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DRACOPHYLLUM SCRUB EXPANSION
ON SUBANTARCTIC CAMPBELL ISLAND,
NEW ZEALAND.

A thesis
submitted in partial fulfilment
of the requirements for the Degree of
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By
Kim Bestic

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**Abstract of a thesis submitted in partial fulfilment of the
requirements for the Degree of M.Sc.**

***DRACOPHYLLUM* SCRUB EXPANSION
ON SUBANTARCTIC CAMPBELL ISLAND,
NEW ZEALAND**

by K. L. Bestic

Campbell Island lies c. 600 km to the south of New Zealand in the Southern Pacific Ocean and is covered mostly by *Dracophyllum* scrub, tussock-grassland, and upland tundra associations. European contact with the island began in the early 1800s. The earliest accounts (1840) and photographs of the island's vegetation (1888 and 1907) indicate that scrub was highly restricted, occurring mainly as shoreline fringes and extending upslope in sheltered gullies. The island's vegetation was severely modified by widespread burning possibly from the early 1800s up to 1931 and sheep grazing from 1895 to 1991.

Photographs have been retaken periodically from fixed photo-points (the places photos were taken from in 1888, 1894, 1907, and 1941) since the 1960s, to document changes in the distribution of scrub. Photo-sequences show that *Dracophyllum* scrub cover has increased since photographs were taken in the 1800s. To estimate the changing distribution of *Dracophyllum* scrub since 1888, 33 of these photographic sequences were analysed. Scrub has increased since the earliest photographs, in particular since 1941. Yearly mean rate of increase in percent scrub cover, calculated from each photo-sequence, ranged from 0.02% to 1.85%. Some sequences did not feature any change in scrub cover. Increase has occurred partly as a thickening and expansion of pre-existing scrub patches. The photographic sequences were also analysed in terms of landscape elements to

determine if topography was a factor influencing change in scrub. *Dracophyllum* scrub generally expanded and became more dense earlier on the foreshore, lower slopes and gullies. Expansion on the mid slopes down to the foreshore and on flat bogs occurred in later stages of photo-sequences. Upper slopes (>200 m a.s.l.) remained clear of scrub.

Fifteen *Dracophyllum* stems were sampled from each of 17 plots along three transect types. Plots within any transect type had the same fertility and similar drainage conditions as each other. The age structure of the *Dracophyllum* population was estimated from annual rings. Graphs were drawn of *Dracophyllum* age structure, and related to changing land use and regional climate change to assess their relative influences. The photographic record and data on the *Dracophyllum* population age structure show that *Dracophyllum* scrub expanded dramatically from the 1930s. Phases in scrub recruitment coincided with major changes in land use. Broad climate trends of warming and drying may have encouraged recruitment, but expansion of *Dracophyllum* seems to be driven mainly by land use changes. The timing and magnitude of *Dracophyllum* expansion are determined by the presence or absence of burning and/or grazing. Differences in site fertility, and differences in drainage, probably affected by climate trends, also play a role in where *Dracophyllum* expands. *Dracophyllum* established preferentially in better-drained sites and grew faster on fertile sites at lower elevations.

The dramatic expansion of *Dracophyllum* scrub has implications for understanding human impacts and climate change, and for the management of Campbell Island for conservation values.

Keywords: *Dracophyllum*, scrub, scrub expansion, subantarctic, Campbell Island, New Zealand, photographic sequence, grazing, burning, climate change.

Preface

"The difficulties of collecting adequately representative data in remote field situations are exacerbated by limitations of time and weather conditions..." (Meurk *et al.*, 1994) ...and charismatic megafauna in the form of threatened/threatening marine mammals:



New Zealand sea lions (*Phocarctos hookeri*) breed on Campbell Island.

"The Frolicsome Sea Lions...Because sea lions spend much time ashore (on Campbell Island) sleeping in dense tussock or among scrub, it was necessary in negotiating such country to tread rather warily to avoid suddenly confronting or even stepping on one...Their agility on land was such that one had to run to escape from a threatening bull. The younger animals were rather cheeky and inclined to pester one with their attentions." Sorensen, (1951).

"Thus a Tussock-bog, for so a tract of land covered with this grass is called, becomes often a labyrinth, and sometimes a dangerous one to the visitor; for these spots are the resort of sea-lions, which, when incautiously disturbed, bite very severely." Joseph Hooker *in* Ross (1847).



Plate 1. Top: *Dracophyllum longifolium* on Campbell Island. Middle: View north from above mouth of Garden Stream, Campbell Island. *D. hybrid*, *D. scoparium*, and *D. longifolium* in foreground. Bottom: *D. scoparium* in flower on Campbell Island.

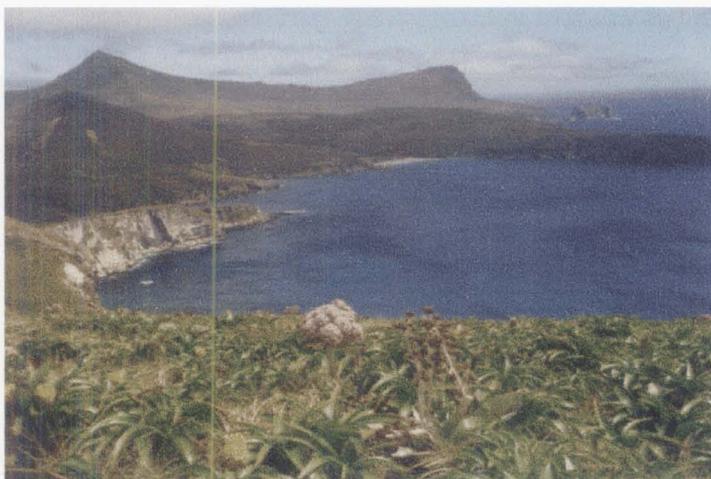
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View across Northwest Bay, Campbell Island, to Menhir, Mt Paris, and Yvon Villarceau Peak. Macroforbs in foreground are *Anisotome latifolia* (pink flowers), *Pleurophyllum hookeri* (brown flowers), and *Bulbinella rossii* (yellow flowers).

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View from Garden Cove to Beeman Hill (left) and Perserverance Harbour, Campbell Island. *Bulbinella rossii*, *Blechnum* spp. and *Poa litorosa* in foreground, *Dracophyllum* in midground.

Thankyou

- K!M..

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Chapter One: Introduction

History

Campbell Island lies c.600 km to the south of New Zealand in the cool stormy seas south of the Subtropical Convergence. First European contact with the island occurred in 1810 when explorers and sealers visited. Farming began in the late 1800s and continued into the 1930s. Formal protection of the island occurred in 1954 (all dates are A.D. unless otherwise stated) (Bell, 1970; Department of Conservation, 1997). Eradication of the feral sheep, abandoned with the cessation of farming, took place progressively in the 1970s and 1980s. Campbell Island became part of a World Heritage Area in 1998 (Department of Conservation, 1998).

***Dracophyllum* scrub expansion**

Pollen records show that 7000-3000 years B.P. (before present) *Dracophyllum* scrub (woody species < 5 m in height) was much more abundant on Campbell Island than it is now (McGlone *et al.*, 1997). *Dracophyllum* may have been more extensive at first European contact in 1810 than in 1840 when the first description of the vegetation was made, its 1840 distribution restricted to the shore and gullies (Hooker, 1844; Buchanan, 1883) possibly due to extensive fires made over those 30 years by the sealers present in the early days of sealing. It is improbable that a cold climate period like that occurring in the late 1700s and early 1800s (D'Arrigo *et al.*, 1995) would have forced down its natural elevational limit from 200 m a.s.l. to near shoreline. Photographic records extending back to 1888, and observations in the literature from 1840 on (Hooker, 1844; Buchanan, 1883) show there have been major recent changes in the distribution of *Dracophyllum*

scrub on Campbell Island. The low forest and scrub was highly restricted during the mid to late 1800s, occurring mainly as a narrow fringe on the shoreline and extending upslope in sheltered gullies. A clear increase in woody vegetation, apparent as a thickening and expansion of pre-existing *Dracophyllum* scrub, has since occurred (Zotov, 1965; Meurk, 1980; Rudge, 1986). This expansion has been most dramatic since the 1930s. Scrub has been expanding outwards from well-drained sites such as the coastline and gullies, onto more poorly drained areas such as cushion bogs and sedge swamps, and grassland on the lower and middle slopes. This change in the vegetation cover of the island provides insight into human impacts, possibly climate change, and also has implications for the management of the island for conservation values.

Hypotheses to account for scrub expansion

Two, not necessarily exclusive, hypotheses have been put forward for the increase in *Dracopyllum* scrub on Campbell Island. The first is that changes in land use over the sealing and farming periods on the island have permitted the scrub to expand (McGlone *et al.*, 1997). The second is that an increase in mean annual temperatures of at least 1 °C since the beginning of the 1900s south of the subtropical convergence (New Zealand Meteorological Service, 1941-1993; Salinger & Gunn, 1975; Adamson *et al.*, 1988), decreasing mean annual precipitation since 1860 (New Zealand Meteorological Service, 1941-1993; Salinger & Gunn, 1975; Adamson *et al.*, 1988), and accompanying drying of soil surfaces has extended the habitat suitable for woody growth (Meurk, 1977; Rudge, 1986; McGlone *et al.*, 1997).

Study objectives

This study seeks to determine the nature and cause of *Dracophyllum* scrub expansion on Campbell Island by looking at changes in the distribution of scrub cover using photographs, and by reconstructing the pattern of spread using annual rings to date *Dracophyllum* establishment.

By determining the timing, pattern and rate of expansion of *Dracophyllum* on Campbell Island and comparing this to variation in regional climate change, and changes in frequency of burning and grazing, I aim to determine which of the two hypotheses, climate change or changes in burning and grazing, can account for *Dracophyllum* scrub expansion on the island.

Chapter Two provides background on Campbell Island's physical environment and vegetation, and on *Dracophyllum* biology. The primary aim of Chapter Three is to see if historical information, in particular photographs documenting major changes in the distribution of *Dracophyllum* scrub on Campbell Island, can be used to answer questions about the dynamics of scrub in the 1800s and 1900s. I address three questions in Chapter Three: (i) to what extent was scrub restricted in the early years of European visitation? (ii) to what extent was scrub distribution affected by burning and grazing? and (iii) what was the timing and rate of scrub expansion? Chapter Four uses data from the age structure and height growth rate of the *Dracophyllum* population to determine the driving force behind *Dracophyllum* scrub expansion on Campbell Island by assessing the relative influence of changes in land use and regional climate. In this part of the study I sampled (i) the age structure of the *Dracophyllum* population, and (ii) biological and physical factors likely to affect growth, on plots located along transects on Campbell Island. Chapter Five provides a general discussion and

conclusions on *Dracophyllum* scrub expansion on Campbell Island. Future implications are also discussed.

Chapter Two: Background

Campbell Island

Location and Physical Environment

Campbell Island (11 331 ha) is an isolated subantarctic island with numerous smaller islets and stacks, lying at 52° 33.7'S, 169° 09'E (Fig. 2.0) (Meurk & Given, 1990), in a zone of persistent, strong, westerly winds (de Lisle, 1965). The climate is superoceanic (mean daily temperature range and extreme range of monthly means are both c. 5 °C), cool (mean January temperature at sea level is 9.3 °C), with a moderate sea level rainfall of 1400 mm per year over 250 rain days, and is humid and cloudy (de Lisle, 1965; New Zealand Meteorological Service, 1973).

The island is the eroded remains of a Pliocene volcanic cone, with a basement of schists overlain by sedimentary rock. The steep cliffs on the western coast are the remnants of the eastern rim of the caldera (Wardle, 1991; McGlone *et al.*, 1997), which was removed by marine erosion (Fleming, 1980). The valleys to the east of the island are glaciated (Fleming, 1980; Wardle, 1991) and some are flooded by the sea, forming fiord-like inlets (Fleming, 1980). The highest point is Mt Honey (558 m). Soils are predominantly blanket peats which cover all except the cliffs and steepest slopes and the cold exposed tundra fellfields above 400 m (Campbell, 1981).

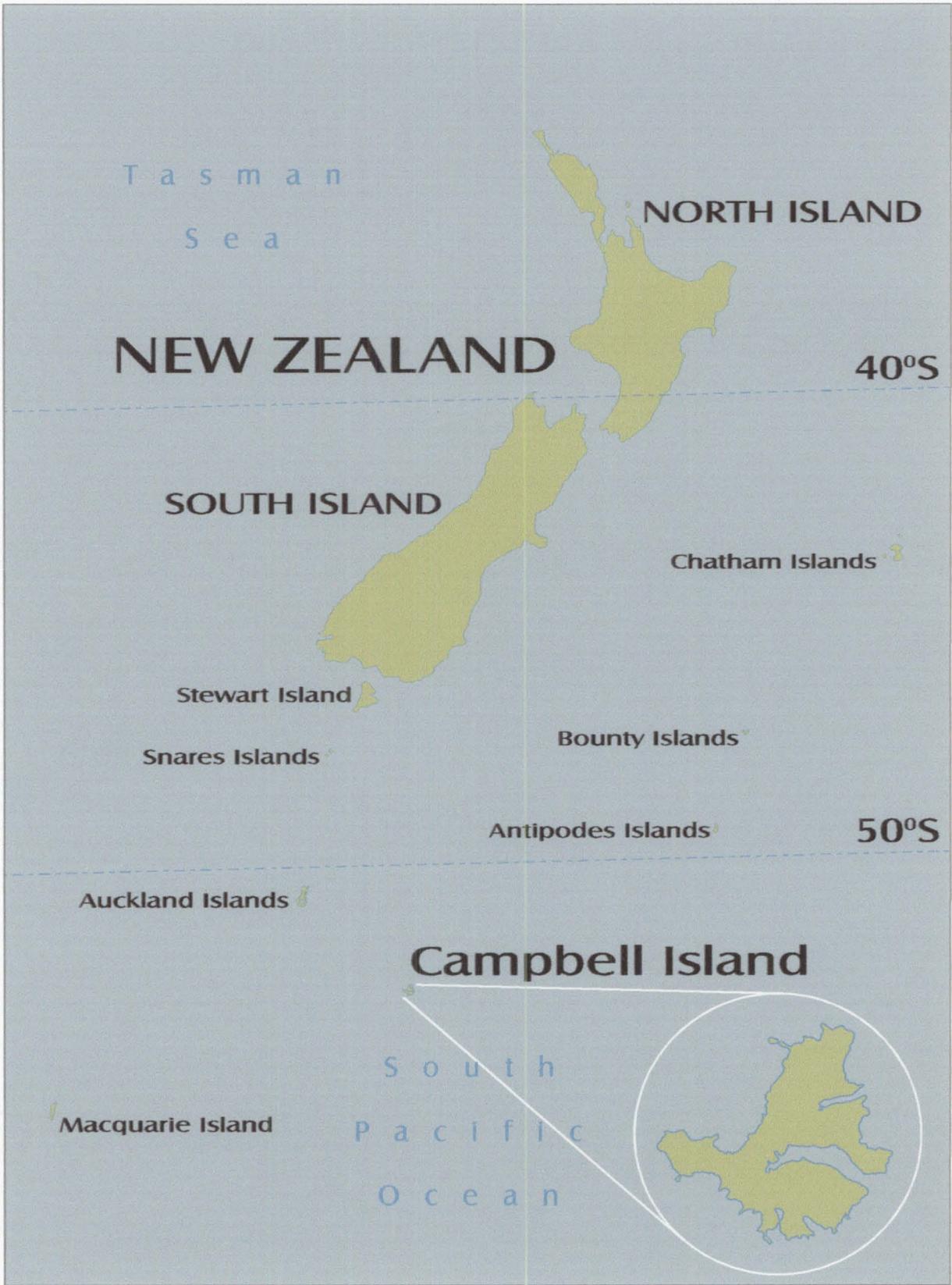


Figure 2.0. Location map of Campbell Island showing its position in relation to mainland New Zealand and other offshore islands. Insert is enlarged view of Campbell Island.

Vegetation types

Campbell Island's vegetation is subalpine in character as a result of the subantarctic maritime climate (Moore & Moffat, 1990). Scrub, tussock-grassland and upland tundra associations form most of its current vegetation cover (Meurk *et al.*, 1994). The main vegetation cover of the lowlands below 200 m is maritime tussock grassland and macrophyllous forb (macroforb) herbfields, low scrub consisting of *Dracophyllum* spp, *Myrsine divaricata* and *Coprosma* spp, and cushion bog. *Chionochoa antarctica* and *Poa litorosa* tussock-grassland occur at intermediate altitudes and tundra-like rushlands, turf grasslands and cushion fell fields above 300 m (Meurk, 1977; Meurk *et al.*, 1994). Scrubland is especially common below 200 m altitude on the eastern leeward side of the island, apart from extensive areas of oligotrophic cushion bog on poorly drained, gently-sloping interfluves (Meurk *et al.*, 1994).

There are no trees (woody species > 5 m in height) and only seven woody species on the island. *Hebe benthamii* is found in upper grass/scrubland up to 400 m in altitude, never forming more than a minor component of the vegetation. *Hebe elliptica* occurs in mixed tussock-scrub associations in sheltered harbour-side sites (Meurk *et al.*, 1994). *Dracophyllum longifolium* and *D. scoparium* are the canopy dominants in the extensive scrub associations (up to 5 m in height), especially on stable, deep, well-drained soils (Wardle, 1991). These species hybridise freely, and both may be stunted on acid bogs (Wardle, 1987; Meurk *et al.*, 1994). The divaricating shrubs *Coprosma ciliata*, *C. cuneata*, and *Myrsine divaricata* form extensive patches of low, dense, springy scrub on steep slopes, exposed sites, and on slips. They are subsidiary species in *Dracophyllum* scrubland, and form patches of low-growing scrubland in *Chionochoa antarctica* and *Poa litorosa* tussock (Wardle, 1991; Meurk *et al.*, 1994; Dawson, 1998).

Pollen history

Pollen, wood and radiocarbon analyses provide information about changes in pre-historical vegetation distribution (McGlone & Moar, 1998; McGlone, 2001). The pollen record shows dramatic long-term changes in the distribution of scrub on Campbell Island. *Dracophyllum* became common there only c. 8000 years B.P. (Wardle, 1987; McGlone *et al.*, 1997), and reached its greatest expanse and highest elevational limits (with a greater abundance than now) between 7000 and 3000 years B.P. (McGlone *et al.*, 1997).

***Dracophyllum* biology**

Dracophyllum means 'dragon leaf', alluding to their resemblance to the leaves of the 'dragon tree', *Dracaena* of Teneriffe. *Dracophyllum* are members of the Epacridaceae (Mole, 1993), a Southern Hemisphere offshoot of the Ericaceae (Evans, 1987). The Epacridaceae is a family of 31 genera (of which New Zealand has six, including *Dracophyllum*), and 400 species, which is centred in Australasia (Mole, 1993). New Zealand is the headquarters of the *Dracophyllum* genus, with only a few other species living in temperate Australia and New Caledonia (Mole, 1993). There are 35 species of *Dracophyllum* listed in Allan (1961) but more recent unpublished listings put the figure at 24 species and nine infraspecific taxa (Mole, 1993).

Usually leaves of the Epacridaceae are small and ericoid but this is not always the case with *Dracophyllum*. Leaves vary from short and needle-like to 60 cm long with a broad base (Mole, 1993). Species in the *Dracophyllum* subgenus *Oreothamnus*, to which Chatham and subantarctic island species belong, have needle-like leaves with variation in size and leaf-length proportionate to their ecological range (Wardle, 1987). The small seeds are mostly shed from capsules

and are not released en masse after fire (Wardle, 1991). *Dracophyllum* habit is fastigiate, and they range from prostrate shrubs to medium-sized trees 10 m tall (Mole, 1993). They are found in moist lowland and montane forest, and subalpine to alpine scrub (Wardle, 1991; Mole, 1993). The largest number of growth rings reported for *Dracophyllum* on the mainland of New Zealand are as follows: *D. longifolium*, 220 (Wardle, 1991); *D. traversii*, 600 (Haase, 1986); and life expectancy of *D. subulatum* c. 80 years (Rogers & Leathwick, 1994), although the longevity of *Dracophyllum* has not been widely studied.

***Dracophyllum* on Campbell Island**

The *Dracophyllum* species found on Campbell Island are *D. scoparium* Hook. f., and *D. longifolium* var. *cockayneanum* (Du Rietz) Oliver (Allan, 1961; Wardle, 1987), which both belong to the subgenus *Oreothamnus* (Wardle, 1987). Wardle (1987) suggests that *D. scoparium* is conspecific with *D. paludosum*, of the Chatham Islands, and dispersed to Campbell Island during the Holocene.

D. scoparium is otherwise endemic to Campbell Island. It is a variable shrub, with rigid leaves crowded at the branch tips and flowered racemes growing on side-branchlets (Wardle, 1987; Smith-Dodsworth, 1991). *D. longifolium* is a large erect shrub or small tree. As well as being found on Campbell Island it is widely distributed on the New Zealand mainland, where it is also known as inaka, grass tree, or turpentine scrub. Its leaves are grass-like, pale green tinted with pale orange (Wardle, 1987; Mole, 1993), tufted at the branch tips, much larger in juveniles, and persistent along the stem. The flowers are clustered, and are white with reddish tips (Wardle, 1987; Wilson, 1996). It is a major dominant of upland heaths throughout most of the South Island, with closely related species or varieties found from the Coromandel Peninsula to Campbell Island.

D. longifolium and *D. scoparium* hybridise freely and fire and sheep grazing

are thought to have encouraged development of a continuum of hybrid populations (Wardle, 1987). Oliver and Sorensen (1951) referred to the hybrid between *D. scoparium* and *D. longifolium* (hereafter referred to as *D. hybrid*) as *D. insulare*. I will use the classification for *Dracophyllum* on Campbell Island as used in Meurk (1982), ie. *Dracophyllum longifolium*, *Dracophyllum scoparium*, and *Dracophyllum hybrid*.

Chapter Three: Investigation of recent expansion of *Dracophyllum* scrub using human history and photographic records

Introduction

The earliest accounts of the vegetation of Campbell Island (Hooker, 1844; Buchanan, 1883) and early depictions and photographs of the vegetation indicate that the low forest and scrub was highly restricted, occurring mainly as a narrow fringe to the shoreline extending upslope in sheltered gullies. A clear increase in woody vegetation apparent as a thickening and expansion of pre-existing scrub has occurred since 1941 (Zotov, 1965; Meurk, 1980; Rudge, 1986).

The primary aim of Chapter Three is to try to answer questions about the pattern of Campbell Island's *Dracophyllum* scrub expansion in the 1800s and 1900s by using historical information, especially photographs, which document major changes in scrub distribution. Photographs were taken at various locations around Campbell Island during infrequent expeditions in the early years. The number of photographs taken has increased greatly since the stationing of coast watchers during World War II, the subsequent establishment of a Meteorological Observatory in 1941, and declaration of the island as a Reserve for the Preservation of Fauna and Flora in 1954 (Bell, 1970; Department of Conservation, 1997). Since the 1960s a systematic effort has been made to locate old photographs, relocate old photo points, and to retake photographs at intervals to document the changing vegetation, along with an intensive photo documentation campaign at new sites (Meurk, 1980). All photo-sequences available were analysed to document changes in the scrub and these are discussed in the context of the human history of the island.

History of human contact

Campbell Island was discovered in 1810 on a voyage of the *Perserverance*, owned by Campbell and Co. of Sydney and captained by Frederick Hasselburg, on a voyage in search of fresh sealing-grounds. The island was heavily exploited for sealskins for several decades (Laing, 1909), although the trade became unprofitable with declining numbers of seals (Bailey & Sorensen, 1962). Sealers were sometimes abandoned on the island for months (Eden, 1955; Kerr, 1976).

Expeditions setting out for the Antarctic used Campbell, Macquarie, and the Auckland Islands for reprovisioning, as their water and wood supplies could help prolong a voyage (Ross, 1847; Kerr, 1976). Fires occurred on Campbell Island at least as early as 1840 (Wardle, 1991). In 1874 the French expedition for the observation of the transit of Venus visited Campbell Island (Laing, 1909), and in the early 1840s Ross's expedition to the Antarctic regions also visited. The botanist Hooker on Ross's expedition gave a description of the eastern harbours; "...the narrow, sinuous bays...are often margined by a slender belt of brushwood, with an abundant undergrowth of Ferns, stretching up the steep and confined gulleys (sic)...the mountains...are almost bare of vegetation, the rocky sides presenting a larger proportion of Grasses, Mosses and Lichens than in Lord Auckland's group." (Hooker, 1844, p.3). A whaling station with eleven workers operated in Northwest Bay from 1909 to 1915 (Timms *et al.*, 1978). Another whaling-station was operated by the sheep-station manager in Northeast Harbour from 1911 to 1914, with a gang of fifteen men trying oil for six months of each year, and another team started a similar operation in 1917 (Timms *et al.*, 1978). The whaling industry had ceased by 1954 (Eden, 1955). Sheep (*Ovis aries* L.), goats (*Capra hircus* L.), pigs (*Sus scrofa*), and rabbits (*Oryctolagus cuniculus*) were liberated on Campbell Island between 1880 and 1890 in an attempt to

provide food for castaways. None of these animals survived for long (Sorensen, 1950).

Farming cattle and sheep began on the island in 1895. The number of cattle (*Bos taurus* L.) never seemed to vary beyond 10 to 20 over the 70 years they were there (Timms *et al.*, 1978), although sheep numbers fluctuated. The effects of sheep and destruction of scrub by cutting and burning were evident in 1903 (Cockayne, 1903), and Cockayne observed that the scrub on the north side of the entrance to Perserverance Harbour had been “much burned”. This area is marked “Fire Wood” for cutting on A. Spence’s map (Spence, 1968). Burning was also noted by Cockayne (1903) as being used to get rid of scrub to make travelling easier for the shepherds and the sheep. Burnt scrub was noted in 1907 in the west of the island (Kerr, 1976).

Sheep numbers were estimated at 3000 in 1902, and peaked at 8540 in 1909 (Table 3.0).

Table 3.0. Campbell Island sheep population 1902-1983. 3000 sheep were imported to Campbell Island by 1902 (Kerr, 1976) and final ones removed in 1991.

Estimated sheep population	Year	Reference
3000	1902	Kerr 1976
4500	1903	Kerr 1976
7000	1907	Kerr 1976
8540	1909	Kerr 1976
8000	1916	Kerr 1976
5000	1924	Kerr, 1976; Meurk, 1977
4000	1928	Kerr 1976
4000	1931	Rudge 1986
1500	1949	Eden 1955
907	1961	Wilson and Orwin 1964
3000	1969	Kerr 1976
3500	1983	Moore and Moffat 1990

By 1912, “most of the sheep were in the south of the island around Mount Honey and (Puisseux Peak)” (Timms *et al.*, 1978). In 1916, the time of the peak sheep population, “...we did a bit of burning around Mt Faye...and we burnt ground around Lyall Peak where it was mostly scrub.” (Timms *et al.*, 1978).

Before this time, the north of the island “was all in fairly big scrub... and the sheep never went down there.” (Timms *et al.*, 1978). Burning was a regular practice in the South Island of New Zealand during this era and provided young tussock growth for sheep grazing (Zotov, 1965). Regrowth in burnt areas on Campbell Island consisted of grasses and tussocks (Timms *et al.*, 1978). Dense scrub covered “over a third” (Spence, 1968, p.65) of the island from 1929 to 1931, including “all the lower slopes” (Spence, 1968, p.65). The shepherds burnt off the tussock “when (they) could” (Spence, 1968). To fuel the wood-burning stove, the shepherds used their dinghy to tow *Dracophyllum* wood in a punt large enough to hold twenty bales of wool, up Perserverance Harbour to Tucker Cove (Spence, 1968). Little regeneration of *Dracophyllum* stands had occurred by 1952 along the northern side of Perserverance Harbour where this cutting and burning had reduced it considerably (Bailey & Sorensen, 1962). Burning and cutting stopped with the end of farming, which had met with “indifferent success” due to logistical and economic problems, in 1931. Four thousand sheep and about twenty cattle were abandoned on the island (Rudge, 1986).

Wartime Coastwatchers were stationed in Perserverance Harbour on Campbell Island from 1941-1945 (Sorensen, 1950). The Campbell Island Station then remained in place as a Meteorological Station (Sorensen, 1950), staffed until its automation in 1990. Campbell Island became a Nature Reserve in 1954 (Bell, 1970), and a World Heritage Area in 1998 (Department of Conservation, 1998).

Sheep numbers decreased from their peak in 1909, until the 1960s. They then increased unexpectedly (Wilson & Orwin, 1964; Kerr, 1976) (Table 3.0). This was a catalyst for a controversial proposal by the Ecology Division of the Department of Scientific and Industrial Research to evaluate the effects of sheep on the flora and fauna by erecting a fenceline across the island from Tucker Cove to the cliffs west of Col Peak, in 1970, to restrict the sheep to half the island

(Taylor *et al.*, 1970). Sheep were then eradicated from north of the “1970 fenceline”. The sheep population south of the fence increased from 2500 to 3500 by 1983. A second fence was erected in 1984, restricting sheep to the southwestern-most part of the island. The foliage of many of the woody plants (*Dracophyllum*, *Myrsine*, and *Coprosma*) were browsed so heavily on the west side of the 1984 fence that some of them died (Moore & Moffat, 1990). In 1991 the remaining sheep were shot (Moore & Moffat, 1990).

Methods

Changing *Dracophyllum* scrub cover on Campbell Island between 1888 and 1998 was assessed through the interpretation of photographs taken first by early visitors in the 1800s, and subsequently retaken at various intervals from the same place by visiting scientists in the 1900s. Table 3.1 shows the 33 photo-sequences analysed for change in percent scrub cover with data on locations of the photo-points, years the photographs were taken, and photographers, with percent annual rate of change in scrub cover between consecutive photos. These form a collection of 83 individual photographs (archived by Landcare Research, Lincoln), consisting of 33 photo sequences, with intervals between photographs ranging from 3 to 110 years.

Table 3.1. Photograph sequences used in this study to analyse the changes in percent *Dracophyllum* scrub cover showing date, photographer, location, and annual rates of change (a, b, and c refer to photographs with more than one distinct view, such as the near and far sides of a harbour).

Date of photograph	Photographer	Location (aspect = N,S,E,W)	Sequence i.d.	Percent annual rate of change between consecutive photographs (nc = no change)
1888 1970	Dougall Meurk	N face Mt Honey from Perserverance Harbour	17	0.21
1888 1971	Dougall Meurk	N side North East Harbour from S side	18	nc
1888 1971 1998	Dougall Meurk Meurk	Beeman Hill from boat	24	0.36 1.48

1888 1971 1998	Dougall Meurk Meurk	Garden Cove from Camp Cove	25	0.24 0.19
1888 1971 1998	Dougall Meurk Meurk	Homestead Ridge from Camp Cove	26	0.36 1.85
1888 1984 1998	Dougall Meurk Meurk	Looking SW up Lyall Ridge from its E end, above North East Harbour	20a 20b	0.03 0.71 nc
1888 1998	Dougall Meurk	Smoothwater Bay from E end Lyall Ridge	21a 21b 21c	0.18 nc 0.18
1894 1984 1995 1998	Morris Meurk Meurk Meurk	Spur of Lyall Ridge towards Moubray	22	nc
1907 1960 1970 1998	Kidson Godley Meurk Meurk	Shoal Point from Camp Cove campsite	3a 3b	0.38 135 0.36 0.38 1.5 0.36
1907 1971	Marshall Meurk	Panorama N-NE-E from Mt Paris summit	12a 12b	0.63 0.31
1907 1971	Opie Meurk	Head of Hooker Valley	7	nc
1907 1971	Opie Meurk	East slopes Faye from E spur Mt Faye	8	0.39
1907 1971	Marriner Meurk	Camp Cove campsite from Venus Bay	2a 2b	0.78 1.41
1907 1971	Kidson Meurk	North West Bay from S	15	0.31
1907 1971 1975 1984	Marshall Meurk Meurk Meurk	My Lyall summit-rock	11	nc
1907 1971 1998	Marshall Meurk Meurk	Menhir from 1984- stile on Dumas	13	0.16 1.48
1907 1971 1998	Marriner Meurk Meurk	Grave site, Tucker Cove	1	0.63 -0.37
1907 1971 1998	Marshall Meurk Meurk	1970 fenceline from Col Peak	5a 5b	0.31 0.37 -0.63 0.37
1907 1998	Marriner Meurk	Head of Kirk Valley	14	0.14
1941 1960	Cape Expedition -Knowles Godley	Six Foot Lake from Honey/Filhol saddle	36	2.11
1941 1960 1970	Cape Expedition Godley Meurk	Lyall/Beeman saddle from Tucker Camp	4	1.58 3
1941 1970 1998	Cape Expedition Meurk Bestic	Homestead Ridge from Beeman Hill summit	37	1.9 0.54
1941 1971	Cape Expedition Meurk	Northeast Valley from N side west Lyall Ridge	9	0.17
1941 1971	Cape Expedition -J.A.C. Meurk	W cliffs of Col	16	nc

1941 1971	Cape Expedition Meurk	Tucker Valley from Lyall/Col saddle	28	0.5
1941 1971	Cape Expedition Meurk	W slopes Beeman from W Tucker Valley	29	0.67
1941 1971	Cape Expedition Meurk	E Tucker Valley from Tucker camp	30	1.33
1941 1975	Cape Expedition Meurk	Homestead site, Tucker Cover	27a 27b	0.44 1.32
1961 1970 1998	Godley Meurk Meurk	Shag Point from E of Mt Honey summit	32a 32b 32c	nc nc nc 0.56 nc nc
1961 1970	Godley Meurk	Monument Harbour from S slopes Mt Honey	33a 33b	nc 0.56
1961 1970 1998	Godley Meurk	Tucker Cove from Mt Honey summit	34a 34b	nc nc 0.56 0.89
1970 1998	Meurk Bestic	Tucker Cove from Beeman Hill summit	38	1.07
1970 1998	Meurk Meurk	Tucker Camp from Beeman Hill summit	39	0.36

The method used is comparable to that used by Mark (1978) to follow vegetation changes in Mount Aspiring National Park, and also to that described in Debussche *et al.* (1999), who used old postcards to look at changes to landscapes and vegetation in the Mediterranean. Comparison of photographs taken over time in this way has been found to be an effective method for assessing cover of visually dominant species in studies of vegetation changes in transects in the Waitaki Basin, (Hunter & Scott, 1997) and alpine tree-lines in Glacier National Park, Montana U.S.A. (Butler *et al.*, 1994).

Sequences of photographs were selected for analysis if all photographs showed landscapes with clearly recognisable vegetation boundaries and were not obscured by low cloud or cloud-shadows. Each photo-sequence was divided into landscape elements comprising: upper slope (>200 m a.s.l.), mid slope (50-200 m a.s.l.), lower slope (<50 m a.s.l.), foreshore (area extending c.10m inland from high tide line), flat bog (flat area with poor drainage), and gully/stream (steep-sided narrow valley or alongside waterway). One to six of these could be visible in any one photo-sequence. Landscape elements were chosen to relate to topography

rather than vegetation or other variable features and thus remained constant throughout the sequence. Percentage cover of scrub was visually estimated for the whole of each photograph with the assistance of a standard foliage cover scale (Payton *et al.*, 1999). Percentage cover is measured from the oblique perspective shown in photographs and not from vertical. Rates of change between whole photographs in each sequence were calculated and expressed as percentage change in cover of scrub per year.

Landscape elements were also assessed separately as to whether they showed an increase, decrease or no change in scrub cover between consecutive photographs, to determine whether topography was a factor influencing change. A tally was made of occurrences of increase, decrease or no change in scrub cover for each landscape element in each view (a photograph could have more than one distinct view, such as the near and far sides of a harbour) of each photo in each sequence.

Results

The location of the photo-points is shown in Fig. 3.0, and the area covered in each photo-sequence is shown on Fig. 3.1 and Fig. 3.2, a-e.

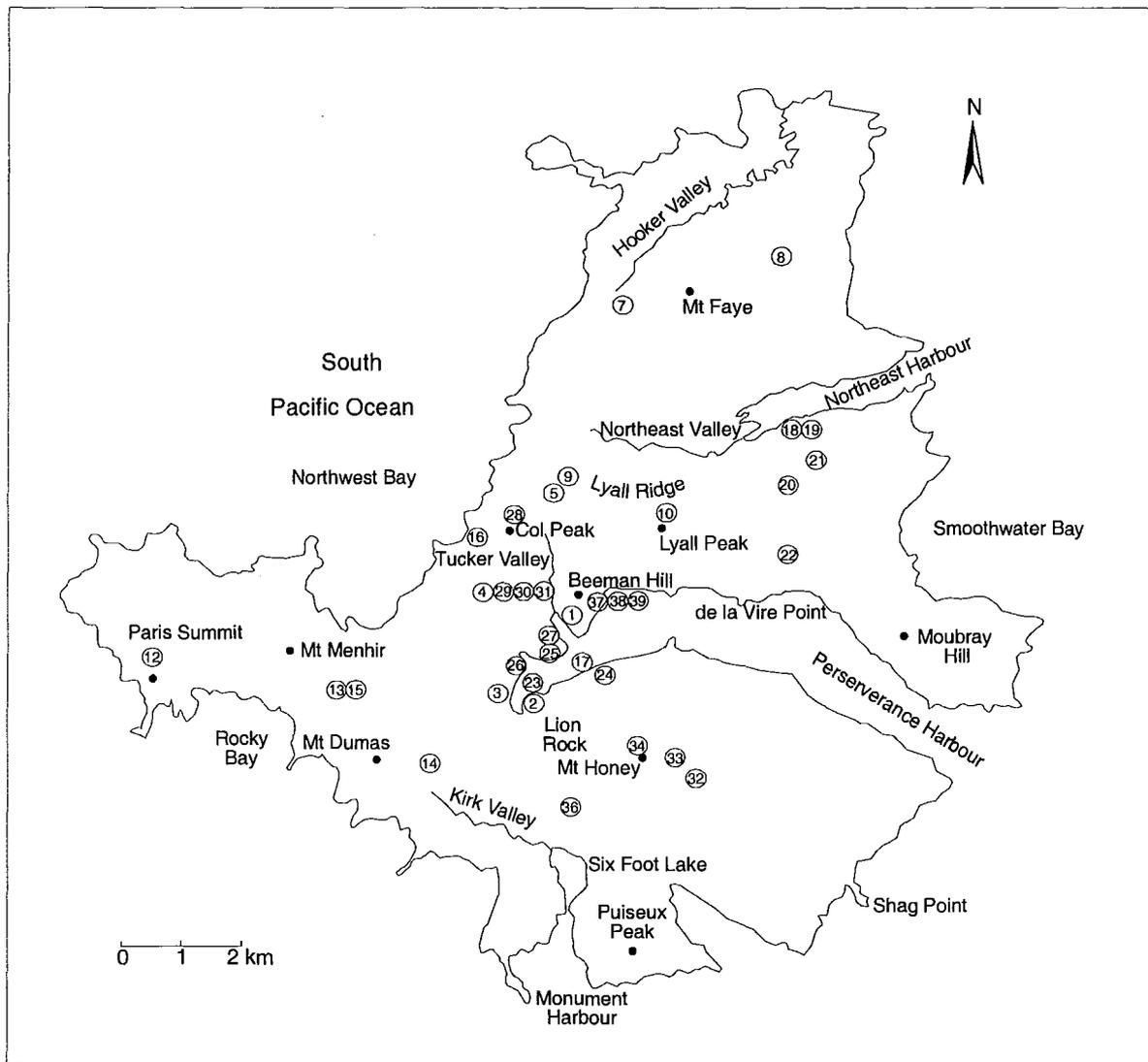


Figure 3.0. Location map of all photo points that photograph sequences were taken from on Campbell Island. The photo point numbers correspond to the numbers in Fig. 3.2.

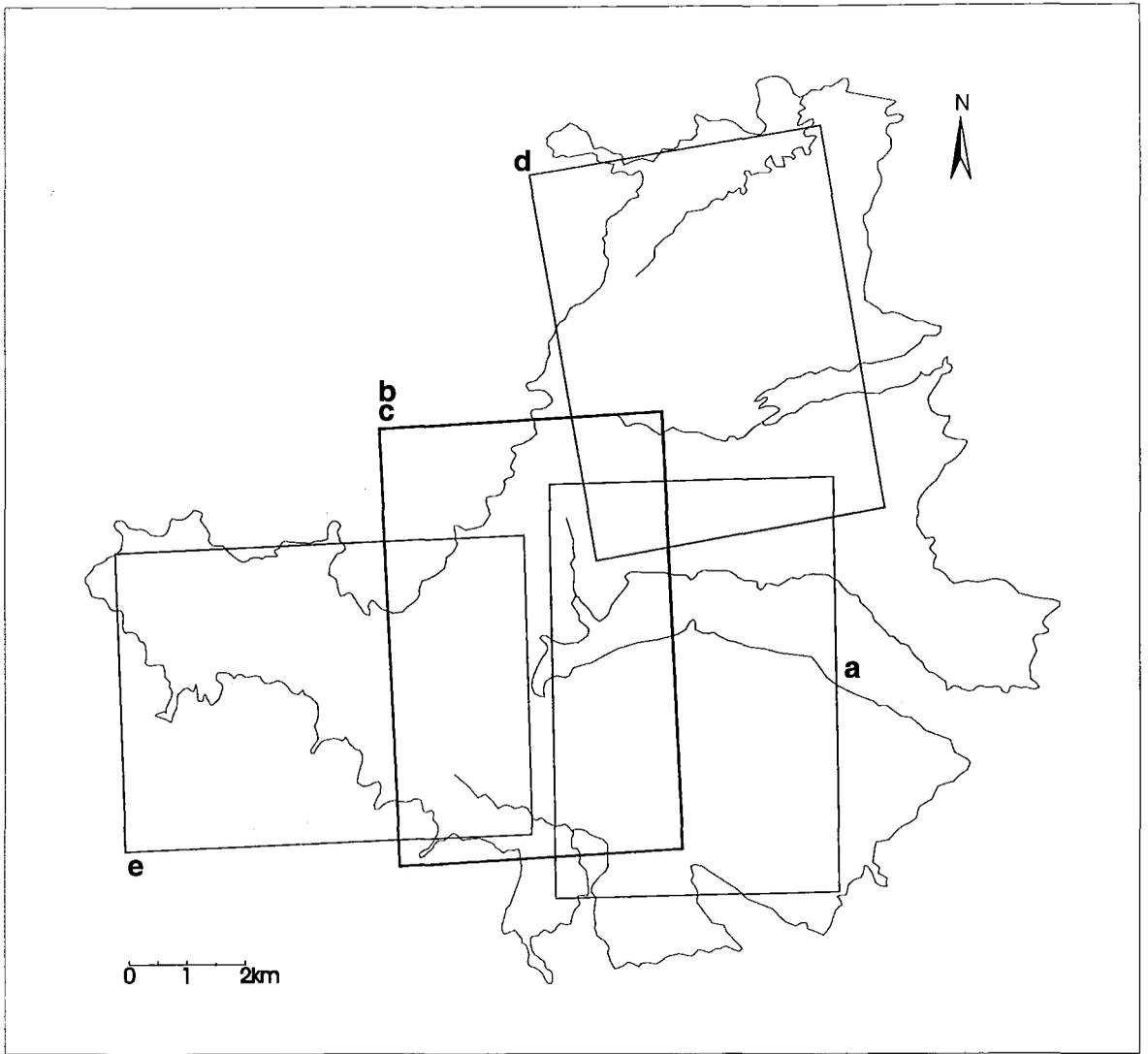


Figure 3.1. Map of Campbell Island. Boxes a, b, c, d and e show the areas covered in Fig. 3.2 a, b, c, d and e.

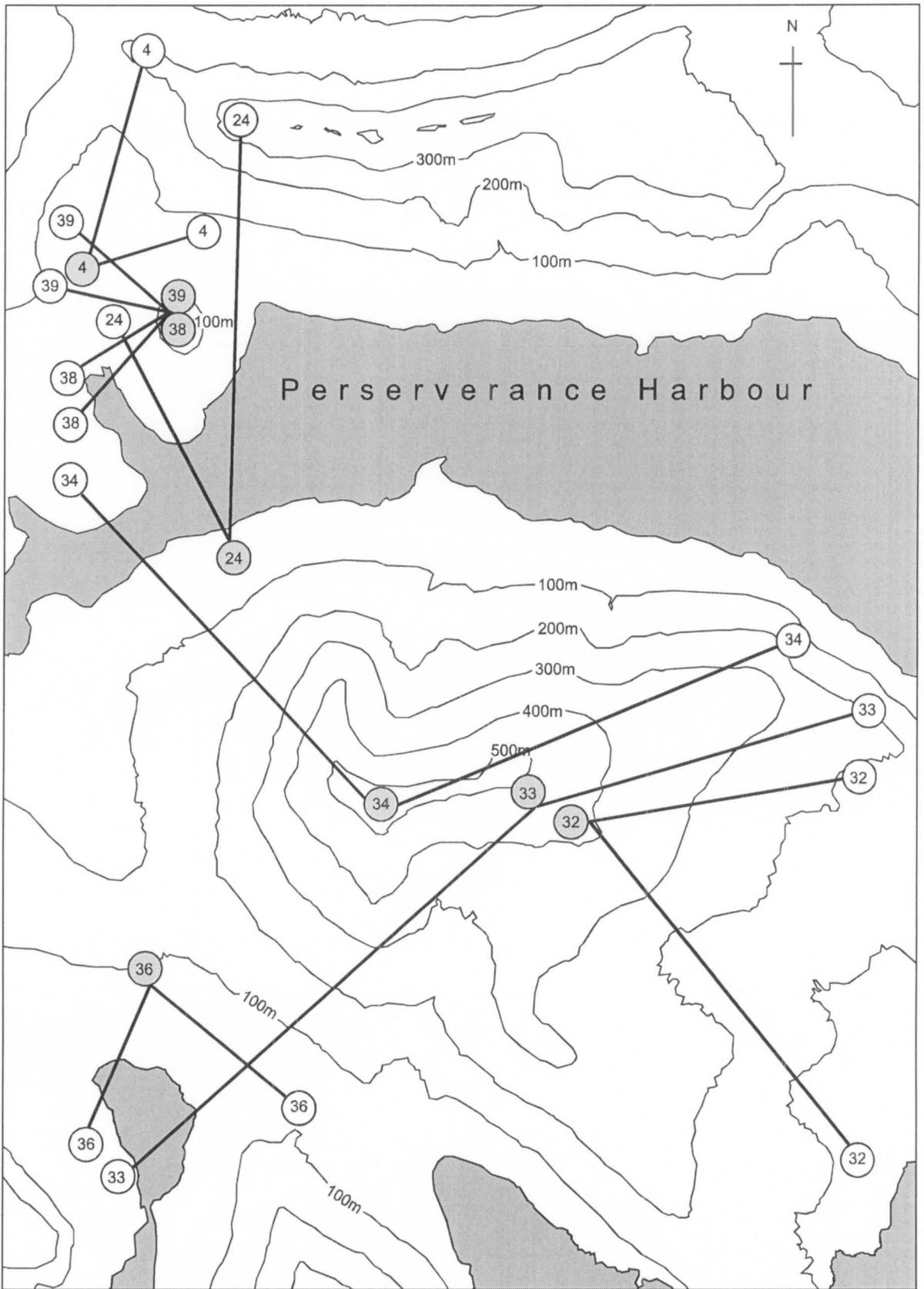


Figure 3.2 (a) shows a section of Campbell Island (a, Fig. 3.1) and the location of the photo points within that section. Shaded circles mark the location the sequence was photographed from. Numbers in open circles identify outer margins of each photo sequence. Straight lines between shaded circles and open circles of the corresponding number indicate the edge of the field of view. The area between two straight lines of corresponding number is the area visible in the photo-sequence of that number.

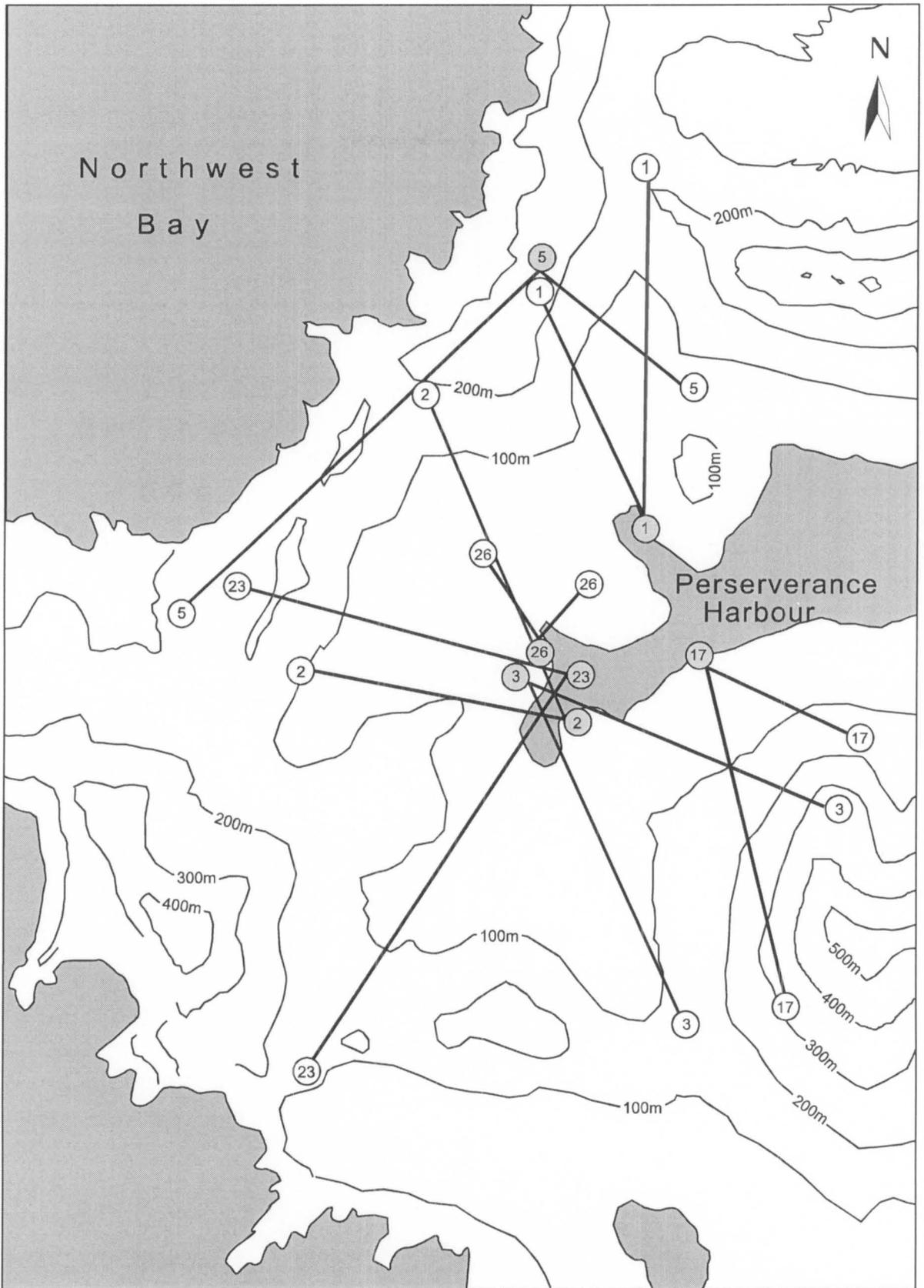


Figure 3.2 (b) shows a section of Campbell Island (b, Fig. 3.1) and the location of the photo points within that section. Shaded circles mark the location the sequence was photographed from. Numbers in open circles identify outer margins of each photo sequence. Straight lines between shaded circles and open circles of the corresponding number indicate the edge of the field of view. The area between two straight lines of corresponding number is the area visible in the photo-sequence of that number.

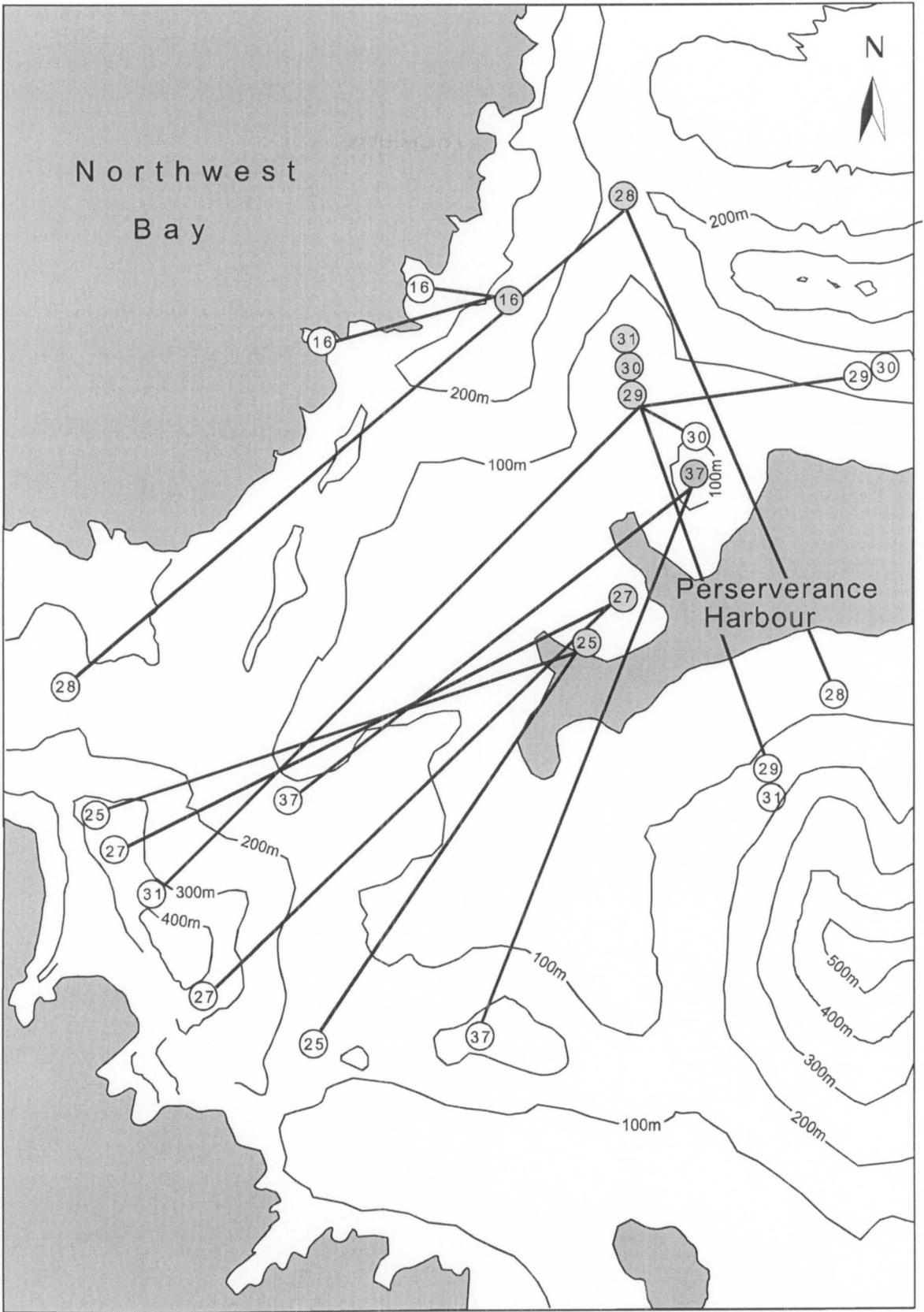


Figure 3.2 (c) shows a section of Campbell Island (c, Fig. 3.1) and the location of the photo points within that section. Shaded circles mark the location the sequence was photographed from. Numbers in open circles identify outer margins of each photo sequence. Straight lines between shaded circles and open circles of the corresponding number indicate the edge of the field of view. The area between two straight lines of corresponding number is the area visible in the photo-sequence of that number.

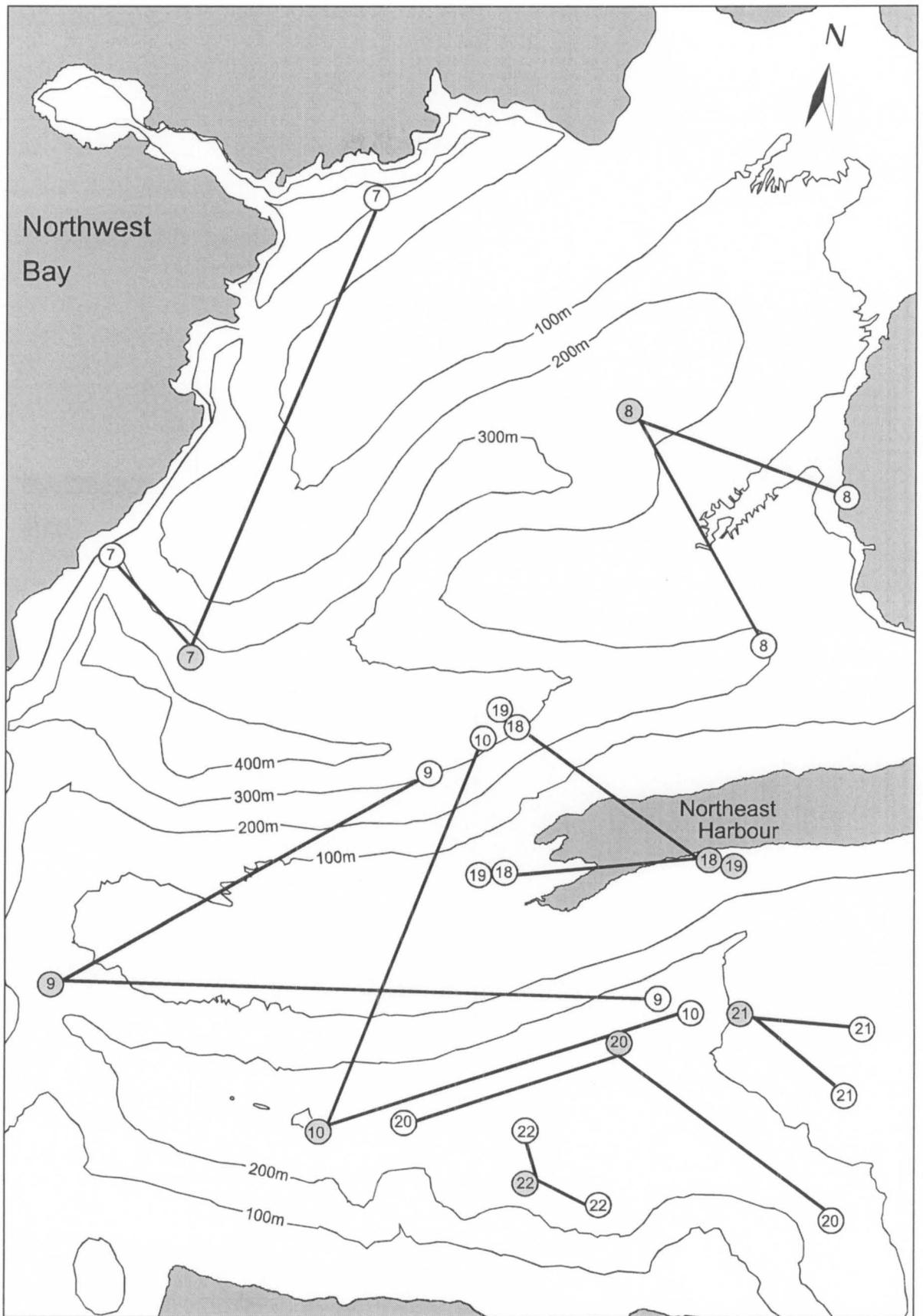


Figure 3.2 (d) shows a section of Campbell Island (d, Fig. 3.1) and the location of the photo points within that section. Shaded circles mark the location the sequence was photographed from. Numbers in open circles identify outer margins of each photo sequence. Straight lines between shaded circles and open circles of the corresponding number indicate the edge of the field of view. The area between two straight lines of corresponding number is the area visible in the photo-sequence of that number.

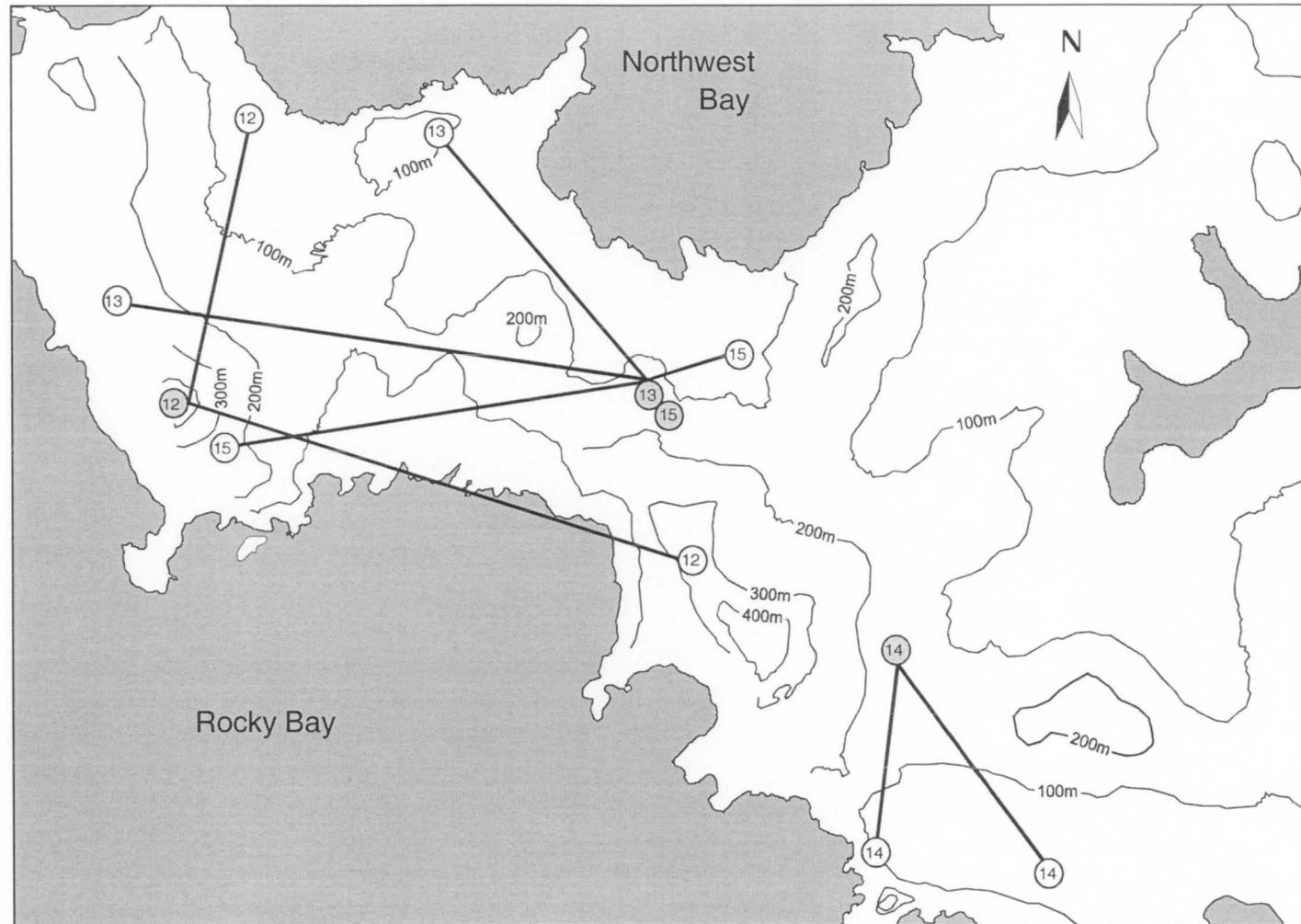


Figure 3.2 (e) shows a section of Campbell Island (e, Fig. 3.1) and the location of the photo points within that section. Shaded circles mark the location the sequence was photographed from. Numbers in open circles identify outer margins of each photo sequence. Straight lines between shaded circles and open circles of the corresponding number indicate the edge of the field of view. The area between two straight lines of corresponding number is the area visible in the photo-sequence of that number.

Figures 3.3, a-f, are a selection of the photo-sequences used in this study.

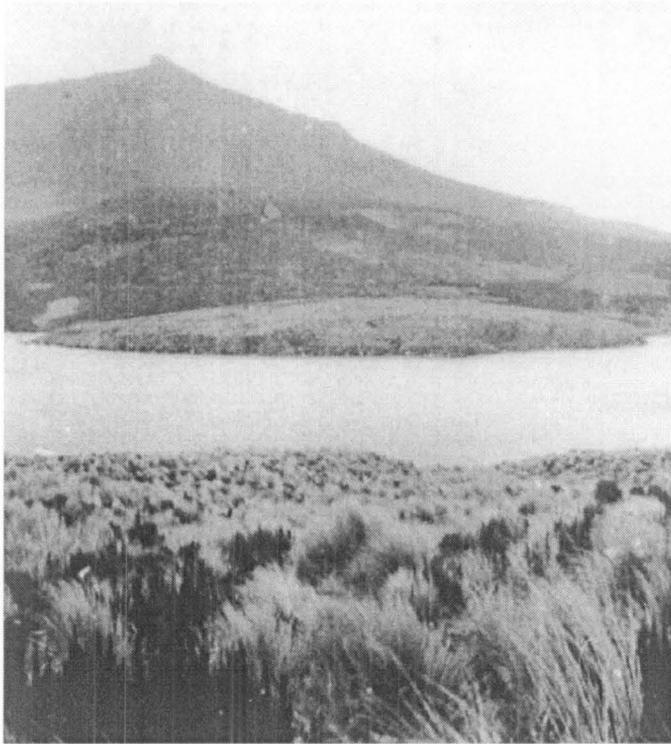


Figure 3.3 a. Photograph sequence 3.

Top: 1907, *Dracophyllum* scrub does not reach beyond Lion Rock at c. 150m elevation (rock outcrop halfway down photo). The low plateau at the base of Mt Honey, and Camp Cove in the foreground, are dominated by tussock with only scattered pockets of scrub. Photo: Kidson.

Bottom: 1960, *Dracophyllum* scrub has spread into areas that were previously covered with tussock, but not above the Lion Rock outcrop. Photo: Godley. (0.4% increase in scrub cover per year).



Figure 3.3 a (continued).

Top: 1970, *Dracophyllum* scrub has expanded into areas of 1961 tussock, but there has been no spread upslope. Photo: Meurk. (1.5% increase in scrub cover per year).

Bottom: 1998, again, *Dracophyllum* scrub has spread into areas featuring tussock in 1970, but with no spread upslope. Photo: Meurk (0.4% increase in scrub cover per year).

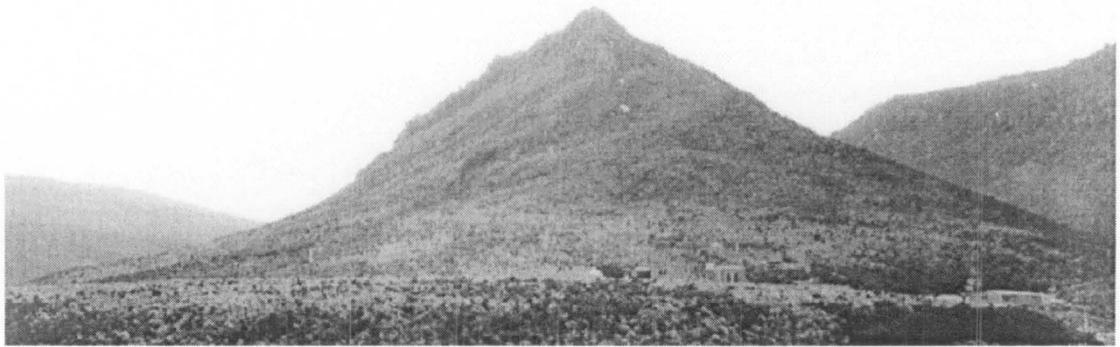
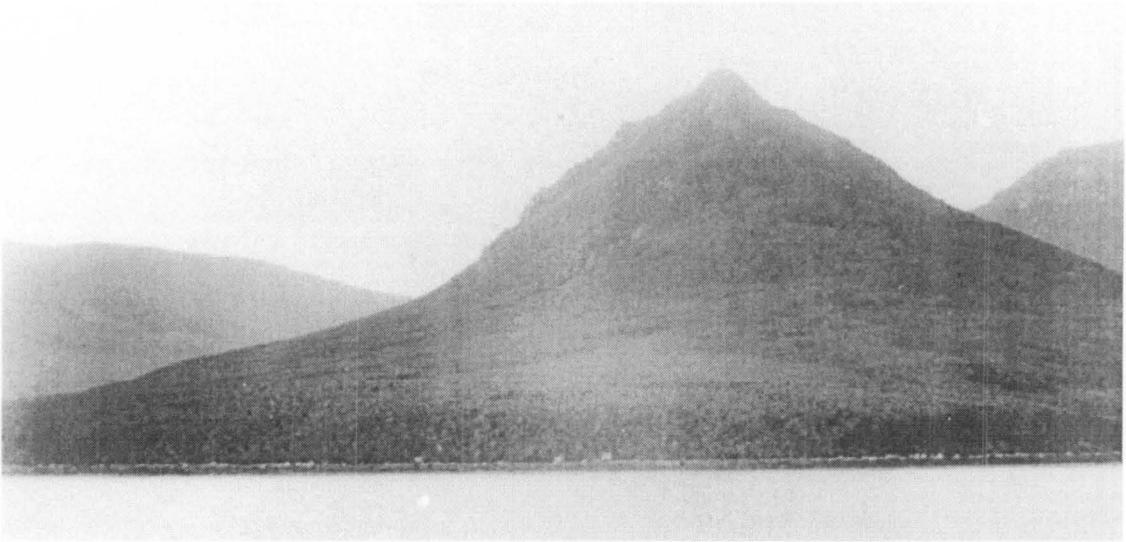


Figure 3.3 b. Photograph Sequence 24.

Top: 1888, shows *Dracophyllum* scrub confined to lower coastal fringes of the eastern side of Beeman Hill, with tussock dominating above. Photo: Dougall.

Middle: 1971, distinct spread of *Dracophyllum* scrub up the slopes of Beeman Hill. Photo: Meurk. (0.4% increase in scrub cover per year)

Bottom: 1998, *Dracophyllum* scrub has spread over much of Beeman Hill, right up to the summit at 187m. Photo: Meurk (1.5% increase in scrub cover per year).

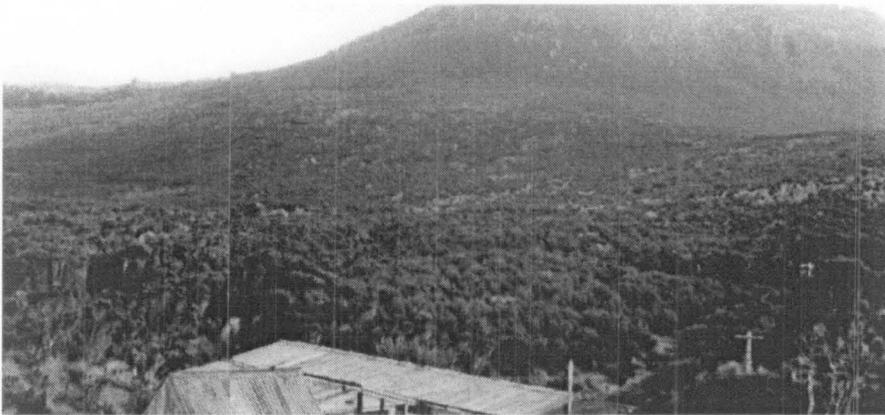


Figure 3.3 c. Photograph Sequence 4.

Top: 1941, a fringe of *Dracophyllum* scrub can be seen behind Tucker hut, behind which is extensive tussock. Photo: Cape Expedition.

Middle: 1960, *Dracophyllum* has spread behind huts and upslope. Photo: Godley. (1.6% increase in scrub cover per year)

Bottom: 1970, *Dracophyllum* scrub has expanded into areas of 1960 tussock, but there has been no further spread upslope. Photo: Meurk (3% increase in scrub cover per year).

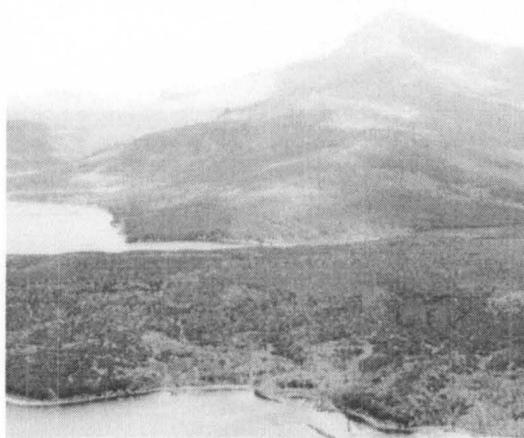
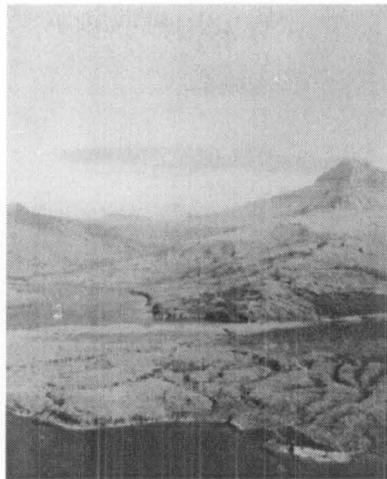


Figure 3.3 d. Photograph Sequence 37.

Top: 1941, *Dracophyllum* scrub is confined to the gullies, parts of the foreshore, and alongside streams, with a few patches higher up on ridges. Photo: Cape Expedition.

Middle: 1970, *Dracophyllum* scrub has spread into areas that were previously covered with tussock, but there has been no spread above the previous upper limit. Photo: Meurk. (1.9% increase in scrub cover per year).

Bottom: 1998, *Dracophyllum* scrub has become denser in areas covered by it in 1970, with the upper limit remaining the same. Photo: Bestic (0.5% increase in scrub cover per year).

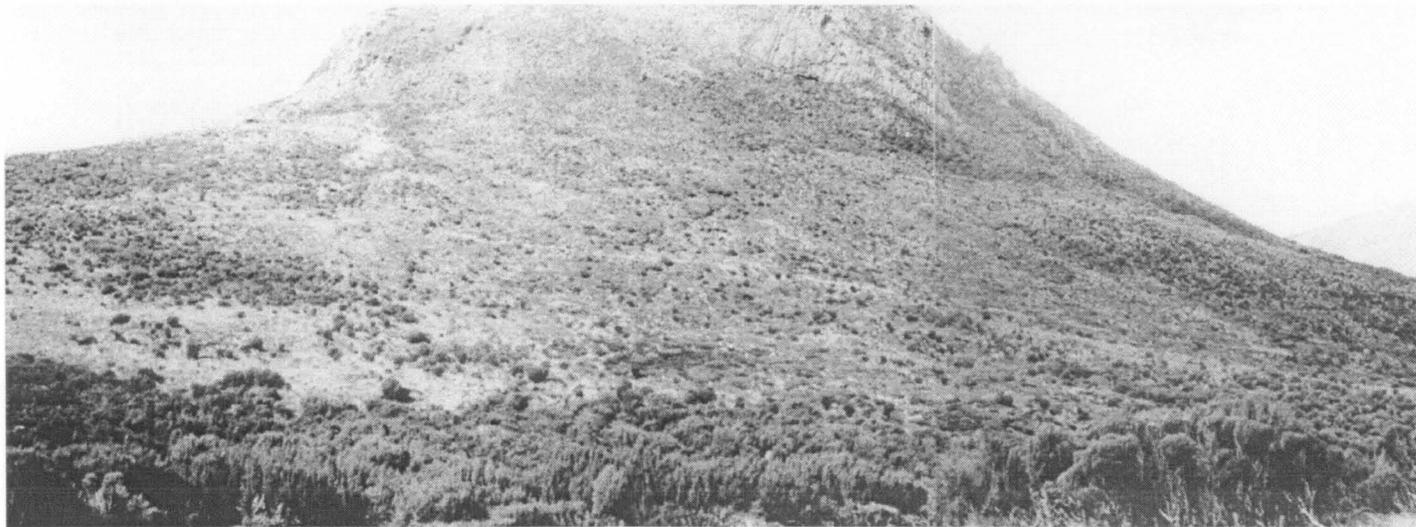


Figure 3.3 e. Photograph Sequence 29.

Top: 1941, *Dracophyllum* scrub is mainly confined to the foreground of the panorama, on the banks of Tucker Stream. A few small patches are scattered on the hillside. Photo: Cape Expedition.

Bottom: 1970, the riparian scrub is expanding onto the lower slopes of Beeman Hill, and both larger patches of *Dracophyllum* scrub and individual bushes are much more thickly scattered across its slopes. Photo: Meurk (0.7% increase in scrub cover per year).



Figure 3.3 f. Photograph Sequence 36.

Top: 1941, *Dracophyllum* scrub is visible on the slopes north of Six Foot Lake, and in gullies. Photo: J. Knowles.

Bottom: 1960, the scrub has expanded down to the shore of the lake, and expanded from the gullies onto Puiseaux Peak. Photo: Godley (2.1% increase in scrub cover per year).

A summary of mean increases in percent scrub cover per year between the first and most recent photos from each photo-sequence is shown in Fig. 3.4.

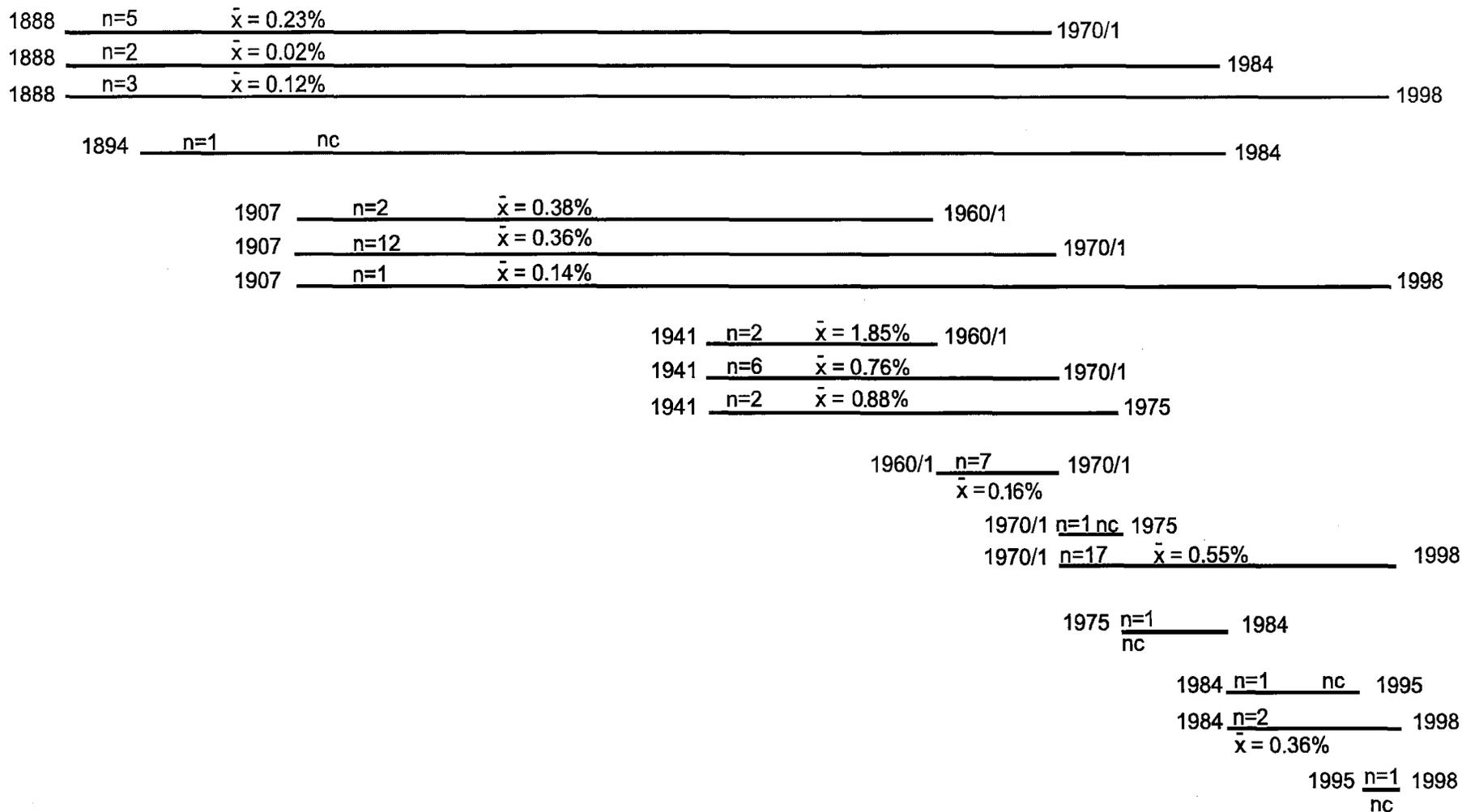


Figure 3.4. Mean rates of change in percent scrub cover per year between the photo in a sequence taken in the year at the left end of the line and the photo in a sequence taken in the year at the right end of the line. nc = no change, n = number of comparisons between consecutive pairs of photos in a sequence multiplied by the number of views in a sequence (a photograph could have more than one distinct view, such as the near and far sides of a harbour), and \bar{x} = mean of rates of change of percent scrub cover per year.

The mean increases in percent scrub cover per year ranged between 0.02 and 1.85. The photo-sequences with the longest times between photograph re-takes from the same positions are those starting before 1941. Yearly rates calculated for intervals starting in 1888, 1894, or 1907 are likely to be less informative because of the possibility of long periods of no increase in scrub.

Table 3.2 shows that change in percent scrub cover per year is dependent on topography. *Dracophyllum* scrub infilled during the period between the earliest and most recent photos, except on slopes more than 200 m above sea level which remain clear of scrub.

Table 3.2. Total number of photo-sequences featuring increase, no change, or decrease in scrub cover per year on upper slopes, mid slopes, lower slopes, gully/stream, flat bog or foreshore. A photo-sequence could include one-six of these six landscape elements.

Landscape element	Increased % scrub cover per year	No change in % scrub cover per year	Decreased % scrub cover per year
upper slopes	0	34	0
mid slopes	24	15	2
lower slopes	36	6	0
gully/stream	13	5	0
flat bog	19	3	0
foreshore	23	6	0

Dracophyllum scrub cover increased on 62% of landscape elements, decreased on 1%, and showed no change on 37%. Sequences showing no change included those where scrub was not present in any of the years that a photo was taken, or those where the sequence only showed areas above the upper scrubline or on extremely exposed coastal slopes. Other sequences where no change occurred featured either erosive peat 'blowouts', poor drainage, or had only fourteen years between photos with no change in land use in between. The first photo in one 'no-change' sequence starting in 1961 showed solid scrub, with open tussock only on extremely exposed coastal ridges and oligotrophic bogs.

The biggest differences in percentage scrub cover between any two consecutive photos occurred between photos taken in 1960/1 and the photos preceding them in their sequence (taken in 1907 or 1941) that featured much less scrub. The increase in scrub between 1960/1 and more recent photos was not as great. Photographs taken before the farming era showed *Dracophyllum* scrub in only two landscape elements: foreshore and gully/stream. *Dracophyllum* scrub generally expanded and became denser earlier on the foreshore, lower slopes, and in gullies. Expansion on to middle slopes and flat bogs occurred in later stages of photo-sequences.

Discussion

Examination of the photographic sequences has established the following.

(i) Restriction of scrub to sheltered coastal fringes and steep-sided gullies is evident in the photographs before the farming era. (ii) Most photo-sequences show an increase in scrub cover since the first photograph was taken. Percentage *Dracophyllum* scrub cover increases in almost all photographic sequences (Fig. 3.4), remaining the same only in sequences starting in 1984 and one 1970-1975 sequence. It did not decrease overall in any sequence. (iii) A resurgence in the spread of scrub is apparent in the first post-war photographs (1960/1) and continued to 1984. (iv). Scrub, initially confined to gullies and the coastal fringe, has first reclaimed lower slopes and later, upland sites. However, there is no indication of scrub spreading above 200 m a.s.l. The highest occurrences of outlying small *Dracophyllum* are c. 250 m a.s.l. Growth of these individuals is slow (McGlone *et al.*, 1997).

I address three questions: (i) to what extent was scrub restricted in early days of European visitation? (ii) what was the timing and rate of recent scrub expansion? and (iii) to what extent was *Dracophyllum* scrub distribution affected by burning and grazing?

The distribution of scrub shown in the photos before the farming era (taken in 1888 and 1894), where it is restricted to foreshore and gullies, was the same distribution as described by Hooker (1844). This suggests that any visually obvious effect the sealers and sailors had on the scrub occurred between 1810 and Hooker's visit in 1840.

The fact that the biggest differences in percentage scrub cover between any two consecutive photos occurred between photos taken in 1960/1, 1970/1, and 1975, and the photos preceding them in their sequence (except for sequences starting in 1960/1 and 1970/1 which had small differences in scrub cover), suggests that changes occurring before 1960 had a dramatic effect on scrub but were not obvious in 1907 or 1941 (the most recent prior dates when photos had been taken). These differences suggest that timing of the start of scrub expansion occurred between 1907 or 1941 and 1960, or between 1907 and 1941 but without being visually obvious in photos until 1960/1. Figure 3.4 shows that rates of change were $< 0.4\%$ / year for sequences starting before 1941, ranged from no change to 1.85% / year for sequences starting from 1940 and 1971, and from 1975–1998 there was no change in *Dracophyllum* scrub distribution in any sequences except between 1984 and 1998. This pattern suggests a low rate of *Dracophyllum* recruitment before the cessation of burning, concurrent with the end of farming, had time to have any visually obvious effect on *Dracophyllum* scrub distribution, after which the distribution of scrub expanded dramatically, levelling off again following sheep removal. The lack of change in scrub cover between pre-farming and post-farming photos coincides with a

period of burning associated with sealing and farming, which may have suppressed *Dracophyllum* recruitment. There was little increase in sequences from 1984 to 1998, during which time grazing had ceased on all parts of the island included in photo-sequences since then.

Firm conclusions are limited by the location and date of the photographs. No photographs taken before 1888 were available, and none in the 34 years after 1907. Since 1941 photographs were taken opportunistically as availability of transport to the island permitted. The photographic sequences do not cover the entire island, and the longer sequences are confined to the most accessible and heavily modified part of the island centred on the head of Perseverance Harbour.

Human activities on the island are poorly documented before 1895. Between 1811 and 1899 the cumulative total of time that sealers or whalers were living on the island was at least 3 years and 6 months. From the occasional reference in the literature (Hooker, 1844; Ross, 1847; McNab, 1907; Kerr, 1976) it seems clear that the early sealers, whalers, and transient visitors had a local impact on the woody vegetation. A great deal of wood for heating and cooking was needed by those who stayed on the cool, windy island, and visiting ships needed to replenish their fuel stocks (Ross, 1847; Kerr, 1976). Sealers needed easy access from the main harbours to make travel easier because they had to travel overland to sites inaccessible by boat (Timms *et al.*, 1978). Wardle (1991) states that fires occurred at least as early as 1840. It is likely that sealers burnt the highly flammable and slowly regenerating *Dracophyllum* to aid passage through the dense scrub and dwarf forest and waist-high tussock grasslands, as shepherds did during the farming era (Spence, 1968), and Ross's officers did in the Auckland Islands in the 1840s (Ross, 1847). "Some of our officers finding it very laborious walking through the dense brushwood in their way to the western hills, opened a road by setting fire to the dried grass and

sticks, which being fanned by a strong breeze, spread with great rapidity in all directions...The whole country appeared in a blaze of fire at night.” (Ross, 1847, p.153). The botanist Hooker on Ross’s voyage noted that *Chionochloa antarctica* dried easily and “on being ignited a rapidly devouring flame quickly spreads from one hummock to another, until many acres are blazing in a most alarming manner...after consuming all the tussocks in its neighbourhood, it communicated with the brushwood which borders the woods, and thence to the low dense forest itself...” (Hooker, 1844, p. 97). Although the fire Hooker referred to occurred on the Auckland Islands this illustrates the way fires would have travelled on Campbell Island in the *Chionochloa* tussock, which formed the major proportion of the upland vegetation (Hooker, 1844) in the 1800s, and the surrounding *Dracophyllum* scrub.

Comments made in the brief accounts about farming leave no doubt that burning was the only tool for farm management and *Dracophyllum* the main domestic fuel supply for the farm staff of up to twelve men (Spence, 1968; Kerr, 1976; Timms *et al.*, 1978). Although burning was concentrated in the tussock it must also have affected the lower scrub zone, especially at the head of Perserverance Harbour. Browse probably only had a minor direct effect on the *Dracophyllum* scrub, the browsing occurring west of the 1984 fence (Moore & Moffat, 1990) probably due to the confinement of the sheep. Although there is historic evidence of wood clearance such as firewood collection since the lowest documented quantity of scrub, prior to farming, there is no photographic evidence of this and these activities probably degraded but did not change the overall pattern.

Summary

- ◆ Historical records indicate that *Dracophyllum* scrub was confined to foreshores and gullies in the 1840s.
- ◆ Photo-sequences showed that *Dracophyllum* scrub cover has increased since the first photographs were taken in the 1880s.
- ◆ Where *Dracophyllum* scrub expands depends on topography. *Dracophyllum* scrub generally expanded and became denser earlier on the foreshore, lower slopes and gullies. Expansion on to middle slopes and flat bogs occurred in later stages of photo-sequences. Upper slopes (> 200 m a.s.l.) remained clear of scrub.
- ◆ Yearly mean rate of increase in percent *Dracophyllum* scrub cover, calculated from each photo-sequence, ranged from 0.02% to 1.85%. Some sequences did not feature any change in scrub cover.

Chapter Four: Population age structure and height growth rate of *Dracophyllum*

Introduction

Dracophyllum was much more widespread on Campbell Island 3000 years B.P. than it is now, as shown by pollen records (McGlone *et al.*, 1997). However, by 1840 it was restricted to the foreshore and low elevation gullies (Hooker, 1844; Buchanan, 1883). Earlier extensive fires by sealers (Chapter Three) probably caused this restriction. It is improbable that a cold climate period, like that occurring during the 1800s (Norton *et al.*, 1989; Norton & Palmer, 1992; D'Arrigo *et al.*, 1995; Villalba *et al.*, 1997), would have forced the natural elevational limit of *Dracophyllum* down from 200 m a.s.l. to near shoreline.

Dracophyllum scrub has been expanding on Campbell Island since some time between 1907 and 1960 (Chapter Three), and two hypotheses have been proposed to explain this (Chapter One): (i) changes in burning and grazing regimes (land use changes), and (ii) climate trends. Land use changes followed the phases of human contact with Campbell Island: sealing and exploration (1810-1895), farming (1895-1931), and feral grazing (1931-1991). Regional climate trends featured a move from a variable period characterised by cold, wet conditions from the late 1700s to the 1800s to a warmer, drier period from c.1950 (Norton *et al.*, 1989; Norton & Palmer, 1992; Villalba *et al.*, 1997; Burrows, 1976; D'Arrigo *et al.*, 1995).

I assessed the influence of both (i) changes in land use, and (ii) recent climatic trends on *Dracophyllum* scrub expansion, by measuring the *Dracophyllum* population age structure and examining differences between transects with different soil fertilities

and drainage, across a range of elevations. I also examine variation in *Dracophyllum* height growth rate. Investigation of the age structure of the *Dracophyllum* population reveals its patterns of recruitment. Height growth rate provided an index for determining site suitability for *Dracophyllum* growth.

Methods

The relative influence of changes in land use and regional climate change on *Dracophyllum* scrub expansion was determined by assessing changes in Campbell Island's scrub cover. The age structure of the *Dracophyllum* population and biological and physical factors likely to affect establishment and height growth rate were sampled on circular plots located along transects (Fig. 4.0). Year of *Dracophyllum* recruitment was then compared with changes in land use and regional climate data, and height growth rate compared with biological and physical factors affecting it.

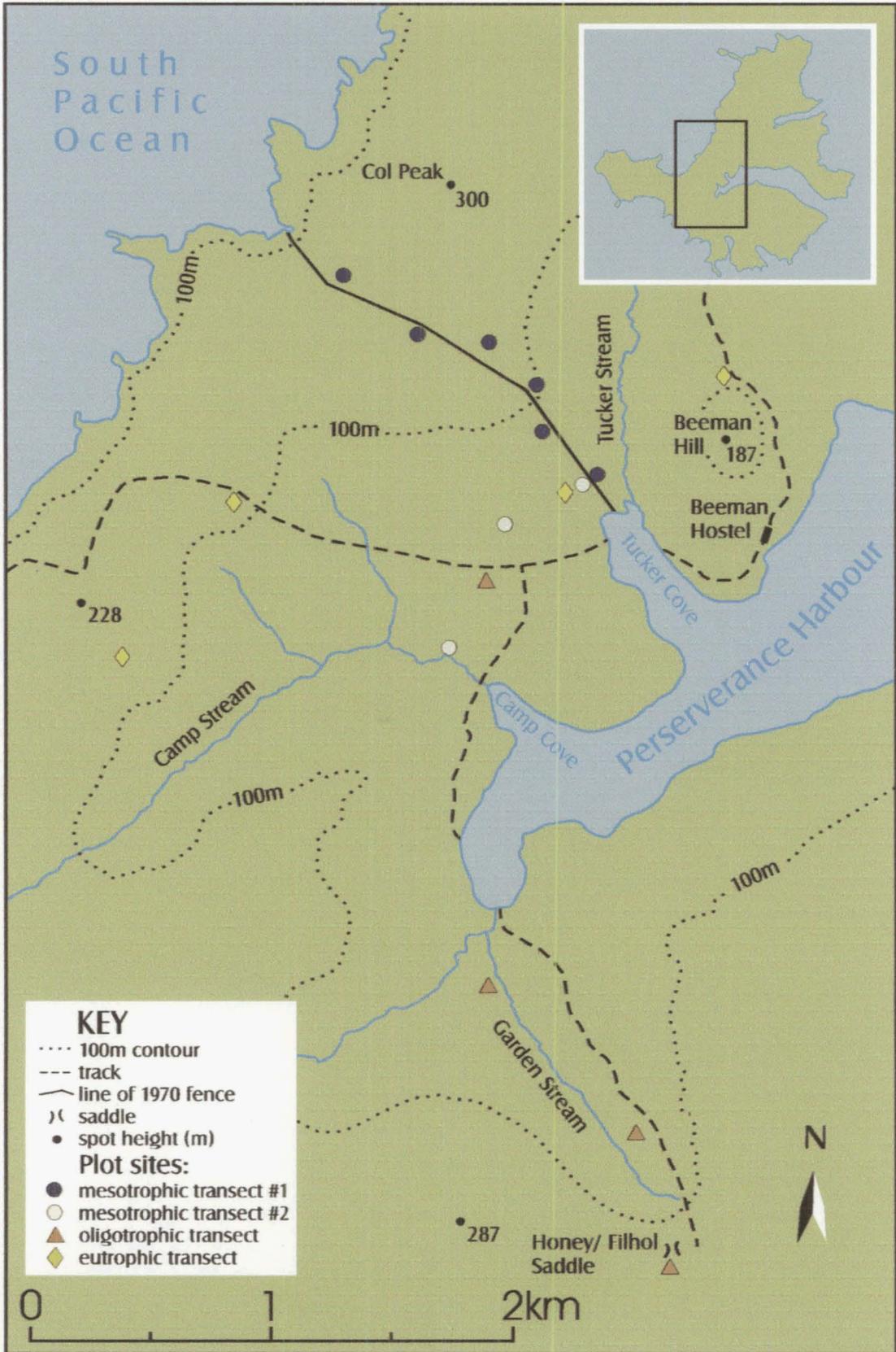


Figure 4.0. Map showing plot sites around the head of Perserverance Harbour, Campbell Island. Inset shows the location of the main map on Campbell Island. Photographs of each plot site are in the Appendix.

Field techniques

Four transects were located around the head of Perserverance Harbour (Fig. 4.0) in December 1998 – January 1999. The two physical environmental gradients that are known to be the main limiting factors for Campbell Island's vegetation are a soil fertility gradient and an elevational (or thermal) gradient (Meurk *et al.*, 1994). To avoid fertility becoming a confounding factor each transect was located on only one fertility type, and all transects except one were spread over elevations from near sea level to the scrub-line. Three to six circular plots were spaced at intervals of, on average, 35 elevational metres (measured with an altimeter) along each transect.

Species diagnostic of soil and drainage states, and observation of drainage conditions were used to determine the type of area for plot placement. Drainage was closely linked with soil fertility, and plots within any transect type all had the same fertility and similar drainage conditions as each other (Table 4.0).

Table 4.0. Relationship between transect type, fertility and drainage conditions.

Transect type	Mesotrophic	Oligotrophic	Eutrophic
Drainage	well-drained	poorly-drained	very poorly-drained
Fertility	medium fertility	low fertility	high fertility

Drainage classes were determined in the following ways: in a plot with very poor drainage, water pooled in footprints. In a poorly-drained plot a hand pressed firmly on to the substrate surface would come up damp. In a plot with good drainage a hand pressed firmly on to the substrate surface would come up dry. Moderate drainage was midway between the categories "poor" and "good". Drainage was not assessed during or immediately following rainfall.

The two Mesotrophic transects were mostly on spurs in *Dracophyllum* scrub, sometimes interspersed with *Chionochloa antarctica* tussock patches. The highest

mesotrophic plot, at 245 m a.s.l., was in *Chionochoa*/macroforb herbfield. Mesotrophic plots had moderate or good drainage. Meurk (1980) found the water table under Mesotrophic areas to be 1-2 m below the surface in dry weather. The first transect, Mesotrophic 1, sampled back into an invasion front: an area of scrub identified from historic photograph sequences as having expanded since 1940. This transect comprised six plots on a continuous line from 15 m a.s.l. to 245 m a.s.l., perpendicular to the known direction of expansion (Fig. 4.0). The second transect, Mesotrophic 2, comprised three plots with an elevational range of 10 m a.s.l. to 30 m a.s.l.

The diagnostic plant species used to identify eutrophic areas was the sedge *Carex appressa* (Meurk *et al.*, 1994), which appeared in over 5-25 % of eutrophic plots' area, while only featuring at <1 % in any mesotrophic or oligotrophic plots. Eutrophic plots had very poor or poor drainage. One transect containing four plots was located in eutrophic areas, very poorly drained sedge-swamps. Meurk (1980) found the water table under such sedge-swamps to be less than 0.1 m below the surface in dry weather. This transect had an elevational range of 13 m a.s.l. to 160 m a.s.l. (Fig. 4.0)

The Oligotrophic transect featured the turf-forming cushion plants *Oreobolus pectinatus* at 5-25 % of the area and *Astelia subulata* at 1-5 % or 5-25 %. *Phyllachne* species, *Isolepis aucklandica* (= *Scirpus aucklandicus*) and *Centrolepis ciliata* were also common turf-forming or cushion species in the Oligotrophic transect. Oligotrophic plots had poor drainage. The four plots in this transect were on poorly drained cushion bogs with an elevational range of 20 m a.s.l. to 112 m a.s.l. (Fig. 4.0)

Only the Mesotrophic 1 transect was located on a continuous line. This could not be achieved for the Oligotrophic and Eutrophic transects, because there was no suitable oligotrophic or eutrophic habitat that occurred in a continuous line from sea

level to the scrub-line. Within the patches of homogeneous mesotrophic, eutrophic and oligotrophic vegetation and drainage conditions selected for sampling, stratified random sampling was used to locate individual plots. Randomly selected numbers were used as the x and y co-ordinates to locate the point which would form the centre of each circular plot. The areas of vegetation each plot was located in were relatively large and physiognomically homogeneous, in a physiographically uniform site, as described for a vegetation survey on Campbell Island in Meurk *et al.*, (1994). From the centre of each plot, the 15-16 closest individual *Dracophyllum* plants were located for sampling. The plot diameter was set as the distance to the furthest of the closest 15-16 *Dracophyllum* plants. The height, number of stems, and stem diameter of each of the *Dracophyllum* plants in a plot were measured.

Discs were taken from the stems of all *Dracophyllum* plants in a plot (because their diameter was too small for coring) to determine the age structure of the population by counting growth rings. For multi-stemmed individuals the stem with the greatest diameter was assumed to be the oldest and sampled. Stems were cut with a pruning saw. Stems less than 10 mm in diameter were not counted or sampled.

Stems were cut as near to ground level as possible to obtain as old a sample, and therefore as accurate an estimate of recruitment date, as possible. However, in some areas it could not be assumed that ground level had been constant over time in relation to the plants' stems, because the peat surface had risen since the plants had established. To allow for this peat was scratched away where possible to reveal whether there was more, older, stem buried beneath the peat surface. If there was, discs were cut as low as possible but still above the roots' branching-point. Stem diameter was measured at the level of the cut using callipers. Dead stems were not sampled because their rings could not be seen clearly. Each disc was marked with a

code indicating its transect, plot, and individual number so other data could later be related to its age.

Besides drainage other physical variables recorded at each plot were elevation, slope angle, and aspect. Elevation was measured using an altimeter set at sea level, slope angle estimated using a protractor, and aspect measured using a compass. Vegetation type was also recorded in the categories scrub, cushion bog, sedge swamp, scrub/tussock interface, and macroforbfield (Meurk *et al.*, 1994).

A list of the vascular plant species present was recorded, along with tier and cover estimates, for each plot. To measure the proportion of the plot covered by each plant species New Zealand Forest Service Reconnaissance Description Survey percentage cover classes; <1 %, 1-5 %, 5-25 %, 25-50 %, 50-75 %, 75-100 % were used (Allen, 1992). Tier classes with a smaller range of heights per tier than the New Zealand Forest Service Reconnaissance Description Survey categories were used to measure which tier/s species were in (Allen, 1992), to allow for Campbell Island's maximum vegetation height of five metres. Categories used were tier 6 (0-0.3 m), tier 5 (0.3-1 m), tier 4 (1-2 m) and tier 3 (2-5 m).

Laboratory techniques

Dracophyllum discs were trimmed, so their cut faces were parallel to each other, and glued to hardboard, with the face from furthest down the stem uppermost. They were then sanded using graded sandpapers until they were highly polished and the rings clearly visible. I counted growth rings on three radii to minimise error using a binocular microscope, with the highest count being used as the individual *Dracophyllum* plant's age. Growth rings were assumed to be annual (Wardle, 1991).

Data analysis

I used age-class distributions to investigate patterns of *Dracophyllum* recruitment (Miller & Halpern, 1998). I plotted *Dracophyllum* recruitment patterns and the phases of land use change (Chapter Three) to visually assess any relationships between them. To see whether there were any relationships between *Dracophyllum* recruitment and climate trends I superimposed line graphs of average annual temperature and average annual rainfall on the age-class distribution (New Zealand Meteorological Service, 1941-1993). I also plotted climate trends from the literature (Burrows, 1976; Adamson *et al.*, 1988; Norton *et al.*, 1989; Norton & Palmer, 1992; D'Arrigo *et al.*, 1995; Villalba *et al.*, 1997) to visually assess relationships between them and *Dracophyllum* recruitment patterns. Age-class distributions were studied for the combined transects as well as for each individual transect type. To detect if there was any difference in *Dracophyllum* recruitment between grazed and ungrazed areas I compared recruitment frequency on either side of the "1970 fenceline" (Chapter Three).

To detect if there were any relationships between *Dracophyllum* SPECIES and AGE I plotted these variables together for each individual transect. In case ELEVATION was a confounding factor in the relationship between *Dracophyllum* SPECIES and AGE, SPECIES was also plotted against ELEVATION.

To allow for the age-height relationship I plotted height growth rate (height/age) for all TRANSECTs combined, as well as for each individual TRANSECT type to visually assess relationships between them and the following variables: (i) ELEVATION, (ii) SLOPE, (iii) INSOLATION (sunny sites were defined as north-facing

or flat without obstruction such as hills), (iv) SPECIES, and (v) TRANSECT (fertility and drainage).

I used generalised linear models to determine if there were significant relationships between height growth rate and the five variables (i – v) above. I used five univariate analyses to separately test the relationship between height growth rate and the factors SPECIES, TRANSECT, INSOLATION, SLOPE and ELEVATION.

To find whether the relationships found to be significant at the univariate level were already explained by other variables I fitted a multivariate generalised linear model with height growth rate as the response variable. I used multivariate analysis to investigate height growth rate. I looked at Multivariate p-values and F-values from Tests of Between-Subjects Effects to determine significance, and Multivariate R^2 -values from the same to determine the percentage of growth rate explained by the different variables. I studied Multivariate B-values from Parameter Estimates to determine the direction of the relationships' slope.

Results

Patterns of expansion

Dracophyllum recruitment

The broad patterns

There are three broad periods of increased *Dracophyllum* recruitment (Fig. 4.1). A period of steady but low establishment occurred between 1840 and 1900. Between 1900-1940 recruitment appears more erratic, with several periods of low or no recruitment. A major pulse of *Dracophyllum* recruitment began about 1940 and dropped away about 1970, but is followed by another pulse of recruitment beginning about 1980. The curve drops off beyond about 1985. Young *Dracophyllum* age classes, typically with stem diameters of less than c. 10 mm, were under-represented because it was difficult to count their annual rings.

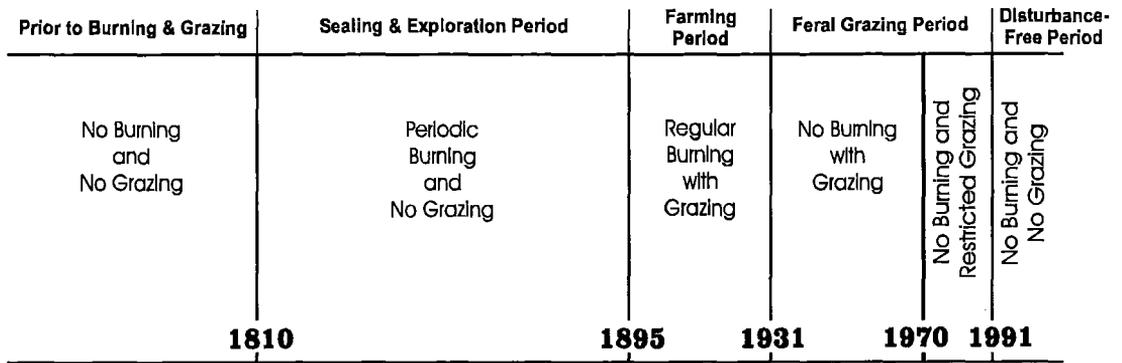


Figure 4.2. Timeline showing periods of land use on Campbell Island prior to 1810 until present day.

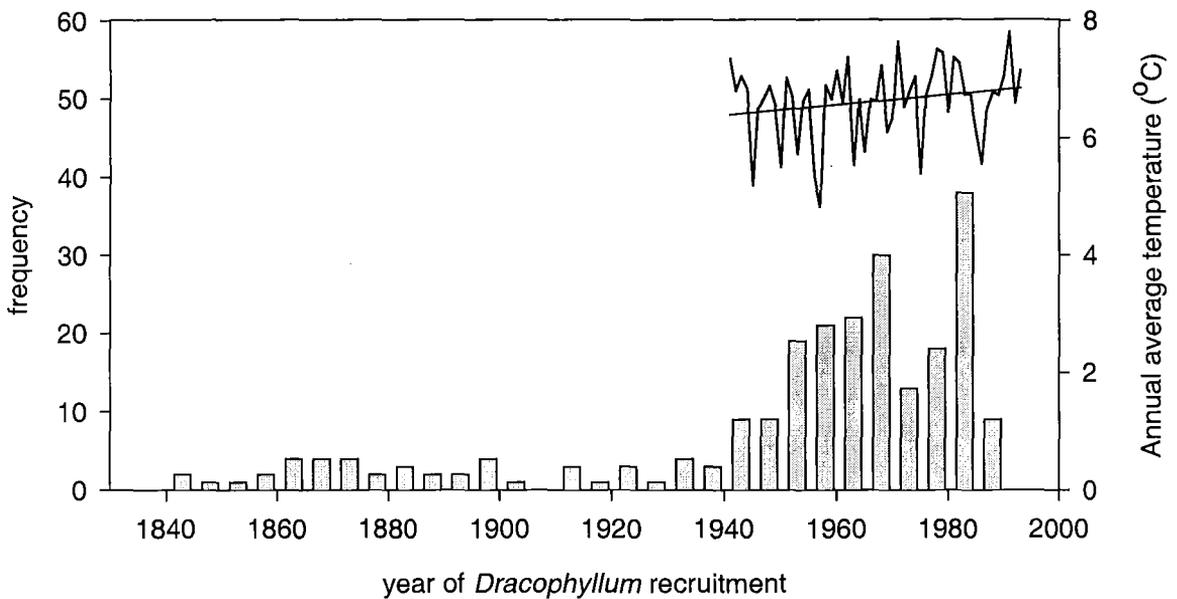


Figure 4.1. Histogram showing frequency of *Dracophyllum* year of recruitment from 1840 to 1998 in plots on Campbell Island ($n = 234$) and line graph showing mean temperature on Campbell Island from 1941 to 1993, with line of best fit ($r^2 = 0.04$).

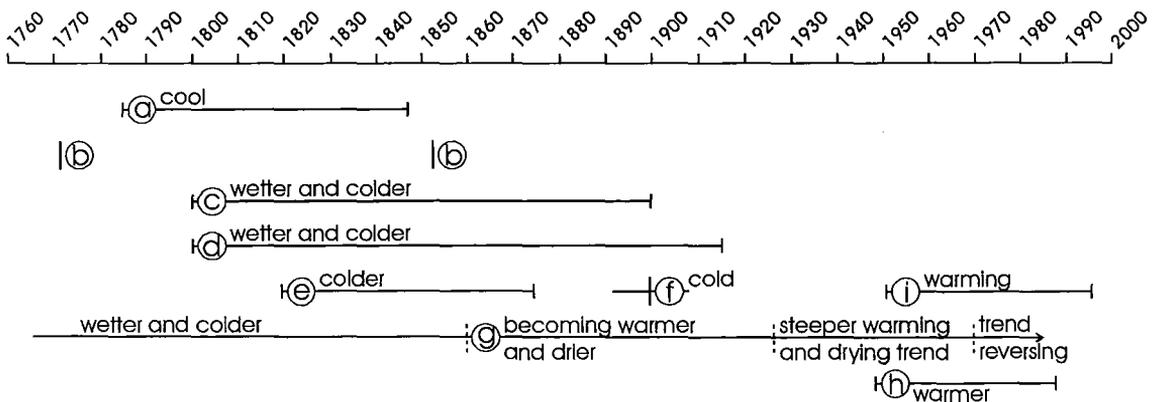


Figure 4.6. Timeline showing broad climate trends in the southwest Pacific Ocean and New Zealand sector of the subantarctic from 1770-1995. a) (Norton *et al.*, 1989; Norton & Palmer, 1992). b) Records of iceberg sightings in low latitudes (Burrows, 1976) suggest that unusually high numbers of icebergs were present in the early 1770s and early 1850s. c) (Villalba *et al.*, 1997). d) (D'Arrigo *et al.*, 1995). e) (D'Arrigo *et al.*, 1995; Adamson *et al.*, 1988). f) (D'Arrigo *et al.*, 1995). g) (Villalba *et al.*, 1997). h) (Adamson *et al.*, 1988). i) (D'Arrigo *et al.*, 1995).

Relationship to changes in land use

Changes in the recruitment pattern of *Dracophyllum* appear to coincide with changes in land use (Fig. 4.2). The Sealing and Exploration Period (1810-1895) featured infrequent burning. The decrease in *Dracophyllum* recruitment at the end of the 1800s coincides with the start of the Farming Period in 1895, with grazing and regular burning. The major increase in *Dracophyllum* recruitment from c.1940 closely follows the end of burning when farming ceased in 1931. Sheep were still present on the island until 1991 when the Feral Grazing Period ended.

Differences with and without grazing

Following the cessation of grazing there is an abrupt drop in *Dracophyllum* recruitment (Fig. 4.3). *Dracophyllum* recruitment frequency on all plots combined (Fig. 4.3) was greater with grazing than without. This was also true on mesotrophic and eutrophic plots (Fig. 4.4).

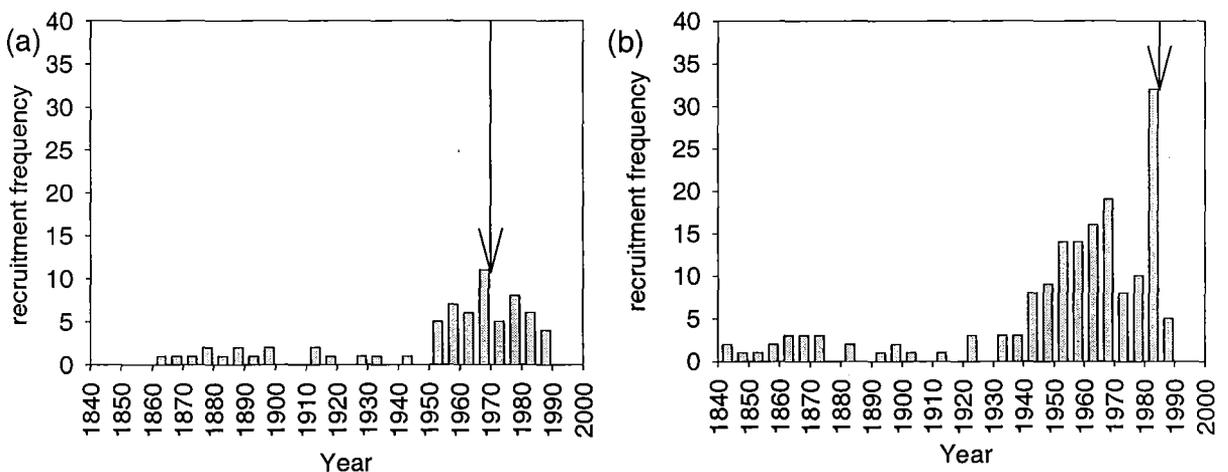


Figure 4.3. *Dracophyllum* establishment in plots (a) north of the "1970 fenceline" where sheep were present from 1895 until 1970 and (b) south of the "1970 fenceline" where sheep were present from 1895 until 1984. Arrows show when sheep were removed.

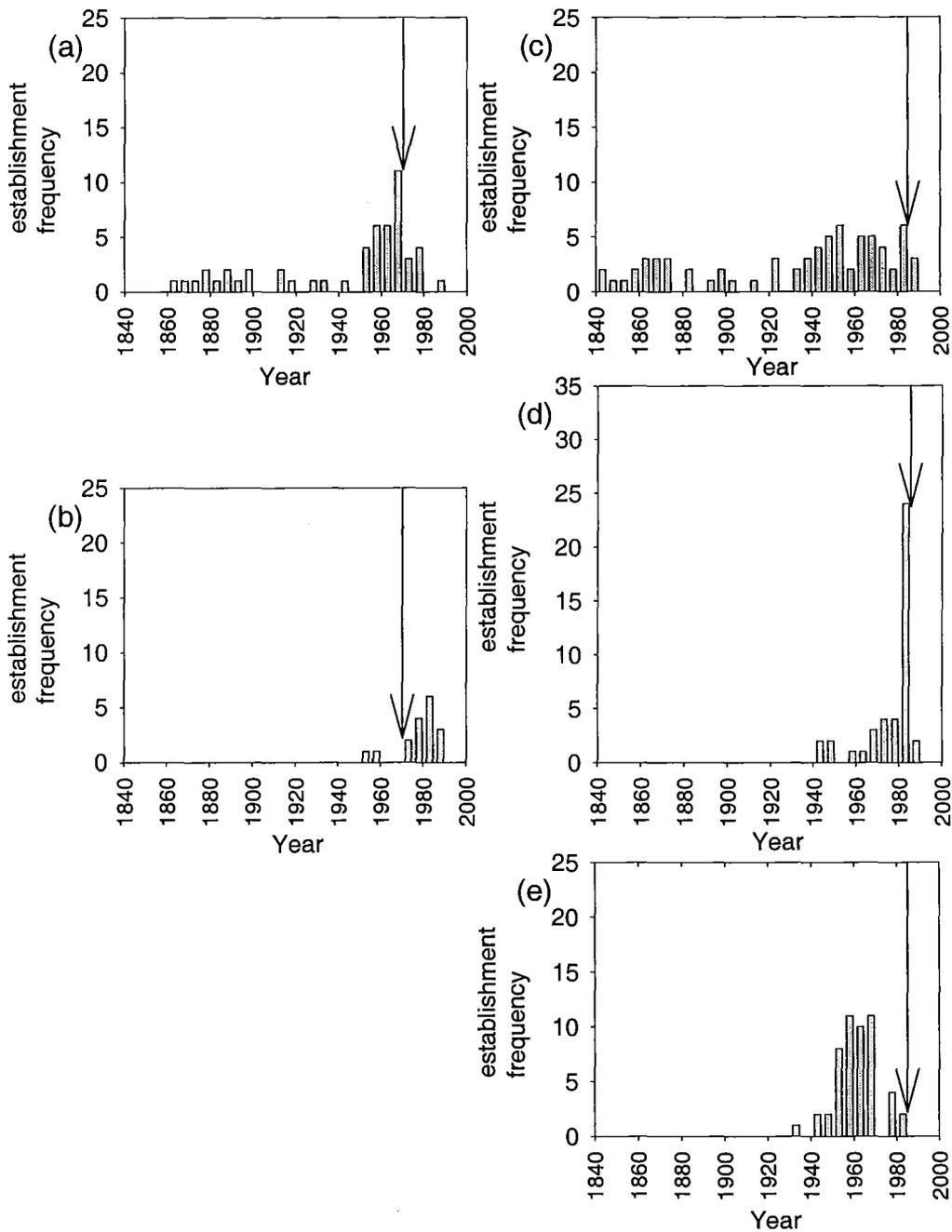


Figure 4.4. *Dracophyllum* recruitment frequency in plots (a), (b) north of the “1970 fenceline” where sheep were present from 1895 until 1970 and (c), (d), (e) south of the “1970 fenceline” where sheep were present from 1895 until 1984. Graphs (a) and (c) show Mesotrophic plots, (b) and (d) show Eutrophic plots, and (e) shows Oligotrophic plots. Arrows indicate when sheep were removed.

Relationship to temperature and rainfall patterns

The recruitment frequency of *Dracophyllum* over time was studied alongside Campbell Island's annual average temperature and rainfall (New Zealand Meteorological Service, 1941-1993), and regional climate trends from the literature (Burrows, 1976; Adamson *et al.*, 1988; Norton *et al.*, 1989; Norton & Palmer, 1992; D'Arrigo *et al.*, 1995; Villalba *et al.*, 1997). There is an increasing trend in temperature ($r^2 = 0.04$) (Fig. 4.1) and a decreasing trend in rainfall ($r^2 = 0.03$) (Fig. 4.5) on the island. The southwest Pacific Ocean and New Zealand sector of the subantarctic experienced generally cool conditions from the late 1700s until about 1900. Since then there has been a general warming trend (Fig. 4.6, page 50).

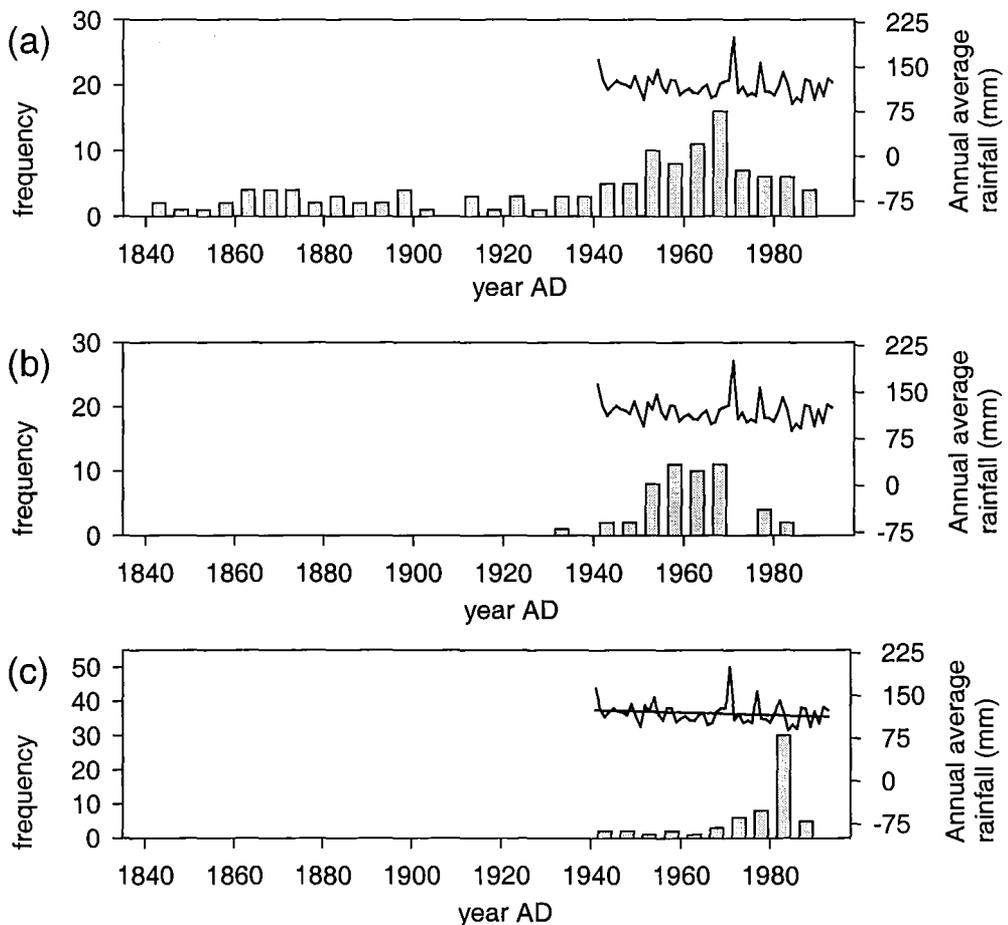


Figure 4.5 Histograms showing frequency of year of recruitment of *Dracophyllum* between 1840 and 1998 on each type of transect; (a) Mesotrophic transects ($n = 123$), (b) Oligotrophic transect ($n = 51$) and (c) Eutrophic transect ($n = 60$), alongside line plots showing annual average rainfall on Campbell Island from 1941 to 1993. Plot (c) shows line of best fit for mean annual rainfall ($r^2 = 0.003$).

Mean annual temperature followed an increasing trend from 1941 to 1993. This may have magnified the increase in *Dracophyllum* recruitment occurring at the same time (Fig. 4.1). Mean annual rainfall followed a decreasing trend from 1941 to 1993 (Meteorological Service 1941 – 1993) with a large peak in 1971.

Differences between transects

Dracophyllum recruitment in the well-drained Mesotrophic transects has been occurring at least since the 1840s with low but steady recruitment from c.1840 - c.1900, an erratic period from c.1900 – c.1940 with little or no recruitment occurring in many years, and a major pulse beginning in c.1940 which slows after 1970 (Fig 4.5). In the poorly-drained Oligotrophic transect, *Dracophyllum* did not establish at all until the 1930s. It increased at a similar rate as in the Mesotrophic transects but the increase started a little later, in the 1950s rather than the 1940s. Following a drop in 1971 to a level of no establishment *Dracophyllum* started establishing again in the late 1970s (Fig. 4.5). In the very poorly-drained Eutrophic transect *Dracophyllum* had a low level of recruitment which started in 1940, while a major pulse occurred about 1980 (Fig. 4.5).

***Dracophyllum* species dominance**

***Dracophyllum* species dominance and elevation between transects**

Each species of *Dracophyllum* was found over the complete elevational range sampled (from near sea level to the scrub line), but species dominance changed with elevation. *D. scoparium* was dominant at lower elevations (< 60 m a.s.l.) ($n = 148$) (Fig. 4.7) and *D. hybrid* at higher elevations (> 60 m a.s.l.) ($n = 126$), while *D. longifolium* was not sampled between 60 m a.s.l. and 240 m a.s.l., and was not

dominant at any elevation ($n = 7$). This pattern suggests *D. scoparium* and *D. hybrid* have elevational preferences. The sample size of *D. longifolium* is too small for inferring a preference.

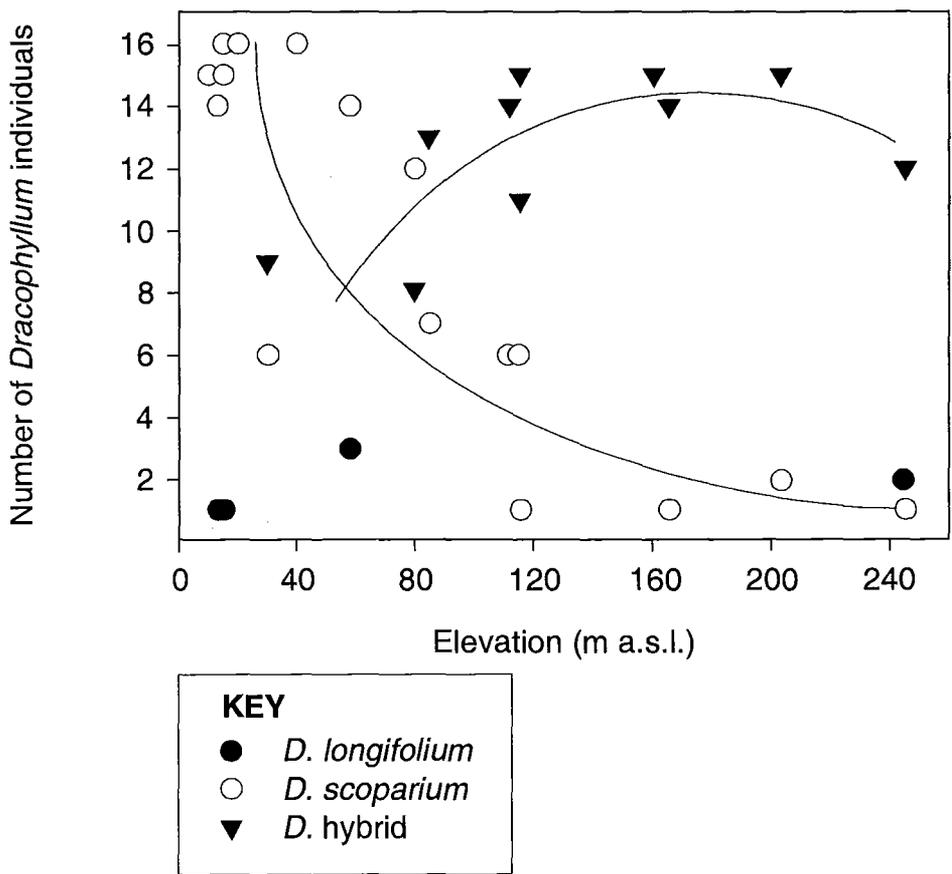


Figure 4.7 Elevational range of sampled individuals of each of the three Campbell Island *Dracophyllum* species (*D. scoparium*, *D. longifolium*, and *D. hybrid*) for all transect types combined.

***Dracophyllum* species dominance within transects**

In the Mesotrophic transect, the *Dracophyllum scoparium* plants ranged in age from 15-152 years (Fig. 4.8), whereas *D. hybrid* had an age range mainly between 9-66 (except one plant 100 years old). This apparent imbalance in age between *D. scoparium* and *D. hybrid* may be an elevational preference, with *D. scoparium* found on lower elevations (Fig. 4.8) where *Dracophyllum* are older, and *D. hybrid* on higher elevations where *Dracophyllum* are younger, rather than an inherent relationship

between age and species. *D. longifolium* ages ranged from 25 to 135, all but one of those sampled being over 100 years old.

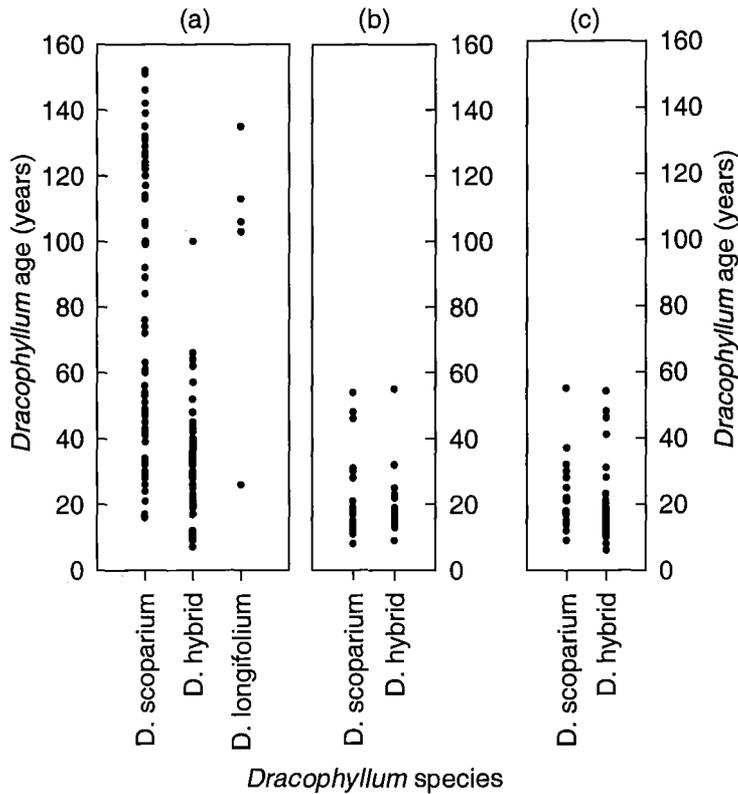


Figure 4.8. Ages of sampled individuals of the three Campbell Island *Dracophyllum* species; *D. scoparium*, *D. longifolium*, and *D. hybrid* on (a) Mesotrophic, (b) Oligotrophic, and (c) Eutrophic transects.

D. hybrid ages were clustered in the lower age range in both the Eutrophic and Oligotrophic transects, with only one aged over 35 ($n = 13$) in the Oligotrophic transect and only c. 20 % ($n = 21$) aged over 35 in the Eutrophic transect. *D. scoparium* had a more even age-spread in both these transects but only one was aged over 40 in the Eutrophic transect and only c. 20 % ($n = 16$) aged over 35 in the Oligotrophic transect. *D. scoparium* was dominant on Mesotrophic and Oligotrophic transects (Table 4.1) and *D. hybrid* was dominant on the Eutrophic transect, which suggests a fertility and/or drainage preference between the species.

Table 4.1. Distribution (%) of *Dracophyllum* species in each transect type.

Species	Transect type		
	Eutrophic n = 60	Mesotrophic n = 127	Oligotrophic n = 51
<i>D. scoparium</i>	39	56	55
<i>D. hybrid</i>	58	38	45
<i>D. longifolium</i>	3	6	0

One *D. longifolium* sample was taken from the Eutrophic transect but proved too small to count, so that species does not feature in Figure 4.7 (c).

Height Growth Rate

Dracophyllum height was significantly positively related to *Dracophyllum* age ($p < 0.0001$, $F = 610.9$). There is a strong relationship between height and age on the Mesotrophic and Eutrophic transects, but the relationship is less strong in the Oligotrophic transect, where there is little variation in height with age (height range of 0.05 m to 0.60 m) compared to that in the Eutrophic or Mesotrophic transects (height range of 0.10 m to 1.4 m, and 0.10 m to 4.5 m respectively) (Fig. 4.9).

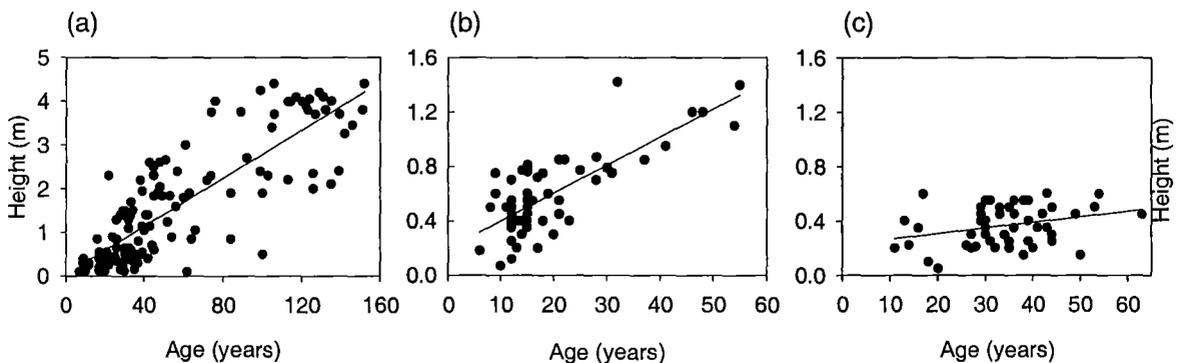


Figure 4.9. Relationship between height and age of *Dracophyllum* for (a) the Mesotrophic transect (linear regression, $r^2 = 0.69$, $n = 132$), (b) the Eutrophic transect (linear regression, $r^2 = 0.60$, $n = 60$), (c) the Oligotrophic transect (linear regression, $r^2 = 0.09$, $n = 51$).

Height growth rate variation with biological and physical variables

Univariate analysis

To allow for the age-height relationship I looked at growth rates (height/age) (Table 4.2).

Table 4.2 Results of generalised linear models with height growth rate as the response variable for (a) univariate and (b) multivariate analyses. df = degrees of freedom; B is the regression coefficient, and shows the direction of slope of the relationship between height growth rate and the variable; F is a ratio of between variable variance and within variable variance; *P* is the probability of the F-value being that extreme or more if the null hypothesis is true; *r*² is how much of the variation in the data is explained by the model. *P*-values in bold indicate significant relationships.

(a)

Variable	Category	df	B	F	<i>P</i>	<i>r</i> squared
Elevation		1	-0.0001	42.3	<.0001	0.15
Slope		1	0.0007	27.5	<.0001	0.1
Transect type		2		38.8	<.0001	0.25
	Oligotrophic		-0.0095			
	Mesotrophic		-0.0089			
	Eutrophic		0			
Insolation		1		34.8	<.0001	0.13
	Sun		0.0047			
	Shade		0			
Species		2		1.7	0.183	0.01
	<i>D. scoparium</i>		0.0041			
	<i>D. hybrid</i>		0.0141			
	<i>D. longifolium</i>		0			

(b)

Variable	Category	df	B	F	<i>P</i>	<i>r</i> squared
						0.504
Elevation		1	0.0001	70.7	<.0001	
Slope		1	0.0002	4.4	<0.05	
Transect type		2		42.6	<.0001	
	Oligotrophic		-0.0226			
	Mesotrophic		-0.0045			
	Eutrophic		0			
Insolation		1		0.2	0.625	
	Sun		0.0009			
	Shade		0			
Species		2		1.7	0.179	
	<i>D. scoparium</i>		0.0044			
	<i>D. hybrid</i>		0.0074			
	<i>D. longifolium</i>		0			

Height growth rate decreased with increasing ELEVATION and increased with increasing SLOPE. It was greatest on the Eutrophic transect and faster on shaded sites. There was a wider range of height growth rates at lower elevations (Fig. 4.10), and height growth rate was greater on steeper slopes (Fig. 4.11).

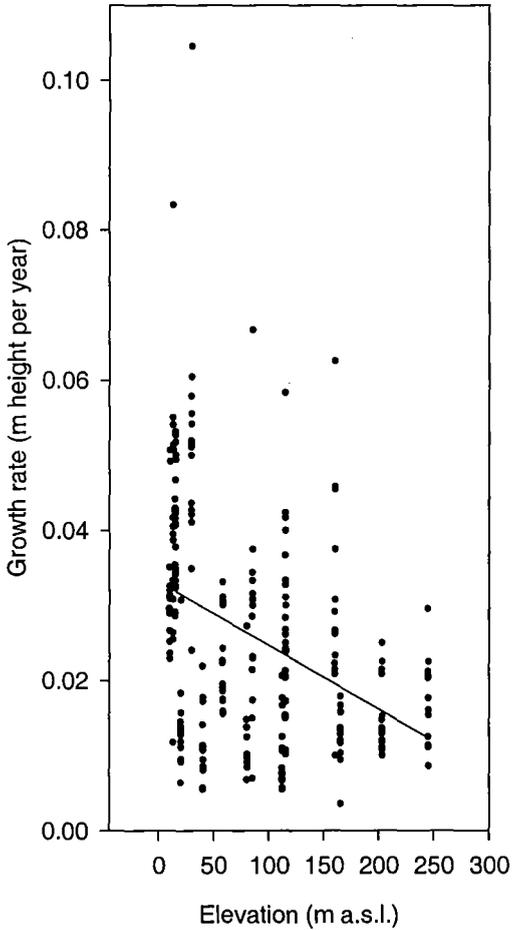


Figure 4.10. Height growth rate (m height per year) of *Dracophyllum* across the range of elevations found in plots (linear regression, $R^2 = 0.15$, $n = 241$, $P < 0.0001$). Regression line fitted.

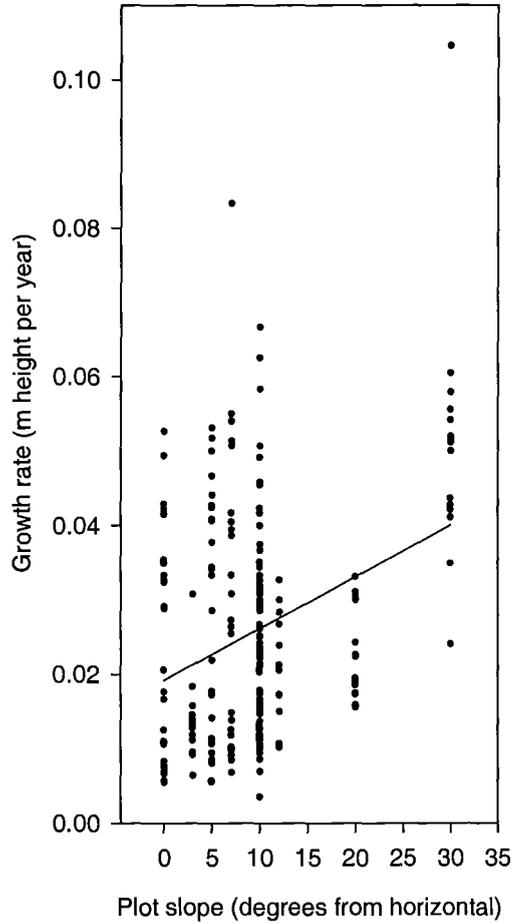


Figure 4.11. Height growth rate (m height per year) of *Dracophyllum* across the range of slopes (degrees from horizontal) found within plots (linear regression, $r^2 = 0.10$, $n = 241$, $P < 0.0001$). Regression line fitted.

Height growth rate was three times as fast in the Eutrophic transect as in the Oligotrophic transect, and c. 2.7 times as fast in the Mesotrophic transects (Fig. 4.12). Height growth rate appeared to be faster on shaded sites (Fig. 4.13).

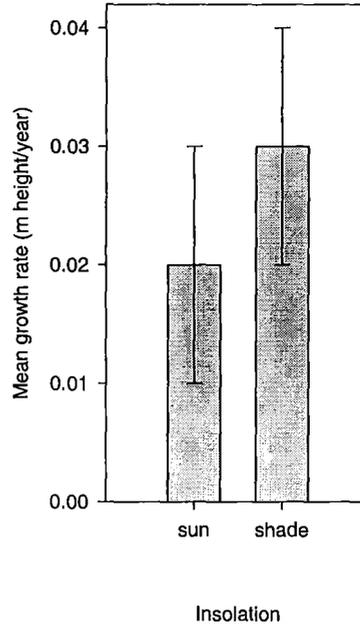
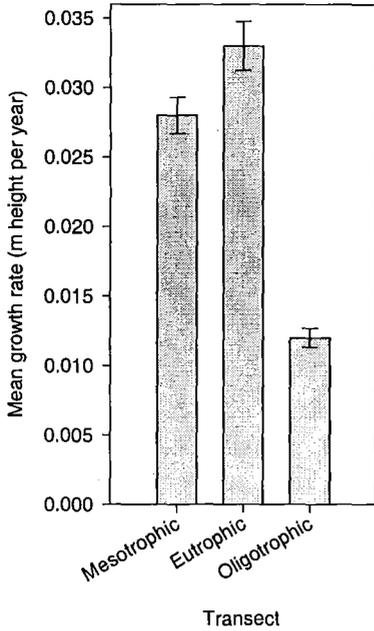


Figure 4.12. Mean height growth rates (m height per year) for each transect. (Generalised linear model, $r^2 = 0.25$, $n = 131$, (Mesotrophic transects), $n = 62$ (Eutrophic transect), $n = 55$ (Oligotrophic transect), $P < 0.0001$). Error bars show standard error.

Figure 4.13. Mean *Dracophyllum* height growth rate (m height/year) in sunny and shaded plots. (Generalised linear model, $r^2 = 0.127$, $n = 69$ (sunny), $n = 172$ (shaded), $P < 0.625$). Error bars show standard error.

In the Mesotrophic transects *D. scoparium* had the fastest height growth rate of the three *Dracophyllum* species and *D. hybrid* had the slowest (Fig. 4.14). In the Eutrophic transect *D. scoparium* had a faster height growth rate than *D. hybrid*, the other *Dracophyllum* species sampled. *D. scoparium* grew 0.8 mm more per year than *D. hybrid*, although *D. hybrid* was the dominant species there (Table 4.1). *D. scoparium* and *D. hybrid* had the same height growth rate as each other on the Oligotrophic transect (Fig. 4.14).

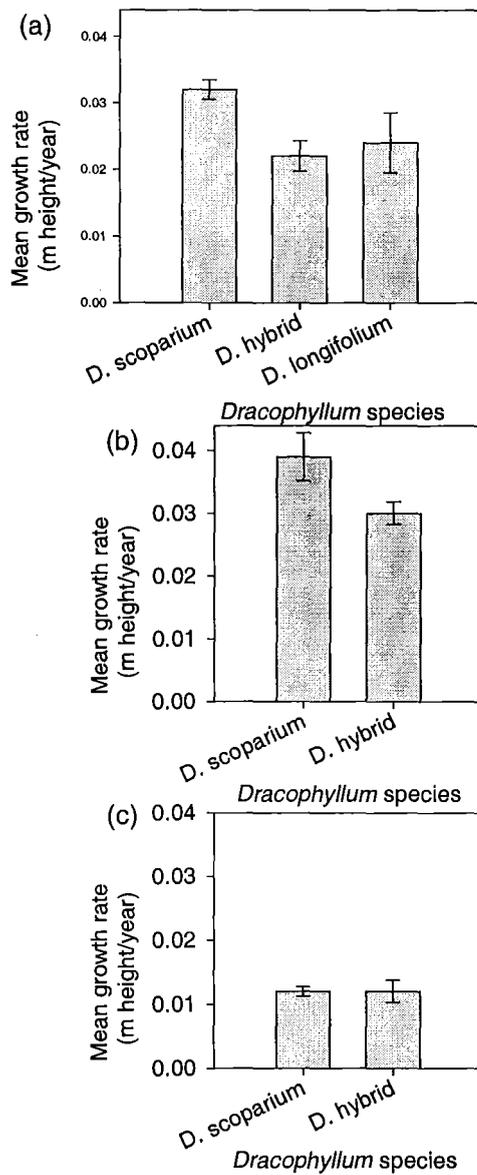


Figure 4.14. Mean growth rate of each *Dracophyllum* species in (a) the Mesotrophic transects, (b) the Eutrophic transect, and (c) the Oligotrophic transect. (Generalised linear model, $r^2 = 0.01$, $n = 69$ (Mesotrophic transects, *D. scoparium*), $n = 5$ (Mesotrophic transects, *D. longifolium*, $n = 53$ (Mesotrophic transects, *D. hybrid*), $n = 20$ (Eutrophic transect, *D. scoparium*), $n = 40$ (Eutrophic transect, *D. hybrid*), $n = 40$ (Oligotrophic transect, *D. scoparium*), $n = 13$ (Oligotrophic transect, *D. hybrid*), $P = 0.179$. Error bars show standard error.

When considered in univariate analysis of variance all of the variables except SPECIES were significant predictors of height growth rate (Table 4.2).

Multivariate analysis

Only ELEVATION, TRANSECT and SLOPE were significant predictors of height growth rate in multivariate analysis. The effect of ELEVATION on height growth rate is more significant than the relationship between TRANSECT and height growth rate as shown by the F-values (Table 4.2). Height growth rate decreases with increasing ELEVATION (as does height) and is lowest in the Oligotrophic transect and highest in the Eutrophic transect.

SLOPE had only a weakly significant effect, with height growth rate increasing on steeper slopes (Table 4.2). INSOLATION did not have a significant relationship with height growth rate in the multivariate analysis, probably because 60 % of the sunny sites were from a single transect, the slow-growing Oligotrophic transect (Table 4.2). SPECIES did not have a significant relationship with height growth rate in the multivariate analysis either (Table 4.2).

Any apparent significance of SPECIES shown by the univariate analysis (Fig. 4.14) is not because of any inherent difference in height growth rate between the species, but because of the strong relationships between SPECIES and ELEVATION and differences in height growth rate across elevations and between transects. *Dracophyllum* plants at lower elevations on the Mesotrophic 1 transect were, on average, older and taller with faster height growth rates. At higher elevations on the same transect they were, on average, younger and shorter with slower height growth rates. In contrast, there was a fairly uniform age range across all elevations for both the Eutrophic and Oligotrophic transects, but differing height growth rates, eutrophic plots having an average height growth rate of 0.03 m per year, and oligotrophic plots an average height growth rate of 0.01 m per year.

Discussion

Dracophyllum recruitment patterns appear to be mainly related to changes in land use, with recruitment phases closely following major land use changes but varying with differences in fertility and drainage. Temperature and rainfall patterns play a more minor role. Elevation, slope, and transect type (site drainage and site fertility) were found to be significant predictors of height growth rate.

Role of land use changes in *Dracophyllum* recruitment

Different combinations of land use factors result in different recruitment phases

Plant communities affected by fire and grazing can have distinct phases dependent on the presence or absence of these disturbance factors (Wardle, 1991). Burning occurred on Campbell Island during the Sealing and Exploration Period from 1810 to 1894, burning and grazing characterised the Farming Period, 1895 to 1931, the Feral Grazing Period featured grazing in the absence of fire from 1932 to 1991, and was followed by the Disturbance-Free Period, without either burning or grazing, from 1989 onwards (Fig. 4.2).

Dracophyllum expansion on Campbell Island has been largely driven by land use changes, namely grazing and cessation of burning. The curve of Figure 4.1 is not the reverse J-curve expected for constant recruitment. Rather, it shows phases of different levels of *Dracophyllum* recruitment, suggesting a response to a variable factor such as changes in land use. The changes from one phase of recruitment to another coincide with major changes in land use (Fig. 4.2), and, to some extent, climate trends (Fig. 4.6).

Scrub expansion is associated with burning and grazing in many parts of the world (Johnston, 1963; Franklin *et al.*, 1971; Primack, 1978; Vale, 1981; Walker *et al.*, 1981; Burrows *et al.*, 1984; Jacoby, 1984; Beaudoin, 1989; Wardle, 1991; Jakubos & Romme, 1993; Rogers, 1994; Rose *et al.*, 1995; Taylor, 1995; French *et al.*, 1997; Hessel & Baker, 1997; Villalba & Veblen, 1998; Van Auken, 2000), but direct parallels could not be drawn between these and Campbell Island, because of the absence of fire resistant woody species on Campbell Island and environmental disparity.

Sealing and Exploration Period: Fire alone

The lack of increase of *Dracophyllum* recruitment between the year of establishment of the oldest *Dracophyllum* sampled (1840) and the end of the 1900s is likely to be mainly due to burning by sailors and sealers in the early 1800s (Chapter Three). Fire kills mature plants and depresses the establishment of scrub by killing seedlings (Smale, 1994), and occasional fires would have easily ignited the highly flammable *Dracophyllum*, which burns well, even when wet, due to its terpene-rich wood (Godley, 1979; Evans, 1987; Wardle, 1991).

The lack of *Dracophyllum* recruitment during the Sealing and Exploration Period, compared with that in the Feral Grazing Period, could be explained by competition with ungrazed tussocks combined with the cold period in the 1800s, as well as fire killing trees that did establish. Observations made on Campbell Island in 1998 agreed with Zotov's (1965) suggestion that *Dracophyllum* seedlings did not establish in dense vegetation such as the tussock regrowth that would result from fires. Seedlings were noted in 1998 to have established on patches of sunlit moss or liverwort pads, or on dead wood (pers. obs.). The chance of successful seed establishment may have been reduced by damage of these types of sites by burning during the Sealing and Exploration Period.

The recruitment level during this period may be underestimated in Fig. 4.1 because of self-thinning and natural mortality. Scrub establishment can occur to a certain extent when burning is only periodic (Rogers, 1994), as it was on Campbell Island during the Sealing and Exploration period, which contrasts with the lack of recruitment during the Farming Period when burning occurred frequently. There were periods when no sealers or sailors visited the island, during which no burning occurred, as well as many areas of the island not reached by fire. Thus, *Dracophyllum* would have time to set seed, keeping a near-constant level of recruitment. However, because grasses have a growth advantage over woody species in the absence of grazing, following periodic fires (Wardle, 1991; Rogers, 1994), *Dracophyllum* recruitment could not increase during this period.

Farming Period: Fire & grazing

Low, erratic *Dracophyllum* recruitment throughout the Farming Period was probably due to the land management practices that occurred during this time; burning was carried out whenever possible to provide young tussock growth for sheep grazing (Zotov, 1965; Spence, 1968). Grassland can be maintained free of scrub species by extensive fires (Vale, 1981; Rogers, 1994) accompanied by grazing (Wardle, 1991). Although sheep grazing would have reduced competition from tussocks (Zotov, 1965; Wardle, 1991; Rogers, 1994; Jensen *et al.*, 1997) the effects of fire on the scrub would have prevented this from being an advantage to the *Dracophyllum*, until burning stopped.

During this Period *Dracophyllum* scrub was constrained at three levels by the management regime. As well as fires killing mature plants and reducing the chance of them setting seed, sheep and fires would have caused the death of *Dracophyllum* seedlings. Seedlings would have been even more sensitive to fire than mature plants

(Van Auken, 2000) and under the management conditions of more frequent and more widespread burning (Cockayne, 1903; Spence, 1968; Timms *et al.*, 1978) *Dracophyllum* would not have had time to mature and set seed between fires (Haase, 1986), keeping establishment levels low (Rogers, 1994; Jensen *et al.*, 1997).

Sheep ate young *Dracophyllum* seedlings, but only when fencing restricted them and their high density had caused overgrazing. Browsing and opening up of the scrub zone by sheep was observed to have caused death of some smaller *Dracophyllum* plants, and *Dracophyllum* plants more than 0.1 m high more than doubled in number once grazing pressure was removed (Wilson, 1980; Meurk, 1982; Moore & Moffat, 1990).

Feral Grazing Period: Grazing with a history of fire

The dramatic pulse of *Dracophyllum* recruitment (Figure 4.4) and increase in scrub density (Chapter Three) in the Feral Grazing Period was probably caused by continued grazing following recent burning, which followed abandonment of the farming venture in 1931. This recruitment pulse required grazing by stock in the absence of fire, to reduce density of tussock and encourage establishment of *Dracophyllum* seedlings (Zotov, 1965; Wardle, 1991; Rogers, 1994; Jensen *et al.*, 1997), along with a recent history of burning (Wardle, 1991; Rogers & Leathwick, 1994). Both these factors were in place when *Dracophyllum* recruitment increased dramatically around 1940.

Campbell Island showed several of the characteristic symptoms of overgrazing following the Farming Period; soil erosion in the form of peat scarring or 'blowouts', the elimination of palatable plants (*Chionochoa antarctica* and macroforbs) and an increase in the abundance of unpalatable and woody plants (both *Bulbinella rossii* and *Poa litorosa*, and *Dracophyllum* species respectively) (Laing, 1909; Meurk, 1980;

Meurk, 1982; Wardle, 1991; Crawley, 1998). Dr Leonard Cockayne observed the effect of sheep on the tall tussock early in the farming era. He noted that the sheep ate the *Chionochloa* down to the stump, allowing water to accumulate in and between the stems. Tussocks dying in this way did not seem to be replaced (Laing, 1909). Sheep also targeted macroforbs (apart from *Bulbinella*), and grazing restricted these to places inaccessible to stock (Laing, 1909). Hundreds of acres of tussock meadows and macroforb herbfields were destroyed in this way (Laing, 1909; Moore & Moffat, 1990).

The naturalist, Guthrie-Smith (1936), was greatly saddened at "...the defilement by stock of this splendid natural sanctuary..." on his visit to Campbell Island on board the castaway-depot resupplying voyage of the Tutanekai in the 1920s. Restriction by fencing, and gradual removal of the feral sheep population led to recovery of plant communities (Meurk, 1982; Meurk, 1989; Moore & Moffat, 1990). *Chionochloa* tussocks increased by over 400 % in some induced *Poa litorosa* meadows and macroforbs also recovered dramatically (Meurk, 1982). Sheep grazing, in the absence of fire, reduces the density of tussock encouraging establishment of *Dracophyllum* seedlings. Wardle (1991) and Primack (1978) found that dominance of scrub in parts of the South Island of New Zealand will be perpetuated as long as grazing continues.

Burnt-off *D. longifolium* in the Lammerlaw Ecological Region, South Island, New Zealand, was replaced temporarily by *Chionochloa* tussocks, with *Dracophyllum* re-establishing if burning then ceased and concentrated grazing occurred (Wardle, 1991). A similar situation occurred in the central North Island of New Zealand where decreased burning, following a regime of frequent fires, which had previously maintained grassland, triggered invasion of woody species including *Dracophyllum* (Rogers & Leathwick, 1994). This is consistent with the situation on Campbell Island:

occasional early burns clearing *Dracophyllum* scrub, allowing *Chionochloa* tussocks to move in, then moving to a later stage of *Dracophyllum* dominance in the presence of sheep grazing.

Reduced seed source can limit recruitment of scrub after disturbances such as fire (Wardle, 1991). Conversely, continued shrub recruitment can be fuelled by a mosaic of seed sources from sites topographically sheltered from fires (Rose & Platt, 1992; Rogers & Leathwick, 1994), which appears to be the case on Campbell Island. The wind-dispersed nature of *Dracophyllum*'s abundant dust-like seed meant that seeds were able to be blown significant distances from the seed-source (Rogers & Leathwick, 1994; McGlone *et al.*, 1997), especially in Campbell Island's windy climate. The combination of seed availability and dispersal, and the continued grazing of feral sheep reducing the competitive effect of grasses, may have contributed positively towards *Dracophyllum* expansion. Establishment would have increased in more poorly-drained sites as seed rain increased with cessation of burning. With the end of burning there would have been greater availability of seed from sources in more well-drained sites (M. McGlone pers. comm. 11-2001).

Disturbance - Free Period: No grazing or fire

Possible future trends of *Dracophyllum* scrub are: (i) scrub may continue to increase, (ii) the area featuring scrub may remain stable (Primack, 1978; Wardle, 1991), or (iii) areas of scrub may eventually revert to a 'scrub-free' condition, although timescales for this are variable and unpredictable (Vale, 1981; Walker *et al.*, 1981).

Differences in recruitment frequency with and without grazing

The abrupt drop in *Dracophyllum* recruitment following cessation of grazing after 1970 to the north of the “1970 fenceline” and after 1984 to the south of the “1970 fenceline” (Fig. 4.3, Fig. 4.4), in all but the Eutrophic plot north of the “1970 fenceline”, was probably due to the recovery of *Chionochloa* tussock. The dense canopy of ungrazed *Chionochloa* makes establishment difficult for *Dracophyllum* seedlings (Zotov, 1965).

The drop in *Dracophyllum* recruitment may also be partly due to the under-representedness of younger age-classes of *Dracophyllum* which were too small to sample. Definite conclusions were not possible because of the small sample size when differences in drainage and fertility were controlled for.

Role of climate in differences in *Dracophyllum* recruitment

Dracophyllum scrub expansion above the 200 m a.s.l. treeline would be likely if climate was the main driver of *Dracophyllum* recruitment. However, as this has not occurred, it seems that land use changes are the major driver of the expansion of *Dracophyllum* on Campbell Island. Climate does, however, appear to contribute to broad trends, and may control differences in recruitment patterns between areas of different drainage types.

Dracophyllum has become established in more poorly-drained areas more recently than well-drained areas (Fig. 4.5), suggesting that some factor has changed over time, drying wetter areas and allowing *Dracophyllum* to establish in relatively poorly-drained areas. This can perhaps be attributed to climate change.

New Zealand Meteorological Service records show increasing mean annual temperature and decreasing mean annual rainfall on Campbell Island from 1941-1993 (Fig. 4.1, Fig. 4.5). There has been a warming of c. 1 °C since the beginning of the 1900s south of the subtropical convergence, associated with a decrease in precipitation (New Zealand Meteorological Service, 1941-1993; Salinger & Gunn, 1975; Adamson *et al.*, 1988). Dendrochronological evidence suggests that New Zealand summer temperatures were relatively cool in the 1780s to early 1790s and the late 1840s (Norton *et al.*, 1989; Norton & Palmer, 1992). Records of iceberg sightings in low latitudes (Burrows, 1976) suggest that unusually high numbers of icebergs were present in the early 1770s and early 1850s, therefore conditions were colder than usual. In the 1800s there was more cyclonic activity hence wetter conditions and lower summer temperatures in the New Zealand sector of the subantarctic (Villalba *et al.*, 1997). 1800 was the start of a poor growing period on Stewart Island, ending about 1915 (D'Arrigo *et al.*, 1995). From 1820 to the 1870s, Stewart Island temperatures and tree growth indices show below average growth, reflecting colder temperatures (D'Arrigo *et al.*, 1995). There was also significant glacier expansion in the Southern Alps in the middle of the 1800s. Temperature trends in the subantarctic area and the New Zealand mainland have been closely correlated since the mid-1900s (Adamson *et al.*, 1988). The instrumental record for New Zealand and vicinity indicates cold surface-air temperatures in the years around 1900 (D'Arrigo *et al.*, 1995). From 1860 there were relatively less low-pressure systems and increasingly relatively warmer and drier conditions, this trend steepening from 1926 until 1970. In 1970 this trend was reversed (Villalba *et al.*, 1997). There has been an upward trend of c. 1 °C since 1949 on Macquarie Island (Adamson *et al.*, 1988). Annual surface-air temperatures warmed between 0.4 and 0.8 °C in Australia,

New Zealand and the southwest Pacific region since 1951. The 1950s to the 1970s was the highest 20-year growth period for the past 300 years on Stewart Island (D'Arrigo *et al.*, 1995).

The combination of increasing mean annual temperature and decreasing mean annual rainfall (Fig. 4.6) would have led to increasingly dry soil surfaces over time. Establishment occurred much more recently on these more poorly-drained transects, suggesting that soil surface wetness or drainage is a limiting factor for *Dracophyllum* establishment. The drying effect of climate change on the more poorly-drained transects, Oligotrophic and Eutrophic, could have been a vital factor in enhancement of *Dracophyllum* recruitment there.

A sudden drop in *Dracophyllum* recruitment in 1971 coincided with a dramatic peak in mean annual rainfall (Fig. 4.5). The recruitment drop was detected in the Mesotrophic and Oligotrophic transects, but did not appear to affect recruitment in the Eutrophic transect. The Oligotrophic transect is poorly drained, although not as poorly as the Eutrophic. Additionally the Oligotrophic transect is the least steep, therefore is the most likely to become saturated after heavy rainfall. This could explain why *Dracophyllum* recruitment levels dropped to zero in the Oligotrophic transect, but some recruitment continued in the Mesotrophic transect, which had a greater proportion of more steeply-sloping plots. While the peak in rainfall may have contributed towards the drop in *Dracophyllum* recruitment in 1971, the main reason for the drop and repression of recruitment levels since is more likely to be the cessation of grazing (Fig. 4.3) and resulting recovery of *Chioncochloa* tussock and other dense grass.

While the oldest sampled *Dracophyllum* plant established in 1840 on the well-drained Mesotrophic transects it wasn't until the 1940s that any established in the

poorly-drained Oligotrophic transects, and the 1950s for the very poorly-drained Eutrophic transects (Fig. 4.5). This suggests that drainage limits *Dracophyllum* establishment, because establishment occurs in the most well-drained transect first and the most poorly-drained transect last.

Climate change may have enhanced *Dracophyllum* expansion, making its range more extensive than it would otherwise have been (Zotov, 1965; Meurk, 1980; Meurk, 1982). Warmer, drier, summer conditions are thought to have favoured *Dracophyllum* expansion on Campbell Island between 7000 and 3000 years B.P. (McGlone *et al.*, 1997). More recently the subantarctic has again experienced warming and drying conditions (Fig. 4.6) which may have extended the habitat suitable for woody growth on Campbell Island, both by direct evapotranspiration, and due to reduced condensation of fog on tussocks (Meurk, 1977; Rudge, 1986; McGlone *et al.*, 1997).

Competition may have been another factor that delayed the expansion of *Dracophyllum* onto the cushion bogs of the Oligotrophic areas. *Chionochloa* tussocks were historically protected from burning and therefore grazing by their discontinuity on these bogs and have only declined there more recently (Meurk, 1982), so may have been competing with, and delaying recruitment of, the *Dracophyllum* on the Oligotrophic areas longer than on Mesotrophic areas.

Height growth rate

Height Growth Rate allows for the age-height relationship of *Dracophyllum*. It showed that the most suitable sites for *Dracophyllum* establishment were not entirely the most suitable for *Dracophyllum* growth (Table 4.3). While establishing much earlier in drier areas its height growth rate is limited more by site fertility than by

drainage. However, this pattern differs to some extent between species. ELEVATION, TRANSECT and SLOPE were all found to be significant predictors of height growth rate (Table 4.2), suggesting variation in environmental factors affects height growth rate. SPECIES and INSOLATION were not found to be significant predictors of height growth rate.

Table 4.3. Relationship between drainage conditions and order of *Dracophyllum* establishment, and site fertility and *Dracophyllum* height growth rate, within each transect type.

Transect type	Mesotrophic	Oligotrophic	Eutrophic
Drainage	well-drained	poorly-drained	very poorly-drained
Order of establishment of <i>Dracophyllum</i> (since 1840)	1 st	2 nd	3 rd
Fertility	medium	low	high
<i>Dracophyllum</i> height growth rate	medium	slowest	fastest

Fertility and drainage appear to have an affect on both *Dracophyllum* height (Fig. 4.9) and height growth rate (Fig. 4.12). Laing (1909) stated that the Campbell Island *Dracophyllum* was “distinctly xerophytic” (adapted to a dry habitat) and that the *Dracophyllum* scrub had affinities with the xerophytic scrub communities found in the drier parts of South Island subalpine areas. Soil fertility and soil moisture were found to be important determinants of vegetation patterns among scrub where *Dracophyllum* was an important feature (Hnatiuk, 1993; Meurk *et al.*, 1994; Rogers & Leathwick, 1994; Burns & Leathwick, 1996). French *et al.* (1997) also found well-drained sites to be important for expansion of the range of scrub in Scotland.

Dracophyllum on Campbell Island grows taller in well-drained areas. Of the variables measured, drainage is the primary limiting factor of *Dracophyllum* height; *Dracophyllum* plants with the greatest mean height occur on the well-drained areas,

and *Dracophyllum* plants with the least mean height occurred on the very poorly-drained areas. Fertility is the secondary limiting factor of height; of those plots not in the well-drained areas, *Dracophyllum* plants with the greatest mean height occurred on the most fertile areas, and *Dracophyllum* plants with the least mean height occurred on the least fertile areas.

For height growth rate the factors are reversed: *Dracophyllum* on Campbell Island grow fastest in fertile areas. Of the variables measured, fertility is the primary limiting factor of *Dracophyllum* height growth rate, as *Dracophyllum* plants with the fastest height growth rate occur on the most fertile areas, and *Dracophyllum* plants with the slowest height growth rate occur on the least fertile areas. Drainage is the secondary limiting factor of height growth rate; of those plots not in the most fertile areas, *Dracophyllum* plants with the greatest mean height growth rate occur in the most well-drained areas, and *Dracophyllum* with the least mean height growth rate occur in the most poorly-drained areas. Height growth rate is more limited by fertility than by drainage. Establishment rate is more affected by site differences in drainage, which may be related to recent changes in climate.

The dominance of *D. scoparium* on Mesotrophic and Oligotrophic transects as a proportion of the total (Table 4.1), and *D. hybrid* on the Eutrophic transect, suggests a fertility and/or drainage preference for establishment sites for these two species. The faster growth of *D. scoparium* on Mesotrophic transects (Fig. 4.14) may have given it a competitive advantage, contributing to it being the most common *Dracophyllum* species on those areas (Table 4.1). However, *D. longifolium* and *D. hybrid* had similar height growth rates on Mesotrophic transects, but *D. hybrid* was almost 20 times as common there as *D. longifolium*, and although *D. scoparium* had the fastest height growth rate on the Eutrophic transects the most common *Dracophyllum* species there is *D. hybrid*. This suggests competition between species

is not solely reliant on height growth rate. On the Oligotrophic transect there are similar proportions of *D. scoparium* and *D. hybrid*, both of which have slow height growth rates. These findings are not conclusive because SPECIES was not found to have a statistically significant effect on height growth rate.

D. longifolium possibly needs fertile but preferably well-drained conditions. With the small sample size for this species I cannot draw definite conclusions, however Rogers & Leathwick (1994) found *D. longifolium* to prefer steeper slopes, which are likely to be positively correlated with good drainage. Faster height growth rates were associated with steeper slopes (Fig. 4.11), however, this may be a function of drainage rather than an inherent relationship between height growth rate and slope, because drainage would be more efficient on steeper slopes and would promote faster height growth rate. Rates of *Dracophyllum* invasion in North Island tussock grasslands were found to be fastest on steep slopes (Rogers & Leathwick, 1994).

The distribution of species across different elevations (Fig. 4.8) and between transect types suggests that *D. scoparium* thrives in more infertile areas and is dominant at lower elevations, while *D. hybrid* can cope with more poorly-drained conditions and is dominant at higher elevations. I found *D. scoparium* to be far more plentiful than *D. longifolium*, as did Oliver and Sorensen (1951). *D. scoparium* was dominant at low altitudes and *D. longifolium* was found over the range of elevations, but more common at low elevations. These findings agree with those of Wardle (1987).

There was a trend for *Dracophyllum* plants on the continuous Mesotrophic transect to be, on average, older and taller with greater stem diameters and faster height growth rates at lower elevations, and, on average, younger and shorter with slower height growth rates at higher elevations (Fig. 4.10). These differences suggest

that variation in environmental factors, such as temperature and shelter over elevational range (Meurk *et al.*, 1994; French *et al.*, 1997), affects height growth rate of *Dracophyllum* scrub (Burns & Leathwick, 1996) and limits height and stem diameter. B.C. Aston's 1907 report includes his comments on *Dracophyllum* on the Auckland Islands, recording the same patterns there; *Dracophyllum* growing to greater size at lower elevations, and being of a more dwarfed habit and more sparsely spaced at higher elevations (Godley, 1979). The trend of *Dracophyllum* plants being younger at higher elevations and vice versa also suggests that *Dracophyllum* expanded into areas of higher elevation more recently, which agrees with the historical accounts of a narrow band of scrub around the coastline in the Sealing and Exploration Period (Hooker, 1844; Buchanan, 1883).

Summary

- ◆ Data from the *Dracophyllum* population age structure shows that scrub expansion patterns coincided with phases of land use change on Campbell Island.
- ◆ Broad climate trends of warming and drying may have encouraged recruitment, but had less influence on the overall pattern than major changes in land use.
- ◆ When *Dracophyllum* expands, and the magnitude of expansion, are determined by the presence or absence of burning and/or grazing.
- ◆ Where *Dracophyllum* expands depends on drainage, fertility, and elevation.
- ◆ *Dracophyllum* established more readily in better-drained sites and grew faster on fertile sites at lower elevations.

Chapter Five: Overview

Discussion

Pollen and wood records (McGlone *et al.*, 1997) show that *Dracophyllum* was more abundant on Campbell Island 7000-3000 years B.P. than it is now. Photographic evidence showed that *Dracophyllum* scrub was restricted to the sheltered coastline and gullies before the farming era. From there it has spread on to lower and well-drained areas and, more recently, more poorly-drained sites and higher areas, but not above 200 m a.s.l.. The photo sequences show that scrub cover has increased since the first photos were taken. Scrub expansion shown in photos taken in 1960/1 continued until 1984 then plateaued.

The photographic sequences (Chapter Three) and *Dracophyllum* age structure graphs (Chapter Four) clearly show how the scrub has expanded since 1940. Scrub expansion patterns coincided with phases of land use change that occur on the island; changes from sealing to farming and farming to feral grazing, and then no grazing. Broad climate trends of warming and drying may have encouraged recruitment, but had less influence on the overall pattern than major changes in land use. The expansion dynamics of the *Dracophyllum* scrub are more likely to have been influenced by changes in land use than by regional trends in the climate. Phases of *Dracophyllum* recruitment suggest a response to a variable factor such as burning. Also, there has been no rise in treeline as would have been expected if warming climate was the dominant controlling factor. Ridley (1997) points out "It is remarkable how strong remains the wishful thinking for finding an excuse to believe in climatic change," instead of human impacts. However, climate trends may have

played a role in the differences in recruitment patterns between poorly-drained areas and well-drained areas.

The history of the island points to land use change as the major driver of the expansion. The early sealers, whalers, and explorers had an impact on the woody vegetation of the island (Hooker, 1844; Ross, 1847; McNab, 1907; Kerr, 1976). Burning the highly flammable *Dracophyllum* in order to aid passage through the dense scrub would have had the greatest effect. Burning occurred on Campbell Island at least as early as 1840 (Wardle, 1991).

Burning was the only tool for farm management from 1895 to 1931 (Spence, 1968; Kerr, 1976; Timms *et al.*, 1978), and regular burning was accompanied by sheep grazing over this period. Localised burning and felling of *Dracophyllum* during the farming era probably had the most noticeable impact on the environs of Perseverance Harbour (Timms *et al.*, 1978), however, photos of the area from just before the farming era show the same situation of restricted *Dracophyllum* distribution as described by Hooker in 1840 (Chapter Three). Therefore, if the natural scrub cover was decreased by human activities, most of the impact must have occurred between 1810 and 1840.

Phases of *Dracophyllum* recruitment coincided with distinct phases of land use on Campbell Island (Fig. 4.2). These phases were the Sealing and Exploration Period (1810-1894), Farming Period (1895-1931), and Feral Grazing Period (1932-1988). Occasional fires lit by sealers and sailors would have depressed the recruitment of scrub by killing mature plants and seedlings (Smale, 1994), and dense tussock regrowth following fires would not have provided suitable conditions for *Dracophyllum* seedling establishment (Zotov, 1965).

The low, erratic recruitment of *Dracophyllum* during the Farming Period was probably caused by the burning and grazing regime. Although grazing of tussocks would have created better conditions for *Dracophyllum* seedling establishment (Rogers, 1994; Zotov, 1964; Jensen *et al.*, 1998; Wardle, 1991) the frequent burning (Cockayne, 1903; Spence, 1968; Timms *et al.*, 1978) would have killed many *Dracophyllum* seedlings, keeping establishment levels low (Rogers and Leathwick, 1994; Jensen *et al.*, 1997). In addition, mature *Dracophyllum* plants were killed by fire (Rogers, 1994; Vale, 1981). Sheep also damaged some smaller *Dracophyllum* plants, but only ate them when confined to restricted areas with little other food available (Wilson, 1980; Moore & Moffat, 1990; Meurk 1982).

The Feral Grazing Period featured a dramatic pulse of *Dracophyllum* recruitment, probably caused by continued grazing with a history of fire (Rogers & Leathwick, 1994; Wardle, 1991; Zotov, 1965; Rogers, 1994; Jensen *et al.*, 1997). Sheep grazing in the absence of fire reduced density of tussock grassland, thus encouraging establishment of *Dracophyllum* seedlings (Zotov, 1965). Similar situations have occurred in both the South Island (Wardle, 1991) and North Island (Rogers & Leathwick, 1994) of New Zealand. *Dracophyllum* establishment is aided by dispersal via abundant wind-dispersed seeds (Rogers & Leathwick, 1994). Therefore, recruitment levels increase after cessation of burning.

Climate trends may have played a role in recent *Dracophyllum* recruitment patterns, controlling differences between timing of recruitment in areas of differing drainage and fertility. *Dracophyllum* moved into wetter areas more recently than well-drained areas. Soil surfaces became drier from about the early 1900s due to the combination of increasing mean annual temperature and decreasing mean annual rainfall (Fig. 4.1, Fig. 4.5) (New Zealand Meteorological Service, 1941-1993; Salinger

and Gunn, 1975; Adamson *et al.*, 1988). Wetter areas therefore became progressively drier and more similar to the well-drained areas preferred by *Dracophyllum* seedlings.

Dendrochronological evidence suggests that there were generally cool, wet conditions from the 1780s and throughout the 1800s with an intense cool episode centred on the early 1900s (Fig. 4.6) (Norton *et al.*, 1989; Norton & Palmer, 1992; Burrows, 1976; Villalba *et al.*, 1997; D'Arrigo *et al.*, 1995). It is possible that scrub was restricted by cool summer temperatures and wet soils during the 1700s and failed to recover lost ground in the course of the 1800s, because milder climatic periods were too short-lived until the sustained post-1950 warming (Villalba *et al.*, 1997; Adamson *et al.*, 1988; D'Arrigo *et al.*, 1995).

The effect of grazing on *Dracophyllum* recruitment frequency was looked at by comparing *Dracophyllum* population structures with and without, and before and after grazing, but definite conclusions were not possible due to the small sample size once differences in drainage and fertility were controlled for. Some apparent change was partly due to the under-representedness, in the age structure data, of younger age-classes of *Dracophyllum* which were too small to sample.

Height growth rate of *Dracophyllum* is affected by elevation, site fertility and drainage. While *Dracophyllum* established earlier in well-drained areas, its height growth rate was more limited by the fertility of a site than its drainage. This pattern differed between *Dracophyllum* species. Transect type, (fertility and drainage of sites), slope, and elevation were all significant predictors of height growth rate. Soil moisture and soil fertility were also found to be important factors in patterns in scrub featuring *Dracophyllum*, in other parts of New Zealand and the subantarctic islands

(Hnatiuk, 1993; Meurk *et al.*, 1994; Rogers & Leathwick, 1994; Burns and Leathwick, 1996; Laing, 1909). Faster height growth rates on steep slopes may have been a function of more efficient drainage, rather than an inherent relationship between height growth rate and slope. Height growth rate was slower at higher elevations, probably because environmental factors are more extreme (colder and windier) than at low elevations (Meurk *et al.*, 1994; Burns and Leathwick, 1996).

Conclusions

Two objectives were defined for this study: 1) Determine (i) pattern and (ii) rate of expansion of *Dracophyllum* on Campbell Island. 2) Assess relative influence of (i) changes in frequency of burning and grazing and (ii) regional climate change. I reached the following conclusions: The photographic record and data on the *Dracophyllum* population age structure show that *Dracophyllum* scrub on Campbell Island has expanded dramatically since the 1930s. 1(i): Phases of recruitment since 1840 coincide with major changes in land use. The pattern of *Dracophyllum* expansion depends on the presence or absence of burning and/or grazing for timing and magnitude. It also depends on drainage, fertility, and topography, especially elevation, for siting. 1(ii): Yearly mean rate of increase in percent scrub cover, calculated from each photographic sequence, ranged from 0.02% to 1.85%, and some sequences showed no change. 2(i): Timing of *Dracophyllum* expansion appears to be driven mainly by changes in burning and grazing regimes. 2(ii): Differences in drainage, probably affected by climate trends, and differences in site fertility play a role in where *Dracophyllum* expands.

These findings could be applicable to New Zealand's other subantarctic islands and possibly also subalpine areas of the South Island of New Zealand. However, it is

questionable how much further afield the same scrub expansion dynamics would apply, because they rely to a certain extent on the traits of the plant species and environment of Campbell Island.

Future

Possible future trends of *Dracophyllum* scrub, following removal of feral sheep, are: (i) continue to increase, (ii) remain stable, or (iii) revert to a 'scrub-free' state. *Dracophyllum* expansion is unlikely to remain at the same level as that following the end of burning (Fig. 4.1, Fig. 4.2). Meurk (1982) suggested it was likely that *Chionochloa* tussock would grow back sufficiently to limit further expansion of *Dracophyllum* scrub after the removal of grazing, by providing a canopy too dense for *Dracophyllum* establishment (Zotov, 1965) and it appears (Fig. 4.3, Fig. 4.4) that this is occurring above 200 m a.s.l. The abrupt drop in *Dracophyllum* recruitment following cessation of grazing is probably due to the recovery of *Chionochloa* tussock. Recruitment levels are liable to be low from now on. The areas currently occupied by *Dracophyllum* may become denser, but are not likely to expand much beyond current boundaries. Moreover, reduction of the current range of scrub is unlikely because *Chionochloa* tussock is probably not capable of expanding into areas occupied by mature *Dracophyllum* scrub (Meurk, 1980) without further change in burning regimes or major climatic change. The prospects for ongoing global warming may induce further expansion of scrub.

The pollen and wood fossil record (McGlone *et al.*, 1997) shows *Dracophyllum* scrub used to cover more of Campbell Island up to 3000 years B.P. than it does now. Therefore, although present expansion is human-caused it may be returning the

extent of *Dracophyllum* scrub to an earlier, pre-human state, rather than establishing a new one. Therefore, if scrub were to expand vigorously into areas currently occupied by other vegetation types, philosophically it would be difficult to decide which management option ('hands-off' or intervention) to use. Any consequences of *Dracophyllum* scrub expansion on seabirds such as albatross spp. (Diomedidae) must be considered in this context. Although albatross survived the 7000-3000 B.P. *Dracophyllum* expansion, their populations were not then undergoing the additional pressure of deaths through longlining bycatch.

Despite the prognosis of only limited *Dracophyllum* scrub expansion, there are management issues that need to be considered. Scrub expansion may be of concern because of the potential effects on nesting success and survival rate of the many species of sea birds that breed on Campbell Island, including the southern royal and grey-headed albatross, for which Campbell Island is the major breeding site (Clark & Dingwall, 1985). Sorensen (1951) noted that many fledged albatross chicks on Campbell Island crash-landed in scrub on their practise flights, and, being unable to take off again, would have died there if not rescued. Albatross nesting and take-off sites situated on the tussock ridges would be encroached upon if the scrub expanded into those areas. However, this is unlikely because *Dracophyllum* shows no sign of expanding above 200 m a.s.l. Growth of the isolated *Dracophyllum* plants above 200m a.s.l. is slow (McGlone *et al.*, 1997). Continued monitoring of the permanent vegetation plots (Meurk, 1982) is needed, because any further changes in vegetation due to the removal of the influences of burning and grazing may be slow to become apparent. For example, the range of *Pleurophyllum criniferum* has expanded to higher elevations on Campbell Island from about the mid-1990s (D. Given pers. comm., 1-2002).

Vegetation changes may have major consequences for the distribution and abundance of other ground-nesting birds, particularly the flightless species, Campbell Island teal (*Anas aucklandica nesiotis*) and Campbell Island snipe (*Coenocorypha* spp.), that may be re-introduced from offshore Dent and Jacquemart Islets, following the elimination of rats (*Rattus norvegicus*) from mainland Campbell Island. Both Campbell teal and snipe are Category A species, the highest priority of threatened species (Clark & Dingwall, 1985). Intensive management is being undertaken for the Campbell Island teal (Department of Conservation, 1998). Campbell Island snipe are predominantly an open ground or edge species, so an increasing proportion of scrub may not maintain their preferred habitat (D. Given, pers. comm. 1999). Although the Department of Conservation's Subantarctic Islands Conservation Management Strategy (C.M.S.) states that habitat manipulation for threatened species (such as kakapo), should exclude major changes in composition of the community (Department of Conservation, 1998), it leaves the way open for small manipulations if Campbell Island snipe remain in a precarious state. Small patch burning of *Dracophyllum* would not adversely affect the distribution of scrub, but be very effective in providing edge habitat for the Campbell Island snipe.

The expansion of *Dracophyllum* on Campbell Island has several parallels with the establishment of *Olearia lyallii* on the Auckland Islands: *O. lyallii* occurs naturally on the Snares group (Lee *et al.*, 1991). It is now dominant on the small Ewing Island in the Auckland group and has established on the nearby shoreline of main Auckland Island. As it is thought to have reached there within the time of human contact, it is an open question as to whether it reached the Auckland Islands through natural immigration, or, conversely, by human activity (Lee *et al.*, 1991), which would make it an alien species on the Auckland group (Department of Conservation, 1998). The *O.*

lyallii situation is an example of the conundrum Atkinson (1990) describes, as to whether to control the biotic processes on conservation islands or not. The current extent of *Dracophyllum* on Campbell Island is, similarly, possibly due to human-induced change, and has the potential to be controlled if this was deemed necessary. *Dracophyllum* is naturally present on Campbell Island but is known to have expanded dramatically less than 70 years ago, coincident with major changes in human land use activity. It is now dominant in many areas that featured other vegetation types prior to 1940. Evidence suggests human influence is the likely cause, however, 7000-3000 years B.P. *Dracophyllum* covered a greater proportion of the island than at present, so posing a dilemma as to whether *Dracophyllum* expansion should be regarded as a natural process on Campbell Island.

Considering the similarities with the *O. lyallii* situation, and the fact that the pre-historic distribution of *Dracophyllum* was greater than its current one, the most sustainable and feasible option is probably to take the hands-off approach, as with the *O. lyallii* spread (Department of Conservation, 1998), and accept the expansion of *Dracophyllum* as an interesting phenomenon in its own right. Monitoring should, however, be continued to assess trends in *Dracophyllum* scrub in relation to wildlife values and Campbell Island's status as a World Heritage Site. This should be done in accordance with visitor impacts rules as set out in the C.M.S.

Burning is a practicable, semi-natural means of scrub control and may be a legitimate approach to conservation management in some circumstances, as herbaceous communities decline in the presence of unnatural levels of disturbance. Prescribed burning in fire-adapted communities is one approach to this. In the central North Island of New Zealand, nature and heritage conservation, along with military training and pastoral production, may all require interventionist burning to eliminate

invasive shrubs and trees (Rogers and Leathwick, 1994). However, in the presence of exotic species better adapted to fire, there is a danger of gradually converting to exotic vegetation. On Campbell Island the most serious competitors among the exotic plants are the grasses *Holcus lanatus* and *Dactylis glomerata*, which could replace burned *Dracophyllum* scrub in place of desired native herbaceous plants. There is no legislative provision for deliberate burning of shrubland and tussock grassland to perpetuate flora of tussock grassland, in New Zealand, if ever proposed for Campbell Island (Rogers and Leathwick, 1994), as suggested above for snipe habitat. It is unlikely that burning would be considered for Campbell Island if albatrosses become highly threatened, requiring such extreme action. It could be assumed, if it was ever deemed necessary for deliberate burning to be proposed for control of *Dracophyllum* on Campbell Island, that without grazing to follow, *Dracophyllum* expansion would be slow. However, the C.M.S. gives highest priority to prevention, control and suppression of fires (Department of Conservation, 1998). Also, the potential logistical problems of deliberate burning, including expense, fire control, weed infestation, and ecosystem degradation, especially for rare wildlife (Rogers and Leathwick, 1994), as well as the ethical issues of such interventionist management in a World Heritage Area, would raise huge uncertainties, and not follow the precautionary approach advocated in the C. M. S.

Campbell Island exemplifies the conflict between using islands for (i) protection of mainland species that have survived on islands but not survived well on the mainland, (ii) recovery of nationally endangered mainland species that were not originally part of the island's biota (such as, in Campbell Island's case, the kakapo (*Strigops habroptilus*)), and (iii) island restoration (Atkinson, 1990).

Summary

- ◆ Historical records indicate that *Dracophyllum* scrub was confined to foreshores and gullies in the 1840s.
- ◆ The photographic record and data on the *Dracophyllum* population age structure show that *Dracophyllum* scrub on Campbell Island has expanded dramatically since the 1930s.
- ◆ Yearly mean rate of increase in percent scrub cover, calculated from each photo-sequence, ranged from 0.02% to 1.85%. Some sequences did not feature any change in scrub cover.
- ◆ Scrub expansion patterns coincided with phases of land use change on Campbell Island.
- ◆ Broad climate trends of warming and drying may have encouraged recruitment, but had less influence on the overall pattern than major changes in land use.
- ◆ The timing and magnitude of *Dracophyllum* expansion are determined by the presence or absence of burning and/or grazing.
- ◆ Where *Dracophyllum* expands depends on drainage, fertility, and topography, especially elevation.
- ◆ *Dracophyllum* established more readily in better-drained sites and grew faster on fertile sites at lower elevations.
- ◆ The area of *Dracophyllum* may become denser but is unlikely to expand beyond, or reduce, its current range in the absence of further major changes in land use.
- ◆ Although present expansion is human-caused it may be that these impacts are merely accelerating the return of *Dracophyllum* scrub to an earlier, pre-human state reminiscent of a previous post-glacial warmer era, rather than establishing a new condition.

- ◆ Monitoring of *Dracophyllum* should be continued to assess trends in *Dracophyllum* scrub in relation to wildlife values on Campbell Island and the island's status as a World Heritage Site.

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Appendix



Plate 2. Sites of plots on Mesotrophic 1 transect, in descending order of elevation from left to right and top to bottom of the page: 245 m, 203 m, 165 m, 115 m, 58 m, and 15 m a.s.l. Plot locations shown on Fig. 4.0.



Plate 3. Sites of plots on Mesotrophic 2 transect, in descending order of elevation from left to right and top to bottom of the page: 30 m, 15 m, and 10 m a.s.l. The horizontal orange measuring pole in the top left photo is 1 m above ground level. Plot locations shown on Fig. 4.0.



Plate 4. Sites of plots on the Oligotrophic transect, in descending order of elevation from top to bottom and left to right of the page: 112 m, 80 m, 40 m, and 20 m a.s.l. Plot locations shown in Fig. 4.0.





Plate 5. Sites of plots on the Eutrophic transect, in descending order of elevation from top to bottom of the page: 160 m, 115 m, 85 m, and 13 m a.s.l. Photograph on right shows the vicinity of the plot at 85 m a.s.l. Plot locations shown on Fig. 4.0.

