

Reconstructing the fire history of D'Urville island, and its ecological consequences

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Abstract

Modification of offshore island ecosystems in New Zealand began with the arrival of Polynesians c. 1280 AD. European settlement in the early 19th century lead to further transformation. The introduction of regular burning from both waves of settlement has left lasting legacies on New Zealand's fire-sensitive native vegetation communities. D'Urville Island has a rich human history in large part because its abundance of metamorphosed indurated mudstone provided an excellent lithic resource for tool building and subsequent trade for Polynesian settlers. We analysed pollen, charcoal and magnetic susceptibility from three different locations, and developed a 2200 year record that begins c. 1550 years before human arrival, and spans c. 650 years of human occupation. The prehuman vegetation on D'Urville Island was a heterogeneous mosaic of Nothofagaceae-Podocarpus forest with a broadleaf sub-canopy and diverse shrub and small tree layer; a ground layer of ferns was also common. Coastal locations and those surrounding lakes and wetlands would have been abundant in Rhopalostylis and Dysoxylum forest. Previous research places human settlement of D'Urville Island at c. 1500 AD (albeit with a substantial potential error range); but multiple proxy analysis from our study suggest an earlier date of c. 1300 AD. The first wave of Polynesian settlement brought with it a transformation from closed to open forest synonymous with previous paleoecological studies throughout New Zealand. Fire was a major contributor to this transformation and charcoal is common in the record during both Polynesian and European settlement waves. With European settlement a decline in charcoal accumulation occurs, but there is a conspicuous lack of recovery of native forest. During this European period, exotic plant species appear and subsequently spread rapidly across the landscape. Despite the loss of much of the closed-canopy Nothofagaceae-Podocarpus forest, typical with much of the New Zealand mainland and offshore islands,

D'Urville Island posses many areas worthy of conservation. In particular, D'Urville island supports a number of threatened mistoloe, ultramafic communities and regionally rare species.

I. INTRODUCTION

³⁰ Anthropic changes to fire regimes have resulted in drastic and rapid shifts in ecosystem function,
³¹ structure and composition, especially in locations whose ecosystems are ill-adapted to frequent
³² fire (McWethy et al., 2013). New Zealand has been no exception. In comparison to a number
³³ of its Gondwanan neighbours, New Zealand's vegetation shows little evidence of adaptation to
³⁴ frequent fire, as fires occurred only once every 1-2 millennia prior to human settlement Ogden
³⁵ et al. (1998). Infrequent fire, combined with New Zealand's maritime climate prompted Ogden
³⁶ et al. (1998) to suggest the pre-human frequency of fires had the potential to be millennial in
³⁷ some sites. Perry et al. (2014) argue that the charcoal analysis used to decipher fire frequencies is
³⁸ highly biased towards the east coast of the South Island, making it somewhat difficult to derive
³⁹ conclusions that encompass all of New Zealand. It is likely that some ecosystems experienced
⁴⁰ fire more often than others. For example, the combination of physical conditions and vegetation
⁴¹ type in wetlands make them relatively more fire prone (McGlone, 1983, 2009, Perry et al., 2014).
⁴² Evidence from the eastern North Island suggests increasing fire activity from the mid-Holocene
⁴³ onwards (Horrocks et al., 2001, Rogers et al., 2007), possibly as a result of increasing droughts
⁴⁴ from the greater intensity and frequency of El Niño-Southern Oscillation (ENSO) events (McGlone
⁴⁵ et al., 1992, Perry et al., 2014).

46 Regardless of the precise fire frequencies throughout both the North and South Islands, the
47 evidence overwhelmingly suggests that most of New Zealand's indigenous woody vegetation
48 was not adapted to frequent fire (Wilmshurst & McGlone, 1996). New Zealand's tree species
49 typically have seeds that are vulnerable to fire and lack the fire-stimulated re-sprouting capabilities
50 of species in ecosystems where fire is more common such as much of Australia (Perry et al.,
51 2014). New Zealand's tree species also lack the traits fire-prone systems exhibit, such as thick bark
52 capable of protecting cambium from lethal temperatures experienced during fires (Richardson
53 et al., 2015). This lack of fire-adapted vegetation, and extended period of recovery, contributed
54 to the rapid conversion of New Zealand forest upon human arrival to open bracken-shrubland
55 (McGlone, 1983). Indeed the significant increase in bracken spores (*Pteridium esculentum*) and
56 abundance of charcoal towards the late Holocene, coinciding with the decline in forest pollen taxa,
57 indicates increased fire frequency that accompanied Polynesian arrival (McGlone & Wilmshurst,

58 1999). A synthesis of charcoal records from 16 lakes across the South Island suggests that forest
59 decline was both rapid and severe, reducing forest cover from 85-90%, to as little as 40% within
60 100 years (McWethy et al., 2009, 2014).

61 To date most ecologically-oriented fire history research in New Zealand has focused on trying
62 to understand the process and pattern of initial deforestation by human-lit fires immediately
63 following Polynesian settlement in the 13th century (McGlone & Wilmshurst, 1999, McGlone et al.,
64 2005, McWethy et al., 2009, Perry et al., 2012, Wilmshurst et al., 2004, Wilmshurst & McGlone, 1996).
65 European arrival was marked by significant changes to New Zealand landscapes yet the impact of
66 this second wave of colonization has not been well explored. European settlers rapidly changed the
67 landscape. Slash and burn techniques were used to convert native bush into agriculture; however,
68 the difficulties of controlling such fires often led to large areas of land burning unintentionally
69 (Pawson & Brooking, 2002). Landholders were, by law, required to improve their land and to
70 many the most efficient way to achieve this was by clearing forest with fire (Salmon, 1975). The
71 combined result of both those Polynesian and European fire and deforestation footprints was a
72 reduction of native forest to just 23% of the land surface area (Ewers et al., 2006).

73 The impact of European land-use during the past 1-2 centuries has been responsible for creating
74 feedbacks leading to dramatic shifts in ecosystem dynamics, yet these more recent impacts are
75 yet to be well examined. The exotic flammable species that arrived with Europeans (e.g. *Pinus*
76 spp., *Ulex* spp., *Hakea* spp.) have helped create interesting positive fire-vegetation feedbacks (Perry
77 et al., 2014) and declines in dispersal and pollination services (Keeley et al., 2011, Kitzberger et al.,
78 2016). The introduction of seed and seedling predators (Perry et al., 2015, Sullivan et al., 2010)
79 have potentially driven landscapes into 'traps' whereby recovery of native vegetation is severely
80 inhibited. In the absence of intensive restoration efforts which are difficult to implement on a large
81 scale, recovery of native vegetation is unlikely. Despite these feedbacks, interactions leading to
82 landscape 'traps' affecting many parts of the North and South Island, we know little of the fire
83 regimes and ecosystem dynamics that caused them to emerge.

84 Although the frequency of fire in New Zealand has declined in the late 20th century (Anderson
85 et al., 2008, Perry et al., 2014), climate change may further challenge restoration of native forests
86 (Harris et al., 2006, McGlone & Walker, 2011, Zavaleta & Heller, 2009) as warmer conditions
87 further promote fire. Here we set out to evaluate the legacy of Polynesian and European land-use
88 activities and the feedbacks and interactions responsible for conditions that prevent recovery and
89 challenge restoration of native forests. We ask these questions

- What are the consequences of human settlement on D'Urville Island's vegetation communities?
 - Did the modification of D'Urville Island following human settlement differ to other locations in New Zealand given its archaeological significance?
 -

and test these hypotheses x, y, zâ€œ results provide important information for guiding conservation and management. Better understanding of historic fire-related drivers of vegetation change will increase our fundamental knowledge of New Zealand's fire history and inform decisions when applying restoration baselines and conservation efforts in modern landscapes.

We used high-resolution pollen and charcoal reconstructions from a partially forested island in southern New Zealand to determine pre-human vegetation baselines and fire frequency. From these reconstructions we estimate Polynesian arrival and discuss the role human settlement had in shaping the modern vegetation assemblages now witnessed. We discuss the implications of such altered plant communities, while also considering the valuable conservation opportunities available.

II. STUDY SITE

D'Urville Island, Rangitoto ke te Tonga, sits at the north-western entrance to the Marlborough Sounds, South Island, New Zealand ($40^{\circ} 50' S$ $173^{\circ} 52' E$). At 150 km^2 it is New Zealand's eighth largest island. The coastline is typical of those throughout the Marlborough sounds, and its convoluted form results from river valleys that were drowned during the post-glacial rise in sea level (Wellman, 1962). Topographically the island incorporates a range of features including headlands, strong ridges, confined flats, inlets, steep hills and cliff systems. A series of islets and rock stacks surround the island, along with several coastal lagoons (Wellman, 1962). The highest point sits at 728 m (Attempt Hill) and is located close to the island's center (Fig: 1).

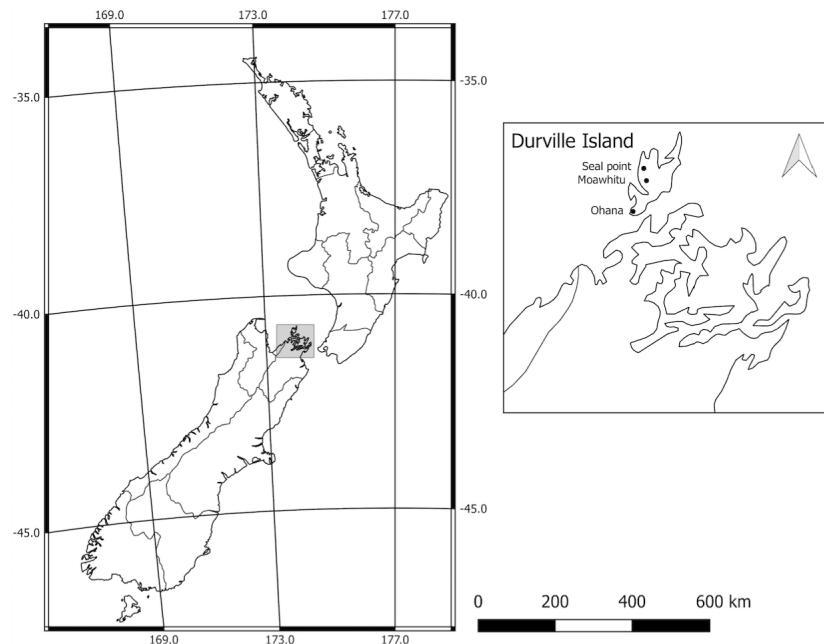


Figure 1: Location of study sites (black circles), New Zealand

114 D'Urville's climate is maritime and consists of prevailing north-west winds, reliable rainfall,
115 frequent gales, mild winters and warm summers (Walls, 2009). Temperatures during the summer
116 months of January to March reach an average daily maximum of 24°C and are among the warmest
117 in the South Island of New Zealand. Typical winter daytime temperatures are in the range 10°C -
118 15°C. Drought-like conditions are sometimes experienced within the region. On average, D'Urville
119 Island receives over 1000mm of rain annually (NIWA, 2017).

120 The island's geology is comprised of igneous conglomerate, Permian argillite and widespread
121 areas of mafic and ultramafic rocks, collectively known as the 'Mineral Belt' (Walls, 2009) or the
122 'Dun Mountain Ophiolite Belt' (Lee, 1992). As a result, the soils in parts of the island contain
123 high concentrations of heavy metals such as iron, copper, magnesium and nickel. Thus, it is a
124 component of the small (0.4%) part of the NZ landmass that can be described as 'serpentine'
125 (Lee, 1992). The ultramafic areas create an environment difficult for most plant species, and are
126 characterised by unique plant communities able to tolerate the high concentration of metallic
127 minerals in the soil.

128 D'Urville Island was an important cultural setting for early Polynesians. Argillites strength and
129 ability to hold a sharpened edge made it ideal for making weapons and tools. Adzes, a tool dating

130 back to the Stone Age, commonly used to smooth or carve wood, were a key instrument used
131 for trade. Flakes of argillite dominate the occupation layers in the cores analysed by Wellman
132 (1962), leading him to estimate a total of 60 tonnes was extracted during the island's Polynesian
133 occupation, or enough to manufacture not less than 15,000 adzes, acknowledging this is likely an
134 underestimate due to the amount of flakes still hidden. Lithic exchange was extremely important
135 to Polynesian settlers, and we see argillites from the northern South Island appearing in the Bay of
136 Plenty (central eastern New Zealand) less than 10 years after quarries appearing on the landscape
137 (Walter et al., 2010). The evidence suggests that D'Urville was the centre of flourishing trade given
138 the inferior quality of rock in other parts of New Zealand. Midden deposits are found in every
139 bay on D'Urville Island, as are stone walls associated with gardens (Walls, 2009). The occupation
140 layer examined by Wellman (1962) provides evidence that horticulture was likely to have been
141 prominent on the sandy flats, as shown by the uniform distribution of pebbles associated with
142 growing kūmara (*pomoea* spp.).

143 The following vegetation descriptions have been summarised with permission from Walls (2005,
144 2009); other descriptions also appear in Lee (1992) and Beever et al. (1989). As with much of New
145 Zealand, human arrival on D'Urville Island brought about a significant loss of native forest, and
146 what remains can be best described as a complex mosaic of exotic plantations, forest remnants,
147 pasture and areas undergoing secondary succession following clearing. The most accessible and
148 fertile low areas have, unsurprisingly, been converted into grazed pasture, yet areas of fernland
149 and shrub have survived in the areas not suited to farming. The expansion of fern and shrubland
150 into previously grazed regions due to a cessation of farming is noticeable in several areas and these
151 are, predictably, dominated by the early successional species such as *Kunzea* spp., *Leptospermum*
152 *scoparium*, bracken (*Pteridium esculentum*), *Cyathea medullaris*, *Coprosma robusta*, *Melicytus ramiflorus*
153 and *Cordyline australis*. *Fuscospora truncata* dominates on many of the ridges and slopes from 500 m
154 above sea level (asl) to sea-level, often in association with *Fuscospora solandri*, *Dacrydium cupressinum*
155 and *Elaeocarpus dentatus*. At higher elevation, and in the cooler, moister areas, *Fuscospora truncata*
156 is replaced by *Lophozonia menziesii*, *Lophozonia fusca*, *Prumnopitys ferruginea*, *Metrosideros umbellata*
157 and other broadleaf species. Coastal flats and some coastal slopes, along with gullies, contain
158 many of the broadleaf species abundant throughout of the North Island of New Zealand; of these
159 species, *Dysoxylum spectabile* is most abundant, but *Rhopalostylis sapida*, *Laurelia novae-zelandiae*,
160 *Beilschmiedia tawa*, *Alectryon excelsus*, *Piper excelsum*, *Aristotelia serrata*, *Hedycarya arborea*, *Cyathea*
161 spp. and *Carpodetus serratus* are common. Small examples of the low-forest climax vegetation on
162 ultramafic areas still exist, but are limited to higher elevations and consist of *Fuscospora truncata*,

¹⁶³ *Dacrydium cupressinum*, *Metrosideros umbellata*, *Pseudopanax crassifolius* and *Leptospermum scoparium*.
¹⁶⁴ Although the ultramafic soils exclude many common woody weeds found in the region, wilding
¹⁶⁵ pines such as *Pinus contorta* and *Pseudotsuga menziesii* are invading some locations. D'Urville
¹⁶⁶ Islands possum-free (*Trichosurus vulpecula*) status has also allowed for an abundance of mistletoe to
¹⁶⁷ adorn the island; also present are examples of endangered species such as *Anemanthele lessoniana*
¹⁶⁸ and *Euphorbia glauca*. Mammalian pests associated with much of New Zealand exist on D'Urville
¹⁶⁹ Island and include feral pigs (*Sus scrofa*), rodents, hedgehogs (*Erinaceus europaeus occidentalis*) and
¹⁷⁰ mustelids (Walls, 2009).

¹⁷¹ III. METHODS

¹⁷² A D-section hand corer was used to collect a 250 cm long soil core from Moawhitu Swamp. Cores
¹⁷³ from the lakes at Seal Point (143 cm length) and Ohana (136 cm length) were collected using a
¹⁷⁴ simple gravity lake corer.

¹⁷⁵ i. Pollen Analysis

¹⁷⁶ We subsampled 2 mL of soil from the Moawhitu Swamp core every 4 cm for pollen analysis.
¹⁷⁷ Standard preparation techniques were used to make microscope slides suitable for palynological
¹⁷⁸ analysis (Moore et al., 1991). On each slide pollen from trees, shrubs, herbs and bracken spores
¹⁷⁹ were recorded until a total of 250 grains was reached. Reference collections (Landcare Research)
¹⁸⁰ and atlases (e.g. Moar, 1993) were used to identify pollen to the highest possible taxonomic
¹⁸¹ resolution. Distinct and unprecedented changes in vegetation and charcoal inputs were used
¹⁸² to isolate initial human activity. Pollen and charcoal diagrams were constructed using the C2
¹⁸³ software package (Juggins, 2007)

¹⁸⁴ ii. Charcoal Analysis

¹⁸⁵ Charcoal was examined at high-resolution as per Whitlock & Larsen (2002) to reconstruct local fire
¹⁸⁶ activity. Samples from Moawhitu Swamp, Seal Point and Ohana cores were taken at contiguous
¹⁸⁷ 1 cm intervals using a brass sampler with a rectangular cutting edge. Sub-samples were taken
¹⁸⁸ at a volume of 2 cm³ where sufficient material was available, and 1 cm³ if not in the Moawhitu
¹⁸⁹ Swamp core. At both Seal Point and Ohana sub-samples were taken at a volume of 5 cm³. All

190 samples were soaked in 6% bleach for 24 hours. At Moawhitu Swamp samples were washed
191 through Petri dishes 250 µm, 125 µm and 63 µm, at Seal Point and Ohana samples were washed
192 through 125 µm Petri dishes. Charcoal particles were counted using a stereomicroscope at 50-100x
193 magnification. Charcoal concentration (number of particles/cm³) was determined using total
194 charcoal counts divided by the volume of sediment sieved. Charcoal accumulation rates were
195 calculated by dividing charcoal concentration by deposition time (yr/cm) between each sample.

196 iii. Radiocarbon dating

197 We submitted three twig samples from the Moawhitu Swamp core to the Waiakto Radiocarbon
198 Dating Laboratory, New Zealand for accelerator mass spectrometry (AMS) radiocarbon dating.
199 Ages of all dated material are expressed as calibrated ¹⁴C age before present (cal. year BP). The
200 samples from Moawhitu Swamp were taken from 32 cm, 59 cm and 94 cm. Three cal. year BP
201 dates were supplied from Ohana at 94 cm, 103 cm and 122 cm, and three from Seal Point at 80 cm,
202 105 cm and 115 cm. These dates are courtesy of Dr. David McWethy, Montanta State University,
203 USA. Age-depth modelling, as per the algorithm of (Haslett & Parnell, 2008) and the Southern
204 Hemisphere (SHCal13) calibration curve (Hogg et al., 2013), were constructed using the Bchron
205 package (Parnell, 2014) in the R statistical suite (R Core Team, 2015) version 3.1.3 (Fig: 2).

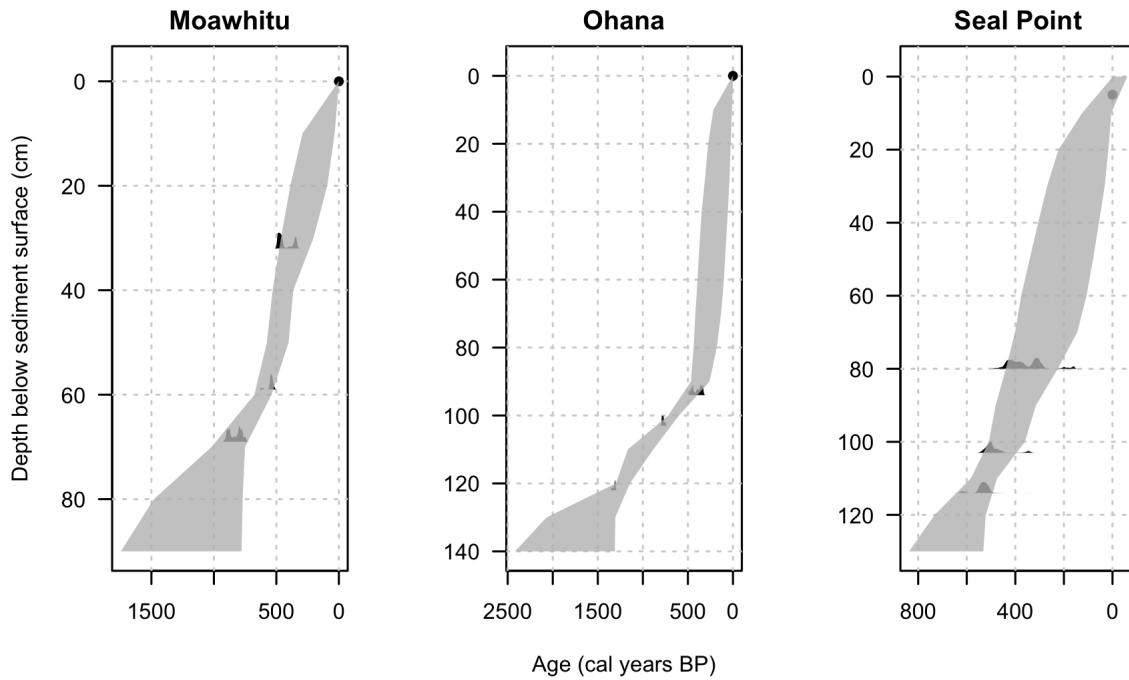


Figure 2: Age depth models for each site constructed using the compound Poisson-Gamma chronology model of Haslett & Parnell (2008). Light grey distributions indicate probability distributions from calibrated ^{14}C dates.

²⁰⁶ iv. Statistical analysis

²⁰⁷ Statistical analysis was conducted using the R statistical package (R Core Team, 2015), version
²⁰⁸ 3.2.3. Constrained cluster analysis that honoured the location of sites (CONISS), and nMDS
²⁰⁹ ordination, using the Bray-Curtis measure (Faith et al., 1987) were performed on the pollen
²¹⁰ reconstruction from Moawhitu Swamp using the rioja (Juggins, 2015) and VEGAN (Dixon &
²¹¹ Palmer, 2003) packages. Permutational multivariate analysis of variance (PERMANOVA) using
²¹² distance matrices (Anderson, 2001) were performed using the adonis command to statistically
²¹³ evaluate the dissimilarity between settlement and prehuman zones. Temporal auto-correlation
²¹⁴ between charcoal and magnetic susceptibility was conducted using the acf and ccf functions.

²¹⁵ v. Magnetic Susceptibility

²¹⁶ Not sure of the methods here.... Only for Seal Point and Ohana

217

IV. RESULTS

218 The timing of human arrival was estimated using a combination of distinct changes in pollen taxa
 219 (e.g. the introduction of exotic species), charcoal reconstructions and accompanied by statistical
 220 analysis of the pollen reconstruction from Moawhiti Swamp. Three zones were initially identified
 221 as a result of nMDS ordination on pollen taxa from the Moawhiti Swamp core: Zone 3 (0-20 cm,
 222 0-125 cal. years BP), zone 2 (20-64 cm, 150-650 cal. years BP) and zone 1 (64-250 cm, 650-2200 cal.
 223 years BP) (Fig: 3). Vegetation changes are demonstrated by a rapid rise in bracken and Poaceae,
 224 accompanied by a decrease in native forest taxa (Fig: 4, 5, 6), and the increase of charcoal into the
 225 Moawhiti Swamp, Seal Point and Ohana cores (Fig: 4, 7, 8).

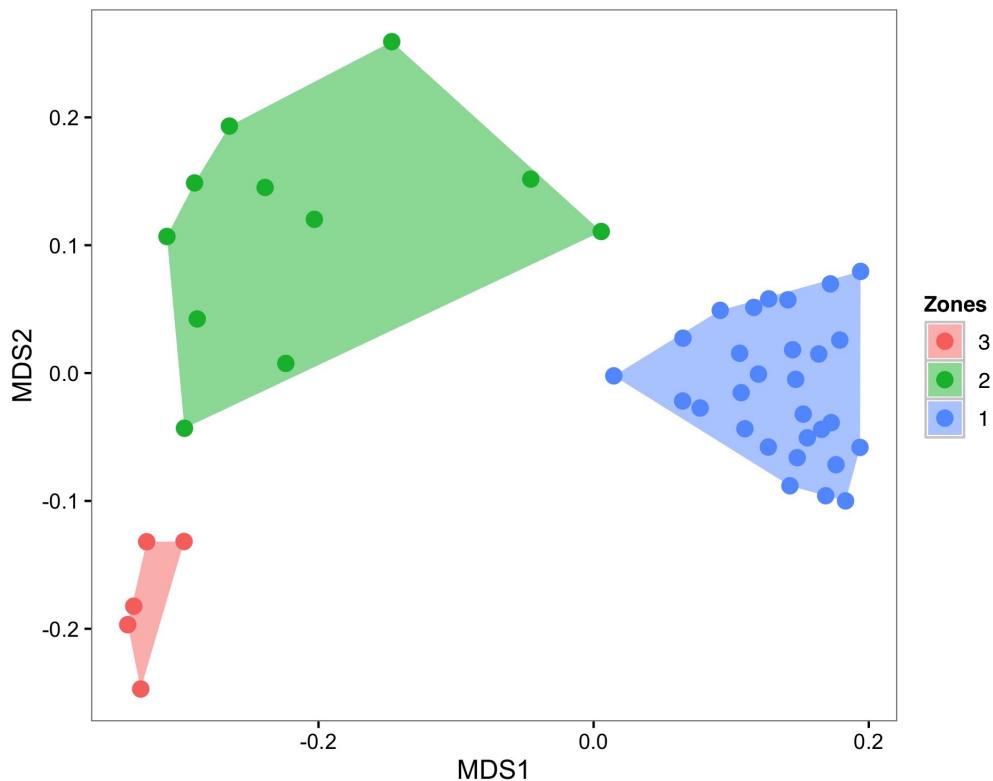


Figure 3: nMDS Ordination of settlement and prehuman zones identified from cluster analysis. Zones identified by different colors. Stress level = 0.1. Polygons indicate minimum bounding box.

²²⁶ i. Zone 1 - 650 - 2120 cal. years BP

²²⁷ Based on the pollen present, zone 1 comprises a *Nothofagaceae-Podocarpus* mosaic with a broadleaf
²²⁸ sub-canopy and a ground layer of ferns (Fig: 4, 5). Also notable is the presence of *Rhopalostylis*
²²⁹ *sapida* and *Dysoxylum spectabile*, which is indicative of a rich coastal, lake and wetland forest. There
²³⁰ are no discernible shifts in vegetation during this part of the core and pollen sum percentages
²³¹ remain relatively consistent. The podocarp taxa are the most variable component of the palynoflora
²³² (Fig: 4).

²³³ ii. Zone 2 - 150 - 650 cal. years BP

²³⁴ The decline in podocarps as forest was cleared is an indication of change in zone 2 from zone 1
²³⁵ (Fig: 4, 6). The biggest drivers of this difference are the decrease in podocarps, and increase in
²³⁶ grasses and bracken, as forest taxa are replaced by disturbance-tolerant species. The creation of
²³⁷ young and seral forest is evident in the increase in *Leptospermum scoparium* and *Cordyline* pollen
²³⁸ (Fig: 4, 6). Large fire events during this period are evidenced by spikes in bracken, *Typha* and
²³⁹ monolete fern spores.

²⁴⁰ iii. Zone 3 - 0 -150 cal. years BP

²⁴¹ The arrival or establishment of several exotic species, including *Taraxacum* spp., *Pinus* spp., and
²⁴² the non-native *Plantago*, marks zone 3. Pollen of disturbance-related taxa such as bracken, *Typha*
²⁴³ spp., and monolete fern spores contribute most to the differences observed. Monolete fern spores
²⁴⁴ and *Typha* decline during this modern period and this is likely due to the reduction in fire-related
²⁴⁵ disturbance events (Fig: 4, 6). Exotics, such as *Pinus* and non-native *Plantago*, are also important
²⁴⁶ contributors to the different vegetation communities observed. Forest taxa, particularly podocarps,
²⁴⁷ have the lowest pollen sum percentage observed across all three zones. The open forest favours
²⁴⁸ the growth of light-demanding and pioneer species such as *Leptospermum scoparium*, *Kunzea* spp.
²⁴⁹ and *Cordyline*.

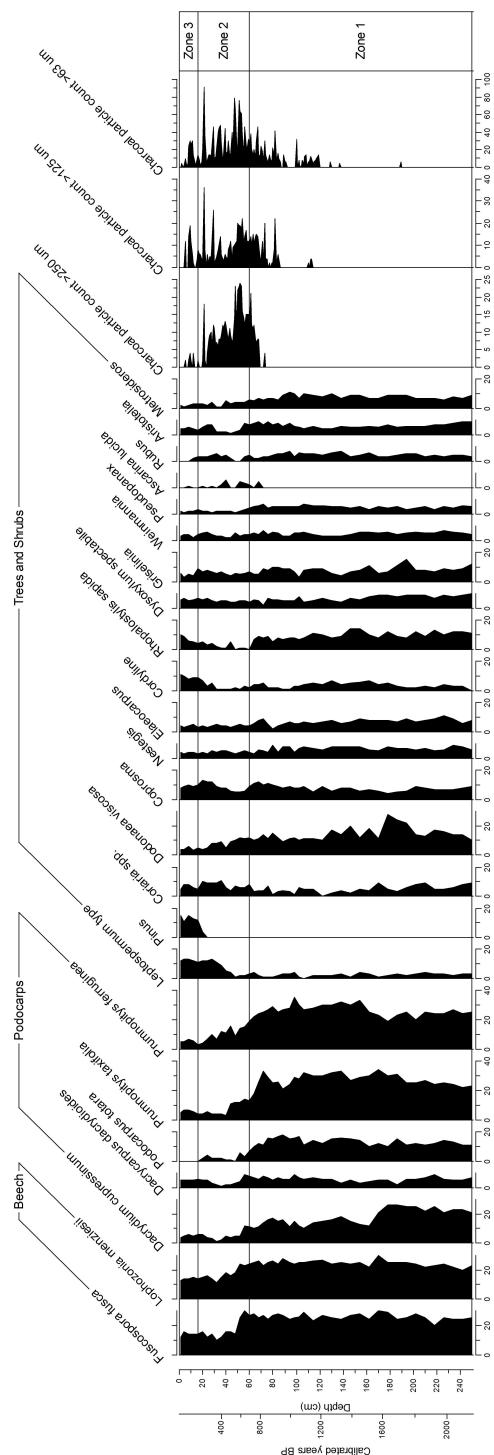


Figure 4: Nothofagaceae, Podocarpaceae and small trees and shrubs pollen identified at Moawhītu Swamp. Pollen sum given as a percentage of total pollen count.

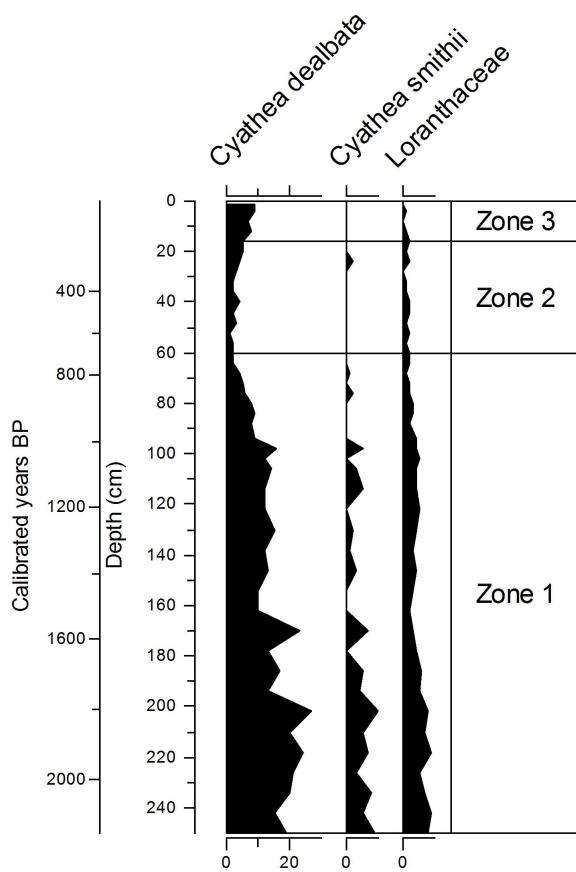


Figure 5: Ferns and mistletoe identified in the pollen reconstruction from Moawhiti Swamp. Pollen sum given as a percentage of total pollen count.

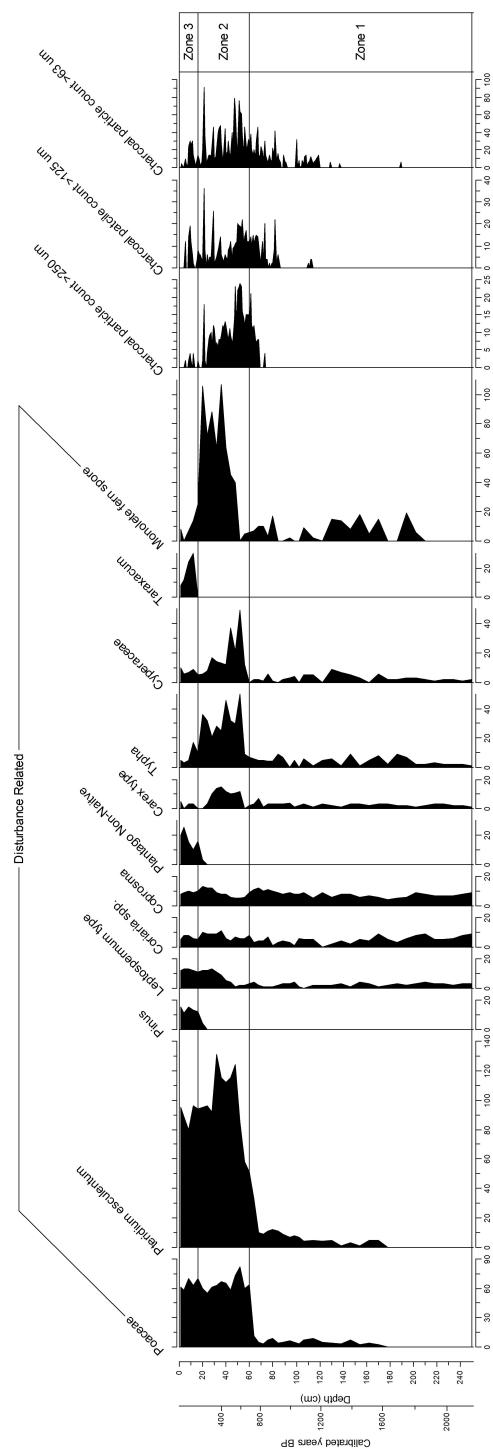


Figure 6: Changes in species associated with disturbance in pollen reconstruction from Moawhitu Swamp.

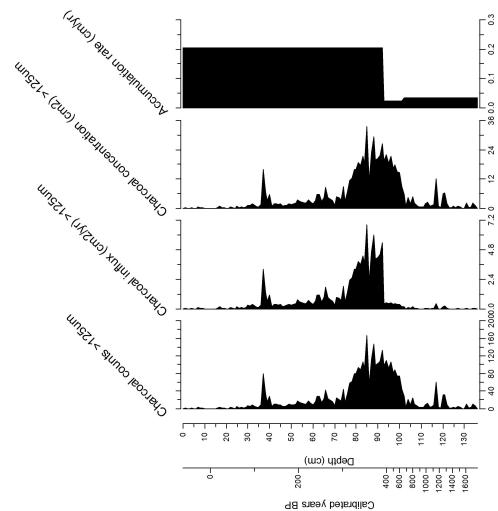


Figure 7: Macroscopic charcoal from the Ohana profile, expressed as concentrations and influx. Sedimentation rates expressed as accumulation (cm/yr).

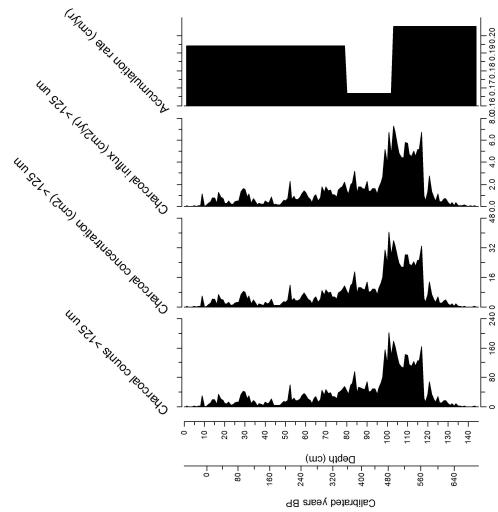


Figure 8: Macroscopic charcoal from the Seal Point profile, expressed as concentrations and influx. Sedimentation rates expressed as accumulation (cm/yr).

²⁵⁰ iv. Sediment-charcoal records

²⁵¹ Charcoal is absent from much of zone 1 in the Moawhitu Swamp core (Fig: 4). Consistent inputs
²⁵² of microscopic charcoal at Moawhitu Swamp begin around 1100 cal. years BP, with three peaks
²⁵³ at c. 490, 470 and 228 cal. years BP. All three sites show increasing macroscopic charcoal inputs
²⁵⁴ from around 650 cal. years BP onwards, with charcoal concentrations being highest from 400
²⁵⁵ - 600 cal. years BP (Fig: 4, 7, 8). The Ohana Lake profile also exhibits another charcoal peak
²⁵⁶ at 120 cal. years BP after a steady decline, with Seal Point also showing higher concentrations
²⁵⁷ around this period (Fig: 7, 8). The Moawhitu Swamp core is more temporally variable in terms of
²⁵⁸ charcoal concentration, but shows a similar pattern of increased burning at around 100 cal. years
²⁵⁹ BP (Fig: 4). A visual comparison of charcoal concentration and influx from the Moawhitu and Seal
²⁶⁰ Point cores reveals close agreement in temporal pattern across size classes (Fig: 4, 8). A dramatic
²⁶¹ increase in accumulation after nearly three centuries of increased charcoal inputs correlates with
²⁶² increases in charcoal influx just after 400 cal. years BP in the Ohana core (Fig: 7).

²⁶³ v. Magnetic susceptibility

²⁶⁴ Corresponding with Polynesian arrival, magnetic susceptibility increases from c. 600 cal. years BP
²⁶⁵ in the Seal Point core. This rise in magnetic susceptibility peaks c. 175 years later, and then shows
²⁶⁶ a fluctuating decline until European arrival (c. 150 cal. year BP), when magnetic susceptibility
²⁶⁷ increases until a peak c. 120 cal. years BP, gradually declining thereafter. Polynesian settlement
²⁶⁸ does not give a clear signal in the Ohana core, with magnetic susceptibility declining c. 600
²⁶⁹ cal. years BP. This decline continues for c. 200 years before we see increases to the highest
²⁷⁰ magnetic susceptibility levels seen in the core. European settlement provides a clearer signal in
²⁷¹ the Ohana core, with similar magnetic susceptibility increases c. 150 cal. years BP to those in
²⁷² Seal Point. Charcoal and magnetic susceptibility were not significantly correlated in either the
²⁷³ Seal Point or Ohana profiles, ($r=0.179$ and $r=0.157$, respectively), however there is a significant
²⁷⁴ lagged correlation between fire activity (as measured by charcoal) and magnetic susceptibility. The
²⁷⁵ maximum correlation occurs when a lag of 22 cm is applied ($r=0.541$, $P < 0.05$) or approximately
²⁷⁶ 60 years to the Seal Point core. Correlation also improves ($r=0.547$, $P < 0.05$) when a 50 year lag is
²⁷⁷ applied to the Ohana profile.

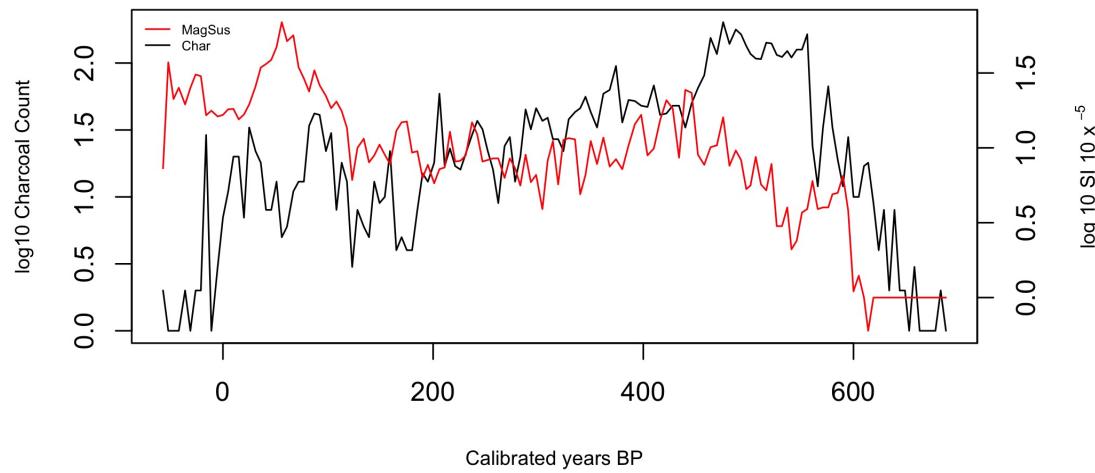


Figure 9: Magnetic susceptibility (\log_{10}) and charcoal particle count (\log_{10}) from the Seal Point core.

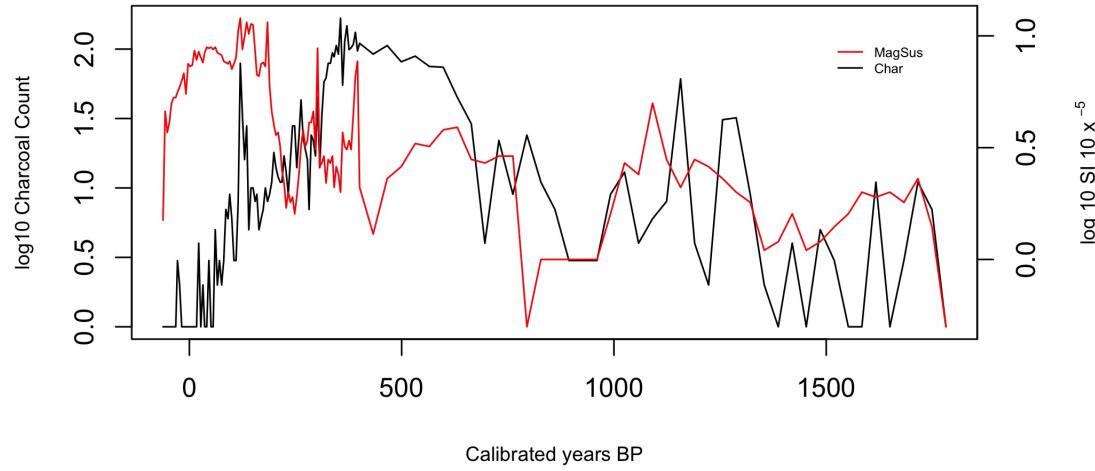


Figure 10: Magnetic susceptibility (\log_{10}) and charcoal particle count (\log_{10}) from the Ohana core.

278 vi. Definition of settlement and prehuman zones using all proxies

279 Previous work by Wilmshurst et al. (2008) places Polynesian settlement of New Zealand at c. 1280
280 AD. Based on the combination of sustained burning, decline of forest (Fig: 4) and increase in
281 disturbance related taxa in the pollen record (Fig: 6), settlement of D'Urville Island likely began c.
282 650 cal years BP, corresponding to a depth of c. 64 cm in the Moawhitu Swamp core (Fig: 6). This
283 Polynesian settlement period represents zone 2 in the ordination presented (Fig:3), and shall be
284 referred to as such hereafter; zone 1 will be identified as prehuman (Table: 1).

285 Exotic pollen taxa are a clear signal of European settlement and so their arrival c. 150 cal. years
286 BP make the European zone easier to identify. *Pinus*, non-native *Plantago* and *Taraxacum* appear at
287 20 cm in the Moawhitu Swamp core. Unfortunately, the lack of radiocarbon dates towards the
288 top of all three cores, combined with the notorious difficulty in dating periods ranging from 1800
289 to 1950 AD (Hajdas, 2008) (a result of increases in fossil fuel combustion during the industrial
290 revolution), creates a high degree of uncertainty in this zone. However, reliable records show
291 permanent European settlement of D'Urville Island followed that of other New Zealand locations
292 in 1840 AD, with the arrival of the first immigration ships at Port Hardy (a large inlet to the
293 north of D'Urville Island) (Walls, 2009). Given these historical dates for European arrival, and the
294 appearance of exotic taxa in the pollen reconstruction, it is safe to assume that European arrival
295 occurred at around 20 cm (c. 150 cal. years BP), encompassing zone 3 (Fig: 3). The relevant depths,
296 mean cal. years BP, zone numbers and subsequent names are given in Table 1.

Table 1: Zones identified as a result of age-depth model, pollen and charcoal analysis from all three cores.

Depth (cm)	Mean estimate of cal. years BP	Zone Number	Zone Name
0 - 20 cm	0 - 150	3	European
20 - 64 cm	150 - 650	2	Polynesian
64 - 250 cm	650 - 2120	1	Prehuman

297

V. DISCUSSION

298 Analysis of the data from the three sites considered in this study provide a first look at the
299 late Holocene vegetation and fire history of D'Urville Island in the Marlborough Sounds, New

300 Zealand. Pollen assemblages, macroscopic and microscopic charcoal in the sediment profile from
301 Moawhitu Swamp provide a 2200 year record of vegetation shifts and fire history. Cores taken
302 from Seal Point and Ohana Lake date back to c. 688 and c. 1782 cal. years BP, respectively. This
303 study confirms that fire was a rare event prior to human arrival on the island, but c. 650 cal.
304 year BP, and coincident with human arrival, it dramatically increased. The introduction of exotic
305 plant species following European arrival c. 150 cal. year BP further complicates an already highly
306 altered ecosystem.

307 i. What were the pre-human plant assemblages?

308 The lack of change in pollen percentages during the pre-human zone suggests relatively stable
309 vegetation assemblages (Fig: 4). It is unlikely that large disturbance events on D'Urville Island
310 occurred with any frequency prior to human settlement, although it has been suggested that a
311 tsunami struck the island around the 16th century (Mitchell & Mitchell, 2007); however, there is no
312 evidence in the pollen reconstruction for such an event. We see a clear and persistent dominance
313 of Nothofagaceae throughout the pre-human period, on average accounting for over 50% of the
314 total pollen sum (Fig: 4). During this pre-human period Nothofagaceae forest is associated with a
315 tall emergent layer of podocarp species including *Dacrydium cupressinum*, *Dacrycarpus dacrydioides*,
316 *Prumnopitys ferruginea*, *Prumnopitys taxifolia* and *Podocarpus totara*. This Nothofagaceae-Podocarpus
317 forest would have been accompanied by a diverse canopy of *Weinmannia* spp., *Nestegis* spp. and
318 *Elaeocarpus* spp. Smaller trees in the sub-canopy include *Coprosma* spp., *Alectryon excelsus* and
319 *Dodonaea viscosa*. Climbers such as *Rubus* spp. also occur in the pollen record. Shrubs associated
320 with forest margins including *Aristotelia* spp., *Melicytus* spp., *Pseudopanax* spp., *Myrsine* spp.,
321 *Coprosma* spp., *Rubus* spp., and bracken are consistent throughout. *Dysoxylum spectabile*, *Aristotelia*
322 *serrata*, *Rhopalostylis sapida* and *Leptospermum scoparium* would have been abundant, likely on
323 coastal slopes and gullies. Tree-ferns, namely *Cyathea dealbata* and *Cyathea smithii*, would have
324 been present in both gully forest and the understory (Fig: 5). Low forest climax vegetation
325 such as *Pseudopanax* spp., *Metrosideros* spp. and *Dacrycarpus dacrydioides* would have been far
326 more prominent and likely not restricted to the higher elevations they are today. Rich palm and
327 *Dysoxylum* forest would have surrounded the lakes, wetlands and coastal areas.

328 Mistletoe are abundant throughout the pre-human phase, and although only identified to the
329 family level, the species are likely *Alepis flava*, *Peraxilla colensoi* and *Peraxilla tetrapetala* given their
330 association with beech (Norton & de Lange, 1999). The historic abundance of mistletoes (up to

³³¹ 8% of total pollen sum, Fig: 5) can offer important baseline guidelines for restoration, given their
³³² current threatened conservation status (Sweetapple et al., 2002).

³³³ ii. Pollen record after Polynesian settlement

³³⁴ The rise in sediment charcoal, combined with shifts in pollen taxa, clearly indicates human arrival
³³⁵ at c. 650 cal years BP. Settlement brought increased fire frequencies on D'Urville Island, and with
³³⁶ this there is a clear shift in both the dominant species and the nature of the plant assemblages. A
³³⁷ common characteristic among the species that follow periods of increased fire activity is they are
³³⁸ favoured in post-fire environments. The evidence provided here certainly follows that pattern, with
³³⁹ bracken and grass abundance dramatically increasing, and subsequently persisting in the pollen
³⁴⁰ reconstruction. Disturbance-related species also drive much of the differences observed between
³⁴¹ the pre-human and Polynesian zones (Fig: 6). *Typha* also increases substantially and comprises
³⁴² up to 15% of the pollen sum in some years (Fig: 6). This increase, in what is a nutrient-loving
³⁴³ species, likely reflects an influx of detritus, sand and silt into both lake and swamp areas as a
³⁴⁴ result of increased burning, and is a common response following deforestation in New Zealand
³⁴⁵ wetlands (McGlone & Wilmshurst, 1999). An increase in sediment accumulation rates from Ohana
³⁴⁶ support this hypothesis (Fig: 7). *Typha* pollen was also used by Maori to make cakes, with the roots
³⁴⁷ providing a food source (Taylor, 2010), and deliberate action to support this practise could have
³⁴⁸ contributed to its expansion. Magnetic susceptibility also increases during this period suggesting
³⁴⁹ inputs from erosion as a result of the loss of forest cover (Fig: 9, 10).

³⁵⁰ iii. Pollen record after European settlement

³⁵¹ Forest taxa show little recovery during the European period, although beech does increase to
³⁵² around 15% of the pollen sum (Fig: 4). Beech is known to colonise small disturbed areas rapidly;
³⁵³ however, its heavy seeds mean that it can be dispersal limited, recovering slowly without adequate
³⁵⁴ seed sources (Wardle, 1984). On D'Urville Island this process is likely hampered by the rise of
³⁵⁵ fire-adapted species such as *Leptospermum scoparium*, *Kunzea* spp., *Pinus* spp. and *Cordyline* spp.
³⁵⁶ The emergence of *Pinus* in the pollen record is a familiar signal of European arrival. Pasture plants
³⁵⁷ such as *Trifolium* spp. and exotic members of the Poaceae also appear. Pines were introduced to
³⁵⁸ NZ early in the 20th century, and can be seen invading serpentine (ultramafic) areas on D'Urville.
³⁵⁹ Bracken and grasses, limited before the introduction of fire, dominate the pollen record (Fig: 6)

³⁶⁰ and we see the arrival of other non-native taxa, including *Taraxacum* and *Plantago*.

³⁶¹ iv. The charcoal record

³⁶² The microscopic and macroscopic charcoal records reveal that fire was not a regular occurrence
³⁶³ on D'Urville Island or the surrounding area until c. 650 cal. years BP. The macroscopic charcoal
³⁶⁴ record shows a similar pattern, and, given the larger particle size, provides a better understanding
³⁶⁵ of localised fire (Leys et al., 2013). The long absence of fire in this record is not surprising given:
³⁶⁶ a) the relatively short period examined, and b) the evidence that fire events were often centuries
³⁶⁷ apart in pre-human New Zealand (McGlone & Moar, 1998, McGlone & Wilmshurst, 1999, Ogden
³⁶⁸ et al., 1998, Wardle, 2001). Interestingly there are some macroscopic peaks between 1288 and 1256
³⁶⁹ cal. years BP, and another at c. 1157 cal. years BP in the Ohana core (pre-human zone). In the
³⁷⁰ Moawhitu Swamp core these peaks are just discernible in the microscopic charcoal record. These
³⁷¹ peaks are likely the result of small wetland fires, common in these environments and unlikely to
³⁷² have impacted the surrounding forest, a dynamic observed in wetland fires elsewhere (McGlone
³⁷³ et al., 1984). The magnetic susceptibility signal also supports the presence of fire in the pre-human
³⁷⁴ zone as we see a clear spike during this period (1288 and 1256 cal. years BP) (Fig: 10). Pollen
³⁷⁵ reconstruction from Ohana would allow further investigation of these fire events.

³⁷⁶ The 'Initial Burning Period' (IBP) in the decades immediately after Polynesian settlement (c. 1280
³⁷⁷ AD) was responsible for transforming large parts of the South Island's native forests (McWethy
³⁷⁸ et al., 2009), and was likely facilitated by positive feedbacks between fire and vegetation (Perry et al.,
³⁷⁹ 2015). Given the limited amount of charcoal prior to this period, no evidence for dramatic climatic
³⁸⁰ shifts (McWethy et al., 2009), we can assume the input of charcoal comes from anthropogenic fire
³⁸¹ on D'Urville Island, and follows a similar pattern of deliberate and systematic fires to those in
³⁸² other locations during the IBP. Fire was also an important part of Maori culture, used to remove
³⁸³ scrub and forest(Stone & Langer, 2015). This process of burning also not only deprived wild
³⁸⁴ game of cover, it aided in the growth of understory shrubs, particularly bracken, an important
³⁸⁵ food source (Guild & Dudfield, 2009, McGlone et al., 2005). Fire also enabled the first settlers to
³⁸⁶ clear land quickly for horticulture, and the cultivation of crops including kūmara (*Ipomoea batatas*)
³⁸⁷ (Simmons, 1969).

³⁸⁸ Inferences beyond the timing of fires on D'Urville Island, as with any interpretation of paleo-
³⁸⁹ charcoal, present challenges. Although we can be confident that fire most certainly occurred in the

390 region from 650 cal. years BP, it is difficult to determine the spatial patterns of this activity. It is
391 likely that human populations were concentrated around argillite quarries (Walter et al., 2010).
392 Burning would likely have commenced in the low land areas with easy access to water that were
393 most suitable for settlement and horticulture. This is the pattern described in Perry et al. (2012)
394 for New Zealand as a whole. The higher elevation areas would probably have been cleared later
395 or accidentally burnt. The episodic nature of the charcoal records suggests temporal variation in
396 fire events corresponding to anthropogenic activity; indeed, the small quantities of macroscopic
397 charcoal earlier in the record indicates that the introduction of regular fire was rapid. Increases in
398 charcoal deposition also correlate with increases in disturbance-related pollen taxa (Fig: 6) and
399 the loss of forest taxa (Fig: 4). These factors, combined with D'Urville Island's distance from the
400 mainland (0.6 km), provide confidence that the macroscopic charcoal record demonstrates the
401 onset of relatively large localised fires. It is important to acknowledge previous work that suggests
402 macroscopic charcoal can travel several kilometres from its source during wildfires (Tinner et al.,
403 1998, 2006). Hence, there is the potential that macroscopic charcoal particles could come from
404 locations outside of D'Urville, but this is unlikely given the abundances seen.

405 Given the loss of closed canopy forest indicated in the pollen record (Fig: 4), it is likely that
406 these post-settlement fire events were consistent re-burns of early successional vegetation rather
407 than in previously unburned areas (Perry et al., 2014). The loss of woody material after the IBP
408 would explain the decrease in macroscopic charcoal inputs, until a small spike occurred during
409 the European period (Fig: 6, 7, 8). It is also likely that Polynesian interests in the islands were
410 diminishing given intensive warfare and decreasing trade in argillite (Wellman, 1962). European
411 settlement did not signal a respite for D'Urville Island, and the charcoal record demonstrates a
412 continuation of burning, albeit somewhat subdued. The decrease in charcoal deposits are, in part,
413 likely due to the adoption of different land clearing methods by European settlers (e.g. physical
414 removal of scrub) and a decrease in fire-related land clearance methods. Despite the reduction in
415 charcoal input, it appears that the beech-podocarp and coastal rich palm forest did not recover
416 after the IBP, and that fire and land management practises continue to be a significant disturbance
417 mechanism.

418 v. Magnetic susceptibility

419 Soil magnetic susceptibility increases with the onset of the IBP but shows a consistent decline
420 thereafter (Fig 9, 10). This trend is more prominent in the Seal Point record; although we do see

421 an increase in magnetic susceptibility at Ohana, it is less pronounced until some time after the
422 IBP. Charcoal and magnetic susceptibility do not correlate well in either the Seal Point or Ohana
423 records ($r=0.179$ and $r=0.157$, respectively, Fig: 9, 10). Interestingly we see the lowest correlations
424 after Polynesian settlement and during the IBP (c. 550 - 420 cal. years BP), and after European
425 settlement (c. 150 cal. years BP) (10). This lack of correlation indicates that an increase in charcoal
426 deposits is not synchronous with changes in magnetic susceptibility. This pattern is supported
427 by strengthened correlation in both Seal Point and Ohana ($r=0.541$ and $r=0.547$, respectively)
428 when approximately 40-60 year time lags are applied to magnetic susceptibility, implying that
429 changes in magnetic susceptibility are, at least in part, likely due to erosion events rather than
430 magnetic enhancement of soils as a result of burning (i.e. the gradual degradation of forest slowly
431 reducing soil cohesion and subsequently increasing input of allochthonous mineral material from
432 erosion). Erosion is certainly well correlated with deforestation in New Zealand, with Wilmshurst
433 (1997) noting significant erosion pulses in lake sediment cores as a result of deforestation during
434 settlement in Lake Tutira, Hawke's Bay area, North Island, New Zealand. McWethy et al. (2009)
435 showed magnetic susceptibility was almost simultaneous with the onset of burning in some sites
436 examined in the South Island, New Zealand, and its decline strongly associated with the end
437 of the IBP. They suggest watershed vegetation was highly impacted, resulting in erosion events
438 almost immediately after fire.

439 We suggest that the time-lags observed in correlations between charcoal and magnetic susceptibility
440 at D'Urville Island are, at least in part, due to a once abundant beech-podocarp forest being slowly
441 degraded, with the associated deposition of allochthonous mineral increasing gradually over
442 time rather than abruptly. The strengthened correlation after the IBP with a lag applied supports
443 this hypothesis, suggesting that the process of burning removed riparian vegetation, and thus
444 deposition rates increased. It can be argued that the gradual decline in magnetic susceptibility
445 towards the end of the Polynesian and beginning of the European zone is due to the increased
446 cover of bracken, known to stabilise soils after deforestation (McGlone et al., 2005, Wilmshurst,
447 1997). The stabilisation afforded by bracken is potentially site-specific, and hence we witness
448 different patterns in accumulation rates between Ohana and Seal Point (Fig: 7, 8).

449 vi. The consequences of human settlement

450 The removal of large quantities of forest, and the decline in species-rich palm and *Dysoxylum* forest
451 leaves parts of D'Urville Island vulnerable to further disturbance events, and ongoing invasion by

452 the exotic species already established. The dominance of bracken and Poaceae in the pollen record,
453 combined with the expansion of *Leptospermum* spp. and *Pinus* spp. is symbolic of a landscape
454 that has been highly disturbed. Such sites can quickly become fire-prone amplifying a 'fire begets
455 fire' feedback dynamic. Colonisation by later successional species is made increasingly difficult
456 by the already limited remnant forest and respective seed sources remaining on D'Urville Island.
457 This positive feedback is suggested by Perry et al. (2014); the post-vegetation landscape is more
458 flammable, making the system more susceptible to fire, and hence harder for later succession
459 species to establish. Gorse (*Ulex europaeus*), although not present in the pollen record but prevalent
460 on D'Urville Island, will contribute to the fire-prone nature of early successional locations given
461 the high ignitability of its litter (Madrigal et al., 2012); it was the most flammable, at the shoot-level,
462 of the 60 species assessed by Wyse et al. (2016). Further disturbance events, be they fire or other
463 natural occurrences such as drought, will result in the colonisation of species well-adapted to
464 disturbed environments. Feedbacks between disturbance and invasive plant taxa can potentially
465 result in broad areas of homogeneous early successional vegetation that reduce the potential of
466 native flora to establish (Gaertner et al., 2014).

467 The 'fire begets fire' pattern is shown by the transition from an old landscape, dominated by
468 the species prominent in the pre-human period, to a young, fire prone system comprised of
469 other species that established in the late Polynesian/early European period on D'Urville Island.
470 Although fire activity has certainly decreased in recent years, the dominant vegetation that remains
471 will be highly susceptible to natural, or accidental fire events. Seedling establishment in these
472 early-successional environments is likely further hampered by browsing from rats (*Rattus rattus*)
473 present on D'Urville Island (Wilson et al., 2003). Breaking this cycle is extremely difficult as the
474 system could be characterised as having shifted to an alternative stable state reinforced by strong
475 positive feedbacks (Bowman et al., 2015). These systems then exhibit a difficult to reverse shift in
476 both vegetation structure and composition (Perry et al., 2014). Such multi-stressed environments
477 increase the complications for restoration as a result of non-independent pressures, requiring each
478 stressor to be addressed simultaneously in order to reduce the potential for arrested succession
479 (Perry et al., 2015).

480 vii. Implications for restoration

481 Offshore islands in New Zealand have benefited from extensive research into best management
482 and restoration practises (e.g. Buxton et al., 2014, Parker & Laurence, 2008, Russell & Broome,

483 2016, Simberloff, 2002, Towns et al., 2013, Towns & Broome, 2003). One key ingredient in these
484 previous projects has been the eradication of pests and invasive weeds, made easier by the
485 uninhabited status of these islands. Glen et al. (2013) argue that it is perhaps time we look beyond
486 uninhabited islands and towards those with a permanent population when considering multi-
487 species eradication efforts. Given the complexities in such projects this is certainly ambitious, and
488 would require the full engagement of local communities (Ogden & Gilbert, 2009). D'Urville Island
489 would be an extremely interesting case-study for such an experiment, and potentially propel it
490 to the forefront of conservation/restoration projects worldwide. The island possesses many areas
491 worthy of conservation, given the number of threatened mistletoe, ultramafic communities and
492 regionally rare species. Complete eradication of pests and invasive weeds is perhaps too ambitious,
493 but the island presents an excellent opportunity for future forest and wetland restoration. A major
494 challenge stems from the potential for arrested succession in the pyrophyllitic exotic/*Leptospermum*
495 *scoparium/Kunzea ericoides* dominated areas of D'Urville Island, for which the adequate control
496 of fire will be required. Further intervention in the form of restorative plantings can aid in the
497 regeneration of closed forest and move these systems further away from their fire prone status.
498 The vegetation baselines that are presented here can inform such restoration efforts.

499 Pollen and charcoal records such as those presented provide an opportunity to inform restoration
500 effort, and aid in the provision of pre-human vegetation baselines. Such information about
501 pre-settlement plant assemblages can help managers in determining the viability of, for example,
502 the reintroduction of species formally present (Wilmshurst et al., 2014). Simulation models as
503 per Perry et al. (2016) can assist in further exploring succession dynamics (i.e. fire begets fire
504 patterns) resulting from increases in fire frequency. These records form the building blocks of
505 such exploration, and will aid us in the construction of modelling tools to resolve some of the
506 questions we have posed.

507

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