to a number of factors, but foremost is the persistence of the Department of Conservation, the foresight of a few rangers, during the 1980s and 1990s, who acted to prevent the widespread invasion of marram grass in the northern dune systems and Sealers Bay, and the commitment of Department managers, rangers and technical staff over the last 21 years. The vision of the former Conservancy Advisory Scientist in the Southland Conservancy and past and present Technical Support Officers was critical to the success of the Programme in the latter phase. Although the Programme has some years or decades to run before the goal of marram grass and tree lupin eradication is achieved, we now have almost complete knowledge of the biology of the target species; confidence in the operational technologies; and evolving and effective methods of monitoring and reporting to prove efficacy. These methods and processes will doubtless continue to evolve, however, we anticipate that new efforts will be made over the next decade to engage with communities and tangata whenua; to better communicate the nature of the Programme; and to better celebrate the landscapes (cultural and physical), ecosystems and biodiversity of active dune systems.

Acknowledgements

The nation is indebted to the Department of Conservation staff of the (then) Southland Conservancy, who showed foresight in launching the Doughboy Bay phase of the Rakiura Dune Restoration Programme in 1999 and then greatly expanding the Programme to include Mason Bay and most other Rakiura dune systems. New Zealand and the Department of Conservation owes a very large debt to Dr Carol West, during her tenure as Conservancy Scientist with the Department of Conservation in Southland. Carol's foresight, in conjunction with Brian Rance (Technical Support Officer, Southland Conservancy), and with the support of senior Conservancy managers, led to the pioneering, large-scale, marram eradication and dune restoration on Rakiura. This work built on the ground operations on Whenua hou (Codfish Island) initiated by Robin Thomas and colleagues, and the critical marram eradication work of Terry Morecroft and other rangers, on the northern beaches of Rakiura.

The work reported in this monograph resulted from a 21-year collaboration between the University of Otago and the Department of Conservation, with significant input from the Rakiura community. This collaboration, which is ongoing, has been central to the success of the Rakiura Dune Restoration Programme. The Department involved the first author in the management of marram in Doughboy Bay in 1997 and the involvement of the University of Otago has continued since this time. The University of Otago is very grateful for this opportunity to contribute.

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The Rakiura Dune Restoration Programme (1999-2021)

Lessons Learned from 21 Years of Operations, Monitoring & Research

Rakiura National Park contains dune systems of exceptional conservation value, in large part because of the relatively late introduction of marram grass and tree lupin. The dunes of Mason Bay, Doughboy Bay and other systems contain biodiversity values, cultural and natural landscapes and landforms that have been largely lost from other coasts in New Zealand. This book examines the knowledge gained from 21 years of dune restoration in Rakiura National Park, commencing with the first helicopter operations at Doughboy Bay in 1999. The current operation is probably the largest of its type in the world. It has evolved and developed into a well-funded, well-organised and executed operation by the Department of Conservation, supported by monitoring and research by the University of Otago. We examine the botany of marram grass; the methods employed to control and eradicate marram grass; the response of marram and marram-formed dunes to herbicide; linkages between landscape development and marram colonisation and eradication; the reasons for the success of the Programme; public perceptions of the Programme; operational challenges and constraints; survey technologies; and strategies for monitoring and reporting restoration activities. Many of these lessons will, we hope, help inform the design and management of other restoration programmes, particularly those associated with coastal ecosystems.

Associate Professor Mike Hilton's research is primarily concerned with the aeolian (wind-blown) geomorphology, ecology and restoration of sandy coasts, with a particular geographic focus on coastal dune systems in New Zealand, Australia and the tropics. He has over 25 years of experience in the field of dune restoration and is currently the Secretary of the International Society for Aeolian Research.

Dr Teresa Konlechner is an authority on the botany and ecology of coastal dunes and has been involved in the Rakiura Dune Restoration Programme for over a decade. She is the foremost authority on marram grass and dune restoration processes. She is an Honorary Fellow in the National Centre for Coasts and Climate, School of Biosciences, at the University of Melbourne and holds the position of Senior Ecologist at Wildland Consultants Ltd.