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Pollen-based temperature and precipitation records of the past 14,600 years in northern New Zealand (37°S) and their linkages with the Southern Hemisphere atmospheric circulation

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Abstract

Regional vegetation, climate history, and local water table fluctuations for the past 14,600 years are reconstructed from pollen and charcoal records of an ombrogenous peatbog in northern New Zealand (38°S). A long-term warming trend between 14,600 and 10,000 cal. yr BP is punctuated by two brief plateaux between 14,200–13,800 and 13,500–12,000 cal. yr BP. Periods of relatively drier conditions are inferred between 14,000–13,400 and 12,000–10,000 cal. yr BP, while a long-term wet period is observed between 10,000 and 6000 cal. yr BP. The last 7000 years feature relatively stable temperatures, a long-term drying trend that culminates with persistent drier conditions over the last 3000 years and cyclical fluctuations in the bog's water table and fires. Present-day climate controls and comparisons with other climate reconstructions from New Zealand, the Southern Hemisphere mid-latitudes and the tropical Pacific suggest that complex and temporally variable teleconnections exist between northern New Zealand and the Southern Hemisphere low- and high-latitude circulation.

Keywords

climate change, ENSO, New Zealand, peatbog, pollen, precipitation reconstruction, Southern Hemisphere paleoclimate, temperature reconstruction

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Introduction

Palynological records have valuable potential for reconstructing temperature and rainfall variability at timescales that extend well beyond the instrumental record. Pollen–climate reconstructions from New Zealand, positioned in the mid-latitudes of the South Pacific Ocean, can additionally provide insight into past teleconnections with the Southern Hemisphere low- and high-latitude circulation systems. New Zealand pollen-based reconstructions have helped to constrain the timing and structure of climate fluctuations during the late-Quaternary glacial cycles (Newnham et al., 2007; Vandergoes et al., 2005) and the transition from the last glacial to the Holocene (McGlone et al., 2010; Newnham et al., 1995a; Newnham and Lowe, 2000). Along with other proxy records, palynological sequences have characterized a series of climate events for the last 30,000 years (Alloway et al., 2007; Barrell et al., 2013). While pollen-based reconstructions are largely based on temperature proxies, much less is known about precipitation variability for two general reasons: (1) precipitation constraints on vegetation are comparatively limited (e.g. McGlone and Moar, 1998) as the oceanic climate lacks pronounced rainfall minima, and (2) precipitation anomalies and their relationship with hemispheric circulation are complex and heterogeneous, especially in northern New Zealand where precipitation regimes are associated with both extra-tropical (westerly) and sub-tropical (easterly) circulation (Ummenhofer and England, 2007). Nevertheless, a west–east precipitation gradient – imposed by the intersection of axial ranges with predominantly westerly circulation – influences the distribution of vegetation communities and certain species to an extent that offers opportunities to reconstruct precipitation from palynological records. Together with the well-established pattern of late Quaternary temperature variability, such precipitation reconstructions can provide a stronger basis for exploring past teleconnections between New Zealand climate and Southern Hemisphere circulation systems.

In this study, we use a highly resolved pollen and microscopic charcoal record from an ombrogenous peatbog in Waikato region, northern New Zealand, to reconstruct the local and regional vegetation history and its association with temperature and rainfall changes over the last 14,600 years. The vegetation setting of the

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Waikato region has two key advantages for developing regional temperature and precipitation proxies. First, the dominance of mixed conifer–broadleaved forest over beech forest offers the possibility of developing quantitative temperature reconstructions without distortions arising from the masking effect of beech pollen (Newnham et al., 2013; Wilmshurst et al., 2007). Second, the relative abundance of the dominant podocarp trees can be related to precipitation changes (McGlone and Topping, 1977). We took advantage of these features to develop pollen-based temperature and moisture reconstructions using quantitative methods and a podocarp pollen ratio, respectively. The integration of these reconstructions with other terrestrial and marine proxies is used to provide insights into large-scale atmospheric controls on New Zealand climate anomalies.

Study region

The physical setting

The Waikato region (18,000 km^2) comprises two main alluvial basins (100–200 m a.s.l.) surrounded by a series of mountain ranges (600–900 m a.s.l.). The lowland basins have been infilled by fluvial aggradation and by volcanic deposits derived from the North Island volcanic centres (Lowe, 1988; Lowe and Green, 1987; Selby and Lowe, 1992). Much of the Waikato lowlands today are occupied by small lakes and wetland areas where the deposition of volcanic and fluvial sediments impeded the drainage of subsidiary riverine valleys (Green and Lowe, 1985; Lowe, 1988). Some of these, including the study site, have developed into peatbogs during post-glacial times (McGlone, 2009). Sedimentary records recovered from these lakes and bogs have included a series of Quaternary tephra layers from the Central North Island volcanic zone, the Egmont–Taranaki volcanic complex and offshore volcanic islands (Green and Lowe, 1985; Lowe et al., 1980).

Climate controls

The Waikato region has a warm-temperate climate with prevailing westerly and south-westerly wind flow. Data from the National Climate database (https://www.cliflo.niwa.co.nz) show that the mean annual temperatures are around 14°C in the lowlands, but they can drop to less than 9°C in the few areas above 900 m a.s.l. During austral summer months (December, January and February), lowland mean temperatures can reach above 18°C, while winter (June, July and August) temperatures are about 10°C. The geographic distribution of precipitation in the Waikato region is largely a result of the prevailing westerly flow and the regional physiography. Annual precipitation is highest in the western uplands (up to 2300 mm/yr) and considerably lower in the lowlands, oscillating between 1100 and 1500 mm. Overall, the whole region experiences a slight rainfall peak during winter months (30% of the annual amount) when south-westerly storms are stronger and more frequent (Ummenhofer and England, 2007). However, summer precipitation may also be significant (20%) and highly variable on an inter-annual basis, especially when sub-tropical storms reach the region.

New Zealand climate variability is largely explained by broad scale modes of climate variations such as the El Niño Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) (Kidston et al., 2009; Kidson and Renwick, 2002; Ummenhofer and England, 2007). El Niño conditions and negative phases of SAM are associated with anomalous westerly and south-westerly flow, bringing colder temperatures to most of the country (Salinger and Mullan, 1999; Thompson et al., 2011; Figure 1). During La Niña years and positive phases of SAM, these patterns are reversed overall, with generally warmer temperature over the country. In northern New Zealand including the Waikato region, El Niño conditions produce strong negative anomalies in summer precipitation (Figure 1), which result from a reduced input of easterly and northwesterly precipitation fronts (Kidson and Renwick, 2002).

Modern vegetation

The native vegetation of the Waikato lowlands has been almost completely destroyed by anthropogenic clearance, and today, the landscape is dominated by agriculture (Clarkson et al., 2007). Soil and pollen analyses suggest that this region was densely covered by mixed conifer–broadleaf forest prior to human settlement in the 13th century (Newnham et al., 1989, 1995a). Relict forest stands in relatively well-drained areas such as alluvial plains, gullies and mountain foothills feature the emergent conifers *Dacrydium cupressinum, Dacrycarpus dacrydioides, Podocarpus totara, Prumnopitys ferruginea* and *Prumnopitys taxifolia*, and broadleaved trees such as *Beilschmiedia tawa, Alectryon excelsus, Elaeocarpus dentatus, Metrosideros robusta, Knightia excelsa, Beilschmiedia taraire, Dysoxylum spectabile, Rhopalostylis sapida* and *Laurelia novae-zelandiae* (Clarkson et al., 2007). The understory of these mixed conifer–broadleaf stands is structurally complex and floristically diverse, featuring multiple small trees and shrubs such as *Melicytus ramiflorus, Hedycarya arborea, Coprosma grandifolia* and the tree fern *Cyathea dealbata* among many others. Small grasses occupying the lower vegetation stratum include *Asplenium bulbiferum, Blechnum discolor, Hymenophyllum demissum* and *Microlaena avenacea.* While *Dacrydium cupressinum* is the dominant conifer tree in low rolling areas with well-drained to waterlogged soils (Franklin, 1968), *Podocarpus totara* and *Prumnopitys taxifolia* tend to become dominant species in relatively drier, exposed areas such as scarps and gullies where sandy and gravel soils prevail.

On poorly drained areas such as swales, low rolling hills, narrow gully floors and around the margins of peatbogs, *Dacrycarpus dacrydioides* and *L. novae-zelandiae* become the dominant tree species in association with *Syzygium maire* and *Cordyline australis*. The understory of this forest type includes a wide range of small trees and shrubs such as *Myrsine australis, C. dealbata, Geniostoma rupestre, Coprosma areolata, Streblus heterophyllus, Freycinetia banksii* and *Ripogonum scandens*. The ground cover features ferns and grasses such as *H. demissum, Asplenium bulbiferum, Astelia fragrans, Astelia grandis* and *Microlaena avenacea* (Clarkson et al., 1997).

Stumps and logs preserved in bogs indicate that the lowland plains north of 38°S once sustained multiple stands of the conifer *Agathis australis* (Clayton-Greene, 1978; Ogden et al., 1992) which, apart from isolated relict individuals, are now restricted to well-drained soils in the mid-elevations of the surrounding eastern and western ranges. In these areas, *A. australis* dominates together with *Fuscospora truncata* and *Phyllocladus trichomanoides* (Newnham et al., 1989), often with *Beilschmiedia tawa, Dacrydium cupressinum* and *K. excelsa* present at the canopy level.

Study site

Moanatuatua (37.92°S; 175.37°W; 60 m; Figure 1) is a raised ombrogenous (rain-fed) bog, formed by the progressive accumulation of post-glacial organic-rich material over poorly drained Pleistocene alluvial terraces (Selby and Lowe, 1992). Today, most of the bog has been converted to agricultural land, following extensive drainage over the past ~100 years. The current extent (1.15 km^2) is less than 2% of its original expanse (Clarkson, 1997) and the height of the peat surface has also sunk considerably (Gehrels, 2009). The bog vegetation is dominated by two species of the Restionaceae family (restiads or jointed rushes), that is, *Empodisma robustum* (hereafter referred to as *Empodisma*) and *Sporadanthus traversii* (*Sporadanthus*). The dense root system formed by these two species provides the main constituent of peat formation although other plant remains are also well preserved (Haenfling et al., 2016). Other common

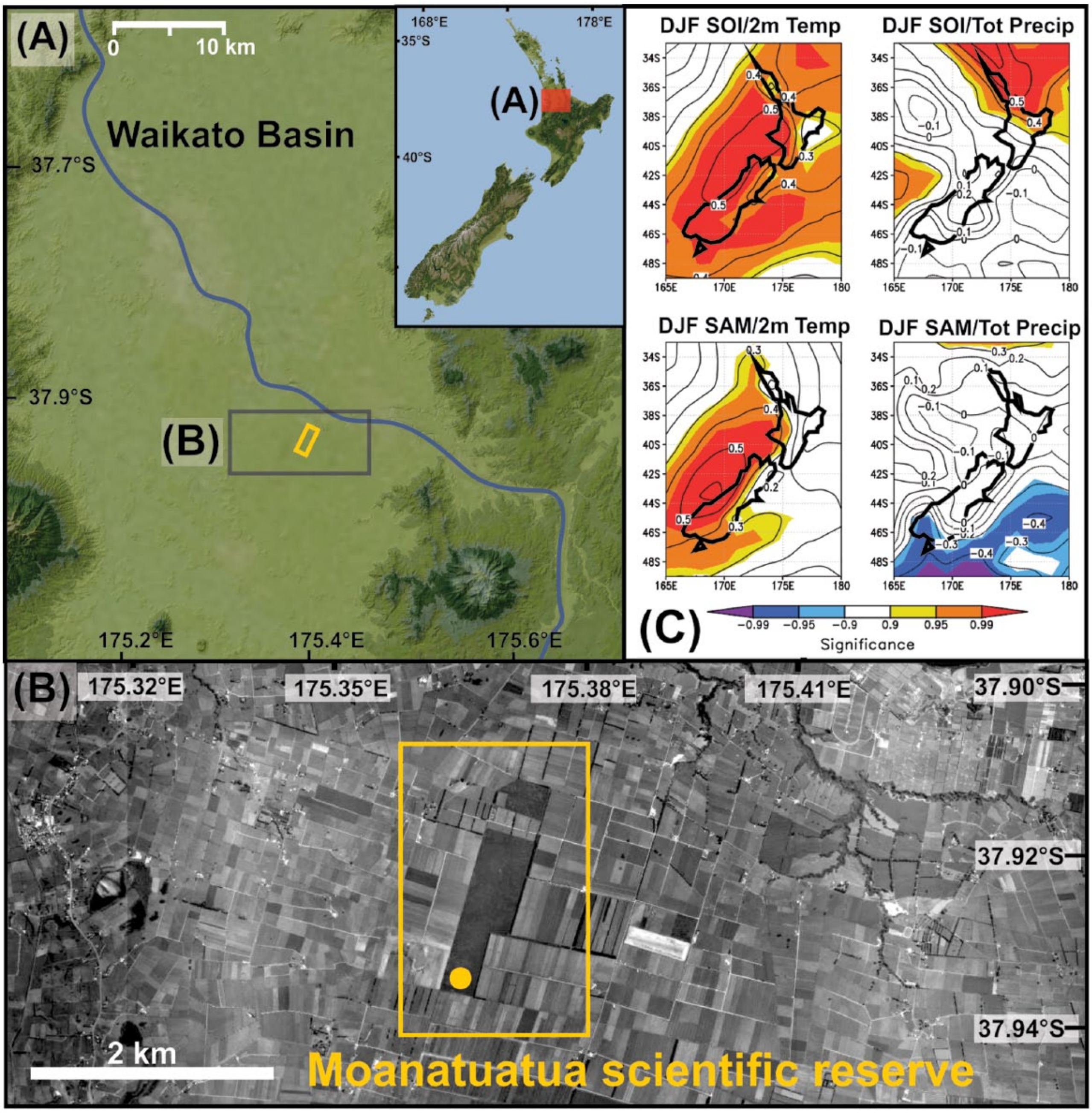

Figure 1. (a) Digital elevation model of the Waikato Basin. (b) Aerial photograph showing Moanatuatua Scientific Reserve, a protected remnant of Moanatuatua Bog. The yellow dot demarks the coring area. (c) Correlation (1979–2014) between New Zealand summer (DJF) surface temperature (2 m above ground level), precipitation and the SAM and ENSO index. The SAM corresponds to the Antarctic Oscillation Index from the National Oceanic and Atmospheric Administration (NOAA), while ENSO corresponds to the Southern Oscillation Index (SOI). Contour intervals are at 0.1 values of detrended correlation coefficients. Two-tailed Student's *t*-test is used to calculate significance values (coloured contours). Atmospheric data correspond to monthly mean ERA-Interim global atmospheric reanalysis (1979–present) employed at 1.5 × 1.5° latitude–longitude resolution.

plants are the shrubs *Leptospermum scoparium* and *Epacris pauciflora*; the sedges *Baumea teretifolia* and *Schoenus brevifolius*; the fern *Gleichenia circinata* (umbrella fern); mosses and liverworts such as *Sphagnum cristatum, Goebelobryum unguiculatum, Riccardia crassa* and the club moss *Lycopodium laterale*. Moanatuatua peatbog has been the focus of several ecological, palaeoecological and paleoclimate studies in the last 30 years (Supplementary Information, available online).

Methods

Coring, stratigraphy and chronology

Two overlapping 8-m-long cores were obtained from the southern edge of the Moanatuatua Scientific Reserve (Figure 1) in November 2012. The cores included 0.5-m-long and 1-m-long sections obtained with a Russian D-section corer (Jowsey, 1966) and a square-rod piston corer (Wright, 1967), respectively. The two cores were able to be matched on the basis of the corresponding organic and inorganic horizons, facilitating the construction of a single, composite section. The stratigraphy of the composite section was described through a combination of visual core inspection and photographs. Glass shard constituents of two macroscopically visible tephra were geochemically characterized using the electron microprobe (EMP) housed at Victoria University (more details in the Supplementary Information). The chronology of the composite section was constrained by 13 AMS radiocarbon dates obtained from plant macrofossils, including wood and charcoal remains. A Bayesian age–depth model was developed using the BACON statistical package (Blaauw and Christen, 2011) in the R platform (https://www.r-project.org/). This age model refines that presented for the same sequence by Haenfling et al. (2016) which was based on 10 ^{14}C dates.

Pollen and charcoal analysis

A total of 149 samples taken from 1-cm-thick slices spaced at 5-cm intervals were analysed for pollen and microscopic charcoal content. A constant volume of 1 cm^3 of sediment was taken at each slice and then processed for pollen following standard procedures for peat deposits (including KOH and HCL treatments and acetolysis reaction; excluding HF treatment). Exotic *Lycopodium* marker spores were added to each sample to enable the calculation of pollen concentrations and pollen influx rates.

Pollen identification was achieved with the aid of the pollen atlas presented by Moar (1993) and modern reference slides. Since the pollen slides revealed a variable degree of deteriorated saccate conifer pollen specimens, one additional morphologic group was assigned to accommodate the varying levels of taxonomic precision that was achievable. '*Podocarpus*/*Prumnopitys undifferentiated*' includes all grains of *Podocarpus* spp. and *Prumnopitys* spp. that could not be differentiated into species level.

Additionally, we calculated the microscopic charcoal (<125 μm) accumulation rate (particles cm^{-2} yr^{-1}, here-after referred to as 'micro-CHAR') based on the charcoal counts in the pollen slides, their corresponding number of *Lycopodium* markers and the depositional times obtained in the age model. Holocene macroscopic charcoal records from Moanatuatua have been previously presented in Hazell (2004) and Haenfling et al. (2016). Our micro-CHAR record was conducted to complement this earlier work with a more regional depiction of fire history.

All pollen and charcoal diagrams were created with the software Tilia version 1.7.16. (E. Grimm, Illinois state Museum, Springfield, IL). A zonation of the pollen diagrams was established based on visual identification of the main transitions and with the assistance of cluster analysis (CONISS) performed using Tilia. The main trends in pollen, fern spore and micro-CHAR were also examined with principal component analysis (PCA) using the R platform with the rioja package (Juggins, 2015). The analysis excluded all taxa that presented <3% abundance in at least one sample. A square root transformation was applied to the percentage data.

Temperature and precipitation reconstructions

We applied the modern analogue technique and partial least squares regression models using the New Zealand pre-deforestation pollen dataset published by Wilmshurst et al. (2007) to develop two quantitative temperature reconstructions. Additionally, we estimated the main changes in precipitation around the site by developing a qualitative pollen moisture index (PMI). The PMI is calculated as the normalized base-10 logarithm of the ratio of *Dacrydium cupressinum* (hereafter referred to as *Dacrydium*) pollen percentage to the percentage of *Prumnopitys taxifolia* and *Podocarpus*/*Prumnopitys* undifferentiated. This pollen ratio is based on the 'rimu ratio' which has been used previously for describing past moisture conditions in central North Island (e.g. McGlone and Topping, 1977) and Waikato (Newnham et al., 1989) based on the documented drought intolerance of *Dacrydium* compared with the other tree podocarps (Wardle, 1991). The use of this ratio is further supported by the strong negative correlation between *Dacrydium* and humidity in austral spring, measured as the October vapour pressure deficit (OCT-VPD) in the pre-deforestation pollen dataset (Wilmshurst et al., 2007), and the strong positive correlation shown by *P. taxifolia* (Table 1). To describe precipitation changes based on variations in the PMI, we normalized the index by its record mean. Thus, positive (negative) values of PMI will indicate the relative dominance (subordination) of the drought-intolerant *Dacrydium* over the other more drought-tolerant podocarp trees under above-average (below-average) rainfall with respect to the average of the last 14,000 years.

Table 1. Mean annual temperature (MAT) and October water vapour deficit (OCT-VPD) correlation (Spearman rank r values) of selected taxa from the pre-deforestation pollen dataset.

Species	MAT	OCT-VPD
Dacrydium cupressinum	**0.51**	**−0.26**
Prumnopitys taxifolia	0.06	**0.23**
Prumnopitys ferruginea	−0.09	**−0.44**
Phyllocladus trichomanoides	**0.64**	**0.23**
Ascarina lucida	**0.46**	−0.02
Agathis australis	**0.59**	0.19

Significant correlations are marked in bold (Wilmhurst et al., 2007).

Results

Stratigraphy and chronology

The Moanatuatua sedimentary sequence features two basal tephra: a 38-cm, grey-coloured, normal-graded, sandy-textured tephra between 731 and 769 cm (not shown) and a 9-cm orange-coloured, fine sandy-textured tephra at 675–684 cm. While the grey tephra was not identified, glass shard major-element determinations of the orange tephra, and comparisons against elemental data from proximal and distal reference tephras, confirm correlation with Waiohau Tephra (14,000 ± 155 cal. yr BP; Lowe et al., 2013) (Supplementary Information). The Waiohau tephra is overlain by homogenous black, well-humified peat sediments until the top of the section (Figure 3). No evidence of other macroscopic tephra is found throughout the section, although several pollen slides show abundant glass shards indicating the likely presence of cryptotephra. There are no marked changes in peat composition in the section although several woody, root and charcoal layers were observed. The uppermost 75 cm of the peat sequence consists of very moist, unconsolidated material comprising mostly root matting, which was unable to be recovered.

Ten of the 13 radiocarbon-dated levels yield ages in chronological/stratigraphic order, but three samples (NZA 58261, NZA 58253 and NZA 58261) in the upper section show reversed ages (Figure 2, Table 2). The lowermost pollen sample is located 1 cm above the deepest level dated (730–731 cm) representing the beginning of peat accumulation above the grey tephra and with a weighted mean of 14,650 cal. yr BP. The uppermost dated level corresponds to the first centimetre of the sediment section and yielded a modern radiocarbon age. The average peat accumulation rate is 0.05 cm yr^{-1}, a value that is within the range of regional peat accumulation (Green and Lowe, 1985). The average resolution for the pollen record is 103 years per sample.

Pollen record

The pollen record shows persistent high levels of trees (>80% throughout), dominated by the lowland trees *Dacrydium* and *Prumnopitys taxifolia*. Six formal pollen zones were established based on the changes in the key taxa (Table 3). Minor terrestrial taxa show successive expansions including *Coprosma* between 14,500 and 12,500 cal. yr BP, *Ascarina* between 12,500 and 7000 cal. yr BP and *Phyllocladus* over the last 7000 years. This later period features a series of semi-regular ~1000-year peaks most notably in *P. taxifolia*, *Podocarpus*/*Prumnopitys undifferentiated* and *Gleichenia spp*. The wetland taxa *Empodisma* and *Sporadanthus* show average abundances of 16% relative to the total amount of terrestrial pollen, whereas the fern taxa *Cyathea* and *Gleichenia* average 10% and 4%, respectively.

PCA

The two main components of the analysis (hereafter referred to as PCA1 and PCA2) explained 16% and 13% of the total variance of the data, respectively. In terms of taxon scores, PCA1 distinguishes between positive correlations with *Coprosma* and *P. ferruginea* and negative relationships with *Ascarina, Empodisma, Sporadanthus, Gleichenia* and *Metrosideros* (Figure 4). PCA2 contrasts highly positive values of *Podocarpus*/*Prumnopitys* undifferentiated with highly negative values of *P. taxifolia*. The stratigraphic arrangement of the first two principal components shows that sample scores from the two basal zones have distinctive positive values of PCA1 and overall negative values for PCA2, while the samples from all the following zones form a cluster with overall negative or near-zero values for PCA1 and high dispersion across PCA2 (Figure 4).

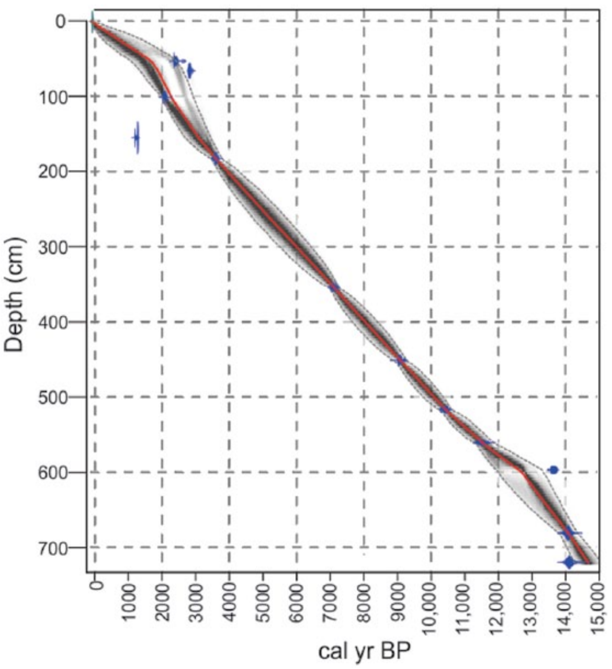

Figure 2. Bayesian age–depth model based on the 13 AMS radiocarbon dates from Moanatuatua peatbog. Age modelling was performed with the Bacon package (Blaauw and Christen, 2011) in the R software platform (R Core Team, 2014). The Southern Hemisphere terrestrial curve (SHCal13) was used to calibrate the radiocarbon dates (Hogg et al., 2013). All calibrated dates with their 95% confident interval are shown in blue. The red line corresponds to the modelled weighted mean and the dotted grey lines demark the modelled minimum and maximum 95% confidence ranges for each centimetre.

Temperature and precipitation reconstructions

The temperature reconstructions obtained by modern analogue technique and partial least squares are similar to one another (Figure 5), although the modern analogue technique presents overall slightly higher temperatures with an average of 13.5°C (averaged standard error = 1.54°C) versus 12.7°C (1.55°C) for the partial least squares. In this regard, the modern analogue technique better reproduces the present-day mean annual temperature of the Waikato lowlands (14°C). Both reconstructions show continuous long-term warming between 14,600 and 10,000 cal. yr BP, although the partial least squares reconstruction shows a more marked peak during the early Holocene (12,000–9000 cal. yr BP) and overall more pronounced variability than the modern analogue technique during the latter part of the Holocene.

The PMI indicates three phases of relatively drier conditions with below-average values between 14,000–13,400, 12,000–10,000 cal. yr BP and during the last 3000 years of the record (Figure 5). One marked long-term wet phase is recorded between 10,000 and 6000 cal. yr BP, while less pronounced short-term wet conditions are also observed between 12,500–12,000 and 5000–4200 cal. yr BP (Figure 5).

Discussion

Vegetation and climate

The pollen record from Moanatuatua indicates that the Waikato lowlands have been extensively forested for at least 14,600 years, consistent with previous studies from this region (McGlone et al., 1984; Newnham et al., 1989, 1995a). High levels of *Dacrydium* and *Prumnopitys* pollen throughout the record indicate that lowland conifer–broadleaved forest was the dominant plant formation, whereas trace abundances of *Fuscospora*/*Lophozonia* (not shown) indicate that beech forest was essentially absent.

The period between 14,600 and 14,000 cal. yr BP (pollen zone MT1 in Figure 3 and Table 3) shows increasing *Dacrydium* values when all other main terrestrial taxa either do not vary appreciably or show overall declines. From these trends, we infer a period of climate amelioration with increasingly warmer and moister conditions. Relatively low levels of micro-CHAR, apart from a single peak, suggest low fire activity and, by inference, relatively wet conditions. Nonetheless, the early fire history of the bog must be

Table 2. Code, depth and calibration curve for all radiocarbon dates at Moanatuatua. Calibration was performed with the Softwater Calib 7.02.

No.	Laboratory code (CAMS#)	Depth (cm)	14C date ± 1 σ (years)	Calibration	Youngest 2σ intercept (cal. yr BP)	Oldest 2σ intercept (cal. yr BP)	Median probability (cal. yr BP)
1	NZA60455	1	0	SHCal12	0	0	0
2	NZA60344	53	2418 ± 24	SHCal13	2338	2676	2403
3	NZA 58253	66	2776 ± 23	SHCal13	2761	2918	2823
4	NZA 60343	101	2141 ± 25	SHCal13	2008	2149	2073
5	NZA 58261	157	1383 ± 23	SHCal13	1185	1304	1277
6	NZA 58257	185	3399 ± 25	SHCal13	3483	3690	3599
7	NZA 58256	354	6251 ± 28	SHCal13	7004	7243	7098
8	NZA 58255	451	8173 ± 33	SHCal13	8996	9244	9069
9	NZA 58258	517	9294 ± 36	SHCal13	10,226	10,554	10,426
10	NZA 58262	561	10,068 ± 38	SHCal13	11,319	11,749	11,518
11	NZA 58254	597	11,867 ± 46	SHCal13	13,490	13,765	13,651
12	NZA 58256	692	12,230 ± 39	SHCal13	13,943	14,251	14,078
13	NZA 58263	731	12,267 ± 47	SHCal13	13,952	14,324	14,121

Table 3. Summary of Moanatuatua pollen zones. Zone-mean abundances are denoted in parenthesis.

Zone	No. of Samples	Stratigraphic position (cm)	Age range (cal. yr BP)	Dominant taxa (zone mean)	Additional information
MT1	8	749–690 cm	14,600–14,000	*Dacrydium* (63%), *Prumnopitys taxifolia* (19%), *Coprosma* (3%)	All other main terrestrial taxa show minimal values. Similarly, the restiads *Empodisma* (3%) and *Sporadanthus* (5%) and the tree fern *Gleichenia* (1%) remain sparse throughout this zone. Apart from a prominent peak at the base of the record, micro-CHAR values are minimal during this zone.
MT2	18	690–590 cm	14,000–12,400	*Dacrydium* (58%), *Prumnopitys taxifolia* (21%), *Coprosma* (4%)	*Coprosma* shows two well-defined expansion pulses peaking at 13,900 and 12,700 cal. yr BP. The bog taxa, *Empodisma* (7%), *Sporadanthus* (6%) and *Gleichenia* (5%) show slightly higher levels than for the previous zone. micro-CHAR displays higher values compared with the previous zone and a marked peak at 13,900 cal. yr BP.
MT3	29	590–520 cm	12,400–8900	*Dacrydium* (56%), *Prumnopitys taxifolia* (20%), *Ascarina* (5%)	Short-lived expansion of *P. taxifolia* (20%), followed by recovery of *Dacrydium* to the previous levels. While *Coprosma* disappears at the beginning of this zone, other broadleaf taxa such as *Griselinia* (<1%), *Nestegis* (1%) and *Metrosideros* (1%) show higher abundances relative to the previous zone. *Empodisma* (15%), *Sporadanthus* (16%), *Gleichenia* (7%) and the tree fern *Cyathea* (16%) experience all notable expansion, while *Dicksonia* (2%) shows overall lower abundances. The bog taxa *Epacris* (0.6%) and *Leptospermum* show minor, albeit noticeable increments in this zone. micro-CHAR displays similar background values as the previous zone and several noticeable peaks throughout this zone.
MT4	18	520–342 cm	8900–7100	*Dacrydium* (62%), *Prumnopitys taxifolia* (14%), *Ascarina* (3%)	*Ascarina* (3%) shows progressive decline during this entire zone as does *Cyathea* (14%). This interval also features further increments in the wetland taxa including *Epacris* (1.1%), *Sporadanthus* (20%) and *Empodisma* (22%), the latter two culminating in maxima for the entire record between 7600 and 7300 cal. yr BP. micro-CHAR displays relatively high background values and two peaks centred at 8600 and 7900 cal. yr BP.
MT5	63	342–52 cm	7100–1000	*Dacrydium* (56%), *Prumnopitys taxifolia* (18%), *Gleichenia* (3%)	The conifer *Phyllocladus* (3%) and the broadleaf *Metrosideros* (1%) both show higher abundances than in the previous zone, with the former featuring a persistent increasing trend throughout. After peak abundances in the previous zone, *Empodisma* (18%) and *Sporadanthus* (16%) show overall lower percentages with the latter exhibiting the same distinctive semi-regular cycles mentioned above. micro-CHAR shows relatively low background levels although several high-magnitude peaks including the record-maxima values are observed in this zone.
MT6	10	52–1 cm	1000–present	*Dacrydium* (53%), *Prumnopitys taxifolia* (20%), *Phyllocladus* (7%)	Marked increments in *Phyllocladus* (5%) and the restiads *Empodisma* (19%) and *Sporadanthus* (19%). The end of this zone features a rapid expansion of Poaceae (2%), the fern *Pteridum* (3%) and the exotic *Pinus* (0.5%). micro-CHAR throughout this zone is characterized by increasing values and by the presence of a prominent peak at 200 cal. yr BP.

interpreted with caution because Haenfling et al. (2016) show that burning of the bog surface was probably not common until the raised bog status was achieved in the early Holocene, which made the bog more susceptible to periods of drying. This suggests that the early peak in micro-CHAR was probably not associated with a local fire event. Minimal abundances of *Empodisma* and *Sporadanthus* pollen suggest that raised peatbog conditions were not yet developed around the core site, and Haenfling et al. (2016) suggest local swamp forest persisted during this period.

Between 14,000 and 12,400 cal. yr BP (zone MT2), the record features two expansion pulses of *Coprosma* peaking at 13,800 and 12,800 cal. yr BP and separated by increases in *Dacrydium* and *P. taxifolia*. The first of these pulses occurs just above the Waiohau Tephra and is associated with a prominent peak in micro-CHAR (Figure 3), and the two of them coincide with brief minor cooling phases in both temperature reconstructions as seen in Figure 5. We note that the *Coprosma* pulses at Moanatuatua show a comparable timing and stratigraphic relationship with patterns of herb pollen at Kaipo bog (Hajdas et al., 2006; Newnham and Lowe, 2000), an upland site close to treeline ~180 km to the southeast. At that site, the deposition of the Waiohau Tephra is followed by (1) a short-lived (>50 years) peak of herb pollen interpreted as volcanic impact and (2) a second and longer expansion of herbs persisting for the next 900–1000 years that has been interpreted as a cooling pulse. These similarities suggest that the *Coprosma* expansions at Moanatuatua may have been associated with an earlier interval of volcanic disturbance (cf. Wilmshurst and McGlone, 1996) and the latter cooling pulse. At a local scale, notable increases in the raised bog indicators *Empodisma, Sporadanthus* and *Gleichenia* between 14,000 and 12,500 cal. yr BP suggest a period of sustained peatbog development. In contrast, Haenfling et al. (2016) show the presence of macroscopic vascular tissue and Cyperaceae cuticles in the plant macrofossil record indicating that the area in the immediate vicinity of the core site lacked raised bog vegetation and was instead experiencing a transition from swamp forest to fen conditions. These contrasting records can be explained by an early phase of localized raised bog development within a wetland mosaic of swamp forest, fen and bog communities, with subsequent extensive peatbog growth likely to have arisen through coalescence of initially discrete patches.

The disappearance of *Coprosma* and the expansion of several broadleaf taxa such as *Metrosideros, Nestegis* and most notably *Ascarina* between 12,500 and 10,000 cal. yr BP signal an increase in the diversity of angiosperm trees as a response to sustained warming and relatively moist conditions. Between 12,000 and 10,000 cal. yr BP, *Dacrydium* features a long-term drop, whereas *P. taxifolia* shows a pronounced increase. The higher drought tolerance of *P. taxifolia* over *Dacrydium* suggests that expansion of the former likely represents a trend towards decreasing precipitation. The plant macrofossil record of Haenfling et al. (2016) indicates the development of raised bog conditions at the core site during this interval – an inference supported by the rapid increase in restiad bog indicators, especially *Sporadanthus* (Figure 3). Haenfling et al. (2016) also argue that local peat burnings

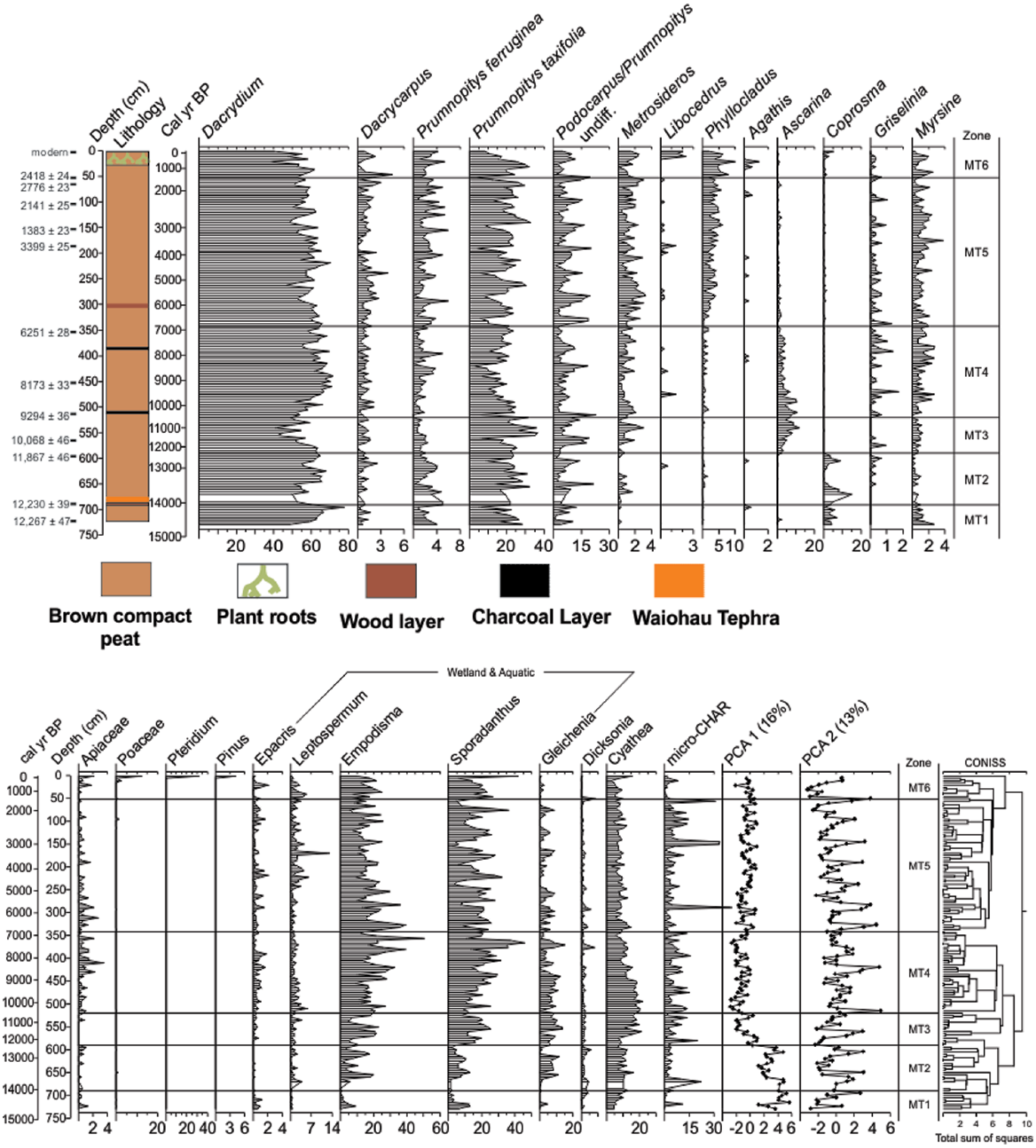

Figure 3. Sediment sequence and pollen stratigraphy. The percent abundance of main pollen and spore types are plotted against the modelled age and lithology. The upper panel includes the dryland tree and shrub taxa, while the lower diagram shows grass, introduced, wetland, aquatic and fern taxa. The lower panel also shows the sample scores for the first two principal components of the PCA and a stratigraphically constrained zonation of the pollen data using CONISS analysis. Note the changing scale for certain taxa. Microscopic CHAR vales are divided by 1000 and the curve has been truncated to 30 particles cm^{-2} yr^{-1}.

accompanied the development of raised bog conditions because water table drawdowns during dry summers could not be replenished by other moisture sources. The micro-CHAR record presented here supports this assumption by showing a period of high fire activity between 12,500 and 9500 cal. yr BP.

Between 10,000 and 8000 cal. yr BP, a shift to warmer and moister climate is indicated by a persistent increase in *Dacrydium*, maximal abundances of *Ascarina* and decreasing abundances of *P. taxifolia*. Other taxa such as the angiosperm trees and shrubs *Metrosideros, Nestegis, Griselinia, Myrsine* and the tree fern *Cyathea* show noticeable expansions, suggesting an increase in floristic diversity at the canopy and sub-canopy level. The presence of considerable amounts of micro-CHAR suggests, however, that such conditions did not prevent the occurrence of periodic fires.

The period between 8000 and 800 cal. yr BP features a long-term decrease in *Dacrydium*, minima in *Ascarina* and an increase in *Phyllocladus* followed by a brief expansion in *Agathis* starting at 2100 cal. yr BP. In this regional setting, *Phyllocladus* pollen almost certainly represents the northern species *P. trichomanoides* and possibly *Phyllocladus glaucus* rather than the southern upland species *Phyllocladus alpinus* (Newnham et al., 1989). Modern observations of the northern *Phyllocladus* and *Agathis* show that they are able to tolerate a range of different precipitation conditions including drought (McGlone et al., 1984; Newnham et al., 1989; Ogden et al., 1992), unlike *Ascarina* and

Table 4. Correlation coefficients (Pearson Product-Moment) of selected pollen variables of Moanatuatua, including percentage of corroded pollen and the main components of the principal component analysis.

Variable	Variable	Correlation	*p*
% Corroded pollen	*Prumnopitys taxifolia*	−0.412	0.018
% Corroded pollen	PCA1	0.19	0.28
% Corroded pollen	PCA2	0.51	<0.01
% Corroded pollen	PMI	−0.028	0.876
% Corroded pollen	micro-CHAR	0.19	0.284
PCA1	MAT temperature reconstruction	−0.75	**<0.01**
PCA1	PLS temperature reconstruction	−0.68	**<0.01**
PCA1	PMI	0.91	**<0.01**
PCA1	*P. Taxifolia*	0.99	**<0.01**
PCA2	*P. taxifolia*	−0.75	**<0.01**
PCA2	MAT temperature reconstruction	0.17	0.04
PCA2	PLS temperature reconstruction	0.15	0.07
PCA2	PMI	0.2	0.012
PCA2	micro-CHAR	0.34	**<0.01**
PCA2	*Gleichenia*	−0.26	**<0.01**
Gleichenia	micro-CHAR	−0.1	0.21

Significant correlations are marked in bold.
PMI: pollen moisture index.

Dacrydium. Similarly, the New Zealand pre-deforestation pollen dataset shows strong positive correlations with OCT-VPD (spring air dryness) for both *Phyllocladus trichomanoides* and *Agathis australis* but near-zero or negative correlations with *Ascarina* and *Dacrydium* (Table 1; Wilmshurst et al., 2007). Together, this set of evidence suggests the onset of a multi-millennial trend towards drier conditions and/or more variable rainfall regimes in the Waikato lowlands from ~7000 cal. yr BP (see also Newnham et al., 1995a).

A sharp rise in taxa indicative of more open vegetation and forest disturbance (i.e. Poaceae, *Pteridium* and *Pinus*) occurs simultaneously at the top 10 cm of the sediment section (top of section MT6 in Figure 3). The standard palynological sequence for anthropogenic forest disturbance in northern New Zealand features two distinctive phases marked by (1) a decrease in *Agathis* and other forest trees and increase in both charcoal accumulation and *Pteridium* indicating initial human settlement at ~800 cal. yr BP (McGlone and Wilmshurst, 1999; Newnham et al., 1998) and (2) a second expansion of *Pteridium* together with exotic elements such as *Pinus* and *Plantago* indicating European settlement from ~150 cal. yr BP (McGlone, 1983; Newnham et al., 1989). The Moanatuatua pollen record shows the two phases of the anthropogenic sequence merged into the two topmost samples, which likely resulted from reduction or loss of the uppermost sediments because of the recent drainage or burning of the bog or, alternatively, by failure to capture these most recent sediments when coring. A similar merging of these two anthropogenic phases reported from pollen sequences at the coastal Bay of Plenty sites of Papamoa and Waihi was attributed to downwards dislocation of pollen in the recently disturbed uppermost sediments (Newnham et al., 1995b). In view of these likely distortions, we refrain from any further discussion of these uppermost samples pertaining to the anthropogenic era.

Holocene water table fluctuations and fire

A series of ~1000-year spaced peaks in *P. taxifolia* percentages are centred at 7100, 6200, 5200, 4300, 3300, 2400 and 1400 cal. yr BP (Figure 3). These cycles are compensated by the corresponding changes in the opposite direction of *Podocarpus*/*Prumnopitys* undifferentiated and represented by the variability of the second axis of the PCA (PCA2, Figure 4). Based on the reported maximal age range of 800–900 years for *P. taxifolia* (Norton et al., 1987; Smale et al., 1997), a straightforward interpretation would attribute those peaks to an ecologically driven dieback and replacement of *P. taxifolia* cohorts. Cyclical fluctuations between *P. taxifolia* and *Podocarpus* have also been observed at shorter timescales in a lake sequence from north-eastern New Zealand between 1350 and 850 cal. yr BP (Wilmshurst et al., 1997), where seasonal fluctuations in pollen deposition or regular masting cycles were proposed as potential causes for the fluctuations. At Moanatuatua, these cycles occur at considerably longer timescales and extend back until at least 7000 cal. yr BP. Critically, a negative correlation between the cycles of *P. taxifolia* and the percentages of corroded pollen indicates that the ~1000-year peaks in *P. taxifolia* are likely driven by changes in pollen preservation (Table 4; Supplementary Information, available online for more details). If so, then these cycles are an artefact of the varying pollen preservation conditions in the peat which governed the ability to identify grains to species rather than generic level. This conclusion is supported by observing that the cycles of *P. taxifolia* are generally in antiphase with the other generic pollen groups that include this species (*Podocarpus*/*Prumnopitys* undifferentiated in Figure 3), further indicated by the opposing directions of these groups across PCA2 in Figure 4. In other words, when pollen is well preserved, it can be more reliably identified to species level such as *P. taxifolia*; whereas during phases of poor preservation, only the more generic grouping is possible. The changing preservation of pollen grains is therefore represented by the variability of PCA2.

In accumulating peat deposits, pollen preservation is most likely controlled by water table variability. The phases of lower/higher water table will encourage/discourage biological activity in the peat surface, leading to greater/lower levels of pollen corrosion, respectively (Lowe, 1982). Thus, the quasi-regular fluctuations in *P. taxifolia* pollen levels and the compensating changes in the other groups point to the possibility of millennial-scale cycles of water table fluctuation. In rain-fed bog complexes such as Moanatuatua Bog, these cycles must be driven by changes in potential evapotranspiration, which are in turn linked to precipitation. The correlation between micro-CHAR and corroded pollen is positive albeit not significant (Table 4), which might be related to the fact that fires in peatbogs are not only controlled by water table levels but also by the accumulation of fuel and ignition occurrence. There is, however, a significant negative correlation between PCA2 and micro-CHAR which indicates that fire is more likely to occur during periods of low *P. taxifolia* preservation and corresponding low water table (Figure 5).

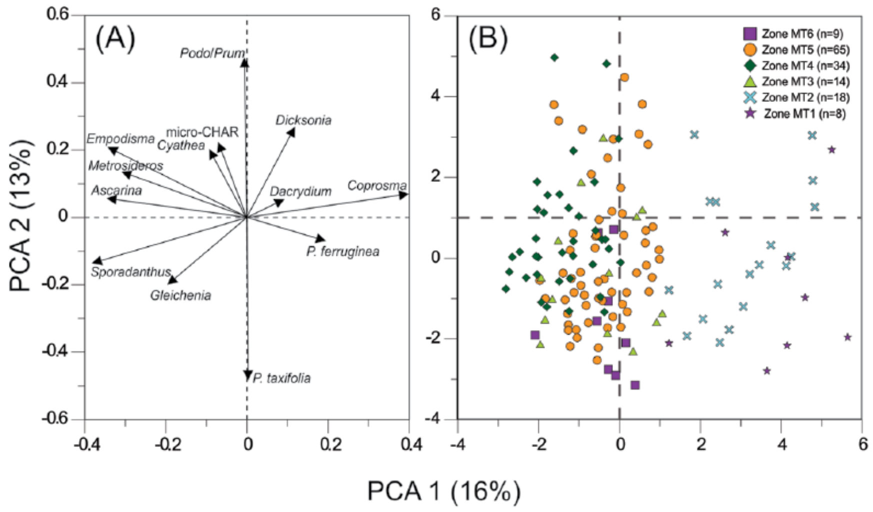

Figure 4. Principal component analysis (PCA) plot of the two principal axes including pollen and charcoal data from the Moanatuatua peatbog. (a) Sample scores with the pollen zones depicted (Table 3). (b) The main pollen taxa including micro-CHAR (taxa loadings; right panel). These sample scores are plotted stratigraphically on the pollen diagrams (Figure 3).

A key element to this puzzle is *Gleichenia*. This fern genus also shows quasi-regular 1000-year cycles, although the expansion/contraction of *Gleichenia* occurs slightly 'out of phase' with the water table and fire cycles discussed above. The significant correlation between *Gleichenia* and PCA2 (Table 4) suggests a close relationship between this taxon and water table fluctuations. However, the *Gleichenia* cycles show no significant correlation with micro-CHAR fluctuations, which might also be a consequence on the dependence of an ignition event. We note that *Gleichenia* is typically present in the early post-fire recovery in bogs, where it can resprout from underground rhizomes or burnt bases (Clarkson, 1997). Nevertheless, its post-fire recovery is slow in comparison with other bog species, and therefore, it might take up to several years to reach its pre-fire abundances (Clarkson, 1997; Timmins, 1992). Thus, a slow recovery of *Gleichenia* might also explain the lack of direct positive relationship with micro-CHAR. Finally, an alternative scenario is that the cyclical fluctuations in bog water table are related to local-scale changes in bog topography. The surface of New Zealand's large restiad bogs is typically characterized by patterns of moist swales and intervening drier hummocks (Clarkson et al., 2004; McGlone, 2009), and it has been suggested that these features may migrate across the surface of the bog over time as part of its natural process of growth dynamics (McGlone, 2009). We contend that these migrations are unlikely to generate the highly regular ~1000-year-long fluctuations of water table inferred from the Moanatuatua pollen record, although autogenic bog processes such as this need to be considered as possible drivers for local-scale changes in bog water table in future studies at this and other bogs in northern New Zealand.

Climate reconstruction and regional atmospheric circulation

In order to characterize regional climate variability, we used our pollen data to develop temperature and precipitation reconstructions. Figure 5 shows these reconstructions with a 7-point weighted average applied to each of them. The two approaches employed for developing temperature reconstructions have different strengths and limitations (discussed in the Supplementary Information), and therefore, we used both in this discussion. The PMI used to assess the regional precipitation trends shows no correlation with the percentage of corroded pollen or PCA2, indicating that this index represents a regional climate signal not significantly affected by local changes in water table levels and associated pollen corrosion (Table 4).

Both temperature reconstructions feature a long, step-wise warming trend between 14,600 and 10,000 cal. yr BP separated by plateaux or minor reversals between 14,200–13,800 and 13,500–12,000 cal. yr BP. Whereas the earlier of these phases may be linked to volcanic disturbance as discussed above, the latter is not associated with tephra and falls within the range of the late-glacial cooling episode as it has been recognized in northern New Zealand (between 13,700 and 12,500 cal. yr BP; Hajdas et al., 2006; Newnham and Lowe, 2000). A comparatively weak expression of the late-glacial cooling episode at Moanatuatua is consistent with other records from northern New Zealand (Carter et al., 2008; Newnham et al., 2012) and with lower sensitivity of lowland vegetation compared with subalpine communities (Newnham and Lowe, 2000). It has also been suggested that seasonal changes in climate may have played a role in the late-glacial reversal which is unable to be captured by pollen data (Sikes et al., 2013). A similar, although not identical, late-glacial pattern to Moanatuatua is evident in records from Onepoto maar, Auckland, 135 km to the north of Moanatuatua, where two plateaux interrupt the long-term late-glacial warming trend (Augustinus et al., 2012; Sikes et al., 2013).

The PMI shows that the late-glacial warming and peak temperature observed at Moanatuatua occur together with an earlier (12,000–10,000 cal. yr BP) below-average and a later (10,000–6000 cal. yr BP) above-average precipitation anomaly (Figure 5). These results are only partially supported by other pollen records from northern New Zealand which, in their majority, show relative warm and moist conditions between 12,000 and 9000 cal. yr BP based on the expansion of the sub-canopy tree *Ascarina* (Augustinus et al., 2011; McGlone et al., 2011; McGlone and Moar, 1977; Newnham et al., 1989, 1995b). Although this expansion is also recorded at Moanatuatua, critical in our interpretation of reduced precipitation is the increase in the canopy taxa *Podocarpus* spp. and *P. taxifolia* and a reduction in *Dacrydium* abundances, reflecting below-average values in the PMI between 12,000 and 10,000 cal. yr BP. Similarly, other records from the Waikato lowlands show noticeable reduction in the Rimu ratio between 12,000 and 10,000 cal. yr BP, which suggests a regional period of relative dry conditions (Newnham et al., 1989). This relatively dry phase coincides with the first period of a documented southwards shift of the northern margin of the SWW which resulted in significantly drier conditions in terrestrial mid-latitudes including New Zealand between 12,000 and 8000 cal. yr BP (Fletcher and Moreno, 2012; Lamy et al., 2010; McGlone et al., 2010). This correlation suggests that this

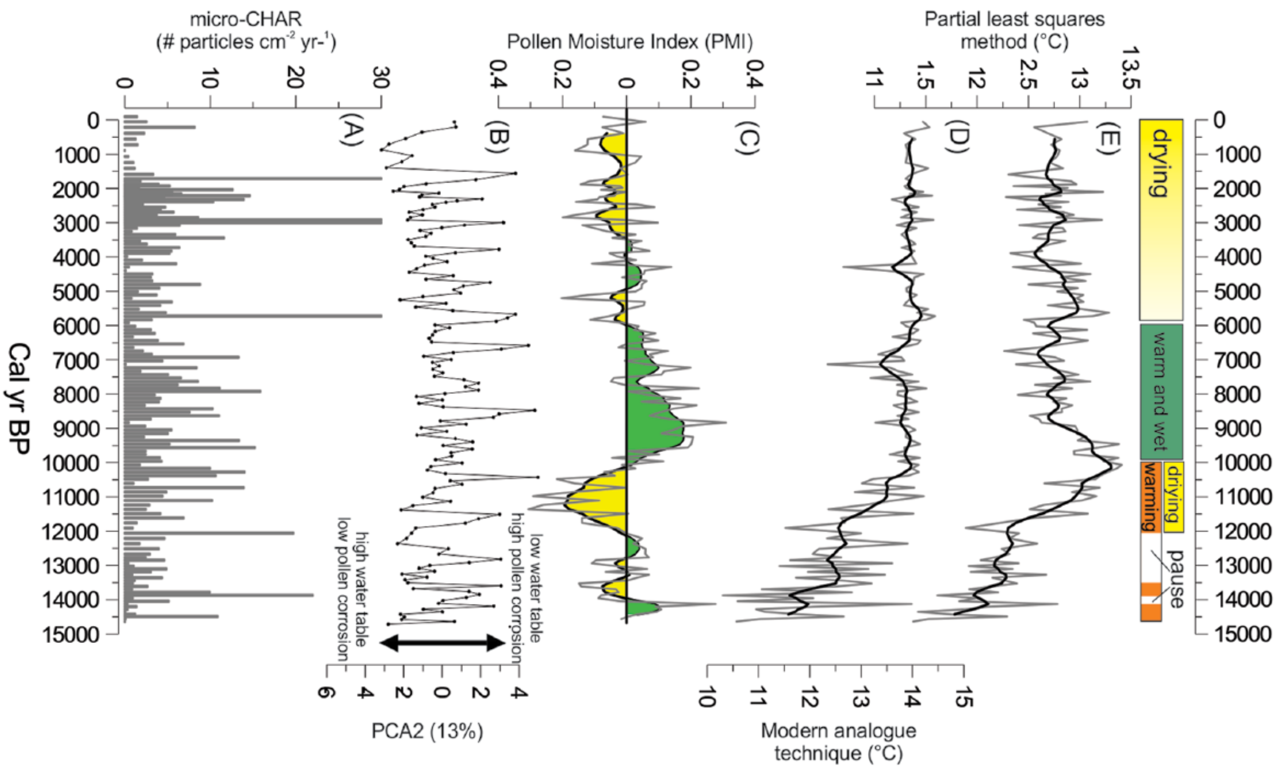

Figure 5. Temperature, precipitation reconstructions and second principal component (PCA2). Both temperature reconstructions were constructed with the pre-deforestation pollen dataset (Wilmshurst et al., 2007). (a) Microscopic CHAR, (b) second principal component, (c) pollen moisture index (PMI) calculated as the normalized base-10 logarithm of the ratio of *Dacrydium cupressinum* pollen percentage to the percentage of *Prumnopitys taxifolia*, and *Podocarpus/Prumnopitys undifferentiated* and (d and e) temperature reconstructions obtained by the modern analogue technique (c) and the partial least squares (d).

period of relative dryness at Moanatuatua was likely the result of a sustained decrease in the SWW flow. This interpretation is also consistent with the differences shown by alkenone-derived sea surface temperature (SST) reconstructions from marine cores taken north and south of the current Subtropical Front on the eastern margin of New Zealand (Bostock et al., 2013). While the southern core MD97-2120 (45.53°S; 174.93°E) shows peak temperatures between 12,000 and 10,000 cal. yr BP indicating a southwards shift of the Subtropical Front and associated SWW, peak warming in the northern core MD97-2121 (40.38°S; 177.99°E) was reached later by 9000–7000 cal. yr BP (Pahnke and Sachs, 2006). This different timing may imply that the reduction in precipitation resulting from the contraction of the SWW at 12,000 cal. yr BP was not compensated by the introduction of sub-tropical moisture before 9000 cal. yr BP in northern New Zealand, an inference compatible with the below-average precipitation at Moanatuatua during that time. A non-climatic explanation for the downward trend in the PMI should also be considered. The Moanatuatua pollen record indicates a period of rapid bog development after 12,500 cal. yr BP with sustained increases in wetland taxa. An expansion of the bog over areas previously dominated by *Dacrydium* forest would have resulted in a decrease in the abundance of this species in the pollen rain, which could have resulted in a drier PMI if the other constituents of the index remained the same or decreased to a lesser extent. However, the accumulation rate of *P. taxifolia* experiences a significant increase during this interval (see Supplementary Information, available online), suggesting that the PMI is signalling a genuine change in the dryland vegetation. Moreover, a subsequent *Dacrydium* rise between 10,000 and 6000 cal. yr BP also occurs in association within a period of extensive bog expansion, judging by the wetland and spore curves presented in Figure 3 and the plant macrofossil – record of Haenfling et al. (2016).

Interestingly, most of the subsequent wet phase at Moanatuatua, from ~10,000 to 7000 cal. yr BP, overlaps with the persistence of southward shifted SWW revealed by records in the terrestrial mid-latitudes (Fletcher and Moreno, 2012; Lamy et al., 2010). Under a scenario of reduced SWW over New Zealand, an intensification of the sub-tropical circulation offers a potential explanation for the wet conditions at Moanatuatua. This explanation is in line with the original interpretation of Rogers and McGlone (1989) of reduced westerly influence along with an increase in the frequency of northerly wind flow during the early Holocene based on pollen and bog sequences in central New Zealand. Although this scenario is difficult to corroborate because of the scarcity of proxies from northern New Zealand and sub-tropical latitudes of the western Pacific, we point out that enhanced sub-tropical moisture in northern New Zealand is consistent with the reported incursion of sub-tropical waters from the Tasman Front by 9000 cal. yr BP (Pahnke and Sachs, 2006). Additionally, SST reconstructions indicate peak warming in the western tropical Pacific between 10,000 and 6000 cal. yr BP (Stott et al., 2004), at the same time that SSTs were relatively colder in the eastern tropical Pacific (Lamy et al., 2010). We note that this early-Holocene pattern is consistent with the Moanatuatua precipitation reconstruction and resembles the present-day La Niña state in which anomalous easterly and northwesterly flows and positive precipitation anomalies are recorded in northern New Zealand (Kidson and Renwick, 2002).

After 7000 cal. yr BP, both temperature reconstructions show more stable values, with minor warming between 7000 and 6000 cal. yr BP and cooling between 6000 and 4000 cal. yr BP. Both trends are more pronounced in the partial least squares reconstruction. The PMI shows the onset of a long-term drying trend by 7000 cal. yr BP, although persistent below-average values are not observed until 3500 cal. yr BP (Figure 5). This drying trend is interesting in relation to the downward sloping in the $\delta^{18}O$ values of a speleothem record in the Waitomo Cave in western North Island, just 45 km southwest from Moanatuatua (Williams et al., 2010). Although the isotope record has mostly been interpreted as a cooling signal, Williams et al. (2010) link this cooling with reduced penetration of sub-tropical precipitation fronts, a climate inference that would explain the drying trend at Moanatuatua. In addition to the PMI, the disappearance of *Ascarina* and the increase in *Phyllocladus* occurring from 7000 cal. yr BP onwards is consistent with an increase in the frequency of drought in New Zealand (McGlone and Moar, 1977; Newnham et al., 1995b). Thus, we suggest that the Moanatuatua mid- and late-Holocene pollen record is predominantly responding to an overall drying trend that commenced ~7000 cal. yr BP, in agreement with other pollen evidence from this area (Newnham et al., 1989, 1995a, 1995b).

The last 3500 years are marked by persistent below-average precipitation in the PMI, representing a culmination of the aforementioned drying trend. This inference is also supported by peak *Phyllocladus* abundance and the later appearance of *Agathis*. Drier conditions at Moanatuatua are in relative agreement with similar trends inferred from high $\delta^{13}C$ values in the Waitomo speleothem record after 3000 cal. yr BP (Williams et al., 2010) and by sediment and pollen records from elsewhere in the North Island suggesting overall drier conditions after 4000 cal. yr BP (Gomez et al., 2013; Green and Lowe, 1994; McGlone et al., 1984; Newnham et al., 1995a, 1995b). At present day, dry conditions in northern New Zealand are strongly associated with El Niño states (Figure 1), when a northward migration of the South Pacific Convergence Zone results in a decrease in the penetration of sub-tropical precipitation fronts (Kidson and Renwick, 2002; Ummenhofer and England, 2007). Increased frequency and intensity of El Niño events in the tropical Pacific have been reported over the last 5000 years (Conroy et al., 2008; Moy et al., 2002). Together, this evidence suggests that climate variability in northern New Zealand has been strongly associated with ENSO variability for at least the last 3300 years. Furthermore, the quasi-regular water table fluctuations after 7000 cal. yr BP discussed above (Figure 3) may also reflect periodic oscillations between El Niño–like and La Niña–like conditions.

Summary and conclusion

The Moanatuatua pollen record is used to reconstruct regional temperature and precipitation trends for the last 14,600 years and also provides evidence for the bog's past water table variability. The combination of the pollen evidence presented here with a plant macrofossil presented by Haenfling et al. (2016) was able to provide a more complete understanding of wetland ontogeny than the one obtained from either proxy alone. Progressive warming is recorded between 14,600 and 10,000 cal. yr BP with indications of a possible volcanic disturbance and minor cooling phase. Warm conditions during the early Holocene occur under an early dry phase between 12,000 and 10,000 and a wet phase between 10,000 and 6000 cal. yr BP, respectively. While temperature proxies remain more or less stable after 7000 cal. yr BP, our precipitation reconstruction shows a long-term drying trend. The sequence of temperature and moisture changes presented here is in overall agreement with previous reconstructions from New Zealand and from the mid-latitudes and the Tropical Pacific, which highlight the regional character of the proposed changes in atmospheric circulation. Clearly however, the moisture level variations we have inferred from pollen and water table changes need to be tested against other records relating to precipitation variability from elsewhere in northern New Zealand. Nonetheless, the Moanatuatua pollen reconstructions show that the millennial-scale temperature and precipitation changes in northern New Zealand since ca 14,600 years BP have resulted from complex and temporally variable connections between New Zealand and the Southern Hemisphere low- and high-latitude circulation systems, including a mid- to late-Holocene strengthening of ENSO teleconnection.

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