Two-step human−environmental impact history for northern New Zealand linked to late-Holocene climate change

Rewi M. Newnham[1*], David J. Lowe[2], Maria Gehrels[3] and Paul Augustinus[4]

[1] School of Geography, Environment & Earth Sciences, Victoria University of Wellington, Wellington, New Zealand

[2] School of Science, University of Waikato, Hamilton 3240, New Zealand

[3] Environment Department, York University, United Kingdom

[4] School of Environment, University of Auckland, Auckland, New Zealand

***Corresponding author:**
Rewi Newnham, School of Geography, Environment and Earth Sciences,
Victoria University of Wellington, PO Box 600, Wellington 6140,
New Zealand.
Email: rewi.newnham@vuw.ac.nz

Citation: Newnham, R.M., Lowe, D.J., Gehrels, M.J., Augustinus, P. 2018. Two-step human−environmental impact history for northern New Zealand linked to late-Holocene climate change. *The Holocene* (on line 22 March 2018, pp. 1-14) https://doi.org/10.1177/09596836187615

See the journal for the definitive version

Abstract

Following resolution of a long-standing debate over the timing of the initial settlement of New Zealand from Polynesia (late 13th century), a prevailing paradigm has developed that invokes rapid transformation of the landscape, principally by fire, within a few decades of the first arrivals. This model has been constructed from evidence mostly from southern and eastern regions of New Zealand, but a more complicated pattern may apply in the more humid western and northern regions where forests are more resilient to burning. We present a new pollen record from Lake Pupuke, Auckland, northern New Zealand, that charts the changing vegetation cover over the last 1000 years, before and after the arrival of people. Previous results from this site concurred with the rapid transformation model, although sampling resolution, chronology and sediment disturbance make that interpretation equivocal. Our new record is dated principally by tephrochronology together with radiocarbon dating, and includes a cryptotephra deposit identified as Kaharoa tephra, a key marker for first settlement in northern New Zealand. Its discovery and stratigraphic position below two Rangitoto-derived tephras enables a clearer picture of environmental change to be drawn. The new pollen record shows an early phase (step 1) of minor, localised forest clearance around the time of Kaharoa tephra (c. 1314 AD) followed by a later, more extensive deforestation phase (step 2) commencing at around the time of deposition of the Rangitoto tephras (c. 1400–1450 AD). This pattern, which needs to be corroborated from other well-resolved records from northern New Zealand, concurs with an emerging hypothesis that the 'Little Ice Age' had a significant impact on pre-European Māori with the onset of harsher conditions causing a consolidation of populations and later environmental impact in northern New Zealand.

KEYWORDS: New Zealand, Polynesian settlement, rapid transformation, palynology, tephrochronology, Rangitoto tephra, Kaharoa tephra, 'Little Ice Age'

Introduction

A long-running debate over the timing of first settlement of New Zealand has eventually been resolved in favour of the late settlement hypothesis (Anderson, 1991) – that is, between *c*. 1250 and 1300 AD (Wilmshurst et al., 2008, 2011; Anderson, 2013, 2015a). Attention has now turned to the question of what happened next. Pollen and charcoal records, along with faunal and plant macrofossil work, have been instrumental in showing widespread forest clearances by fire from *c*. 1250 AD, resulting in a rapid transformation of much of the New Zealand landscape (McWethy et al., 2010; Perry et al., 2012a). The rapid transformation model suggests that extensive forest was replaced by scrub very early in the Polynesian era that persisted through to European contact and settlement in the late 18th and early 19th centuries. This model is based largely on records from southern and eastern regions of New Zealand, where the natural tipping point from forest to scrub is easier to traverse and harder to reverse than in other regions. Less clear is the picture from western and northern regions where, under more humid climates, more frequent and persistent firing would be needed to prevent forest regeneration once the forest-scrub tipping point was crossed (Perry et al., 2014).

Recently, Anderson (2013, 2015b, 2016) has revitalised an earlier argument that climate change during the pre-European era may have strongly influenced early Māori settlement patterns and land-use practice during what he terms a ‘transitional’ phase of New Zealand prehistory. Northern regions, Anderson argues, would have experienced greater environmental impacts later in prehistory as population growth consolidated there under the harsher climate of the ‘Little Ice Age’ after *c*. 1400 AD. If so, palaeoecological records from the north should differ from their southern counterparts in showing a second wave of human-environmental impacts accompanying the ‘Little Ice Age’.

Here, we present a new pollen and charcoal record for Polynesian settlement and forest clearance, dated by tephrochronology, from Lake Pupuke, a maar crater that contains the only extant lake in Auckland, northern New Zealand. Previous paleoenvironmental studies at Lake Pupuke (Horrocks et al., 2005; Striewski et al., 2009) concur with the rapid transformation model, but the data are of low-resolution and their interpretations are equivocal. Elsewhere in the Auckland region, reconstructions of human-environment interaction in prehistory have been thwarted by dating problems and recent disturbance of palaeoecological sites in New Zealand's most densely populated region (Newnham and Lowe, 1991; Horrocks et al., 2002). We trace vegetation and fire history using a short sediment core spanning the last *c*. 1000 years from Lake Pupuke. Using well-dated tephras from both the local Auckland Volcanic Field (AVF) and central North Island, along with key pollen time markers for the European era, we circumvent problems with radiocarbon dating of sediment previously encountered at this site (e.g. Augustinus et al., 2006, 2008; Strieweski et al., 2013). The main motivation for this study is to provide a clearer depiction of human-environment interaction in Auckland over the last *c*. 1000 years. This new record should also show whether the pattern of settlement in this northern New Zealand setting supports the Anderson transitional phase model with re-invigorated forest clearances accompanying climate change after *c*. 1400 AD or is better matched to the southern and eastern records where rapid and sustained forest clearances persisted from initial Polynesian arrival at or soon after *c*. 1250 AD.

Study region

Climate and vegetation

The present climate of Auckland (Fig. 1) is subtropical with warm, humid summers (December-February) and mild winters (June-August) driven by westerly migrating anticyclones and troughs (Chappell, 2013). Maximum daily temperatures in the region range from 14.5°C in July to 23.7°C in February, and frosts are rare. Average annual rainfall is ~1240 mm, with a moderate July peak associated with dominant southwesterly airflow.

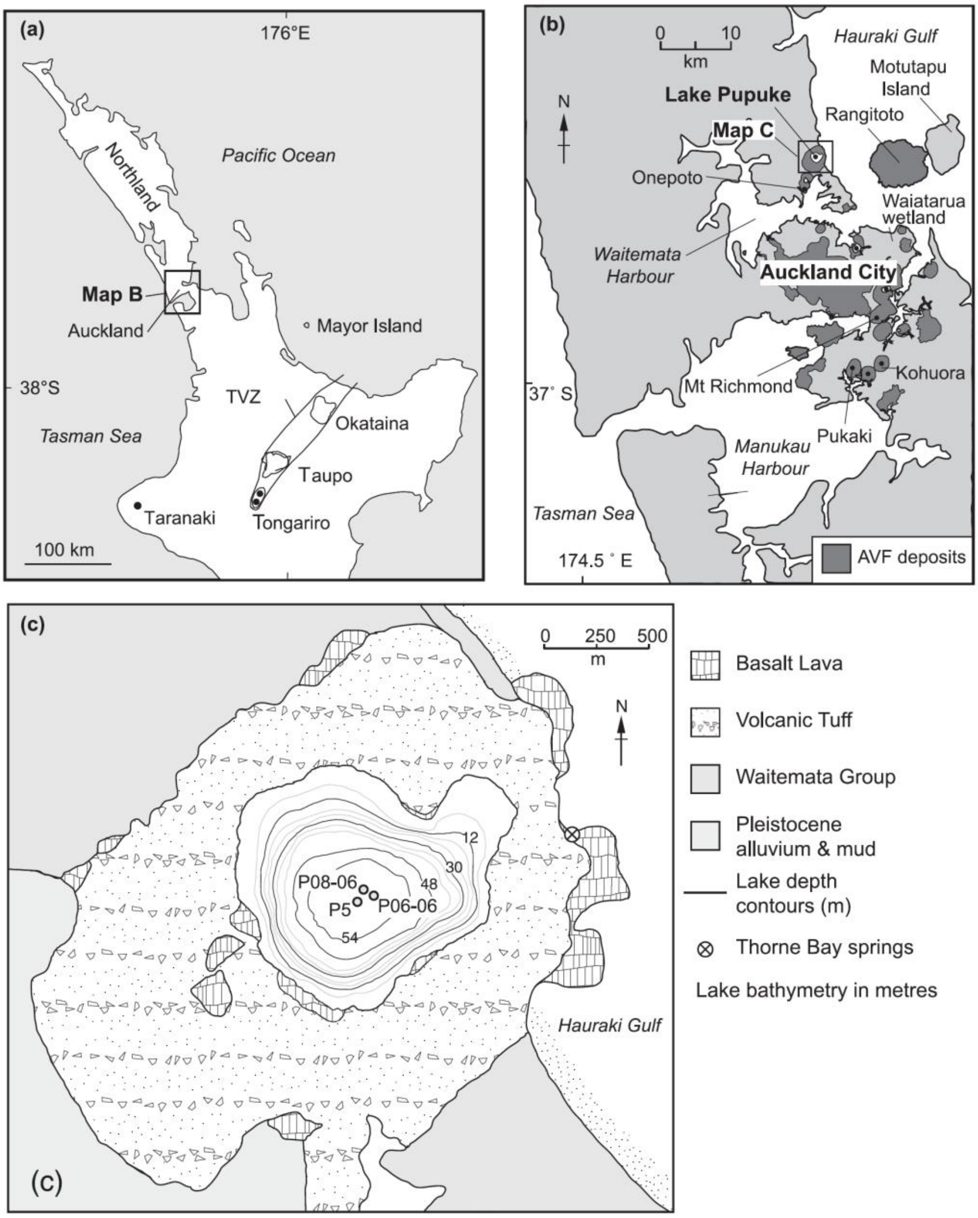


Figure 1. (a) North Island, New Zealand, showing location of Auckland and Taupo Volcanic Zone (TVZ) and main volcanic centres of central North Island. (b) Auckland, showing location of Lake Pupuke and other pollen sites, Rangitoto and deposits of Auckland Volcanic Field (AVF). (c) Lake Pupuke showing catchment geology, lake bathymetry and locations of sites for core P5 and cores P08-06 and P06-06 discussed in the text

The first European settlers in Auckland found a landscape mostly covered in bracken fern (*Pteridium aquilinum*) and scrub (Colenso, 1844), with evidence both for extensive sweet potato (*Ipomoea batatas*) cultivation by Māori and for intertribal warfare. The natural vegetation cover, nevertheless, can be pieced together from isolated remnants together with Holocene palynological records (Cranwell, 1981; Newnham and Lowe, 1991; Horrocks et al., 2005; Newnham et al., 2007). The region supported extensive conifer-angiosperm forest with some distinctive communities characteristic of volcanic landscapes and including several species that are confined to the northern North Island phytogeographic province (Cockayne, 1928; Leathwick et al., 2003). This 'northern' warm temperate group includes *Agathis australis* (kauri), *Beilschmiedia taraire, Vitex lucens, Metrosideros excelsa, Halocarpus kirkii, Ixerba brexioides, Weinmannia silvicola* and *Ackama rosifolia* along with several woody species that are absent from the southern half of North Island, but which reappear in northern South Island, for example, *Libocedrus plumosa*, *Phyllocladus trichomanoides* and *Quintinia serrata*. Conversely, a number of common 'southern' cool-temperate species, notably *Libocedrus bidwillii, Nothofagus menziesii, Phyllocladus aspleniifolius, Halocarpus bidwillii* and *Podocarpus nivalis* attain their northern limits just to the south of Auckland, usually at the highest altitudes. Beech forests, which also characterise southern and montane areas in New Zealand, are generally absent from Auckland northwards, with the exception of isolated stands of *Fuscospora truncata* and *F. solandri var. solandri*.

AVF

The central part of the Auckland region straddles an isthmus connecting the Waikato region to the south with a narrow, northwesterly-trending peninsula to the north (Fig. 1). The AVF, covering an area *c*. 360 km^2 (Kermode 1992) entirely within Auckland City that occupies much of the isthmus, has been active since *c*. 200 ka (Leonard et al., 2017).

The 53 mainly basaltic volcanic centres of the AVF (Fig. 1) include maars and their associated tuff rings that have created superb depositional environments for the accumulation of long sequences of often well-laminated lacustrine sediments interbedded with tephra. Basaltic tephras from the small-scale AVF eruptions have provided an important record for understanding the timing and frequency of these eruptions (Shane and Hoverd, 2002; Molloy et al., 2009; Hopkins et al., 2015, 2017). In addition, the Auckland maar lake sequences include many rhyolitic tephras sourced from the central Taupo Volcanic Zone (TVZ), namely, Okataina and Taupo volcanic centres, as well as numerous mainly andesitic tephras from eruptions of Egmont volcano and Tongariro Volcanic Centre (e.g. Newnham et al., 1999; Shane and Hoverd, 2002; Molloy et al., 2009; Hopkins et al., 2015, 2017) (Fig. 1). More recently, cryptotephra studies have begun on the maar lake sediments (Gehrels, 2009; Shane et al., 2013; Zawalna-Geer et al., 2016). Cryptotephras are tephra-derived glass shard (and/or crystal) concentrations preserved and ‘hidden’ in sediments but insufficiently numerous and too fine grained to be visible to the naked eye as a layer (Lowe, 2011). The maar lakes are mostly closed systems with low surrounding topographic relief and small catchments resulting in minimal currents within the lakes (Striewski et al., 2013). These conditions are considered to provide for a more accurate and complete tephra deposition history than open lacustrine systems, because they do not produce as many re-worked or over-thickened deposits (Molloy et al., 2009; Zawalna-Geer et al., 2016).

Not surprisingly, the Auckland maar lake sedimentary records have underpinned a large number of previous investigations into a range of topics including palaeoclimatic reconstruction (e.g. Sandiford et al., 2003; Newnham et al., 2007; Nilsson et al., 2011;

Augustinus et al., 2011, 2012; Stephens et al., 2012a,b; Barrell et al., 2013; Striewski et al., 2013; Heyng et al., 2014), volcanic history and hazard assessment (Newnham et al., 1999; Molloy et al., 2009; McGee and Smith, 2016; Zawalna-Geer et al., 2016; Hopkins et al., 2017; Leonard et al., 2017), and prehistoric settlement history (Horrocks et al., 2005; Striewski et al., 2009). Most of these studies relate to the pre-Holocene, however, because with one exception – Lake Pupuke – the Auckland maars were breached by postglacial marine transgression and associated marine sediment flux that terminated lacustrine deposition (Hayward et al., 2011).

Rangitoto volcano

The largest and most recent activity in the AVF, representing about half of the estimated total erupted magma, has resulted in the formation of Rangitoto Island, a 6-km-wide basaltic shield volcano located near the entrance to Waitemata Harbour (Fig. 1). Although the volcanoes of the AVF have long been considered to be monogenetic – each essentially formed from one relatively brief eruption episode – Linnell et al. (2016) presented a tephra and lava record for Rangitoto eruptives, based in large part on analyses from a drill core through the edifice, that indicated multiple eruption episodes. These data, along with dated Rangitoto-derived tephra layers in sediments from nearby Lake Pupuke and Motutapu Island (Fig. 1; Needham et al., 2011; Shane et al., 2013), suggest that following initial eruptions *c*. 6000 cal yr BP (phase 1), multiple eruptions of basaltic tephra occurred during the construction of the main Rangitoto edifice, phase 2 being from *c*. 650 to 550 cal yr BP, and phase 3 from *c*. 550 to 500 cal yr BP. This last phase, according to Linnell et al. (2016), generated the scoria cones on Rangitito's summit and concomitantly two prominent tephras, designated informally as 'Rangitoto 1' and 'Rangitoto 2' by McGee et al. (2011), that are manifest as visible, separate but thin (millimetre scale to centimetre scale depending on location) primary tephra deposits in sediment cores from Motutapu and Pupuke (Needham et al., 2011; Shane et al., 2013). Rangitoto 1, dated at 553 ± 7 cal. yr BP, is compositionally alkalic and characterised by a relatively low SiO_2 content (~ 45 wt%); Rangitoto 2, dated at 505 ± 6 cal. yr BP, is subalkalic and characterised by a relatively high SiO_2 content (~ 50 wt%) (Needham et al., 2011; Shane et al., 2013; Zawalna-Geer et al., 2016; Hopkins et al., 2017). Other explosively-generated basaltic Rangitoto tephras occur in Pupuke's lake sediments as cryptotephras with up to four identified in cores P06-06 and P08-06 (Shane et al., 2013). An implication of the recognition of Rangitoto 1 and Rangitoto 2 tephras in Lake Pupuke and on Motutapu Island as stratigraphically separate entities (even though these are informal names) is that the name 'Rangitoto Tephra Formation', which was defined by Froggatt and Lowe (1990) to represent a single eruptive event dated at *c*. 750 ^{14}C yr BP, should be abandoned.

Tephra deposited at the Sunde archaeological site on Motutapu Island (Fig. 1), containing casts of human and dog footprints, has been correlated (via glass-shard major element composition) with Rangitoto 1 (553 ± 7 cal. yr BP) (Shane et al., 2013). This correlation is important because it indicates that phases 2 and 3 of the eruptions of Rangitoto were witnessed by early Māori settlers, whose gardening and other activities must have had an impact in the region from at least that time (Scott, 1970; Davidson, 1978; Nicol, 1981, 1982; Bulmer, 1994; Lowe et al., 2000).

Lake Pupuke

Lake Pupuke (36°46′48″S, 174°45′58″E) is a large, deep, freshwater lake formed in a maar crater, situated ~7 km north of Auckland city centre (Fig. 1). On the basis of recent Ar/Ar dating, Pupuke maar formed *c*. 193,000 years ago (Leonard et al., 2017) and (with nearby Tank

Farm and Onepoto maars) represents one of the three oldest volcanic edifices of the AVF. Although only ~5 m above present sea level and less than 200 m from the current shoreline on its eastern margin, the lake is protected from saltwater influx and erosion by a thick tuff margin (Fig 1; Horrocks et al., 2005), and there is no evidence for marine incursion (Augustinus et al., 2006). The lake occupies ~57% of its catchment area which supplies a small amount of runoff into the lake basin. However, the lake is essentially a hydrologically-closed system receiving most of its inputs from rainwater. Minor outputs from the lake occur in the form of coastal springs but evaporation is the dominant source of water loss (Augustinus et al., 2006). Lake Pupuke has a bowl shaped bathymetry which increases in depth towards the centre (Fig. 1), a total surface area of 1.1 km^2, a volume of 2.9 km^3 and a maximum depth of 57 m (Horrocks et al., 2005). As a result of the growth of Auckland, Lake Pupuke today is surrounded by residential buildings, recreational facilities and parkland.

Previous investigations of human-environment interaction from Lake Pupuke

Striewski et al. (2009) used a range of physical and geochemical proxies measured in a sediment core from Lake Pupuke to conclude that “far-reaching and fundamental changes” in the lake ecosystem accompanied the arrival of people in the area. They argued that Polynesian forest clearance by fire caused enhanced erosional activity in the catchment just prior to the eruption of Rangitoto volcano, which at the time they considered to have occurred *c*. 550–500 cal. yr BP. Earlier, Horrocks et al. (2005) presented a Holocene pollen record from Pupuke that also appeared to indicate rapid and extensive deforestation by people commencing just prior to the Rangitoto eruption (the product of which is referred to in most of the text as ‘Rangitoto Tephra’), although the low resolution of this record precluded a more precise assessment of the timing. Only one post-Rangitoto Tephra sample was analysed and this contained European era pollen. Nevertheless, Striewski et al. (2009) proposed from this evidence that prehistoric human colonisation of the Auckland region commenced *c*. 610

cal. yr B.P and that Rangitoto Tephra (for which an age of *c*. 550 cal. yr BP, *c*. 1400 AD, was adopted, p. 78) may be regarded as a 'settlement layer' for the region (in the same way that Newnham et al. (1998a) and Lowe et al. (2000) designated the Kaharoa tephra as the 'settlement layer' for North Island). These interpretations align strongly with both the short prehistory and rapid transformation models largely derived from southern New Zealand evidence, suggesting no distinction between northern and southern patterns as since argued by Anderson (2016). Furthermore, Striewski et al. (2009) suggested that their estimated Auckland settlement date of ~610 cal. yr BP could mark the onset of continuous human settlement for all of New Zealand because Auckland is believed by some to be among the first places in the country to have been colonised (e.g. Irwin, 1992; McFadgen, 1994).

These important conclusions from previous work at Pupuke have essentially established a settlement template for the Auckland region. Nevertheless the applicability of the rapid transformation model to Auckland is based on interpretations of the precise timing and extent of settlement that remain poorly-resolved in light of the sampling resolution employed in this work, considering subsequent work on Rangitoto eruptive history. Shane et al. (2013) showed that in two Pupuke cores, P08-06 and P06-06, the latest phases of the Rangitoto eruption are represented by the two Rangitoto tephras 1 and 2: Rangitoto 1 (referred to as 'lower' Rangitoto by Shane et al., 2013) is evident as a visible (macroscopic) basaltic tephra layer in both cores and was dated (based on age data in Needham et al., 2011) by Bayesian modelling at 553 ± 7 cal yr BP in P08-06 (63 cm depth) and at 551 ± 7 cal. yr BP in P06-06 (60 cm depth); Rangitoto 2 (referred to as 'upper' Rangitoto) occurs as a visible basaltic tephra layer in P06-06 (57 cm depth), dated at 505 ± 6 cal. yr BP, but as a cryptotephra deposit of the same age in P08-06 (54 cm depth) (Shane et al., 2013). Similarly, Gehrels (2009), Shane et al. (2013) and Zawalna-Geer et al. (2016) showed that the precisely-dated Kaharoa tephra (636 ± 12 cal. yr BP) could be detected as a cryptotephra layer in

Pupuke cores, thereby offering prospect for further resolving the timing of human-environmental impacts in Auckland region prehistory.

Access to archived core material from the P5 core analysed by Horrocks et al. (2005) provided us with an opportunity to review these earlier conclusions in light of subsequent work. We undertook palynology with a higher resolution than that of Horrocks et al. (2005) and combined the findings with tephrochronology to provide a more precise reconstruction of the prehistoric settlement patterns of Auckland region.

Methods

Sediment coring

Lake Pupuke sediment core collection, and sedimentological and geochemical analyses have been described previously (Horrocks et al., 2005; Augustinus et al., 2006, 2008). The lake sediment core for the pollen and charcoal record presented here (P5) was collected from the deepest part of the lake (Fig. 1) using a Mackereth-type corer with 65 mm diameter polyvinyl chloride (PVC) tubes (Augustinus et al., 2008).

Lithostratigraphy

The P5 sediments consist of partially and variably laminated, fine, diatomaceous organic-rich muds (Horrocks et al., 2005; Augustinus et al., 2008). The laminations are millimetre- to sub-millimetre-thick alternating dark and light layers. The laminated appearance results from diatom-rich layers contrasting with background sedimentation (Augustinus et al., 2008) and, although they may be attributed in part to seasonal influence, facies investigations by Striewski et al. (2009) ruled out an annual tempo.

The lacustrine sediments are interrupted by two visible tephra layers. The Taupo tephra occurs at 168 cm depth and consists of a very thin (~2 mm) coarse ash layer. Rangitoto eruptive activity is represented by a single visible basaltic coarse ash layer between 27 and 24 cm depth, 141 cm above the Taupo tephra. Above this Rangitoto-derived tephra deposit, the sedimentary texture changes from laminated to massive.

Palynology

Using the stratigraphic position of the two visible tephras, we estimated that the time interval of interest in this study, the last ~1000 years, was encompassed by the uppermost 75 cm of the P5 core although the top ~15 cm was extremely fluid and considered unreliable for palynology. We subsampled the core from 75 cm to 15 cm for pollen and microscopic charcoal with a total of 23 evenly spaced samples, approximately treble the resolution of the previous palynological investigation at Pupuke (Horrocks et al., 2005).

Preparation of pollen slides followed standard procedures (Faegri and Iversen, 1989) and are described in Supplementary Information (available online).

Tephrochronology

As noted earlier, difficulties with establishing reliable ^{14}C ages for Pupuke and other maar lake sediments have been reported in previous studies (Horrocks et al., 2005; Augustinus et al., 2006; 2008). These problems have been attributed to pervasive hard water and old carbon effects in the lakes that partly arise from the incorporation of Tertiary-aged fossil shells (i.e. calcareous xenoliths) into the basaltic eruptives (e.g. Sandiford et al., 2001) and partly from human-induced inwashing of old carbon from the catchment following Polynesian settlement as has been observed in other lacustrine environments in northern New Zealand (e.g. Newnham et al., 1998a; McGlone and Wilmshurst, 1999). Because the laminations are unlikely to be annual (Striewski et al., 2009, 2013), layer counting was not deemed feasible as a chronological tool.

In contrast, tephrochronology provides three precise age points in the core P5 sequence. The so-called Rangitoto tephra is identified as a single coarse ash layer between 27 and 24 cm depth. In their previous description of P5, Horrocks et al. (2005) reported that two black, coarse ash layers occur at *c*. 28 and *c*. 27 cm depth (2 and 1 mm thick, respectively), separated by laminated lake sediments. These two tephra layers were designated 'lower' and 'upper' Rangitoto, respectively,by Needham et al. (2011), and represent Rangitoto 1 and 2 as described above. However, the two layers could no longer be visibly distinguished from each other at the time of subsampling for the current work and we conclude that the core depth interval 27–24 cm in P5 represents the two layers blended together because of sediment shrinkage. This conclusion is supported by glass geochemistry analyses from this deposit (reported below), which show that both Rangitoto 1 (*c*. 550 cal. yr BP) and Rangitoto 2 (*c*. 500 cal. yr BP) tephras are present, and hence, we refer to this deposit hereafter informally as ‘Rangitoto-1/2’ tephra with an age *c*. 550–500 cal yr BP.

The visible rhyolite Taupo tephra (1718 ± 10 cal. yr BP; Hogg et al., 2012) has been previously identified in the Pupuke cores on the basis of stratigraphy, mineralogy, and glass major element chemistry (Horrocks et al., 2005; Molloy et al., 2009). The Taupo tephra occurs at the base of the P5 sequence at 168 cm and consists of a very thin (~2 mm-thick) coarse ash layer. In addition to these two visible layers, the Kaharoa tephra (636 ± 12 cal. yr BP; Hogg et al., 2003), identified in the current study as a cryptotephra deposit (see below), provides the third precise (crypto)tephra age for the record. In addition, the palynological results presented below provide a fourth robust age point in the form of the known historical timing for the introduction of exotic pollen marking the start of European era, *c*. 1850 AD (Augustinus et al., 2006). Recognition of these four events have enabled us to develop a comparatively robust chronology for the pollen record.

Tephrostratigraphy

Because the Kaharoa tephra is a critical marker for the earliest settlement of northern New Zealand (Newnham et al., 1998a; Lowe et al., 2002) and has been precisely dated by radiocarbon and tree-ring-based wiggle-match dating (Lowe et al., 1998; Hogg et al., 2003), its identification as a cryptotephra layer in the P5 core was an important part of this study.

Core P5 was sub-sampled in 1-cm thick contiguous slices for cryptotephra analysis. Methods for extracting dispersed glass shards in sediments have been described elsewhere (e.g. Davies et al., 2005; Gehrels et al., 2006, 2008) and are included in Supplementary Information (available online). Distinguishing between a primary (in situ) tephra-fall deposit and reworked glass shards is a key step in cryptotephra methodology and requires an analysis of multiple sequences across the depositional site to try to distinguish primary from secondary deposits. We compared the glass-shard concentrations from P5 with comparable records reported previously from two other Pupuke cores, P08-06 (Shane et al., 2013) and P06-06 (Zawalna-Geer et al., 2016; Fig. 1).

A total of two distinct glass-shard types are recognized in the sequences from Lake Pupuke, primarily on the basis of colour (Fig. 2). Prior to chemical analysis, clear (colourless) shards were tentatively identified as originating from rhyolitic (sources) and brown shards from andesitic, dacitic or basaltic sources (Shane, 2000). Glass shards of selected horizons from P5 were analysed as described in Supplementary Information (available online).

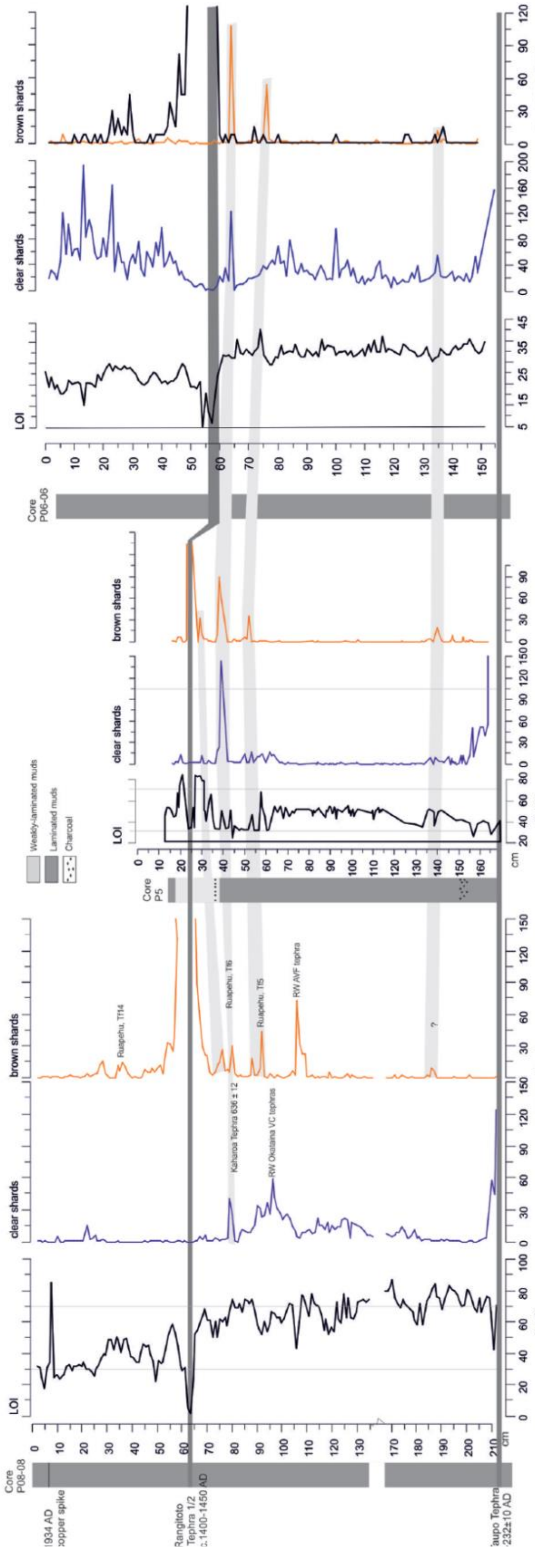


Figure 2. Glass shard concentrations and loss-on-ignition measurements derived from core P08-06 (Gehrels, 2009; Shane et al., 2013), P5 (this study) and P06-06 (Zawalna-Geer et al., 2016). Numbered arrows point to positions in the core of samples containing glass shards that have been analysed by electron microprobe analysis and presented in Table 1. See text regarding stratigraphic status of 'Rangitoto Tephra'.

Age modelling

As discussed above, we have determined four age points within the *c*. 1000-year-long pollen record from the Taupo, Kaharoa, and Rangitoto-1/2 tephras and the advent of European pollen. From these age-depth relationships, we determined ages for each of the pollen samples via linear interpolation between adjacent dated horizons. Linear interpolation is justified because previous age modelling of Holocene sediments in Lake Pupuke indicate near-constant accumulation rates prior to the anthropogenic era (Horrocks et al., 2005; Striewski et al., 2009; Shane et al., 2013; Zawalna-Geer et al., 2016).

Results

Tephrostratigraphy

The results of down-core glass-shard counts for core P5 are shown in Figure 2, alongside those from P08-06 and P06-06. The highest concentrations of shards were found immediately above and below the visible Taupo and Rangitoto-1/2 tephras. Additional peak concentrations of glass formed relatively discrete horizons (narrow bands).

All three cores display distinctive peaks in both clear and brown glass at the same horizon a few centimetres depth below the visible Rangitoto-1/2 tephra layer. In P5, this double peak of clear and brown shards occurs between 38 and 39 cm depth and represents the highest concentration of clear shards (at 143 shards per mg-d-wt.) from a cryptotephra deposit. Both types of shard from this horizon were analysed for major oxide geochemistry (see below). A small number of discrete peaks in brown shards are also observed, typically in lower concentrations than clear shard counterparts (Fig. 2).

Glass major element composition

Shane et al. (2013) and Zawalna-Geer et al. (2016) reported glass major element chemistry for P08-06 and P06-06, respectively, and showed that the Kaharoa tephra is represented by the peak in clear shards that coincides with the distinctive clear and brown shard couplet occurring a few centimetres below the Rangitoto 1 and 2 layers. The yellow or brown shards are of andesite composition, likely to be derived from Ruapehu volcano, Tongariro Volcanic Centre (Shane et al., 2013; Zawalna-Geer et al., 2016). We analysed the corresponding horizon for P5 between 39 and 38 cm depth in the core, 13 cm below the visible Rangitoto-1/2 tephra.

The results of the P5 EMP analysis match those previously reported for the clear and brown shard couplet from P08-06 and P06-06. The brown shards are predominantly dacite with a composition characteristic of Ruapehu-derived Tufa Trig members as identified in core P08-06 (Gehrels, 2009; Shane et al., 2013). The analyses show good correspondence with the composition of Tufa Trig member Tf6 (Donoghue & Neall, 1996; Donoghue *et al.*, 1997; 2007; Zawalna-Geer et al., 2016). For the three analyses obtained of the clear glass in the sample, two show a clear correlation with the compositionally distinct Kaharoa tephra (Fig. 3; Table 1).

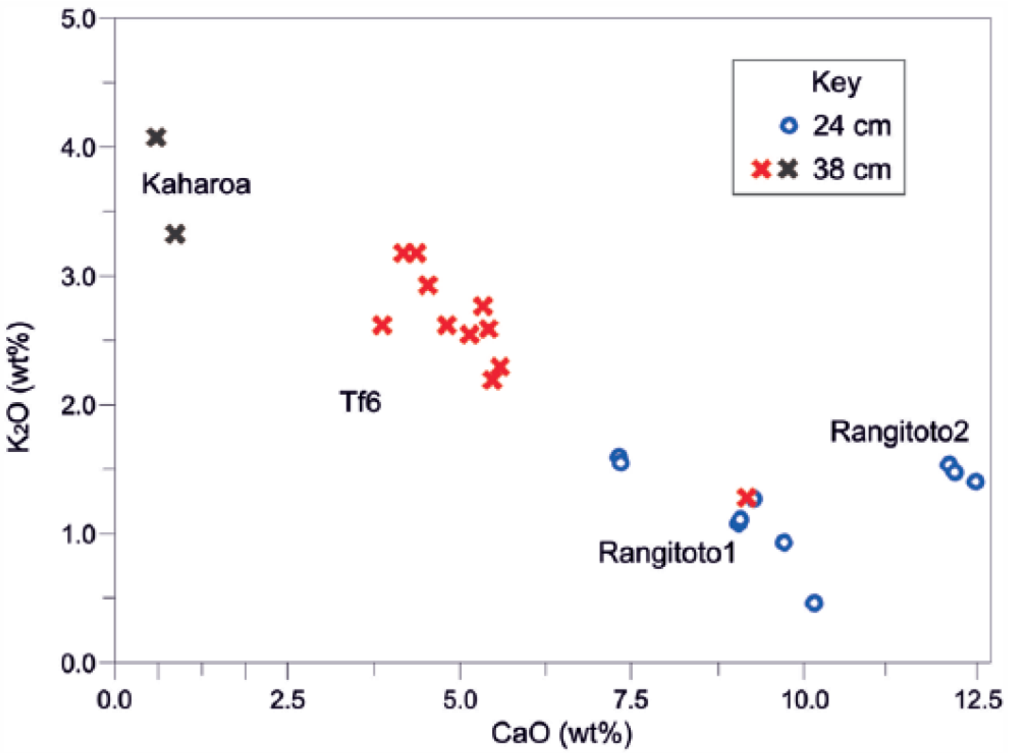
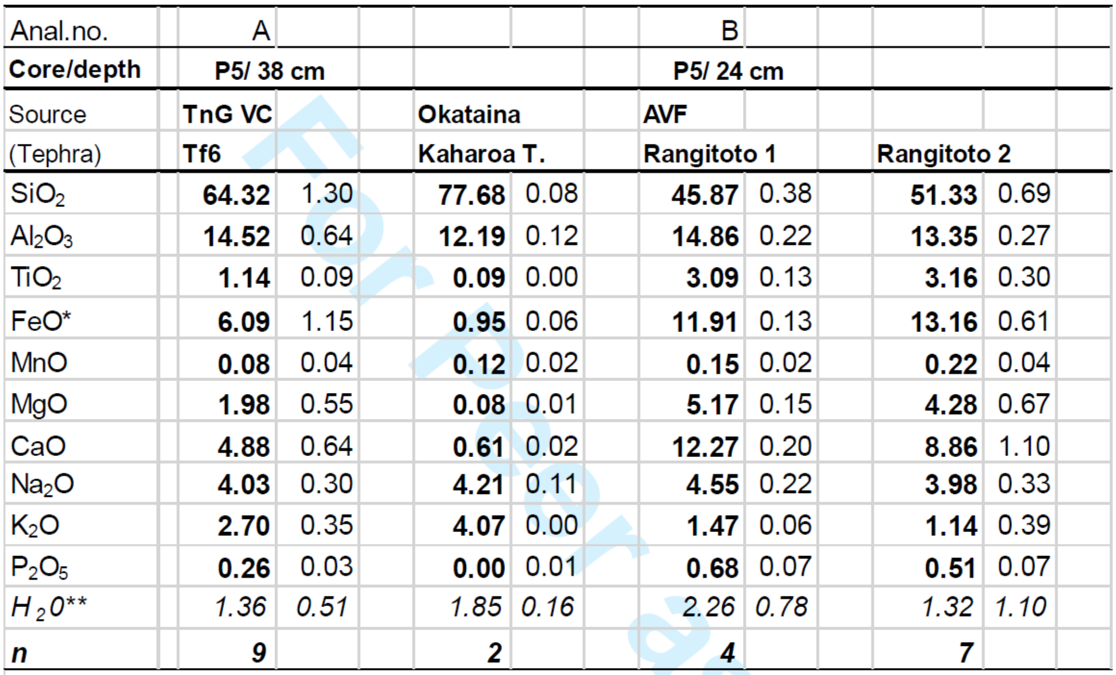


Figure 3. Major element composition of glass shards analysed from two depths in Core P5 and their identification as Kaharoa, Tufa Trig 6 (Tf6) and Rangitoto 1 and 2 tephras. In conjunction with stratigraphic superpositioning, the Kaharoa analyses match glass of magma type T2 (later phase of Kaharoa eruption) reported by Smith et al. (2005) and Zawalna-Geer et al. (2016); the Tf6 analyses are consistent with glass analyses reported by Zawalna-Geer et al. (2016); and Rangitoto 1 and 2 match analyses on glass reported by Horrocks et al. (2005), Needham et al. (2011), Zawalna-Geer et al. (2016) and Hopkins et al. (2017).

Table 1. Electron microprobe major-element analyses of tephra-derived glass shards from two sample depths in P5, Lake Pupuke.



Anal.no.	A				B			
Core/depth	**P5/ 38 cm**				**P5/ 24 cm**			
Source	**TnG VC**		**Okataina**		**AVF**			
(Tephra)	**Tf6**		**Kaharoa T.**		**Rangitoto 1**		**Rangitoto 2**	
SiO_2	**64.32**	1.30	**77.68**	0.08	**45.87**	0.38	**51.33**	0.69
Al_2O_3	**14.52**	0.64	**12.19**	0.12	**14.86**	0.22	**13.35**	0.27
TiO_2	**1.14**	0.09	**0.09**	0.00	**3.09**	0.13	**3.16**	0.30
FeO*	**6.09**	1.15	**0.95**	0.06	**11.91**	0.13	**13.16**	0.61
MnO	**0.08**	0.04	**0.12**	0.02	**0.15**	0.02	**0.22**	0.04
MgO	**1.98**	0.55	**0.08**	0.01	**5.17**	0.15	**4.28**	0.67
CaO	**4.88**	0.64	**0.61**	0.02	**12.27**	0.20	**8.86**	1.10
Na_2O	**4.03**	0.30	**4.21**	0.11	**4.55**	0.22	**3.98**	0.33
K_2O	**2.70**	0.35	**4.07**	0.00	**1.47**	0.06	**1.14**	0.39
P_2O_5	**0.26**	0.03	**0.00**	0.01	**0.68**	0.07	**0.51**	0.07
H_2O**	*1.36*	*0.51*	*1.85*	*0.16*	*2.26*	*0.78*	*1.32*	*1.10*
n	***9***		***2***		***4***		***7***	

TnG VC, Tongariro Volcanic Centre; AVF, Auckland Volcanic Field.

Sampling positions are shown in Fig. 2. Means (in bold) and standard deviations of total number (*n*) analysis (of individual shards) normalized to a 100% loss-free basis (wt%). Analysis undertaken at NERC Tephra Analytical Unit, University of Edinburgh, February and June 2007. Mean values for independently characterized laboratory standards, TB1G and Lipari, are provided in Table S1 (available online).
*Total iron as FeO
**Water by difference

A sample from the top of the visible Rangitoto-1/2 tephra in core P5 was also analysed. A clear distinction can be made between shards that are relatively high in SiO_2 (subalkalic, as in Rangitoto 2 tephra) and shards relatively low in SiO_2 (alkalic, comparable to Rangitoto 1 tephra) (Shane et al., 2013; Zawalna-Geer et al., 2016; Hopkins et al., 2017). As noted earlier, these results showing a mix of both shard types support our conclusion that both previously reported visible tephra layers are likely to be represented by the single visible layer we recognised in P5.

Palynology and vegetation reconstruction

A total of five pollen zones were recognised (Fig. 4), as described below.

*Zone P1***,** extending from *c*. 925 to c. 725 cal. yr BP, and *zone P2*, from *c*. 725 to *c*. 600 cal. yr BP, are dominated by tall tree taxa, mostly representing northern conifer-angiosperm forest communities. *Agathis australis* and *Dacrydium cupressinum* are the main emergent species, each comprising ~ 30% of total dryland pollen. Also common in the emergent or canopy layers were *Dacrycarpus dacrydioides, Prumnopitys taxifolia, P. ferruginea, Podocarpus* spp., *Phyllocladus* spp. and *Metrosideros. Fuscospora* pollen reaches 10% but may represent non-local sources as this taxon is typically over-represented (Bussell, 1988; McGlone and Basher, 2012). The subcanopy layer is represented by a diverse range of mostly angiosperm trees and shrubs, including tree ferns, epiphytes and lianas. Their diversity and persistently low pollen percentages are typical of northern forests in the region today and suggest that the lake was surrounded by closed canopy forest with a littoral margin represented by sedges and *Leptospermum*. The aquatic flora is dominated by the colonial alga *Botryococcus* and *Pediastrum* with occasional *Myriophyllum.* The main change from P1 to P2 is seen in the wetland and aquatic flora with notable declines in *Leptospermum, Botryococcus* and *Pediastrum* whilst *Isoetes* appears for the first time in P2 and remains prominent for the rest of the zone.

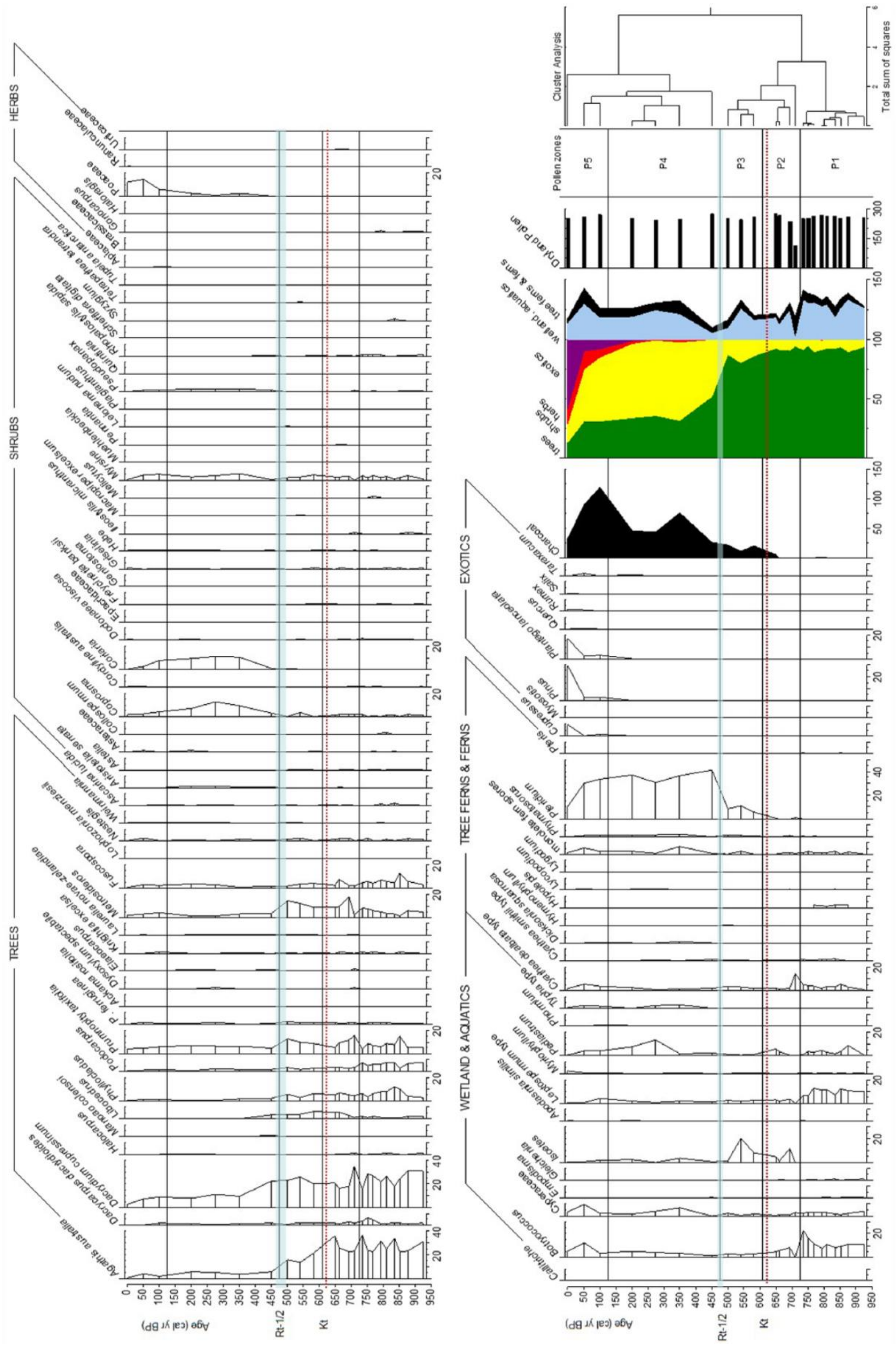


Figure 4. Pupuke (P5) pollen percentage diagram. Rt-1/2: Rangitoto tephra-1/2 (solid blue line); Ka: Kaharoa tephra (dashed red line).

Zone P3 extends from *c*. 600 cal. yr BP (just above the Kaharoa tephra) to *c*. 500 cal. yr BP (top of Rangitoto-1/2 tephra). The assemblages remain dominated by northern conifer-angiosperm forest trees and shrubs with few clear changes in composition or abundance apart from one exception: the previously dominant tree taxon, *Agathis*, declines from ~30% to ~15% during the course of the zone. The other major distinctions are the rise to sustained moderate levels in *Pteridium* and charcoal, both having been rare in previous zones. In the aquatic flora, *Isoetes* rises to a peak of 20% and then declines sharply just below Rangitoto-1/2 tephra.

Above Rangitoto-1/2, in *zone P4*, extending from *c*. 500 cal. yr BP to 100 cal. yr BP, *Pteridium* rises markedly to peak at ~40% and charcoal concentrations also rise. All tree taxa show a clear decline, whilst there are prominent increases in shrub and herb taxa, notably *Coprosma, Coriaria, Myrsine, Pseudopanax* and Poaceae. In the wetland and aquatic flora, Cyperaceae, *Botryococcus* and *Pediastrum* increase. *Zone P5*, from c.100 cal. yr BP to near present, comprises the uppermost three assemblages, characterised by pollen from exotic taxa characteristic of the European era, notably *Pinus, Cupressus and Plantago lanceolata.*

Discussion

An enhanced Auckland tephrostratigraphy for the past 1800 years

The identification of Kaharoa tephra in P5 as well as previously reported for P08-06 and P06-06 cores (Fig. 2) confirms the integrity of this cryptotephra deposit as a robust primary tephra-fall event at the site. This conclusion is also supported by similarities in the pattern of glass concentrations between sequences (Fig. 2) including a double peak in clear and brown shards at an equivalent stratigraphic horizon, and by its stratigraphic position relative to other features in the core. This development improves the chronology we have developed for core P5 over previous investigations of human-environment interaction at Lake Pupuke (Horrocks et al., 2005; Striewski et al., 2009). As this key marker also occurs at a critical time in the Pupuke pollen record (Fig. 4), we are able to pin down the timing of first human impacts and subsequent changes more precisely than was previously possible.

Vegetation of Auckland and human impact over the last ~1000 years: a revised model

The Pupuke pollen record gives the most detailed picture yet of the vegetation and environmental history of the Auckland region over the last millennium. Prior to human arrival, the lake was likely surrounded by northern conifer-angiosperm forest with kauri the dominant emergent tree, as has been depicted in previous Holocene pollen records from the region (Newnham & Lowe, 1991; Horrocks et al., 2005). The first unequivocal evidence for human impact occurs just above the precisely-dated Kaharoa Tephra (636 ± 12 cal. yr BP; Hogg et al., 2003), signifying the beginning of pollen Zone P3. Our new Pupuke pollen record is consistent, apart from a few notable exceptions, with previous palynological work involving Kaharoa tephra that shows characteristic paleoecological disturbances linked to human activity at or soon after its deposition at ~80 % of sites in North Island (Newnham et al., 1998a). At 19 pollen sites where the Kaharoa tephra is found, the start of the sustained decline of tall trees and accompanying rise in bracken fern (*Pteridium*) spores, together with increases in charcoal, essentially coincided with the deposition of the Kaharoa tephra, or soon after, that is, deforestation by human-fired burning began at *c*. 636 cal. yr BP, or a little later. However, at five sites (Kopouatai, Newnham et al., 1995a; Papamoa, Newnham et al., 1995b; Kohika, McGlone, 1981; Holdens Bay, McGlone, 1983b; and Te Rangaakapua, Wilmshurst, 1997), the rise in bracken and charcoal and the decline in tall trees began a short while before the fall of the Kaharoa tephra, indicating that deforestation at these sites was initiated a few decades before *c*. 636 cal. yr BP (Newnham et al., 1998a; Lowe et al., 2002; Lowe and Newnham, 2004).

In contrast to most pollen records showing human impact from southern New Zealand, however, the initial settlement phase had only a minor impact on the northern forests. Of the major tree pollen taxa, only *Agathis australis* (kauri) shows any sustained decline (from *c*. 30% to 15%). Modern pollen rain studies show that kauri tends to be under-represented in pollen assemblages, unless present close to the pollen depositional site (Elliott, 1999; Newnham et al., 2017). A decline in kauri but not in other tree taxa may indicate that local forest clearances occurred only in the vicinity of the lake and were not an extensive feature regionally. It is not until after the deposition of the Rangitoto-1/2 tephra, *c*. 550–500 cal. yr BP, that substantial and progressive forest clearance occurs with observable decline in virtually all tree taxa. From this time through to the European era, indicated by *Pinus* and the pollen of other adventives at *c*. 1845 AD (Augustinus et al., 2006), a fern-scrubland characterised by bracken and a range of angiosperm shrubs developed around Lake Pupuke and presumably across much of the Auckland region.

In addition to the contrasts with southern New Zealand records, our new Pupuke record also questions the applicability of the rapid transformation model to the Auckland region, as proposed from previous work at the site (Horrocks et al. 2005; Striewski et al. 2009). Rather than supporting near-immediate and widespread deforestation before Rangitoto 1 tephra and from *c*. 610 cal yr BP, as proposed by Striewski et al. (2009), this new record suggests that the first c.100 years of human occupation were characterised by lower level activity and minor localised forest clearances. It is not until after deposition of the Rangitoto 1 and/or 2 tephras that rapid transformation of the landscape is clearly observable in this new record.

How might these different interpretations be reconciled? First, the higher resolution pollen record presented here with stronger chronological control afforded by the Kaharoa tephra enables a more rigorous comparison to be made of the first c.100 years of human activity around Lake Pupuke. Second, the conclusion by Striewski et al. (2009) for near-immediate and widespread deforestation before Rangitoto 1 tephra is based largely on indirect evidence – changes in a range of sedimentary and geochemical properties assumed to depict catchment erosion or changes in biomass consequent upon deforestation. Whilst this assumption may well be justified, these indirect proxies lack a point of reference to indicate the extent of deforestation that resulted in the changes. Moreover, the measurement of some of these proxies – notably dry bulk density, magnetic susceptibility, organic carbon and associated chemical ratios – can be strongly affected by cryptotephra deposits in the sediments, which we show to be comparatively high at this critical time (Fig. 2). The presence of glass shards and possibly mineral grains (crystals), in the sediment, even in small amounts, would have an effect on the sediment analyses. In contrast, the pollen percentages are not affected by variability in the amounts of cryptotephra in the sediments, provide a reasonable approximation of the extent of deforestation, and show that major impacts on catchment vegetation did not occur until *after* deposition of the Rangitoto-1/2 tephra. Rather than a single phase of near immediate and widespread impact, this new record portrays a two-step phase where an initial phase of comparatively minor loss of trees chronologically constrained between the Kaharoa and Rangitoto-1/2 tephras (i.e. between *c*. 636 and c. 550 cal. yr BP) is followed by a more extensive phase of clearance during or soon after deposition of Rangitoto tephra-1/2 (i.e. *c*. 550–500 cal. yr BP and after).

Patterns of deforestation in New Zealand: north versus south

Records of deforestation from southern New Zealand (e.g. McWethy et al. 2009, 2010, 2014) describe an ‘initial burning period’ (IBP; *c*. 1280–1600 AD) during which most of the deforestation by deliberate and systematic burning appears to have occurred within a few decades by small, transient populations. The IBP was diachronous, occurring within 180 years between *c*. 1270 AD and 1450 AD at the sites investigated. There is no clear evidence that climate or climate change were significant factors in the burning (McGlone, 1983a; McWethy et al., 2010), unlike most other parts of the world where climate changes are strongly implicated in Holocene fire regimes (e.g. Whitlock et al., 2010). The IBP was followed by a period of less-frequent and less-severe burning in ‘The Late Maori period (*c*. 1600–1850 AD)’ during which, despite reduced fire activity, forest failed to recover at most sites investigated. Subsequently Perry et al. (2012a, 2012b, 2014) have provided a plausible explanation for both the rapidity and extent of forest degradation and the persistence of fire-induced scrub following the IBP. In essence, they explain that the more flammable seral and invasive vegetation and degraded soil conditions created by initial burning provided positive feedbacks that served to both accelerate and maintain the transformation.

The pattern observed in the south is essentially the reverse of that depicted at Lake Pupuke. The IBP at Pupuke occurs early in the 14th century, as in the south, but is characterised by minor levels of charcoal and fire-induced vegetation with little discernible loss of forest. It is not until after Rangitoto 1 and/or 2 (*c*. 1400–1450 AD) that severe and sustained forest clearances by fire occurred. At the same time in the south, the severe initial burning phase had ended at most sites. What might explain this pattern of later extensive firing in the north? Climatic differences between the two regions may play a role. The vulnerability of South Island forests to human-set fires was closely linked with a strong west-east rainfall gradient, and forests in areas with high rainfall (>1600 mm/yr; such as coastal Taranaki: Wilmshurst et al., 2004) were less impacted by fires than drier eastern forests (McGlone, 1983a; McWethy et al., 2010; Perry et al., 2014). It can be argued that forests in the humid Auckland climate are less susceptible to burning than forests in the drier regions of the eastern South Island. Whilst this is undoubtedly true, it does not explain, however, why extensive firing is not observed in Auckland before *c*. 1400–1450 AD during the IBP when the most severe clearances are seen in the south.

Climate change in prehistory

It has long been suggested that climate and climate change could have influenced Polynesian migrations (e.g. Bridgmann, 1983). Subsequently Anderson et al. (2006) suggested that archaeological evidence for an episodic pattern of initial island colonization in Polynesia matches periods of reversal in prevailing wind direction inferred from the millennial-scale history of the El Niño-Southern Oscillation (ENSO). These ideas were further developed by Goodwin et al. (2014) who used a compilation of paleoclimate data to reconstruct Pacific sea-level pressure and wind field patterns at bi-decadal scale during the Medieval Climate Anomaly. Their reconstruction revealed an anomalous climate shift to the central Pacific (Modiki) La Niña pattern during the period 1140–1260 AD. This shift opened up a climate window for off-wind sailing routes to New Zealand, coinciding with the archaeological evidence for first settlement there *c*. 1250 AD or soon after. In summary, there is mounting evidence that marked changes in atmospheric circulation exerted strong controls on the capacity for Polynesian migration and that, allied to this, the first settlement of New Zealand in the middle to late 13th century occurred during an anomalous period of La Niña-like conditions that accompanied the Medieval Climate Anomaly (see also Anderson, 2017).

The climate prevailing at the time of first arrival (*c*. 1250 AD) was unusual in the context of the remainder of prehistory. In broad terms, the intensification and poleward expansion of the Pacific subtropical anticyclone forced the westerlies polewards, temporarily weakening their influence on New Zealand climate and bringing calm, stable conditions accompanied by warmer temperatures. In this context, the speed and extent of colonisation of New Zealand following first contact is more readily understood. In particular, in southern regions where food and lithic resources were attractive to early settlers, a far more hospitable climate seems likely to have prevailed than that which confronted the first European settlers in the early 19th century.

More recently, Anderson (2016) has suggested that initial settlement patterns were not the only example of human-climate response in New Zealand prehistory. He argues that the archaeological record shows a number of significant demographic and cultural trends, commencing around 1400 AD and broadly coincident with climate change. These trends include (1) reduction in populations and abandonment of many previously occupied sites in the south, at the same time as northern New Zealand populations expanded; (2) a northwards retreat by about 150 km of the southern limit of kumara cultivation; and (3) intensification of horticulture in the north. Evidence for such a population decline in the area around Lake Waikaremoana, Huiarau Range, eastern North Island, based on falling *Pteridium* levels prior to the European era, was inferred by Newnham et al. (1998b). These changes among others heralded the beginning of a middle phase of Maori archaeology, transitional between the earlier Colonisation and later Traditional phases (Fig. 5).

There is growing paleoclimate evidence that a substantial deterioration in climate commencing in the period 1400–1500 AD coincided with these marked changes in the archaeological record. Koffman et al. (2014) presented a reconstruction of the westerlies for the past 2000 years, using a dust flux record from the West Antarctic Ice Sheet Divide ice core combined with spatially-distributed climate reconstructions from the Southern Hemisphere middle and high latitudes. In addition to showing that the westerlies occupied a more southerly position during the Medieval Climate Anomaly, their reconstructions indicate a marked equatorward shift at *c*. 1430 AD that persisted until the mid-to-late 20th century. This major shift in the latitudinal positioning and strength of the westerlies is also depicted in a long–term reconstruction of the Southern Annular Mode (SAM), defined as the zonal mean atmospheric pressure difference between the mid-latitudes and Antarctica (Abram et al., 2014; Fig. 5), which exerts a dominant influence on the climate variability across the extra-tropics of the entire Southern Hemisphere (Garreaud, 2007）.

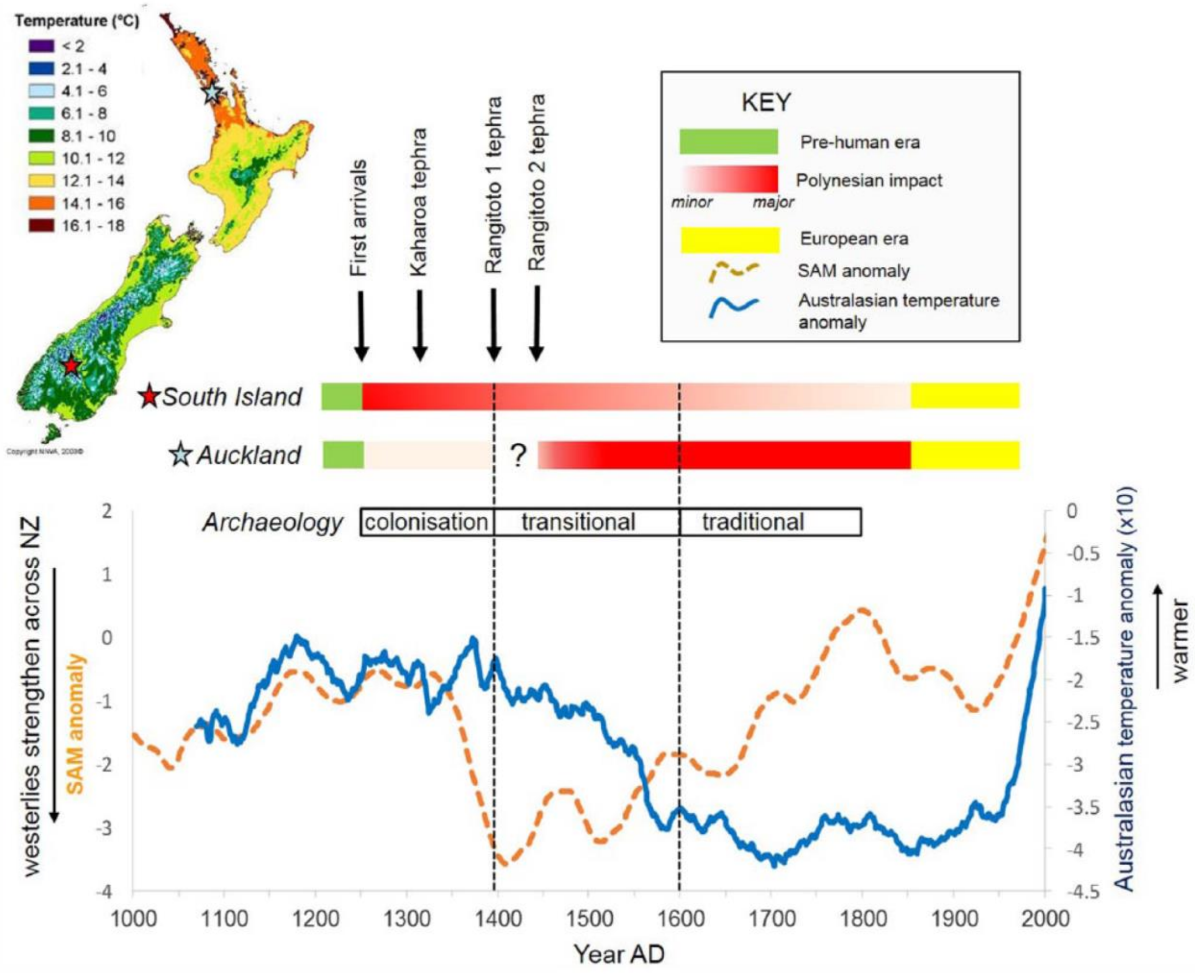


Figure 5. Schematic comparison of human-environment interaction in South Island and Auckland (horizontal bars) alongside reconstructed climate for the past ~1000 years: Southern Annular Mode (Abram et al., 2014) and Australasian summer temperatures (Ahmed et al., 2013). Both climate curves are shown as anomalies relative to 1961-1990 AD with 70-year smoothing. Archaeology refers to the conceptual framework for Māori prehistory proposed by Anderson (2016). Inset map shows mean annual temperature variation in New Zealand for 1971-2000 (www.niwa.co.nz) and location (stars) of Lake Pupuke (Auckland) study site and Lake Kirkpatrick (South Island), a key site for the rapid transformation model (McWethy et al., 2010).

It is now evident from a range of paleoclimate records based on tree-rings, speleothems, and glacier fluctuations that this climate change following the Medieval Climate Anomaly had profound impacts on New Zealand environments (Fig. 5). Separate tree-ring series on *Manoao colensoi* from Oroko and Ahaura, South Westland (Cook et al., 2002a, 2002b, 2006), both show that the strongest cold shift in prehistory and over the last 1000 years occurred at around 1500 AD, when summer temperatures at Oroko are estimated to have fallen by ~1.5 ^{o}C (Cook et al., 2002b). At around the same time, nearby Franz Joseph glacier advanced to >4.5 km beyond its present terminus, consistent with other evidence for ice advance during the Little Ice Age (McKinzie et al., 2004; Putnam et al., 2012; Lorrey et al., 2013). Speleothem δ^{18}O records from Hawke's Bay, eastern North Island, and Fiordland, southwestern South Island, both suggest that the most substantial cooling over the past 1000 years also occurred at c.1500 AD (Lorrey et al., 2008). Lorrey and Bostok (2017) have concluded from this and other paleoclimate evidence that the period from 1500 AD to near present day was characterised by cooler temperatures than the preceding interval, resulting from increased westerly and southerly circulation influences.

Of particular relevance to the Pupuke pollen record is the kauri tree ring record of Fowler et al. (2012) that is closely linked to ENSO variability. This record points strongly to weakening ENSO teleconnection to northern New Zealand during the fourteenth and fifteenth centuries, consistent with a northerly shift of the westerlies and the sub-tropical front during the 'Little Ice Age'.

These various paleoclimate records are consistent with the broader hemispheric pattern of comparative warmth and stable conditions prevailing for the first *c*. 100–200 years of Polynesian settlement, followed by a climate deterioration accompanying strengthening and equatorward-shifting westerlies that culminated *c*. 1500 AD. These changes broadly coincide with the onset of Anderson's (2016) 'Middle or Transitional phase' of Māori archaeology (Fig. 5).

The Anderson model of climate deterioration promoting expansion of populations and intensification of horticulture in the north from around 1400 AD provides a cogent explanation for the two-step pattern of forest clearance depicted in the Pupuke pollen record. The first of these phases, coinciding with Anderson's 'Colonisation' phase and commencing around the time of deposition of Kaharoa tephra (Fig. 5), is characterised by small–scale, localised forest burns under a warm and humid climate with only minor discernible impacts, in strong contrast to the rapid transformation seen in the south at that time. We may surmise that these northern forests offered stronger resistance to initial burning attempts than the forests in southern and eastern regions of New Zealand which, together with an initially warm climate, presented more favourable conditions to early Polynesian settlers. The second phase, coinciding with Anderson’s ‘Middle or Transitional’ period and commencing around the time of deposition of Rangitoto-1/2 tephra, is marked by extensive forest clearance by fire under a deteriorating climate. The conspiring demands of intensifying horticulture and expanding populations now drove a more concerted assault on the northern forests at the same time as burning impacts abated in the south.

Conclusions

Fine resolution palynology supported by enhanced tephrostratigraphy at Lake Pupuke, Auckland, reveals a two-step pattern of forest clearance during pre-European prehistory. The first step, commencing around the time of Kaharoa tephra *c*. 1314 AD, is marked by small-scale localised forest clearance whilst the second, commencing around the time of deposition of Rangitoto-1/2 tephra *c*. 1400–1450 AD, is marked by more extensive deforestation by fire. This pattern is essentially the reverse of that shown by similar records from southern New Zealand where the IBP within a few decades of human arrival resulted in rapid landscape transformation. These results support an emerging hypothesis that climate change exerted a strong effect on human settlement, migration and land-use patterns during New Zealand’s brief prehistory. The north-south contrast is consistent with the environmental impacts expected to have marked a middle or transitional period of Māori archaeology in part response to climate deterioration that accompanied onset of the ‘Little Ice Age’.

Acknowledgements

The paper is an output of the Royal Society of New Zealand Marsden Fund Project UOA1415; of the EXTRAS project ‘EXTending TephRAS as a global geoscientific research tool stratigraphically, spatially, analytically, and temporally within the Quaternary’, an initiative of the International Focus Group on Tephrochronology and Volcanism (INTAV) supported by SACCOM (INQUA); and of the SHAPE IFG ‘Southern Hemisphere Assessment of PalaeoEnvironments’, supported by PALCOM (INQUA). This work has benefitted from and conributes to the *Lakes380: past, present, and future* research programme funded by the Endeavour Fund of the New Zealand Ministry for Business, Innovation and Employment (Award CO5X1707).

References

Abram NJ, Mulvaney R, Vimeux F, Phipps SJ, Turner J, England MH, 2014. Evolution of the southern annular mode during the past millennium. *Naure Climate Change* 4: 564-569.

Ahmed M, Anchukaitis KJ, Asrat A, Borgaonkar HP, Braida M, Buckley BM, Büntgen U, Chase BM, Christie DA, Cook ER et al. 2013. Continental-scale temperature variability during the past two millennia. *Nature Geoscience* 6: 339-346.

Anderson AJ (1991) The chronology of colonization in New Zealand. *Antiquity* 65:767–795.

Anderson AJ, Chappell J, Gagan M, Grove1 R (2006) Prehistoric maritime migration in the Pacific islands: an hypothesis of ENSO forcing. *The Holocene* 16*:,* 1-6

Anderson AJ (2013) A fragile plenty: pre-European Maori and the New Zealand environment. *In*: Pawson, E., Brooking, T. (editors) *Making a New Land: Environmental Histories of New Zealand* (new edition). Otago University Press, Dunedin, pp. 35-51.

Anderson AJ (2015a) Speaking of migration AD 1150-1450*. In*: Anderson, A., Harris, A., Williams, B. (editors), *Tangata Whenua – An Illustrated History*. Bridget Williams Books, Auckland, pp. 42-69.

Anderson AJ (2015b) Emerging societies AD 1500-1800. *In*: Anderson, A., Harris, A., Williams, B. (editors), *Tangata Whenua – An Illustrated History*. Bridget Williams Books, Auckland, pp. 120-130.

Anderson AJ (2016) The making of the Māori Middle Ages. J.D. Stout Lecture 2016. *Journal of New Zealand Studie*s NS23: 2-18.

Anderson AJ (2017) Changing perspectives upon Māori colonisation voyaging, Journal of the Royal Society of New Zealand, 47:3, 222-231, DOI:10.1080/03036758.2017.1334674.

Augustinus PC, Reid M, Andersson S, Deng Y, Horrocks, M (2006) Biological and geochemical record of anthropogenic impacts in recent sediments from Lake Pupuke, Auckland City, New Zealand. *Journal of Paleolimnology* 35: 789-805.

Augustinus PC, Bleakley N, Deng Y, Shane P, Cochrane U (2008) Rapid change in early Holocene environments inferred from Lake Pupuke, Auckland City, New Zealand. *Journal of Quaternary Science* 23: 435-447.

Augustinus P, D'Costa D, Deng Y, et al. (2011) A multi-proxy record of changing environments from ca. 30 000 to 9000 cal. a BP: Onepoto maar palaeolake, Auckland, New Zealand. *Journal of Quaternary Science* 26: 389-401.

Augustinus P, Cochran U, Kattel G, et al. (2012) Late Quaternary paleolimnology of Onepoto maar, Auckland, New Zealand: Implications for the drivers of regional paleoclimate. *Quaternary International* 253: 18-31.

Barrell DJA, Almond PC, Vandergoes MJ, et al. (2013) A composite pollen-based stratotype for inter-regional evaluation of climatic events in New Zealand over the past 30,000 years (NZ-INTIMATE project). *Quaternary Science Reviews* 74: 4-20.

Bridgman HA (1983) Could climatic change have had an influence on the Polynesian migrations? *Palaeogeography, Palaeoclimatology, Palaeoecology* 41: 193 -206.

Bulmer S (1994) Sources for the archaeology of the Maaori settlement of the Taamaki volcanic district. *New Zealand Department of Conservation Science and Research Series* 63: 1–33.

Bussell MR (1988) Modern pollen rain, central-western North Island, New Zealand. *New Zealand Journal of Botany* 26: 297-315.

Chappell PR (2013) *The Climate and Weather of Auckland* (NIWA Science and Technology Series 60). Auckland: NIWA, 40 pp.

Clark RL (1982) Point count estimation of charcoal in pollen preparations and thin sections of sediments. *Pollen et Spores* 24: 523-535.

Cockayne L (1928) *New Zealand Plants and their Story*. Engelmann: Leipzig.

Colenso W (1844). *Excursion in the North Island of New Zealand in the Summer of 1841-2.* Launceston Examiner, Launceston.

Cook ER, Palmer JG, Cook BI, Hogg A, D'Arrigo RD (2002a) A multi-millennial palaeoclimatic resource from Lagarostrobos colensoi tree-rings at Oroko Swamp, New Zealand. *Global and Planetary Change* 33: 209–220.

Cook ER, Palmer JG, D'Arrigo RD (2002b) Evidence for a 'Medieval Warm Period' in a 1,100 year tree-ring reconstruction of past Austral summer temperatures in New Zealand. *Geophysical Research Letters* 29. DOI: 10.1029/2001GL014580

Cook ER, Buckley BM, Palmer JG, Fenwick P, Peterson MJ, Boswijk G, Fowler A (2006) Millennia-long tree-ring records from Tasmania and New Zealand: a basis for modelling climate variability and forcing, past, present and future. *J. Quaternary Sci*. 21: 689–699.

Cranwell LM (1981) *The Botany of Auckland*. Auckland Institute and War Memorial Museum: Auckland.

Davidson JM (1978) The prehistory of Motutapu Island, New Zealand: five centuries of Polynesian occupation in a changing landscape. *Journal of the Polynesian Society* 87**:** 327–337.

Davies S, Hoek W, Bohncke S et al. (2005). Detection of Lateglacial distal tephra layers in the Netherlands. *Boreas* 34: 123–135.

Donoghue SL, Neall VE (1996) Tephrostratigraphic studies at Tongariro volcanic centre New Zealand: An overview. *Quaternary International* 34-6**:** 13-20.

Donoghue S, Neall VE, Palmer AS, Steward RB (1997). The volcanic history of Ruapehu during the past 2 millennia based on the record of Tufa Trig tephras. Bulletin of Volcanology 59: 136-146.

Donoghue SL, Vallance J, Smith IEM, Stewart RB (2007) Using geochemistry as a tool for correlating proximal andesitic tephra: case studies from Mt Rainier (USA) and Mt Ruapehu (New Zealand). *Journal of Quaternary Science* 22: 395-410.

Elliot M **(**1999) Modern pollen–vegetation relationships in Northland, New Zealand. *New Zealand Journal of Botany* 37: 131–48.

Faegri K, Kaland PE and Krzywinski K (1989) *Textbook of Pollen Analysis*. 4th edn. Chichester: Wiley.

Fowler AM, Boswijk G, Lorrey AM, Gergis J, Pirie M, McCloskey SPJ et al. (2012) Multi-centennial ENSO insights from New Zealand forest giants. *Nature Climate Change* 2: 172-176.

Froggatt PC, Lowe DJ, 1990. A review of late Quaternary and some other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume, and age. *New Zealand Journal of Geology and Geophysics* 33: 89-109.

Garreaud RD, 2007. Precipitation and circulation covariability in the extratropics, *J. Clim.* 20: 4789–4797.

Gehrels M (2009) *An enhanced 1800-year record of recent volcanic ash-fall events for northern New Zealand from the analysis of cryptotephra*. PhD thesis, The University of Plymouth.

Gehrels MJ, Lowe DJ, Hazell ZJ et al. (2006). A continuous 5300-yr Holocene cryptotephrostratigraphic record from northern New Zealand and implications for tephrochronology and volcanic hazard assessment. *The Holocene* 16: 173–187.

Gehrels MJ, Newnham RM, Lowe DJ et al. 2008. Towards rapid assay of cryptotephra in peat cores: review and evaluation of various methods. *Quaternary International* 178: 68–84.

Goodwin ID, Browning SA, Anderson AJ (2014) Climate windows for Polynesian voyaging to New Zealand and Easter Island. *Proceedings of the National Academy of Sciences of the United States of America* 111: 14716–14721

Grimm EC (1987) CONISS: A FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences* 13:13-35.

Hayward BW, Murdoch G, Maitland G (2011). *Volcanoes of Auckland: the Essential Guide*. Auckland University Press, Auckland, 234 pp.

Heyng AM, Mayr C, Lücke A, Wissel H, Striewski B (2014). Late Holocene hydrologic changes in northern New Zealand inferred from stable isotope values of aquatic cellulose in sediments from Lake Pupuke. *Journal of Paleolimnology* 51: 485-497

Hogg AG, Higham TFG, Lowe DJ, Palmer J, Reimer P, Newnham RM (2003). A wiggle-match date for Polynesian settlement of New Zealand. *Antiquity* 77: 116-125.

Hogg AG, Lowe DJ, Palmer J, Boswijk G, Bronk Ramsey CJ (2012). Revised calendar date for the Taupo eruption derived by ^{14}C wiggle-matching using a New Zealand kauri ^{14}C calibration data set. *The Holocene* 22: 439-449.

Hopkins JL, Millet M-A, Timm C, Wilson CJN, Leonard GS, Palin JM, Neil H (2015). Tools and techniques for developing tephra stratigraphies in lake cores: A case study from the basaltic Auckland Volcanic Field, New Zealand. *Quaternary Science Reviews* 123: 58-75.

Hopkins JL, Wilson CJN, Millet M-A, Leonard GS, Timm C, McGee, LE, Smith, IEM, Smith EGC (2017) Multi-criteria correlation of tephra deposits to source centres applied in the Auckland Volcanic Field. New Zealand. *Bulletin of Volcanology:* 79, 55.

Horrocks M, Deng Y, Nichol SL, Shane PA, Ogden J (2002) A palaeo-environmental record of natural and human change from the Auckland Isthmus, New Zealand, during the late Holocene. *Journal of the Royal Society of New Zealand* 32: 337-353.

Horrocks M, Augustinus PC, Deng Y, Shane P, Andersson S (2005). Holocene vegetation, environment and tephra recorded from Lake Pupuke, Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics* 48: 85-94.

Irwin G (1992) *The Prehistoric Exploration and Colonisation of the Pacific*. Cambridge University Press, Cambridge.

Kermode L (1992) *Geology of the Auckland urban area. Scale 1: 50,000.* Institute of Geological and Nuclear Sciences geological map 2. 1 sheet + 63 pp. Institute of Geological and Nuclear Sciences, Lower Hutt.

Koffman BG, Kreutz KJ, Breton DJ, Kane1 EJ, Winski D, Birkel SD, Kurbatov AV, Handley MJ (2014) Centennial-scale variability of the Southern Hemisphere westerly wind belt in the eastern Pacific over the past two millennia. *Climate of the Past* 10: 1125–1144

Leathwick J, Wilson G, Rutledge D, Wardle P, Morgan F, Johnston K, McLeod M, Kirkpatrick R (2003) *Land Environments of New Zealand*. Ministry for the Environment/Manaaki Whenua Landcare Research, 184 pp.

Leonard GS, Calvert AT, Hopkins JL, Wilson CJN, Smid ER, Lindsay JM, Champion DE (2017) High-precision ^{40}Ar/^{39}Ar dating of Quaternary basalts fromAuckland Volcanic Field, New Zealand, with implications for eruption rates and paleomagnetic correlations *Journal of Volcanolology and Geothermal Research* 343: 60–74.

Linnell T, Shane P, Smith IEM, Augustinus PC, Cronin S, Lindsay JM, Maas R. (2016) Long-lived shield volcanism within a monogenetic basaltic field: the conundrum of

Rangitoto volcano, New Zealand. *Geological Society of America Bulletin* 128: 1160-1172.

Lorrey AM, Williams P, Salinger J, Martin T, Palmer J, Fowler A, Zhao J.-X, Neil, H **(**2008) Speleothem stable isotope records interpreted within a multi-proxy framework and implications for New Zealand palaeoclimate reconstruction. *Quaternary International* 187: 52–75.

Lorrey AM, Fauchereau N, Stanton C, Chappell P, Phipps S, Mackintosh A, Renwick J, Goodwin I, Fowler A (2013) The Little Ice Age climate of New Zealand reconstructed from Southern Alps cirque glaciers: a synoptic type approach. *Climate Dynamics* 42:3039–3060.

Lorrey AM, Bostock H (2017) The Quaternary climate of New Zealand. In: Shulmeister J (ed.) *Advances in Quaternary Science - the New Zealand Landscape*. Atlantis Press, Paris, pp. 67-139.

Lowe DJ (2011) Tephrochronology and its application: a review. *Quaternary Geochronology* 6: 107-153.

Lowe DJ, Newnham RM, McFadgen BG, Higham TFG (2000). Tephras and New Zealand archaeology. *Journal of Archaeological Science* 27: 859-870.

Lowe DJ, Newnham RM, McCraw JD (2002). Volcanism and early Maori society in New Zealand. *In*: Torrence R, Grattan J (editors) *Natural Disasters and Cultural Change*. Routledge, London, pp. 126-161.

Lowe DJ, Newnham RM (2004) Role of tephra in dating Polynesian settlement and impact, New Zealand. *PAGES (Past Global Changes) News* 12 (3): 5-7.

Lowe DJ, McFadgen BG, Higham TFG, Hogg AG, Froggatt PC, Nairn IA (1998) Radiocarbon age of the Kaharoa Tephra, a key marker for late-Holocene stratigraphy and archaeology in New Zealand. *The Holocene* 8: 487-495.

McFadgen BG (1994) Coastal stratigraphic evidence for human settlement. In: Sutton, D.G. (ed.) *Origins of the First New Zealanders*. Auckland University Press, Auckland, pp. 195–207.

McGee LE, Smith IEM (2016) Interpreting chemical compositions of small scale basaltic systems: a review. *Journal of Volcanology and Geothermal Research* 325: 45-60.

McGee LE, Beier C, Smith IEM, Turner S (2011) Dynamics of melting beneath a small-scale basaltic system: a U-Th-Ra study from Rangitoto volcano, Auckland Volcanic Field, New Zealand. *Contributions to Mineralogy and Petrology* 162: 547–563.

McGlone MS (1981). Forest fire following Holocene tephra fall. In: Howorth R (ed.) *Proceedings of Tephra Workshop* (volume 20 of Geology Department, Victoria University of Wellington Publication). Victoria University of Wellington, Wellington, pp. 80–86.

McGlone MS **(**1983a) Polynesian deforestation of New Zealand: a preliminary synthesis. *Archaeology in Oceania* 18: 11–25.

McGlone MS (1983b). Holocene pollen diagrams, Lake Rotorua, North Island, New Zealand. *Journal of the Royal Society of New Zealand* 13**:** 53–65.

McGlone MS, Wilmshurst JM, 1999. Dating initial Maori environmental impact in New Zealand. *Quaternary International* 59: 5–16.

McGlone MS, Basher L (2012) Holocene vegetation change at treeline Cropp Valley, Southern Alps, New Zealand. *Terra Australis* 34: 343-358.

McKinzey KM, Lawson W, Kelly D, Hubbard A (2004) A revised Little Ice Age chronology of the Franz Josef Glacier, Westland, New Zealand. *Journal of the Royal Society of New Zealand* 34: 381-394.

McWethy DB, Whitlock C, Wilmshurst JM, McGlone MS, Li X (2009) Rapid deforestation of South Island, New Zealand by early Polynesian fires. *The Holocene* 19: 883–897.

McWethy DB, Whitlock C, Wilmshurst JM, McGlone MS,Fromont M, Li X, Dieffenbacher-Krall A, Hobbs WO, Fritz SC, Cook ER (2010). Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. *Proceedings of the National Academy of Sciences of the Inited States of America* 107: 21343–21348.

Molloy C, Shane P, Augustinus P (2009) Eruption recurrence rates in a basaltic volcanic field based on tephra layers in maar sediments; implications for hazards in the Auckland Volcanic Field. *Geological Society of America Bulletin* 121:1666-1677

Needham AJ, Lindsay JM, Smith IEM, Augustinus P, Shane PA (2011) Sequential eruption of alkaline and sub-alkaline magmas from a small monogenetic volcano in the Auckland Volcanic Field, New Zealand. *Journal of Volcanology and Geothermal Research* 201: 126-142

Newnham RM, de Lange PJ, Lowe DJ (1995a). Holocene vegetation, climate and ontogenesis of a raised-bog complex, northern New Zealand, from pollen, plant macrofossils and tephrochronological investigations. *The Holocene* 5: 267–282.

Newnham RM, Lowe DJ, Wigley GNA (1995b). Late Holocene palynology and palaeovegetation of tephra-bearing mires at Papamoa and Waihi Beach, western Bay of Plenty, North Island, New Zealand. *Journal of the Royal Society of New Zealand* 25**:** 283–300.

Newnham RM, Lowe DJ, McGlone MS, Wilmshurst JM, Higham TFG (1998a) The Kaharoa Tephra as a critical datum for earliest human impact in northern New Zealand. *Journal of Archaeological Science* 25: 533-544.

Newnham RM, Lowe DJ, Matthews BW (1998b). A late Holocene and prehistoric tephropalynological record of environmental change from Lake Waikaremoana, New Zealand. *The Holocene* 8: 443-454.

Newnham RM, Lowe DJ, Alloway BV (1999) Volcanic hazards in Auckland, New Zealand: a preliminary assessment of the threat posed by central North Island silicic volcanism based on the Quaternary tephrostratigraphical record. In: Firth CR and McGuire WJ (eds) *Volcanoes in the Quaternary*. *Geological Society, London, Special Publications* 161: 27-45.

Newnham RM, Lowe DJ (1991) Holocene vegetation and volcanic activity, Auckland Isthmus, New Zealand. *Journal of Quaternary Science* 6: 177-193.

Newnham RM, Lowe DJ, Giles T, Alloway BV (2007) Vegetation and climate of Auckland, New Zealand, since ca. 32 000 cal. yr ago: support for an extended LGM. *Journal of Quaternary Science* 22: 517-534.

Newnham RM, Alloway BV, Holt KA, Butler K, Rees ABH, Wilmshurst JM et al. (2017) Last Glacial pollen–climate reconstructions from Northland, New Zealand. *Journal of Quaternary Science* 32: 685–703.

Nichol R (1981) Preliminary report on excavations at the Sunde site, N38/24, Motutapu Island. *New Zealand Archaeological Association Newsletter* 24**:** 237-256.

Nichol R (1982) Fossilised human footprints in Rangitoto Ash on Motutapu Island. *Geological Society of New Zealand Newsletter* 51**:** 11-13.

Nilsson A, Muscheler R, Snowball I, Aldahan A, Possnert G, Augustinus P, Atkin D, Stephens T (2011) Multi-proxy identification of the Laschamp geomagnetic field excursion in Lake Pupuke, New Zealand. *Earth and Planetary Science Letters* 311: 155-164.

Perry GLW, Wilmshurst JM, McGlone MS, McWethy DB,Whitlock C (2012a) Explaining fire-driven landscape transformation during the Initial Burning Period of New Zealand's prehistory. *Global Change Biology* 18:1609–1621.

Perry GLW, Wilmshurst JM, McGlone MS, Napier A (2012b)Reconstructing spatial vulnerability to forest loss by fire in pre-historic New Zealand. *Global Ecology and Biogeography* 21: 1029–1041.

Perry GLW, Wilmshurst JM, McGlone MS (2014) Ecology and long-term history of fire in New Zealand. *New Zealand Journal of Ecology* 38: 157-176.

Putnam AE, Schaefer JM, Denton GH et al. (2012) Regional climate control of glaciers in New Zealand and Europe during the pre-industrial Holocene. *Nature Geoscience* 5, 627–630

Sandiford A, Alloway B, Shane P (2001) A 28 000–6600 cal yr record of local and distal volcanism preserved in a paleolake, Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics* 44: 323–336.

Sandiford A, Newnham RM, Alloway BV, Ogden J (2003). A 28 000–7600 cal yr BP pollen record of vegetation and climate change from Pukaki Crater, northern New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology* 201: 235–247.

Scott SD (1970) Excavations at the 'Sunde site', N38/24, Motutapu Island, New Zealand. *Records of the Auckland Institute and Museum* 7: 13–30.

Shane P (2000) Tephrochronology: a New Zealand case study. *Earth Science Reviews* 49: 223–259.

Shane PAR, Hoverd J (2002) Distal record of multi-sourced tephra in Onepoto Basin, Auckland, New Zealand: implications for volcanic chronology, frequency and hazards. *Bulletin of Volcanology* 64:441–454.

Shane P, Gehrels M, Zawalna-Geer A, Augustinus P, Lindsay J, Chaillou I (2013) Longevity of a small shield volcano revealed by crypto-tephra studies (Rangitoto Volcano, New Zealand): change in eruptive behaviour of a basaltic field. *Journal of Volcanology and Geothermal Research* 257: 174-183.

Smith, V.C., Shane, P., Nairn, I.A., 2005. Trends in rhyolite geochemistry, mineralogy, and magma storage during the last 50 kyr at Okataina and Taupo volcanic centres, Taupo Volcanic Zone, New Zealand. *Journal of Volcanology and Geothermal Research* 148, 372–406.

Stephens T, Atkin D, Augustinus P, Shane P, Lorrey A, Street-Perrott A, Nilsson A, Snowball I (2012a) A late glacial Antarctic climate teleconnection and variable Holocene seasonality at Lake Pupuke, Auckland, New Zealand. *Journal of Paleolimnology* 48: 785-800.

Stephens T, Atkin D, Cochran U, Augustinus P, Reid R, Lorrey A, Shane P, Street-Perrott A (2012b). A diatom-inferred record of reduced effective precipitation during the Last Glacial Coldest Phase (28.8-18.0 cal kyr BP) and increasing Holocene seasonality at Lake Pupuke, Auckland, New Zealand. *Journal of Paleolimnology* 48: 801-817.

Striewski B, Mayr C, Flenley J, Naumann R, Turner G, Lücke A (2009) Multiproxy evidence of late-Holocene human-induced environmental changes at Lake Pupuke, Auckland (New Zealand). *Quaternary International* 202: 69-83.

Striewski B, Shulmeister J, Augustinus PC, Soderholm J (2013) Late Holocene climate variability from Lake Pupuke maar, Auckland, New Zealand. *Quaternary Science Reviews* 77: 46-54.

Whitlock C, Higuera PE, McWethy DB, Briles CE (2010) Paleoecological perspectives on fire ecology: revisiting the fire-regime concept. *The Open Ecology Journal* 3: 6–23.

Wilmshurst JM (1997). The impact of human settlement on vegetation and soil stability in Hawkes Bay, New Zealand. *New Zealand Journal of Botany* 35: 97–111.

Wilmshurst JM, Higham TFG, Allen H, Johns D, Phillips C (2004) Early Maori settlement impacts in northern coastal Taranaki, New Zealand. *New Zealand Journal of Ecology* 28: 1-13.

Wilmshurst JM, Anderson AJ, Higham TFG, Worthy TH (2008) Dating the late prehistoric dispersal of Polynesians to New Zealand using the commmensal Pacific rat.

Proceedings of the National Academy of Sciences of the United States of America 105: 7676-7680.

Wilmshurst JM, Hunt TL, Lipo CP, Anderson AJ (2011) High-precision radiocarbon dating shows recent and rapid initial human colonization of East Polynesia. *Proceedings of the National Academy of the United States of Americ*a 108: 1815-1820.

Zawalna-Geer A, Lindsay J, Davies S, Augustinus P, Davies S (2016) Extracting a primary Holocene cryptotephra record from Pupuke maar sediments, Auckland, New Zealand. *Journal of Quaternary Science* 31: 442-457.

Supplementary Information

Methods for determining pollen percentages and charcoal concentrations

Known quantities of exotic *Lycopodium* spores were added during preparations in order to calculate pollen concentrations. Pollen percentages for dryland pollen taxa were calculated as a percentage of the total dryland pollen sum (250 grains counted per slide). Pollen and spores from wetland and fern taxa apart from *Pteridium* are excluded from the total dryland pollen sum. These taxa are expressed as a percentage of the particular group (e.g. wetland) plus the total dryland pollen. *Leptospermum* pollen is over-represented in the record, indicating local on-site pollen influx, and therefore is also excluded from the dryland pollen sum. Zonation of the pollen diagram was supported by applying stratigraphically constrained cluster analyses (CONISS) to the entire pollen dataset (Grimm, 1993).

During pollen analysis, microcharcoal fragments <125 μm were encountered on some slides and these were quantified from the pollen slides by recording the number of fragments passing a graticule endpoint (after Clark, 1982). Charcoal concentrations were calculated in the same way as for total pollen concentrations using the marker spore method.

Method for determining glass shard concentrations

Organic matter in the samples was removed via digestion in heated H_2O_2 solution 80–90 °C and biogenic silica (diatoms, spicules) were dissolved in heated NaOH solution at 80–90 °C for 3 to 4 hr. Fine clays and other silicate materials were removed by wet sieving through a pair of sieves at 63 μm and 25 μm, with very clean glass shards being retained on the 25 μm sieve. The glass shards were spiked with *Lycopodium* spores to facilitate measurement of glass-shard concentrations, and mounted on slides. The slides were examined at 400X magnification with a polarizing microscope to distinguish and count glass shards. Glass shard concentrations are reported as shards per milligram dry weight as described by Gehrels et al. (2006).

Method for major elemental analysis of selected Pupuke glass shards

Glass shards of selected horizons from P5 were analysed by a CAMECA SX100 electron microprobe (EMP) at the University of Edinburgh using a 10 kV accelerating voltage, 10 nA beam current, and a 4 µm beam diameter to help avoid unwittingly analysing microlites, which are common in basaltic and andesitic glass (e.g. Platz et al., 2007; Shane and Zawalna-Geer, 2011). Analysis times for 'first cycle' elements (Si, K, Mn, Al, Na) were 30 s peak, 30 s background. For Na and Si, the 30 s peak time was split into 6.5 sec intervals and a decay curve procedure employed to correct for count rate decrease or increase in Na and Si, respectively. 'Second cycle' elements counting times were 20 s peak and 20 s background. Replicate analyses on glass standards (including Lipari obsidian and TBIG) and laboratory mineral standards at 3- or 4-hourly intervals during analytical runs demonstrated that these instrumental settings produced high accuracy and precision (Gehrels, 2009; Table S1).

Supplementary Info Table 1

Anal.no.	**Standards**											
Sample	TB1G		**Lipari**		**Wollstonite**		**Spinel**		**Jadite**		**Orthoclase**	
SiO_2	**53.83**	0.37	**74.11**	0.44	**51.46**	0.39	**0.10**	0.02	**60.60**	0.33	**64.57**	0.65
Al_2O_3	**16.06**	0.24	**12.80**	0.23	0.01	0.03	**71.53**	0.94	**25.60**	0.47	**17.56**	0.31
TiO_2	**0.88**	0.04	**0.07**	0.02	**0.00**	0.01	**0.01**	0.01	**0.01**	0.01	**0.02**	0.01
FeO*	**8.49**	0.29	**1.56**	0.15	**0.34**	0.09	**0.01**	0.02	**0.05**	0.05	**0.46**	0.12
MnO	**0.20**	0.07	**0.05**	0.05	**0.07**	0.06	**0.04**	0.04	**0.02**	0.03	**0.01**	0.03
MgO	**3.60**	0.05	**0.04**	0.01	**0.20**	0.05	**28.32**	0.29	**0.01**	0.01	**0.00**	0.00
CaO	**6.89**	0.10	**0.74**	0.04	**47.84**	0.29	**0.01**	0.01	**0.03**	0.02	**0.01**	0.02
Na_2O	**3.30**	0.07	**4.14**	0.09	**0.01**	0.01	**0.00**	0.01	**15.22**	0.23	**1.08**	0.05
K_2O	**4.47**	0.08	**5.18**	0.08	**0.00**	0.01	**0.00**	0.00	**0.00**	0.00	**15.30**	0.10
P_2O_5	**0.59**	0.04	**0.00**	0.02	**0.42**	0.03	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
Total	*98.31*	*0.46*	*98.71*	*0.49*	*100.36*	*0.56*	*100.03*	*0.96*	*101.55*	*0.59*	*99.01*	*0.52*
n	***84***		***63***		**12**		***13***		***9***		***10***	
*Total iron as FeO												

Mean values for independently characterized laboratory standards used for electron microprobe major-element analyses of tephra-derived glass shards presented in Table 1.