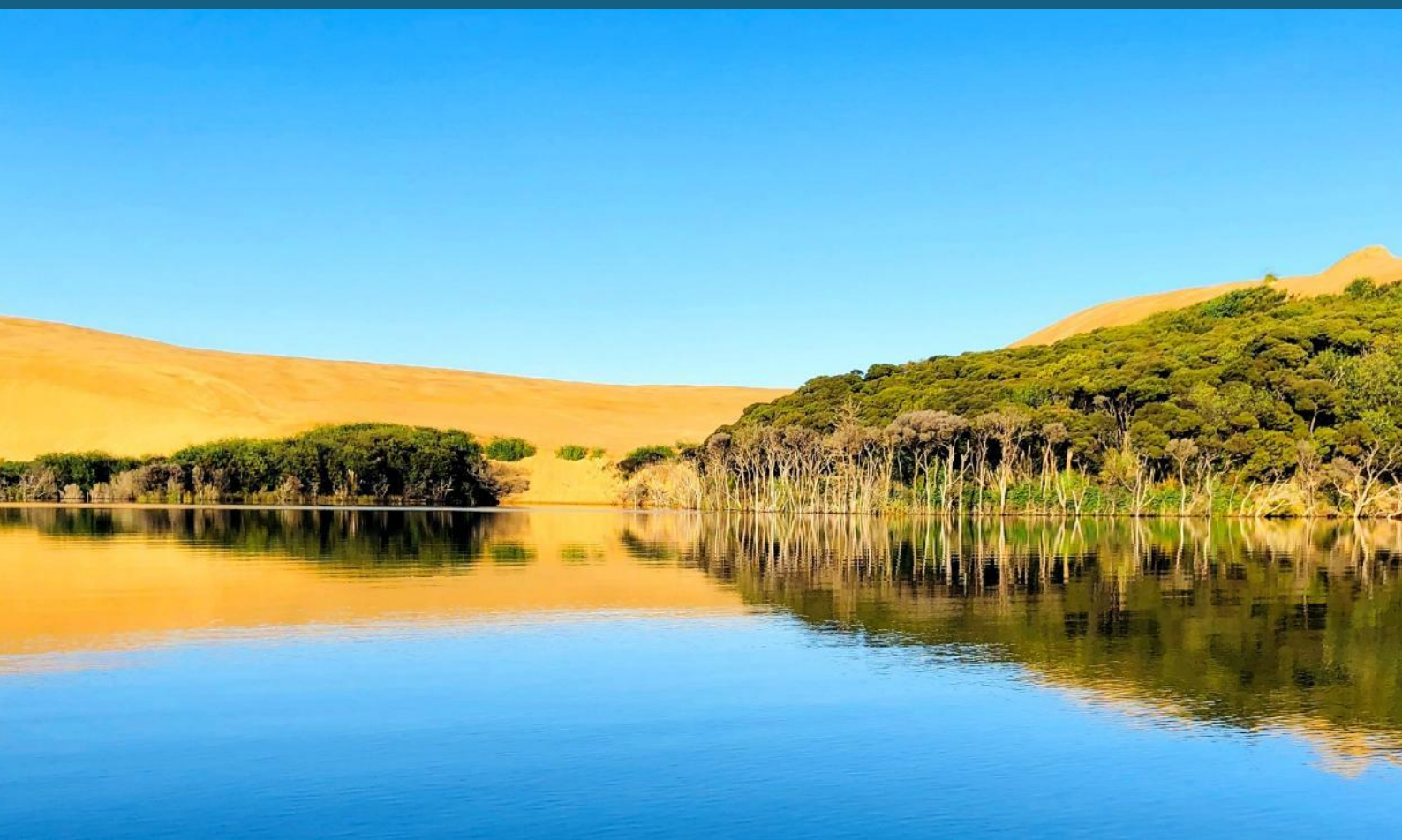


Long-term environmental change and ecological health of Northland lakes: a synthesis of Lakes380 data



Long-term environmental change and ecological health of Northland lakes: a synthesis of Lakes380 data

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Executive Summary

Northland contains more than 300 lakes over one hectare in size, most of which are rare, globally significant dune lakes formed within ancient coastal sand-dune systems. This report synthesises data collected from 37 Northland lakes as part of the national research programme Our lakes' health: past, present, future (Lakes380). It includes single-time-point water chemistry, surface-sediment geochemistry, sedimentary environmental DNA (eDNA), and palaeolimnological archives spanning from 500 to more than 1,000 years.

The synthesis reveals three major insights.

- 1) Despite extensive catchment modification, fifteen dune lakes are likely oligotrophic or mesotrophic, representing nationally rare and significant ecosystems. However, this classification is uncertain, as not all lakes have sufficient data to calculate the Trophic Level Index, with some assessments relying on the sediment bacterial trophic index (SBTI) which is an eDNA-derived metric. In lakes where both datasets were available, discrepancies were sometimes observed.
- 2) Many of the lakes contain substantial stores of potentially mobile phosphorus in their sediments, elevating the risk of internal nutrient loading. Particularly vulnerable are oligotrophic and mesotrophic systems, where sediment phosphorus release could trigger rapid ecological decline.
- 3) Palaeolimnological records demonstrate regionally consistent long-term trends: widespread forest clearance and burning associated with Māori arrival and intensified land-use impacts following European settlement. Records also show a pronounced increase in algal abundance and shifts in microbial communities over recent decades in most lakes.

Although water chemistry data represent only single measurements, they provide valuable first assessments or baseline information, especially for lakes without any long-term monitoring data. Several lakes exhibited elevated trace-metal concentrations likely reflecting geological sources or legacy contamination. Examples include chromium in Rotopokaka, and lead in Katavich and

Rotopokaka. These results warrant targeted resampling and further investigation.

Surface-sediment analyses show high concentrations of metals such as iron, manganese, and other elements in several lakes, while phosphorus-fractionation results indicate large pools of organic and pH-sensitive phosphorus across many systems. These fractions are prone to release under anoxic, or highly productive conditions. Consequently, continuous monitoring of dissolved oxygen, temperature, and pH is recommended in high-risk lakes to further understand the risks posed by internal nutrient cycling. Bacterial and eukaryotic sediment eDNA signatures highlight distinct microbial and ecological communities across lakes, likely shaped by variation in trophic state, catchment influence, and sediment chemistry.

Palaeolimnological records from ten sediment cores reveal consistent regional patterns of ecological transformation but also significant lake-specific nuances probably driven by geology, land use, and stressors such as non-native species. The Lake Kapoai core, the most comprehensively analysed, illustrates the diagnostic power of multi-proxy approaches. It documents a clear shift from macrophyte-dominated conditions to a eutrophic state after ~1950 CE, likely driven by nutrient enrichment, altered catchment vegetation, and internal loading.

To support effective action, this report recommends prioritising protection and tailored management plans for Northland's remaining oligotrophic and mesotrophic dune lakes. Improved monitoring is essential, including repeat sampling and continuous in-lake measurements of dissolved oxygen, temperature, and pH in systems at risk of internal loading. Expanded multi-proxy palaeolimnological analyses, particularly of well-resolved post-European cores, will strengthen understanding of lake-specific trajectories and the impacts of land-use change and non-native species. Scaling up to a regional assessment using eDNA-based tools, such as the SBTI (although further validation is required for the Northland region) and metabarcoding for biodiversity, offers a cost-effective approach to monitoring trophic status and ecological health across a larger number of Northland lakes.

Introduction

Northland contains 307 lakes greater than 1 ha (Schallenberg et al. 2024), the majority of which are dune (also known as aeolian or wind) lakes formed within ancient coastal sand dune systems, primarily along the west coast (Figure 1). These dune lakes are among the rarest and most threatened freshwater ecosystems globally (NRC 2002). The lakes are concentrated on the Aupōuri, Karikari, and Poutō peninsulas, as well as within the Kai Iwi lake group north of Dargaville. Dune lakes are often highly dynamic systems, characterised by fluctuating water levels and shorelines that can shift in response to ongoing sand movement. In addition to dune lakes, Northland also contains a small number of volcanic lakes, alluvial (valley-bottom) lakes, and artificial water bodies.

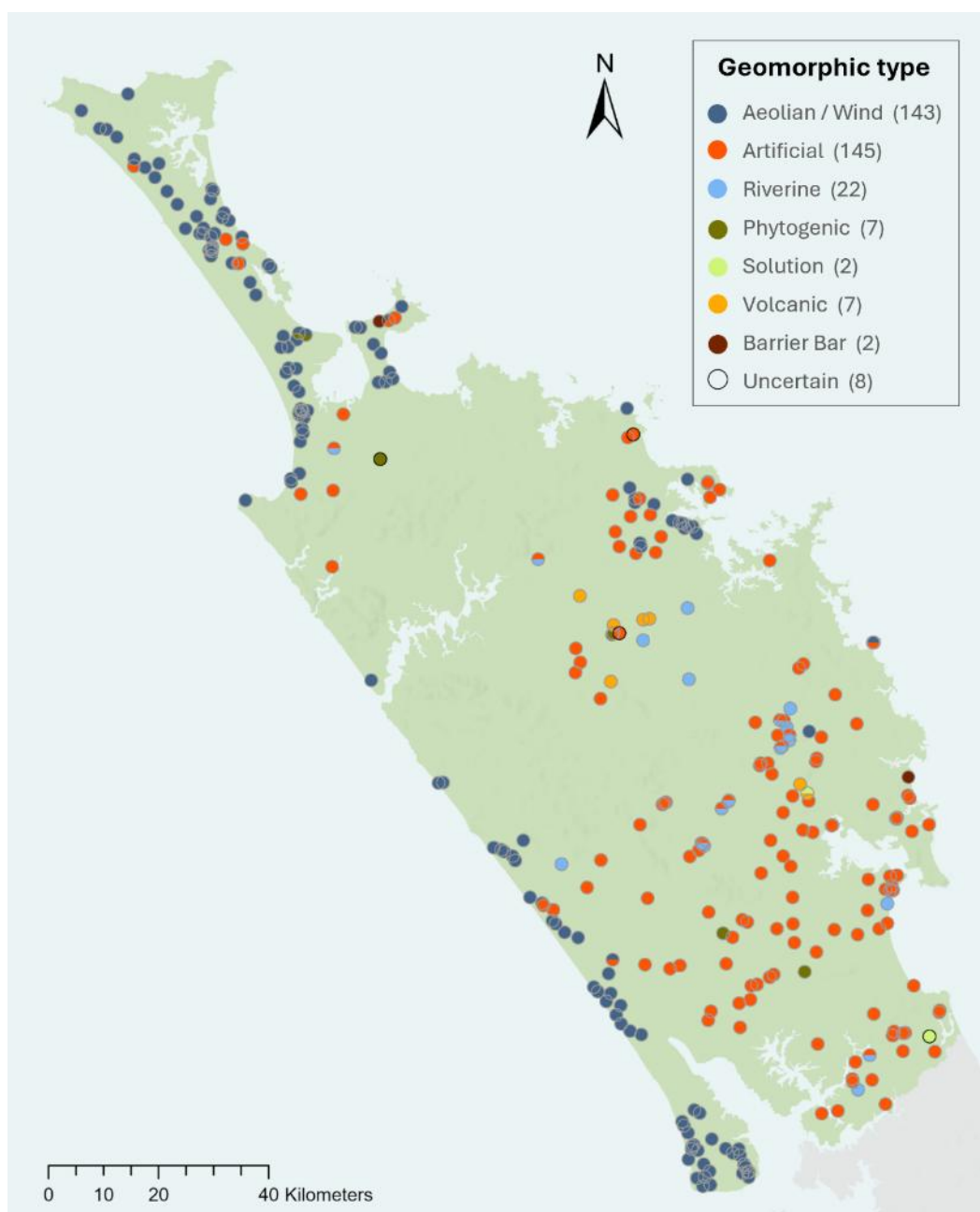


Figure 1. Locations of lakes (> 1 ha) in the Northland Region (n = 307). Lakes are coloured by geomorphic class.

Many of Northland's lakes are under increasing pressure from land-use intensification, the spread of invasive species, and the effects of climate change. As a result, water quality and ecological condition has declined in numerous lakes (NRC 2002). Understanding current and historical lake conditions is therefore critical for identifying realistic restoration goals and supporting effective lake management.

A total of 37 lakes in the Northland Region were included in the national research programme Our lakes' health: past, present, future (also known as Lakes380; www.ourlakesourfuture.co.nz/lakes). As part of this programme, water, surface sediment, and sediment core samples were collected from each lake during one sampling event. Water and surface sediment samples were analysed for nutrients, trace metals, and environmental DNA (eDNA), while sediment cores were analysed using a range of paleolimnological techniques to investigate long-term ecological change and the drivers of lake degradation.

Data from selected Northland lakes have already contributed to several peer-reviewed scientific publications, including a study focused on biodiversity of bacteria and diatoms which is in preparation as well as national-scale assessments of contemporary water quality across Aotearoa New Zealand (Pearman et al. 2022, Wood et al. 2023c). However, the Lakes380 programme has now officially finished and there are no resources to undertake regional-scale synthesis, lake-specific analyses, or to provide guidance on how the data can be applied to regional decision-making.

To ensure that Lakes380 data is used to support lake management in the Northland Region, this project, funded by Northland Regional Council (NRC) collates, analyses, and interprets data from all 37 Northland lakes sampled during the programme. The findings are intended to inform lake reference conditions for restoration planning, guide the setting of pragmatic restoration targets, support ongoing lake projects at NRC and inform lake-specific management plans.

This report compiles and synthesises data collected as part of Lakes380 on water chemistry, sediment nutrient geochemistry, surface sediment microbial communities and information on changes in water quality and the surrounding landscape over the last approximately 1,000 years.

Methods

Lake descriptions

A total of 37 lakes in the Northland Region were sampled as part of the Lakes380 programme (www.ourlakesourfuture.co.nz/lakes). Lakes were selected to represent a gradient of environmental factors, including trophic status, area, depth, and lake type. This selection was undertaken using lakes from across Aotearoa New Zealand, rather than focusing solely on Northland.

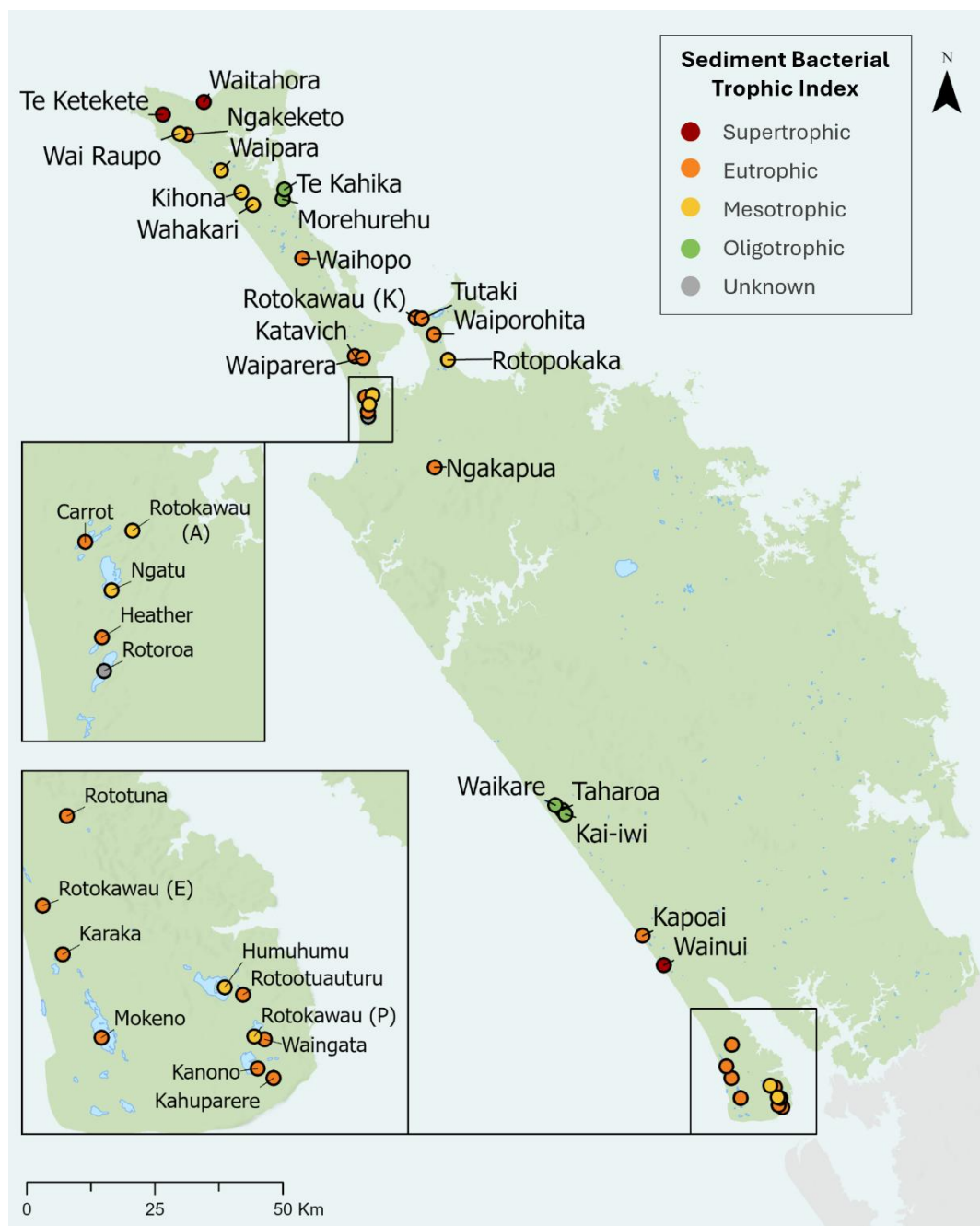


Figure 2. Locations of lakes studied in the Northland Region as part of the Our lakes health: past, present, future (Lakes380) research programme. The colour of the dots represents the lake trophic level as predicted using the Sediment Bacterial Trophic Index (SBTI; Pearman et al. 2022).

The lakes sampled ranged in area from 2 ha (Waipara, Te Ketekete, Waitahora) to 210 ha (Lake Taharoa), and in depth from less than a metre (Lakes Katavich, Te Ketekete, Rotokawau East) to 38 m (Lake Taharoa; Table 1). Although the same types of samples were collected from most lakes (with a few exceptions where no sediment cores were taken), not all samples were analysed due to limited resources. Table 2 shows the analyses undertaken on samples from each lake, with sample and analysis details explained in the sections following.

Lake sampling was conducted over four field campaigns in November 2018 and in June, July, and August 2019. At five lakes, sediment sampling was limited to the collection of surface sediment only with no cores collected (Table 2). At all other lakes, a side-scan sonar survey was carried out prior to sampling to identify the deepest part of each lake, which became the sampling location.

Table 1. Northland lakes sampled as part of the Our lakes health: past, present, future (Lakes380) research programme, depth, surface area, altitude, sediment bacterial trophic index (SBTI), and catchment land use. Land-use categories are from the Land Cover Database V5 and limited to dominant classes in the region. EF = exotic forestry; HPG = high-producing grassland; LPG = low-producing grassland. A = Aupōuri, E = East. K = Karikari, P = Pouto. All lakes sampled are classified as wind/dune formed lakes.

Name	LID	Depth (m)	Surf. area (ha)	Alt. (m)	TLI	SBTI class	SBTI	SBTI class	Land use			
									EF	HPG	LPG	Manuka
Lake Carrot	23690	8	3	42			4.2	Eutrophic	62	29		
Lake Heather	23682	5	8	33			4.4	Eutrophic	3	74		7
Lake Humuhumu	50401	15	130	51	4.2	Eutrophic	3.9	Mesotrophic	49	32		13
Lake Kahuparere	50371	7	7	60			4.1	Eutrophic	49	14	1	19
Lake Kai-iwi	21918	15	28	72	2.9	Oligotrophic	2.7	Oligotrophic	19	46	9	22
Lake Kanono	50373	15	76	60	4.2	Eutrophic	4.1	Eutrophic	66	1	2	18
Lake Kapoai	21759	12	3	48			4.7	Eutrophic	1	98		
Lake Karaka	50320	6	12	10			4.3	Eutrophic	49		23	27
Lake Katawich	13466	1	7	34			4.1	Eutrophic	65	21	1	3
Lake Kihona	24621	8	8	43			4.0	Mesotrophic	84	8		6
Lake Mokeno	50314	6	162	11	5.6	Supertrophic	4.8	Eutrophic	81		3	13
Lake Morehurehu	24628	14	49	18	3.7	Eutrophic	2.9	Oligotrophic	85	3		7
Lake Ngakapua	18717	5	6	42			4.4	Eutrophic	44	35		
Lake Ngakeketa	21433	15	9	37			4.5	Eutrophic		29		69
Lake Ngatu	23691	6	55	39	4.4	Eutrophic	3.9	Mesotrophic	6	64	10	3
Lake Rotokawau (A)	18719	3	6	47			3.5	Mesotrophic	7	25	39	
Lake Rotokawau (E)	24423	4	21	5			4.4	Eutrophic	1	93		2
Lake Rotokawau (K)	24422	2	70	4			4.4	Eutrophic	1	64	3	25
Lake Rotokawau (P)	50413	13	26	62	3.3	Mesotrophic	3.7	Mesotrophic	51	27	1	18
Lake Rotootuauru	50403	6	16	36			4.3	Eutrophic	42	40		11
Lake Rotopokaka	19509	5	12	5			3.2	Mesotrophic				52
Lake Rotoroa	23681	8	32	26								
Lake Rototuna	50345	4	7	103	5.3	Supertrophic	4.7	Eutrophic	84	14	2	
Lake Taharoa	21917	38	210	72	3.3	Mesotrophic	2.5	Oligotrophic	15	51	8	25
Lake Te Kahika	24633	11	14	4			2.7	Oligotrophic	96			1

Lake Te Ketekete	21450	1	2	37			3.9	Mesotrophic	83		1	1
Lake Tutaki	50335	4	3	11			4.4	Eutrophic	98	2	1	
Lake Wahakari	24620	13	84	47	3.6	Mesotrophic	3.9	Mesotrophic	43	36		14
Lake Wai Raupo	21434	21	20	53			3.7	Mesotrophic		19	1	49
Lake Waikare	21926	30	30	81			2.6	Oligotrophic	1	67		29
Lake Waingata	50377	11	13	60			4.7	Eutrophic	1	99		
Lake Wainui	17761	12	5	47	5.4	Supertrophic	5.1	Supertrophic	5	89		
Lake Waipara	19575	5	2	79			3.7	Mesotrophic	96			2
Lake Waiparera	13467	7	109	34	5.1	Supertrophic	4.3	Eutrophic	48	36	1	2
Lake Waiporohita	24415	4	6	12	6.4	Hypertrophic	4.9	Eutrophic		100		
Lake Waitahora	24434	3	2	2			5.9	Supertrophic				91
Waihopo Lake	24511	4	8	40			4.9	Eutrophic	50	36		

Table 2. Lakes sampled as part of the Our lakes health: past, present, future (Lakes380) research programme and the types of samples and analyses conducted for each. Grey shading = not sampled; Y = sampled and analysed; NA = sampled but not analysed; PA = partially analysed. Abbreviations: Zoop. = zooplankton; Phyto. = phytoplankton; S-WQ = surface water nutrients; S-WC = surface water chemistry, H-WQ = hypolimnion water nutrients; H-WC = hypolimnion water chemistry, S-eDNA = surface sediment bacterial and eukaryotic DNA; S-Geo = surface sediment geochemistry; S-Core = sediment core collected; HS = hyperspectral scan; AgeM = age model, iTrax = geochemical analysis; Bact eDNA = bacterial DNA (down sediment core). A = Aupōuri, K = Karikari, P = Pouto, E = East. See Table 3 for a description of each analysis.

Lake	Date	Zoop.	Phyto.	S-WQ	S-WC	H-WQ	H-WC	S-eDNA	S-Geo	S-Core	Pollen	HS	Diatom	AgeM	Bact eDNA	iTrax
Lake Kahuparere	14/08/2019	PA	NA	Y	Y			Y	Y	Y	Y	Y	NA	NA	Y	NA
Lake Kapoai	18/08/2019	PA	NA	Y	Y			Y		Y	Y	Y	Y	Y	Y	Y
Lake Morehurehu	14/11/2018	PA	NA		Y	Y	Y	Y	Y	Y	Y	Y	NA	NA	Y	NA
Lake Ngakeketo	25/06/2019	PA	NA	Y	Y			Y	Y	Y	Y	Y	NA	NA	Y	NA
Lake Ngatu	12/11/2018	PA	NA		Y			Y	Y	Y	Y	Y	NA	NA	Y	NA
Lake Taharoa	06/11/2018	PA	NA		Y		Y	Y	Y	Y	Y	Y	NA	NA	Y	NA
Lake Te Kahika	14/11/2018	PA	NA		Y	Y	Y	Y	Y	Y	Y	Y	NA	NA	Y	NA
Lake Wahakari	28/06/2019	PA	NA	Y	Y			Y		Y	Y	Y	NA	NA	Y	NA
Lake Wai Raupo	26/06/2019	PA	NA	Y	Y			Y		Y	Y	Y	NA	NA	Y	NA
Lake Waiporohita	11/11/2018	PA	NA		Y			Y	Y	Y	Y	Y	NA	NA	Y	NA
Lake Carrot	12/11/2018	PA	NA		Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Heather	01/07/2019	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Humuhumu	07/11/2018	PA	NA		Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Kai-iwi	06/11/2018	PA	NA		Y		Y	Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Kanono	15/11/2018	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Karaka	8/11/2018	PA	NA		Y			Y	Y							
Lake Katavich	5/07/2019	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Kihona	27/06/2019	PA	NA	Y	Y			Y								
Lake Mokeno	08/11/2018	PA	NA		Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Ngakapua	7/07/2019	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Rotokawau (A)	14/11/2018	PA	NA		Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Rotokawau (E)	08/07/2019	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Rotokawau (K)	08/07/2019	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Rotokawau (P)	7/11/2018	PA	NA		Y			Y	Y	Y	NA	NA	NA	NA	NA	NA

Lake	Date	Zoop.	Phyto.	S-WQ	S-WC	H-WQ	H-WC	S-eDNA	S-Geo	S-Core	Pollen	HS	Diatom	AgeM	Bact eDNA	iTrax
Lake Rotootuauro	13/08/2019	PA	NA		Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Rotopokaka	2/07/2019	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Rotoroa	1/07/2019	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Rototuna	15/11/2018	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Te Ketekete	26/06/2019	PA	NA	Y	Y			Y		Y	NA	NA	NA	NA	NA	NA
Lake Tutaki	16/08/2019	PA	NA	Y	Y			Y		Y	NA	NA	NA	NA	NA	NA
Lake Waihopo	12/11/2018	PA	NA		Y			Y	Y							
Lake Waikare	20/08/2019	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Waingata	15/08/2019	PA	NA	Y	Y			Y		Y	NA	NA	NA	NA	NA	NA
Lake Wainui	17/08/2019	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Waipara	13/11/2018	PA	NA		Y			Y	Y							
Lake Waiparera	05/07/2019	PA	NA	Y	Y			Y	Y	Y	NA	NA	NA	NA	NA	NA
Lake Waitahora	27/06/2019	PA	NA	Y	Y			Y								

Physico-chemical analysis of water samples

This methods section is modified from Wood et al. (2023a, 2023b).

Secchi disc depth was measured at all sites. Vertical water column profiles of temperature (°C), dissolved oxygen (DO; % saturation and mg L^{-1}), chlorophyll-*a* (Chl-*a*; $\mu\text{g L}^{-1}$), and photosynthetically active radiation (PAR) were obtained at the deepest point of each lake using an RBRmaestro³ multi-channel logger (Ruskin, USA). These profiles were successfully generated at 17 lakes and are presented in Appendix 1. Profiles for the remaining lakes could not be produced, primarily due to their shallow depth.

Surface water samples (1 L) for Chl-*a* analysis were collected and stored on ice until processing. A subsample (up to 600 mL) was filtered through GF/C filters (Whatman, UK), with the filtered volume recorded. Filters were wrapped in aluminium foil and stored frozen in the dark (-20 °C). Chlorophyll-*a* concentrations were determined at Watercare Laboratories (Auckland, New Zealand) following APHA method 10200 H, with a reporting limit of 0.0006 mg L^{-1} .

Water samples (1 L) were collected using an integrated tube sampler across the surface mixed layer (as defined by the temperature and dissolved oxygen profiles), hereafter referred to as surface samples. Subsamples were taken for analysis of total nitrogen (TN), total phosphorus (TP), and total organic carbon (TOC). Additional subsamples (40 mL) were filtered through low-bleed $0.45 \mu\text{m}$ filters for dissolved organic carbon (DOC) analysis. Total nutrient concentrations were measured using APHA 4500 methods on a flow injection analyser, with reporting limits of 0.1 g m^{-3} for TN and 0.005 g m^{-3} for TP. TOC and DOC were analysed by high-temperature combustion (850 °C) following APHA method 5310 B, with reporting limits of 0.5 g m^{-3} . Where regular monitoring of the lake was, or had been, undertaken by NRC, these samples were not analysed. The rationale for this is that temporal data from multiple time periods provides a more meaningful indication of water quality than a single point sample.

A further subset of surface samples was filtered ($0.45 \mu\text{m}$) and analysed for trace metals using inductively coupled plasma–mass spectrometry (ICP-MS), based on US Environmental Protection Agency method 200.8. Elements analysed, with square brackets showing detection limits in mg kg^{-1} , included arsenic (As) [0.005], cadmium (Cd) [0.00001], chromium (Cr) [0.0002], copper (Cu) [0.0002], lead (Pb) [0.00005], mercury (Hg) [0.00008], nickel (Ni) [0.0002], and zinc (Zn) [0.001].

Temperature/dissolved oxygen profiles indicated that five lakes were thermally stratified at the time of sampling. At these sites, an additional water sample (1 L) was collected from approximately 1 m above the lakebed using a Van Dorn sampler. Nutrients were determined in two of these samples, and elements in all five. These samples were processed and analysed using the same procedures as for surface water samples.

Zooplankton and phytoplankton samples were collected from boats at close to the deepest parts of the lake. A single vertical trawl was taken from $\sim 1.5 \text{ m}$ above the lakebed using a $20\text{-}\mu\text{m}$ (phytoplankton) or $40\text{-}\mu\text{m}$ (zooplankton) mesh plankton net, except when the lakes were shallow ($< 3 \text{ m}$ depth). Shallow lakes were sampled by pouring 10–80 L of surface water through the net with volumes recorded. The concentrated biomass from each trawl was transferred to a 100-mL

bottle and preserved with Lugol's iodine solution (for phytoplankton) or to a 50-mL Falcon tube and preserved with 95% ethanol (for zooplankton). The phytoplankton samples were not analysed. Zooplankton samples were analysed for the presence of *Daphnia* species only, as these large-bodied cladocerans are key grazers of phytoplankton and important indicators of trophic interactions and ecosystem state in lake systems. As several *Daphnia* species in New Zealand are introduced, this analysis also aimed to improve understanding of their distribution across lakes. Samples were analysed by Professor Carolyn Burns (University of Otago) following the methods described in Burns et al. (2024).

Surface sediment analysis

Surface sediment collection for nutrients, elemental characterisation and microbial DNA

Surface sediment samples for geochemical analyses were collected using one of two methods. (1) A Uwitech gravity corer fitted with a 90 mm diameter core barrel was used to retrieve five cores at each site. The upper 2 cm of sediment from each core was removed using a core cutter and composited into a single 500 mL container. (2) A Ponar grab sampler was used with the upper 2 cm of sediment carefully subsampled using a spatula and transferred into a 500 mL container. All samples were stored at 4 °C and transported to the laboratory within 48 hours for subsequent nutrient and elemental analyses.

Surface sediment samples for environmental DNA (eDNA) analysis were collected in triplicate at each site using the Ponar grab sampler. Using sterile spatulas, approximately 2 g of undisturbed surface sediment (representing approximately the upper 1–2 mm) was transferred into sterile tubes containing LifeGuard preservative (Qiagen, Germany). Samples were subsequently stored at –80 °C in the laboratory until DNA extraction.

Surface sediment nutrient and metal analysis

Surface sediment samples collected for nutrient and elemental analyses were homogenised and centrifuged (3000 × g for 40 min at 4 °C), after which pore water was decanted. Sediments for metal analysis were oven-dried, sieved to <2 mm, and analysed for iron (Fe), manganese (Mn), aluminium (Al), calcium (Ca), Pb, Cu, Zn, Cd, phosphorus (P), and sulphur (S) using acid digestion followed by inductively coupled plasma–mass spectrometry (ICP-MS), in accordance with US Environmental Protection Agency method 200.8.

Analytical reporting limits (mg kg⁻¹) were 12.5 for Fe, 0.125 for Mn, 2.5 for Al, 12.5 for Ca, 0.05 for Pb, 0.075 for Cu, 0.05 for Zn, 0.005 for Cd, 10 for P, and 250 for S. Total nitrogen and total organic carbon (TOC) were quantified by catalytic combustion at 900 °C in an oxygen atmosphere, with separation and detection by thermal conductivity detector; reporting limits for both analytes were 1 g 100 g⁻¹.

Sediment bulk density was calculated from the oven-dried mass of a known sediment volume. Organic matter and carbonate content were determined gravimetrically following sequential loss-on-ignition at 550 °C and 950 °C, respectively. Measured values were compared with median concentrations derived from approximately 200 lakes analysed nationally as part of the Lakes380 programme (the number of lakes varies and is provided in figure captions).

Phosphorus fractionation analysis

To characterise the different forms of P in the sediment, chemical sequential extraction was performed on thawed sediment samples following a ‘Psenner’-type scheme, modified from Rydin (2000) and Waters et al. (2021). In this procedure, sediments are agitated in a series of chemical reagents to isolate distinct P fractions, which included:

- **Exchangeable phosphorus (Ex-P):** loosely bound, readily soluble P.
- **Redox-sensitive phosphorus (Red-P):** P that can be released under low dissolved oxygen conditions, typically associated with reducible mineral phases such as iron and manganese (hydr)oxides.
- **pH-sensitive phosphorus (pH-P):** P that may become mobilised under high pH conditions, commonly bound to surfaces of aluminium (hydr)oxides, less reactive Fe and Mn (hydr)oxides, clays, and organic particulates.
- **Organic phosphorus (Org-P):** the labile organic fraction that is readily degradable.
- **Calcium-associated phosphorus (Ca-P):** P bound to calcium-containing minerals, including apatite and carbonates, as well as refractory metal oxides; this fraction is generally considered unavailable to biota.
- **Residual phosphorus (Res-P):** primarily refractory organic material that is not considered bioavailable.
- **Total phosphorus (TP):** the sum of all measured fractions.

The Ex-P, Red-P, pH-P and Org-P fractions represent the more labile, potentially bioavailable P forms (Waters et al., 2021). The Red-P is of especial interest due to it being the fraction that may be released during periods of low dissolved oxygen concentration in lake bottom waters during water column stratification. In shallow lakes the pH-P may also be released when photosynthetically elevated pH (pH > 9.2) occurs in the bottom waters. The combined total of Ex-P, Red-P and Org-P fractions is commonly referred to as “potentially mobile phosphorus”. Results were compared with median values from approximately 180 lakes analysed nationally as part of the Lakes380 programme (the number of lakes varies and is provided in figure captions).

Environmental DNA analysis

DNA was extracted from approximately 0.25 g of surface sediment and from selected depths within the sediment cores using the PowerSoil kit (Qiagen). The V3–V4 region of the bacterial 16S rRNA gene and the V4 region of the eukaryotic 18S rRNA gene were amplified by polymerase chain reaction (PCR). Bacterial 16S rRNA gene amplification employed the primers 341F and 805R (Herlemann et al. 2007; Klindworth et al. 2013), while eukaryotic amplification used Uni18SF and Uni18SR (Zhan et al. 2013). PCR conditions and subsequent library preparation for sequencing on an Illumina MiSeq followed the protocol described in Pearman et al. (2020).

Raw sequencing reads were demultiplexed and processed using cutadapt (Martin 2011), and Amplicon Sequence Variants (ASVs) were inferred with DADA2 (Callahan et al. 2016) according to the pipeline outlined in Pearman et al. (2020). Taxonomic classification of reads was performed using the RDP classifier against the SILVA 138 database (Pruesse et al. 2007) with a minimum bootstrap support threshold of 70.

Bacterial and eukaryotic community compositions in surface sediments were visualised at the class level. Differences in community composition were explored using principal coordinate analysis (PCoA) based on Bray–Curtis distance matrices.

The Lakes380 team developed an approach known as the Sediment Bacterial Trophic Index (SBTI; Pearman et al. 2022). It uses 16S rRNA metabarcoding to characterise the bacterial community in surface sediment, from which key indicator bacteria associated with different trophic levels are identified and the index calculated. Unlike water samples, where there is often high variance in physicochemical parameters and organisms due to climate conditions and seasonality, surface sediments provide a time-integrated representation of the within-lake conditions and organisms, as well as those in the catchment (Schallenberg & Kalff 1993). When the SBTI was compared to the calculated Trophic Level Index (TLI3) in 96 monitored lakes, they were strongly correlated ($r^2 = 0.842$, $P < 0.001$; Pearman et al. 2022). The requirement for only a single time-point sample makes this a rapid and cost-effective tool that can be used for inferring TLI3 in many lakes. The SBTI was determined for all lakes sampled in Northland, except Rotoroa where sequencing was unsuccessful.

Sediment core analysis

Sediment core collection

Four sediment cores were collected near the deepest part of each lake using an Uwitech gravity corer equipped with 2 m long, 90 mm diameter polyvinyl chloride barrels. All barrels were disinfected with 2% sodium hypochlorite (bleach) prior to coring. After retrieval, cores were sealed, stored in darkness at 4 °C, and kept for up to four weeks before sub-sampling. Cores were then split longitudinally using a Geotek core splitter and guillotine, and photographs were taken for documentation.

To minimise cross-contamination during core splitting, the upper 2–3 mm of one half-core per lake was carefully removed with a sterile spatula. Subsamples (~0.5 g) were collected from the centre of the half-core at multiple depths. Sampling intervals were typically every 1–2 cm in the more recent sediment layers and every 4–5 cm in older sediments. Subsamples were either stored frozen at –20 °C in the dark until DNA extraction or kept chilled for other analyses, including pollen, diatoms, and ^{210}Pb measurements.

A description of the type of information provided by each proxy / method related to the sediment cores is listed in Table 3, and detailed methods for each follow.

Table 3. Description of the information provided by each proxy / method used to analyse sediment cores in this report. Samples from selected depths are analysed unless indicated otherwise.

Proxy (method)	Information provided
Age model (chronology)	Provides dates associated with each layer of the sediment core. In this study this is determined using ^{210}Pb analysis and pollen data.
Pollen and charcoal	Indicates changes in catchment and in lake vegetation and provides high-level data that can be used to assess the timing of different human occupation periods. The presence of charcoal can be used to provide evidence of burning in the catchment / region.
iTrax scanning (Entire core is scanned)	Indications of shifts in lake geochemistry, productivity and catchment erosion. In this report, we have selected: - Titanium (Ti) relative concentrations normalised to incoherence (Inc) as a proxy for increased detrital input and fine-grained material.
Hyperspectral scanning (Entire core is scanned)	Shifts in chlorophyll-a concentrations.
Diatoms	Indicates changes in water quality and other parameters such as depth and light availability.
Cadmium	A proxy for fertiliser application on land surrounding the lake. Cadmium is found in phosphate rocks, which are used to make fertilisers such as superphosphate.
Lead	A proxy for increases in population or urbanisation close to a lake. The lead is likely sourced from leaded petrol, which was phased out in Aotearoa New Zealand in 1996.
Manganese and Iron	Manganese (Mn) relative concentrations normalised to iron (Fe) as a proxy for past lake redox conditions.
Environmental DNA of microbial communities (diversity)	Changes in bacterial communities likely related to shifts in water quality.

Sediment core chronology

Lake Kapoai was the only lake an age model was available for, and this is only for the last approximately 3-500 years. For this sediment core, a selection of samples from the upper part of the core were extracted for $^{210}\text{Pb}_{\text{ex}}$ analyses. Total ^{210}Pb activity was estimated using alpha spectrometry at the ESR National Centre for Radiation Science. A Bayesian framework was used to conduct age-depth modelling using OXCAL 4.4 (Ramsey 2009). Briefly, for each studied site, a $^{210}\text{Pb}_{\text{ex}}$ age-depth model and pollen and charcoal biostratigraphy were used in a P_Sequence prior model (with a variable event thickness constant k) to generate probability density functions that were integrated with core depth (Ramsey 2008; Ramsey and Lee 2013) to produce an age model and estimates of age uncertainty.

Pollen analysis

Pollen was identified through microscopy following the methods described in Short et al. (2022). In brief, pollen was extracted from 0.25 cm^3 of sediment using standard laboratory procedures, including treatment with 10% hot hydrochloric acid, acetolysis, and sieving through a $6\text{ }\mu\text{m}$ mesh. Exotic Lycopodium tablets were added to each sample to allow calculation of pollen concentrations. Pollen and spore types were identified using standard reference texts and Aotearoa New Zealand reference collections.

Data are reported as the relative frequency based on a minimum pollen sum of 150 grains. This sum includes pollen from all dryland plants, encompassing trees, shrubs, herbaceous plants, and non-native taxa. Bracken fern (*Pteridium esculentum*) is included in the dryland pollen sum

because, in post-disturbance landscapes, its functional morphology is more similar to shrubs than to ferns, and dense stands are ecologically equivalent to shrubland (McGlone et al. 2005). Pollen from other groups, wetland plants, aquatic plants, ferns, tree ferns, and non-palynomorph particles, was excluded from the dryland sum, but their relative abundances were calculated as a proportion of the dryland pollen plus the respective group.

Pollen data were used in combination to identify periods of human occupation within the sediment cores. Bracken fern serves as a widely used chronological indicator of early Māori activity and settlement across Aotearoa New Zealand, reflecting both landscape disturbance and its use as a food resource (McGlone and Wilmshurst 1999; McWethy et al. 2010; Newnham et al. 2018). Pine (*Pinus* spp.) and other non-native taxa, such as willow (*Salix* spp.), sheep's sorrel (*Rumex acetosella*), and alder (*Alnus* spp.), were introduced during European colonisation.

Itrax scanning

ITRAX scanning was only undertaken on the Lake Kapoai sediment core. Downcore major and trace elemental abundances were measured at 1 mm intervals using a Cox Analytics Itrax μ XRF Core Scanner at the University of Otago Repository for Core Analysis (Dunedin, New Zealand). The top 1–2 mm of the sediment was removed prior to scanning to minimise potential surface contamination. Samples were scanned with a molybdenum X-ray tube set at 30 kV, 55 mA, and 10 s integration time. While multiple elements were analysed, only titanium (Ti) relative to incoherence (Inc) is given in this report where we use it as a proxy for detrital input and fine sediment (Davies et al., 2015).

Hyperspectral imaging scanning

The cores were imaged using a Specim sCMOS-CL-50-V10E-SCB camera, with a spectral resolution of 1.3 nm and a spatial resolution of 41 μ m. Spectral data were analysed using the RABD_{660/670} index, which is a proxy for sedimentary Chl-*a* and its degradation products. The results were expressed as a spectral index with values ranging from 1.0 to 2.5. Higher index values indicate relatively greater concentrations of sedimentary pigments (i.e., higher inferred algal abundance), whereas lower values indicate reduced pigment concentrations. However, as the index is influenced by site-specific sediment characteristics, values are interpreted only within individual sediment cores. Consequently, the index is used to assess relative changes in pigment concentration over time within a lake, rather than to enable direct comparisons of absolute values among different lakes.

Diatom analysis

Diatom analysis was only undertaken on the Lake Kapoai sediment core. Samples were treated with 15% hydrochloric acid and 25% hydrogen peroxide to remove carbonates and organic matter (Smol et al., 2001). Diatom slurries were permanently mounted on slides using Naphrax. Counting and identification were performed at 1,000 $\times$ magnification under a microscope with differential interference contrast. At least 300 valves per sample were counted and identified to the highest possible taxonomic resolution (Foged, 1979; Krammer & Lange-Bertalot, 1986; Cassie, 1989), and species habitat preferences were determined following Round et al. (1990).

Cadmium, Lead, Manganese and Iron analysis

Cadmium, Pb, Mn and Fe were analysed solely in the Lake Kapoai sediment core. Sub-samples of the core were dried, sieved to 2 mm, and subjected to acid digestion followed by ICP-MS analysis, following US EPA Method 200.8. The reporting limits were the same as for surface sediments.

Environmental DNA analysis

DNA was extracted from approximately 0.25 g of sediment from selected depths and bacterial 16S rRNA gene PCRs undertaken as described for the surface sediment. Constrained hierarchical clustering analysis was used to determine bacterial community assemblage zones downcore, constrained by sampling order to determine community shifts leading to different assemblages. A Bray-Curtis dissimilarity matrix was calculated for the plotted data. Hierarchical clustering was then performed using the Constrained Incremental Sum of Squares (CONISS) approach using the 'chclust' function in the 'rioja' package in R.

CONISS is a stratigraphically constrained clustering method that groups adjacent samples based on compositional similarity, producing a dendrogram in which the horizontal axis represents dissimilarity (sum of squares) between samples or clusters. Greater distances indicate larger differences in community composition.

The dendrogram was examined to identify major stratigraphic groupings, and the two most significant shifts in community composition were identified based on changes in cluster structure. ASVs identified as cyanobacterial were extracted from the bacterial dataset, and sequence read abundance was plotted where maximum read abundance exceeded 100. This provides a preliminary indication of relative cyanobacterial abundance, however, due to the universal nature of the bacterial primers used, cyanobacterial signals may be underrepresented. We therefore recommend reanalysis using cyanobacteria-specific primers to enable more detailed assessment of taxonomy, relative abundance and potential community shifts.

Results

Water samples

Nutrients, suspended solids, carbon and chlorophyll-a

Concentrations of nitrogen species, phosphorus, suspended solids, and organic carbon varied widely across the lakes and were frequently elevated relative to the national median values derived from the Lakes380 dataset (Table 4; Appendix 2). Nitrite concentrations were low across nearly all lakes, with the only clearly elevated values occurring in Lakes Kapoai and Rotopokaka. Nitrate concentrations were generally low, with markedly elevated concentrations only in Lakes Kapoai, Wainui and Tutaki.

Ammoniacal nitrogen concentrations were typically low, although higher values were observed in Lake Kapoai (Table 4; Appendix 2). Total nitrogen concentrations were elevated in several lakes, with particularly high values in Lakes Kapoai, Katavich, Tutaki, Waiparera and Rotokawau (Karikari). The most clearly elevated TP values occurred in Katavich, Rotokawau (East) and Wainui. Dissolved reactive phosphorus concentrations were generally low across all sites, with only Lake Kapoai showing an elevated value (Table 4; Appendix 2).

Total and volatile suspended solids were highly variable, with very high concentrations observed in Waitahora and Katavich (Table 4; Appendix 2).

Table 4. Dissolved and total nutrients concentrations, carbon, suspended solid and chlorophyll-a (g/m^3), in surface water samples collected from lakes in the Northland Region, compared to the national median for a selection of lakes in Aotearoa New Zealand. The total number of lakes in the national dataset varies between 226 and 260 depending on the variable measured. A = Aupōuri, E = East, K = Karikari, P = Pouto. $\text{NO}_2\text{-N}$ = nitrite nitrogen, $\text{NO}_3\text{-N}$ = nitrate nitrogen, $\text{NH}_4\text{-N}$ = ammoniacal nitrogen, TN = total nitrogen, DRP = dissolved reactive phosphorus, TP = total phosphorus, TSS = total suspended solids, VSS = volatile suspended solids, DOC = dissolved organic carbon, TOC = total organic carbon, and Chl-*a* = chlorophyll-*a*. Shading is added for visual clarity, representing the gradient from low (light) to high (dark) for each analyte.

Lake	$\text{NO}_2\text{-N}$	$\text{NO}_3\text{-N}$	$\text{NH}_4\text{-N}$	TN	DRP	TP	TSS	VSS	DOC	TOC	Chl- <i>a</i>
Carrot									7.6	9.7	0.0029
Heather	0.0019	0.036	0.08	0.78	<0.002	0.027	8	5.17	7.1	9.7	0.024
Humuhumu	<0.001	0.0089	0.01		<0.002				5.1	5.8	0.0042
Kahuparere	0.0023	0.0547	0.08	0.51	<0.002	0.065	<3	<3	4.5	5.1	0.0074
Kai-iwi									5.8	5.9	
Kanono	<0.001	<0.002	<0.005	0.32	<0.002	0.019	<3	<3	5	5.4	0.0025
Kapoi	0.0352	0.692	0.13	2.1	0.062	0.1	<3	<3	14.9	15.1	0.0045
Karaka									4.3	5.1	
Katavich	<0.001	0.0029	<0.005	1.93	0.005	0.14	23	15.8	30.5	34.9	0.028
Kihona	<0.001	<0.002	<0.005	0.36	<0.002	0.026	<3	<3	3.9	5.1	0.0053
Mokeno									6.4	6.8	0.002
Morehurehu									17	17.3	0.0017
Ngakapua	<0.001	<0.002	<0.005	0.6	<0.002	0.013	5	<3	7.8	8.6	0.0038
Ngakeketo	0.0021	28.3	0.008	0.28	<0.002	0.035	<3	<3	4.3	6.1	0.0035
Ngatu									9.1	9.8	0.0014
Rotokawau (A)									11.8	13	0.0086
Rotokawau (E)	<0.001	0.0289	0.01	0.27	<0.002	0.12	<3	<3	3.4	3.3	0.0009
Rotokawau (K)	<0.001	<0.002	<0.005	0.91	<0.002	0.022	5	3.33	11.1	11.4	0.0073
Rotokawau (P)									5.9	7.3	0.0086
Rotootuauru									16.2	17.3	0.011
Rotopokaka	0.0129	0.36	0.01	0.77	0.006	0.033	4	3.17	22.8	22.9	0.0042
Rotoroa	<0.001	0.0209	0.01	0.74	<0.002	0.0085	<3	<3	13.7	14.5	0.0051
Rototuna	<0.001	<0.002	<0.005	0.94	<0.002	0.028	3	<3	8.7	10.1	0.039
Taharoa									2.1	2	0.0011
Te Kahika									10.5	14.2	<0.0006
Te Ketekete	<0.001	0.0252	<0.005	0.3	<0.002	0.036	<3	<3	4.8	5.1	0.0035
Tutaki	0.0028	0.294	0.03	1.24	<0.002	0.041	6	<3	8.8	10.4	0.0032
Wahakari	<0.001	0.0031	<0.005	0.35	<0.002	0.024	<3	<3	7.3	8	0.0012
Wai Raupo	0.0015	0.126	0.06	0.49	<0.002	0.025	<3	<3	4.4	5.3	0.0006
Waihopo									12.4	13.5	0.0038
Waikare	<0.001	<0.002	<0.005	0.16	<0.002	0.0055	<3	<3	2.8	2.8	0.0008
Waingata	0.0019	0.0488	0.06	<0.1	<0.002	0.029	<3	<3	7	7.3	0.0042
Wainui	0.0034	0.31	0.01	0.59	<0.002	0.12	<3	<3	4.4	4.1	0.0016
Waipara									8.7	9.2	
Waiparera	0.0031	0.151	0.1	1.48	<0.002	0.024	3	<3	15.3	16.5	0.008
Waiporohita									14.3	12.7	0.017
Waitahora	<0.001	<0.002	0.02	0.41	<0.002	0.055	43	16.8	2.2	3	0.0006
Lakes380											
national median	0.0005	0.0001	0.0025	0.4	0.001	0.022	4	1.5	4.1	4.9	0.0022

Hypolimnetic nutrient concentrations differed between lakes, with Morehurehu exhibiting the highest nitrite, TN, DOC, and TOC concentrations, and Rotokawau (P) having the highest $\text{NH}_4\text{-N}$ concentration (Table 5). Te Kahika had the highest nitrate concentration, while Kai-iwi and Taharoa generally had low nutrient concentrations, with several parameters below detection limits.

Table 5. Dissolved and total nutrients concentrations, carbon and suspended solid (g/m^3), in hypolimnion water samples collected from lakes in the Northland Region. P = Pouto. $\text{NO}_2\text{-N}$ = nitrite nitrogen, $\text{NO}_3\text{-N}$ = nitrate nitrogen, $\text{NH}_4\text{-N}$ = ammoniacal nitrogen, TN = total nitrogen, DRP = dissolved reactive phosphorus, TP = total phosphorus, TSS = total suspended solids, VSS = volatile suspended solids, DOC = dissolved organic carbon, TOC = total organic carbon, and Chl-a = chlorophyll-a. Shading is added for visual clarity, representing the gradient from low (light) to high (dark) for each analyte.

	$\text{NO}_2\text{-N}$	$\text{NO}_3\text{-N}$	$\text{NH}_4\text{-N}$	TN	DRP	TP	TSS	VSS	DOC	TOC
Kai-iwi	<0.001	<0.002	<0.005		<0.002				5.3	5.8
Morehurehu	0.01	0.024	0.074	0.63	<0.002	0.024	<3	<3	17.7	17.9
Rotokawau (P)	0.004	<0.002	0.759		<0.002				5.8	6.8
Taharoa	<0.001	<0.002	<0.005		<0.002				2.3	2.1
Te Kahika	0.0035	0.034	0.03	0.54	<0.002	0.016	3	<3	11.4	15.2

Trace metals

Concentrations of trace metals varied across the lakes and were frequently elevated relative to the national median derived from approximately 290 lakes sampled as part of Lakes380 (Table 6; Appendix 2).

The highest arsenic value was observed in Lake Kanono. Cadmium concentrations were uniform and close to the national median with notable elevations only in Lake Waitahora (Table 6; Appendix 2). Chromium concentrations exceeded the Lakes380 national median, most notably Lake Rotopokaka, where the concentration was also well above the recommend value for protection of aquatic species as given in the Australian & New Zealand Guidelines for Fresh & Marine Water Quality (ANZG). Copper concentrations were below or close to the Lakes380 national median, although higher values occurred in Lakes Ngakapua, Rotopokaka, Waitahora and Mokeno.

Lead concentrations were above the national median in several lakes, particularly Lakes Katavich and Rotopokaka. Mercury concentrations were consistent across sites and close to the national median, except for Lake Waitahora, which was elevated and above the ANZG recommend values. Nickel concentrations exceeded the national median notably in Lakes Te Kahika and Rotopokaka (Table 6; Appendix 2). Zinc concentrations were variable, with several lakes exceeding the national median, most notably Lake Te Kahika where the concentration was above the value recommended in the ANZG (Table 6; Appendix 2).

Table 6. Elemental concentrations (mg/m³) in surface water samples collected from lakes in the Northland Region as part of Lakes380 compared to the national median for a selection of lakes in Aotearoa New Zealand (the total number of lakes in the national dataset varies between 253 and 258 depending on the variable measured), the [New Zealand Drinking Water standards](#) (NZDWS) and [Australian & New Zealand Guidelines for Fresh & Marine Water Quality](#) (ANZG) where the value given is for 95% protection of aquatic species. A = Aupōuri, E = East, K = Karikari, P = Pouto. Shading is added for visual clarity, representing the gradient from low (light) to high (dark) for each analyte.

	Arsenic	Cadmium	Chromium	Copper	Lead	Mercury	Nickel	Zinc
Carrot	0.25	0.005	0.01	0.01	0.025	0.05	0.01	0.5
Heather	2.10	0.005	0.22	0.43	0.092	0.05	0.01	2.2
Humuhumu	1.80	0.005	0.01	0.20	0.050	0.05	0.01	3.1
Kahuparere	2.00	0.005	0.01	0.32	0.053	0.04	0.01	5.6
Kai-iwi	0.25	0.005	0.01	0.50	0.025	0.05	0.01	0.5
Kanono	4.90	0.005	0.01	0.01	0.025	0.05	0.01	0.5
Kapoai	2.40	0.005	0.80	0.86	0.140	0.04	0.42	11.0
Karaka	1.30	0.005	0.01	0.01	0.025	0.05	0.01	0.5
Katavich	1.30	0.005	1.90	0.25	0.920	0.05	0.39	3.6
Kihona	0.25	0.005	0.23	0.01	0.025	0.04	0.01	0.5
Mokeno	1.50	0.005	0.01	1.20	0.200	0.05	0.01	6.1
Morehurehu	0.25	0.005	0.50	0.01	0.100	0.05	1.10	2.9
Ngakapua	0.25	0.005	0.01	1.80	0.025	0.05	0.01	0.0
Ngakeketo	0.51	0.005	0.22	0.01	0.025	0.04	0.01	5.4
Ngatu	0.25	0.005	0.01	0.01	0.025	0.05	0.01	0.5
Rotokawau (A)	0.25	0.005	0.01	0.01	0.025	0.05	0.01	0.5
Rotokawau (E)	0.65	0.005	0.37	0.40	0.098	0.05	0.01	4.8
Rotokawau (K)	0.25	0.005	0.29	0.72	0.110	0.05	0.01	10.0
Rotokawau (P)	0.25	0.005	0.01	0.20	0.025	0.05	0.20	0.5
Rotootuauru	0.81	0.005	0.25	0.69	0.150	0.04	0.28	7.5
Rotopokaka	0.25	0.010	12.00	1.60	0.820	0.05	4.50	5.8
Rotoroa	0.78	0.005	0.34	0.25	0.088	0.05	0.01	2.8
Rototuna	0.60	0.005	0.01	0.01	0.025	0.05	0.01	0.5
Taharoa	0.25	0.005	0.01	0.40	0.025	0.05	0.01	0.5
Te Kahika	0.25	0.005	0.50	0.50	0.200	0.05	9.80	20.0
Te Ketekete	0.25	0.011	0.22	0.31	0.052	0.04	0.27	8.3
Tutaki	0.78	0.005	4.60	0.33	0.050	0.04	0.32	10.0
Wahakari	0.25	0.005	0.01	0.32	0.070	0.04	0.28	11.0
Wai Raupo	0.25	0.005	0.01	0.01	0.025	0.04	0.01	1.7
Waihopo	0.25	0.005	0.30	0.01	0.025	0.05	0.01	0.5
Waikare	0.25	0.005	0.41	0.46	0.160	0.04	0.01	4.1
Waingata	0.25	0.005	0.49	0.29	0.071	0.04	0.01	13.0
Wainui	0.97	0.005	0.28	0.01	0.025	0.04	0.01	6.8
Waipara	0.25	0.005	0.01	0.01	0.080	0.05	0.01	2.9
Waiparera	0.98	0.005	0.33	0.33	0.025	0.05	0.01	2.5
Waiporohita	0.25	0.005	0.01	0.01	0.025	0.05	0.01	0.5
Waitahora	2.50	0.100	1.00	1.00	0.250	0.50	1.00	0.5
Lakes380 median	0.5	0.005	0.1	0.62	0.072	0.04	0.2	5.1
NZDWS	10	4	50	2000	10	7	80	-
ANZG	24	0.02	6.7	1.4	3.4	0.06	11	8

Hypolimnetic trace metals were assessed in only five lakes: Te Kahika, Morehurehu, Kai-iwi, Taharoa and Rotokawau (Poutō) (Table 7). Hypolimnetic metal concentrations were generally close to national median values derived from 46 lakes in the Lakes380 programme, with several notable exceptions. Lake Rotokawau (Poutō) showed elevated arsenic concentrations relative to the national median. Lake Te Kahika exhibited substantially higher nickel and zinc concentrations, with chromium and cadmium also elevated relative to the national median. Lake Morehurehu showed elevated chromium and nickel concentrations, with zinc slightly above the national median (Table 7). Mercury was below detection in all lakes (data not shown).

Table 7. Trace metal concentrations (mg/m³) in hypolimnetic water samples collected from lakes in the Northland Region as part of the Lakes380 programme (the total number of lakes in was 46), the [New Zealand Drinking Water standards](#) (NZDWS) and [Australian & New Zealand Guidelines for Fresh & Marine Water Quality](#) (ANZG) where the value given is for 95% protection of aquatic species. P = Pouto. Shading is added for visual clarity, representing the gradient from low (light) to high (dark) for each analyte.

	Arsenic	Cadmium	Chromium	Copper	Lead	Nickel	Zinc
Kai-iwi	0.25	0.005	0.1	0.1	0.025	0.1	3.1
Morehurehu	0.25	0.005	0.6	0.1	0.1	1.3	5.8
Rotokawau (P)	0.8	0.005	0.1	0.2	0.2	0.1	2
Taharoa	0.25	0.005	0.1	0.1	0.025	0.2	3.4
Te Kahika	0.25	0.02	0.5	0.1	0.09	9.8	20
Lakes380 medium	0.25	0.01	0.1	0.38	0.025	0.1	3.2
NZDWS	10	4	50	2000	10	7	-
ANZG	24	0.02	6.7	1.4	3.4	0.06	8

Secchi Disk

Secchi disk depth data from the Lakes380 project were available for 32 lakes. There was substantial variability, ranging from extremely low transparency (≤ 0.3 m in lakes such as Heather and Katavich) to extremely high clarity (>10 m in Lakes Taharoa and Kai-iwi; Figure 3).

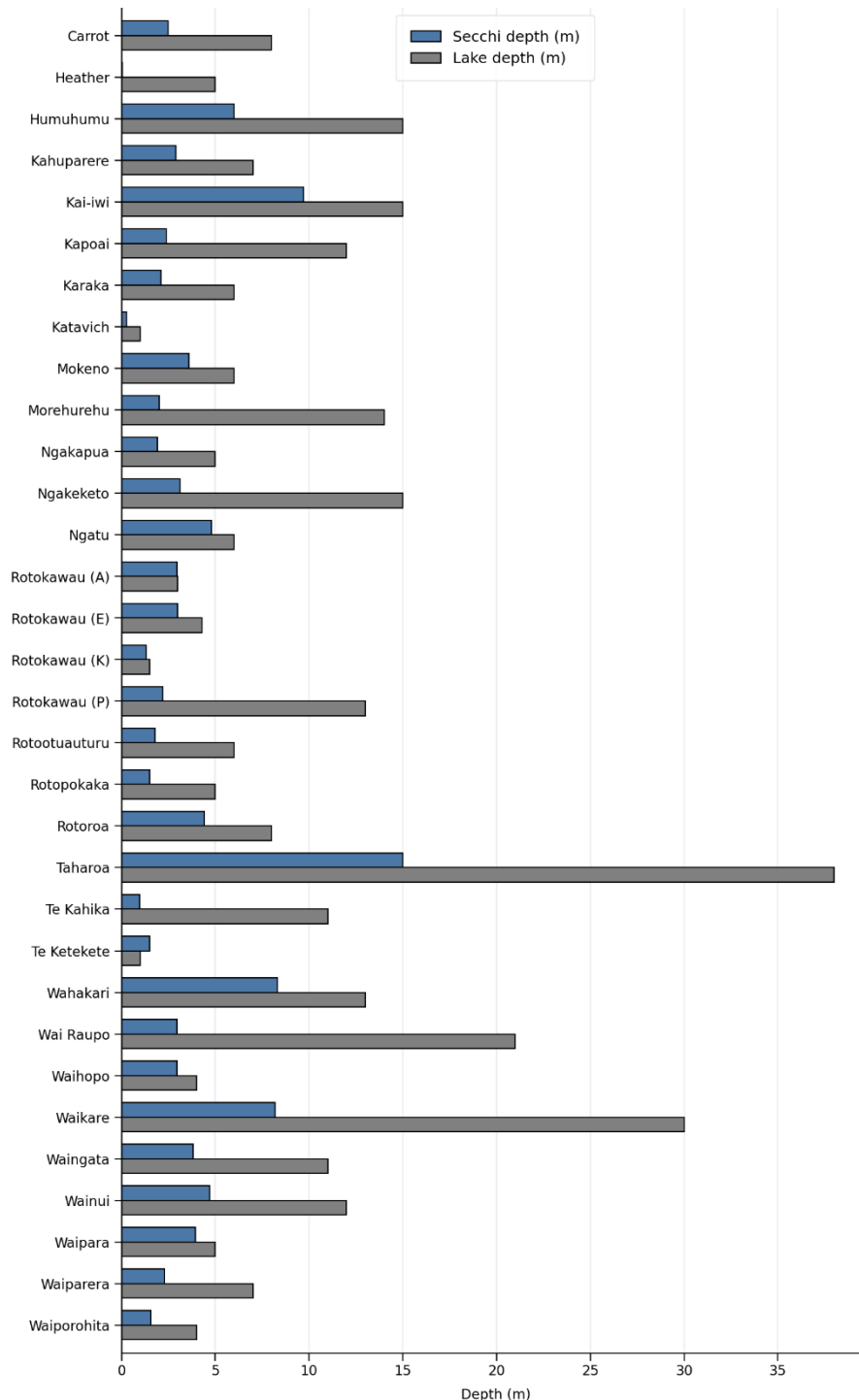


Figure 3. Secchi Disk and maximum lake depths for 32 of the lakes sampled in Lakes380, sorted from lowest to highest Secchi depth.

Sediment Bacterial Trophic Index and Trophic Lake Index

Across the surveyed lakes, SBTI values indicate that 52% are eutrophic, with fewer lakes classified as mesotrophic (28%) or oligotrophic (13%), and a small proportion reaching Supertrophic conditions (5%; Figure 4). Measured Trophic Level Index (TLI) data were obtained from LAWA. Both indices were available for thirteen Northland lakes, showing that SBTI was lower than TLI on ten occasions, with seven of these lakes placed into a lower trophic level category than indicated by TLI. In contrast, three lakes had higher SBTI values than TLI, with one lake assigned to a higher trophic level category based on SBTI (Figure 4).

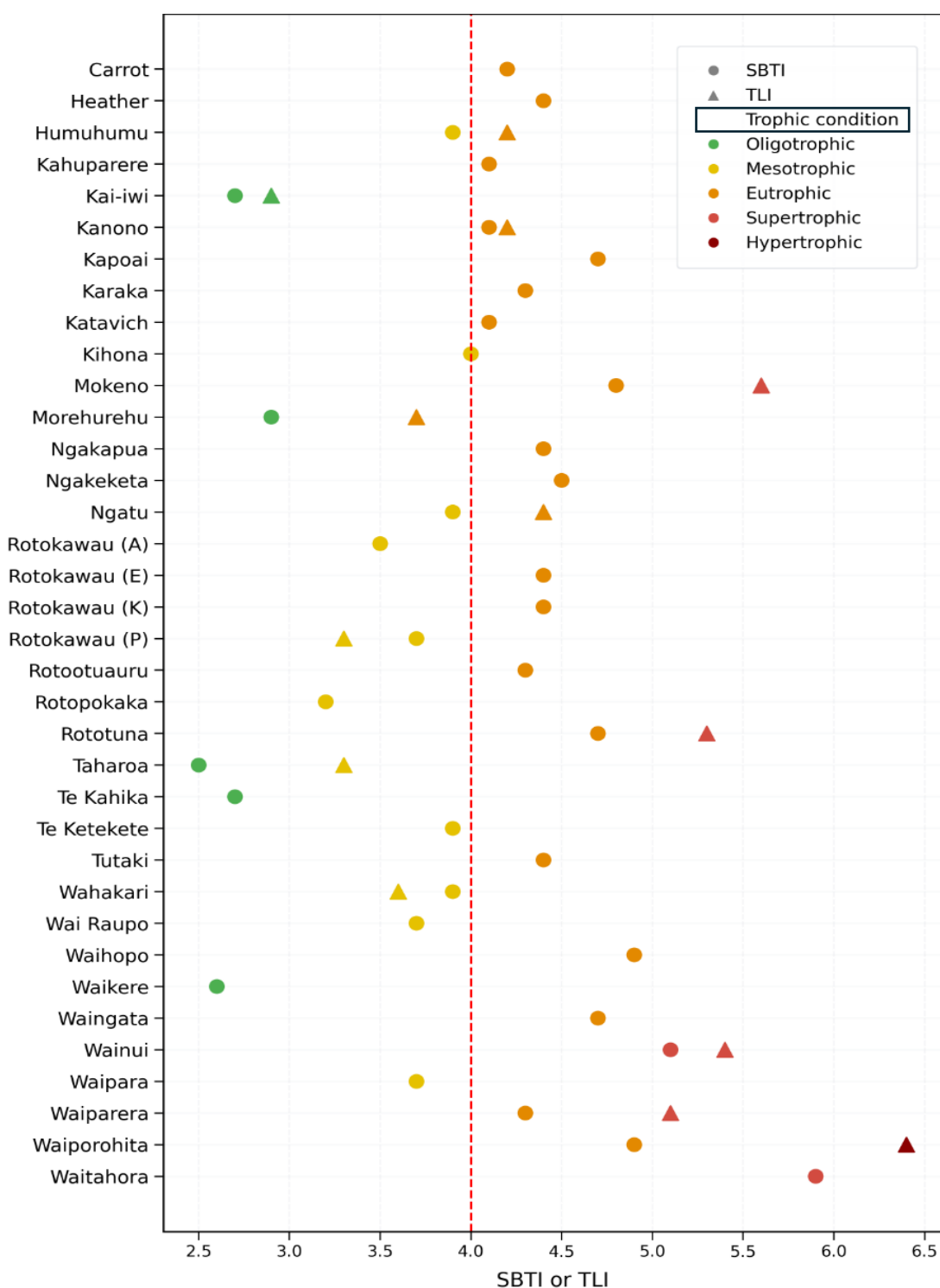


Figure 4. Sediment Bacterial Trophic Index (SBTI) or Trophic Lake Index (TLI). The TLI on this plot is a median of the TLI from the last five years (2020-2025) using Northland Regional Council data. A = Aupōuri, E = East, K = Karikari, P = Pouto.

Daphnia

The presence or absence of *Daphnia* was assessed in 35 lakes (Figure 5). Three species were detected: *D. galeata*, *D. pulicaria/pulex* complex, and *D. thomsoni* (Figure 5). The first two species are invasive, introduced from North America and spread through public access to lakes (Burns et al. 2024). Of these, *D. galeata* was the most common, occurring in 10 lakes, while each of the other two species was found in only one lake. *Daphnia* are key grazers of phytoplankton and important indicators of trophic interactions and ecosystem state in lake systems.

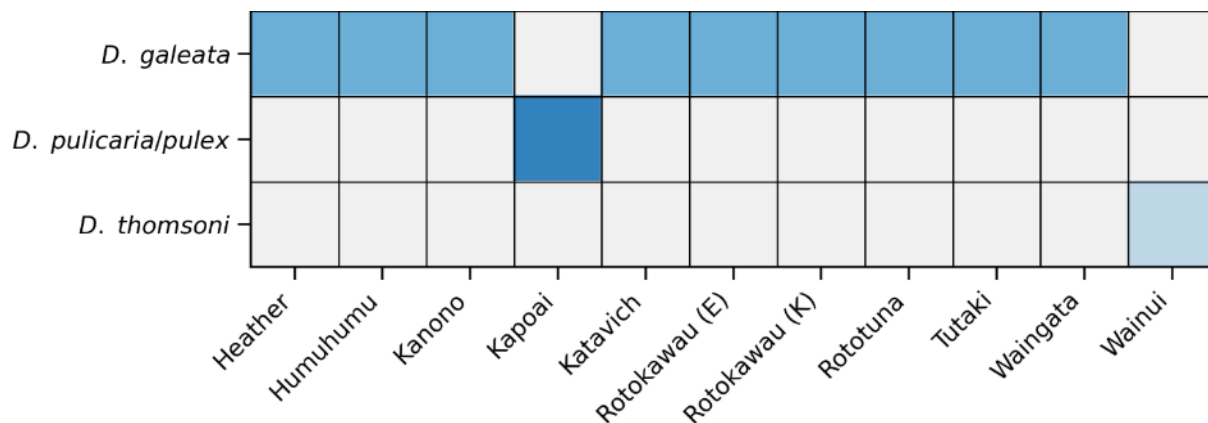


Figure 5. Presence/absence of *Daphnia* species in lakes where it was detected; blue = present, grey = absent. E = East, K = Karikari. Only lakes where *Daphnia* was present are shown.

Surface sediments

Surface sediment chemistry

Surface sediment analyses showed that most metal and sulphur concentrations were generally within or near national median values (Lakes380, $n \approx 200$; Table 8; Appendix 3). Notable exceptions included Lake Mokeno, which had particularly high iron, Lake Rotootuauro with elevated manganese and Lakes Waikare, Taharoa, and Waingata with high aluminium relative to the median. Several lakes, including Lake Carrot and Lake Rotootuauro, exhibited elevated zinc concentrations, while Lakes Waikare and Rotoroa showed high lead concentrations. Cadmium was highest in Lake Waiporohita. Sulphur concentrations were highly variable (Table 8; Appendix 3).

All concentrations measured in surface sediments in this study were below the sediment quality Toxicant Default Guideline Values (DGV) and the Guideline Values – High (GV-high), as defined in the [Australian and New Zealand Guidelines for Fresh and Marine Water Quality](#) (Table 8; Appendix 3). The DGV represent threshold concentrations below which adverse effects on sediment-dwelling organisms are considered unlikely. Concentrations below these values are generally regarded as posing a low risk to benthic ecological health. The GV-high represent concentrations above which adverse biological effects are likely to occur frequently. Values between the DGV and GV-high indicate a range where occasional effects may occur, depending on site-specific conditions and contaminant bioavailability.

Concentrations of OM, TOC, TN, and carbonates were generally above the Lakes380 national median values (Table 8; Appendix 2). Organic matter was particularly high in Carrot, Heather and Rotokawau (Aupōuri). TOC followed a similar pattern, with the highest values in Heather, Ngakapua, and Rotokawau (Karikari). Carbonate content showed substantial variability, with elevated values in Rototuna, Waihopo and Waipara compared to the median. Total nitrogen concentrations were highest in Carrot, Heather, and Rotokawau (Karikari), and lowest in Wainui, Ngakeketo, and Wai Raupo.

Table 8. Metal, sulphur, organic matter, total organic carbon, total nitrogen, and carbonate concentrations in the top 0–2 cm of lakebed sediments from lakes in the Northland Region (Lakes380 programme). The number of lakes in the national dataset ranges from 205 to 215 depending on the variable measured. ANZG = Default Guideline Values (DGV) and the Guideline Values – High (GV-high), as defined in the [Australian and New Zealand Guidelines for Fresh and Marine Water Quality](#). A = Aupōuri, E = East, K = Karikari, and P = Pouto. Units are g/kg dry weight (DW), except zinc, cadmium, and copper (mg/kg DW). TOC, OM, carbonates, and TN are reported in g/100 g dry weight. Fe = iron, Mn = manganese, Al = aluminium, Ca = calcium, Pb = lead, Cd = cadmium, Zn = zinc, S = sulphur, Carb. = carbonates. Shading is added for visual clarity, representing the gradient from low (light) to high (dark) for each analyte.

	Fe	Mn	Al	Ca	Pb	Cu	Cd	Zn	S	OM	Carb.	TOC	TN
Carrot	12.7	0.302	8.22	6.24	21.1	22	0.14	110.0	18.3	73.0	1.5	29.0	2.9
Heather	20.9	0.525	6.33	5.62	16.7	11	0.13	57.6	6.9	68.9	1.4	31.6	3.3
Humuhumu	30.5	0.421	13.70	5.02	5.78	6	0.04	50.9	1.4	18.5	3.4	5.8	0.6
Kahuparere	65.3	0.877	22.50	6.34	6.57	7	0.08	53.1	2.5	14.8	0.9	6.9	1.0
Kai-iwi	5.4	0.243	21.60	5.72	8.23	20	0.07	22.4	7.8	51.3	6.0	21.8	1.1
Kanono	26.0	0.383	23.90	3.49	5.82	9	0.06	34.2	6.0	28.5	5.4	12.2	1.6
Karaka	67.1	0.488	4.36	6.14	3.49	4	0.02	23.0	3.1	26.3	3.6	11.3	1.1
Katavich	29.7	0.237	14.90	8.69	9.9	6	0.15	46.2	13.0	35.9	2.9	16.8	1.7
Mokeno	94.9	0.461	4.58	8.27	3.62	14	0.02	25.3	6.8	43.1	0.1	21.4	2.5
Morehurehu	56.0	0.332	14.50	1.74	4.09	13	0.10	33.4	4.6	27.5	1.3	10.1	0.7
Ngakapua	9.7	0.116	16.60	5.86	7.2	13	0.10	63.7	15.0	50.2	2.1	31.8	2.5
Ngakeketo	41.0	0.880	28.00	2.83	4.7	10	0.06	37.8	2.2	9.8	1.1	2.0	0.3
Ngatu	14.7	0.077	32.90	5.06	14.4	16	0.13	69.1	14.8	45.6	5.3	17.1	1.8
Rotokawau (A)	6.2	0.332	10.90	3.73	12.3	19	0.08	50.1	11.0	70.1	3.5	20.2	2.2
Rotokawau (E)	2.9	0.031	12.90	8.14	12.7	9	0.31	20.0	6.1	19.1	2.1	7.9	0.9
Rotokawau (K)	5.6	0.025	19.80	7.05	17	19	0.22	17.9	8.3	58.5	1.4	29.8	2.9
Rotokawau (P)	19.2	0.180	13.50	3.32	4.91	6	0.09	53.4	3.0	22.1	0.5	7.0	0.6
Rotootuauru	38.0	1.870	35.30	7.49	11.3	16	0.24	102.0	14.0	46.4	2.6	19.4	2.3
Rotopokaka	9.4	0.046	14.10	9.25	20.7	9	0.24	22.2	5.4	58.4	1.1	28.5	1.8
Rotoroa	14.3	0.115	23.20	6.47	24.2	11	0.20	65.4	19.0	45.1	2.5	27.4	2.6
Rototuna	17.7	0.092	23.70	3.95	10	24	0.31	58.6	14.4	29.2	8.5	16.6	1.9
Taharoa	9.6	0.032	43.10	1.96	23.7	16	0.17	44.5	7.6	35.3	3.6	14.6	1.1
Te Kahika	44.6	0.033	16.20	2.46	12.7	6	0.18	94.8	22.0	35.8	5.0	14.9	0.8
Tutaki	32.1	0.140	25.30	4.61	9.45	9	0.13	45.4	8.6	50.5	1.2	17.5	2.1
Wai Raupo	59.1	0.977	10.40	1.37	1.8	4	0.04	17.8	3.4	6.7	1.5	2.7	0.3
Waihopo	25.5	0.266	8.55	4.2	4.46	6	0.05	57.8	19.2	44.6	7.9	16.1	1.7
Waikare	16.8	0.050	48.00	2.37	29.1	16	0.14	40.1	16.0	58.8	2.4	11.8	0.9
Waingata	25.8	0.283	42.40	4.57	9.81	14	0.27	84.2	3.6	38.8	0.1	18.2	2.0
Wainui	14.5	0.103	10.70	2.33	2.8	3	0.03	26.4	1.2	14.6	1.1	1.1	0.1
Waipara	10.7	0.089	7.90	1.71	2.44	4	0.02	25.4	2.7	28.9	8.2	6.1	0.6
Waiparera	30.0	0.170	20.90	7.89	8.89	17	0.17	56.0	29.5	39.5	3.0	21.2	2.3
Waiporohita	4.9	0.032	17.80	5.84	16.6	25	0.45	48.7	9.5	51.7	0.1	24.8	2.4
Waitahora										6	3.1	1.5	0.51
Lakes380 national													
median	32.6	0.584	20.9	5.83	19.7	26	0.13	77.9	2.8	20.8	2.55	8.4	0.88
ANZG (DGV)	-	-	-	-	50	65	1.5	200	-	-	-	-	-
ANZG (GV-high)	-	-	-	-	220	270	10	410	-	-	-	-	-

Total, bioavailable and refractory phosphorus fractions in surface sediments were compared with national medians from the Lakes380 dataset and assessed on an individual lake basis (Figure 6).

Total P contents in the sediments of the Northland lakes were broadly similar, in terms of range and median, to that observed in lakes nationwide (Figure 6). However, several individual lakes had Total P contents substantially higher than the national median. Lakes Carrot, Kai-Iwi, Karaka, Rotokawau (East), Rotokawau (Karikari), Rotootuauro, Rototuna and Waiporohita all had Total P contents higher than the 75th percentile of the national dataset (Figure 7).

Across sampled Northland lakes, the potentially mobile pool of P fractions (Ex-P + Red-P + Org-P; 822 mg P.kg dw⁻¹) was similar to the national median (797 mg P.kg dw⁻¹), however this was influenced by generally higher Org-P and lower Red-P (Figure 6). Lakes Karaka, Kahuparere and Kanono were exceptions with relatively low Org-P and high Red-P contents. Lake Karaka had very high Red-P content with nearly 60 % of Total P being present in this form (Figure 7). Lakes Rotootuauro, Heather and Waikare had relatively high amounts of both Org-P and Red-P. These lakes have greater potential for internal P loading during under anoxic conditions.

The pH-P content across the Northland lakes was similar to the national range and median, however a number of lakes had high contents of this fraction (Figure 7). While in most lakes this fraction may be considered relatively inert, in shallow lakes there is potential for high pH conditions driven by photosynthesis (e.g. algal blooms) to result in P release from lake-bed sediments. Katavich, Rotokawau (East), Rotokawau (Karikari), Rototuna and Waiporohita are all shallow lakes ($\leq 4\text{m}$) with relatively high contents of pH-P, suggesting a strong capacity for P release under changing geochemical conditions.

Of the refractory P fractions (Ca-P and Res-P), Ca-P was generally low across the Northland Lakes relative to the national median (Figure 6). In contrast the Res-P was relatively high with a median of 360 mg P.kg dw in Northland lakes compared with a national median of 240 mg P.kg dw. A substantial amount of the Res-P fraction likely consists of refractory organic compounds; therefore, the elevated Res-P contents are consistent with the elevated organic matter contents of many of the Northland Lakes (Figure 6).

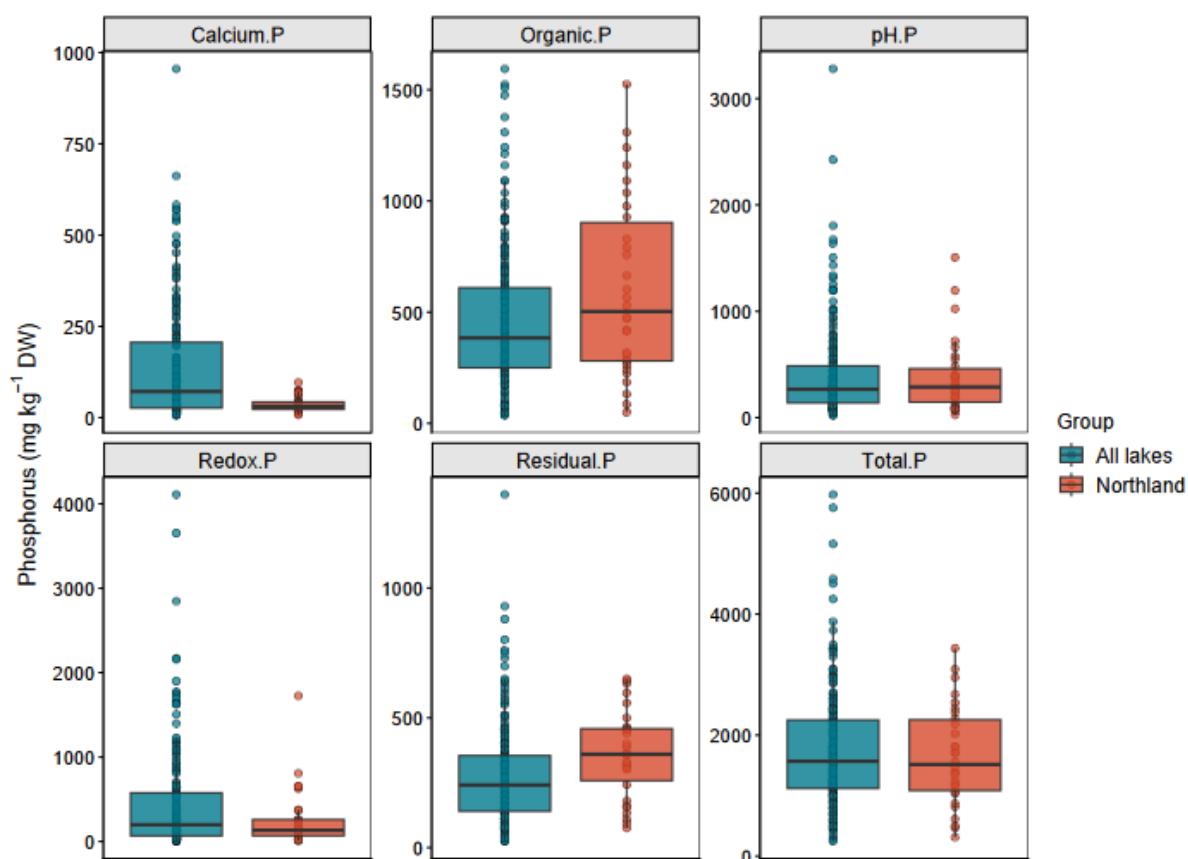


Figure 6. Sedimentary phosphorus fractions in Northland lakes (n=30) compared to the Lakes380 national dataset (n=179).

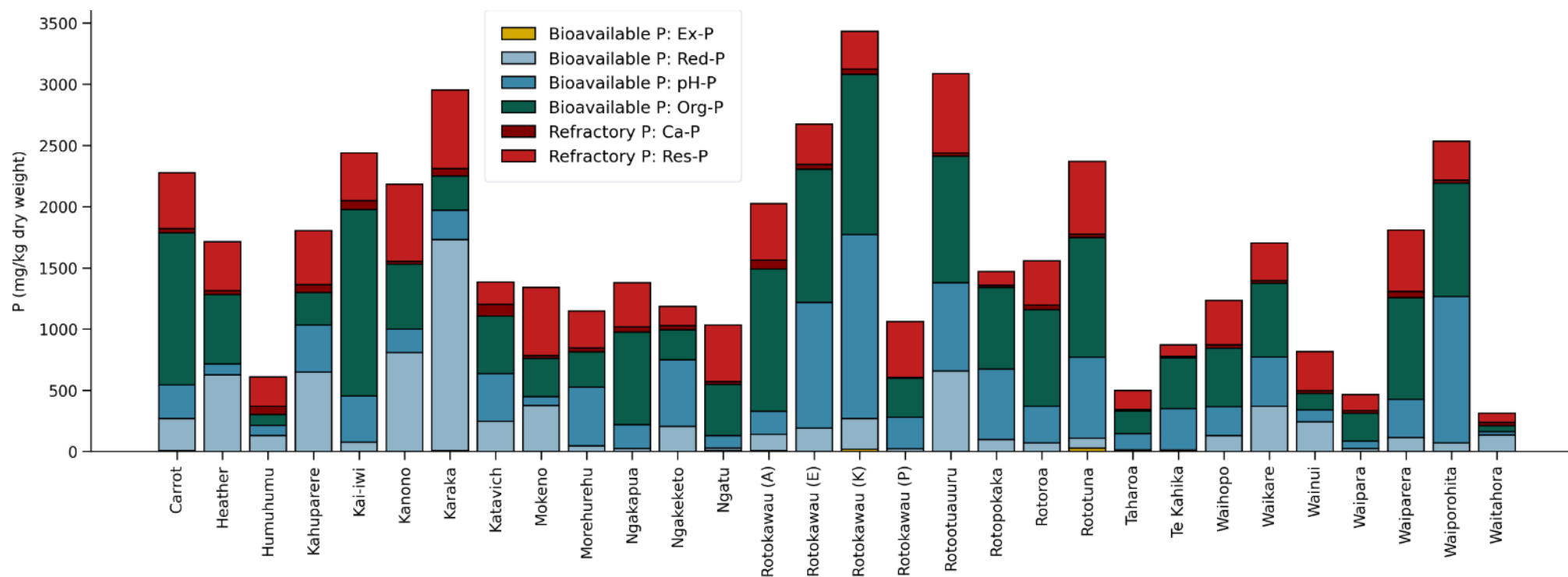


Figure 7. Sediment phosphorus (P) fraction forms in Northland lakes. Ca-P = calcium bound P, Res-P = residual P, Ex-P = exchangeable P, Red-P = redox-sensitive P, pH-P = pH and national -sensitive P, Org-P = organic P. A = Aupōuri, K = Karikari, P = Pouto.

Surface sediment bacterial community composition

Environmental DNA (eDNA) metabarcoding analysis of the surface sediments revealed different bacterial communities among the lakes (Figure 8). The PCoA plot showed clear separation of samples along the first axis (11.2%) and second axis (7.7%), indicating variation in community composition among lakes. Lakes such as Carrot, Ngakapua, Rotoroa, Waingata and Waiporohita and Rotokawau (Aupōuri) clustered toward the upper right side of the plot, suggesting they share similar bacterial communities distinct from those in lakes like Humuhumu, Karaka, and Mokeno, which grouped on the bottom left (Figure 8).

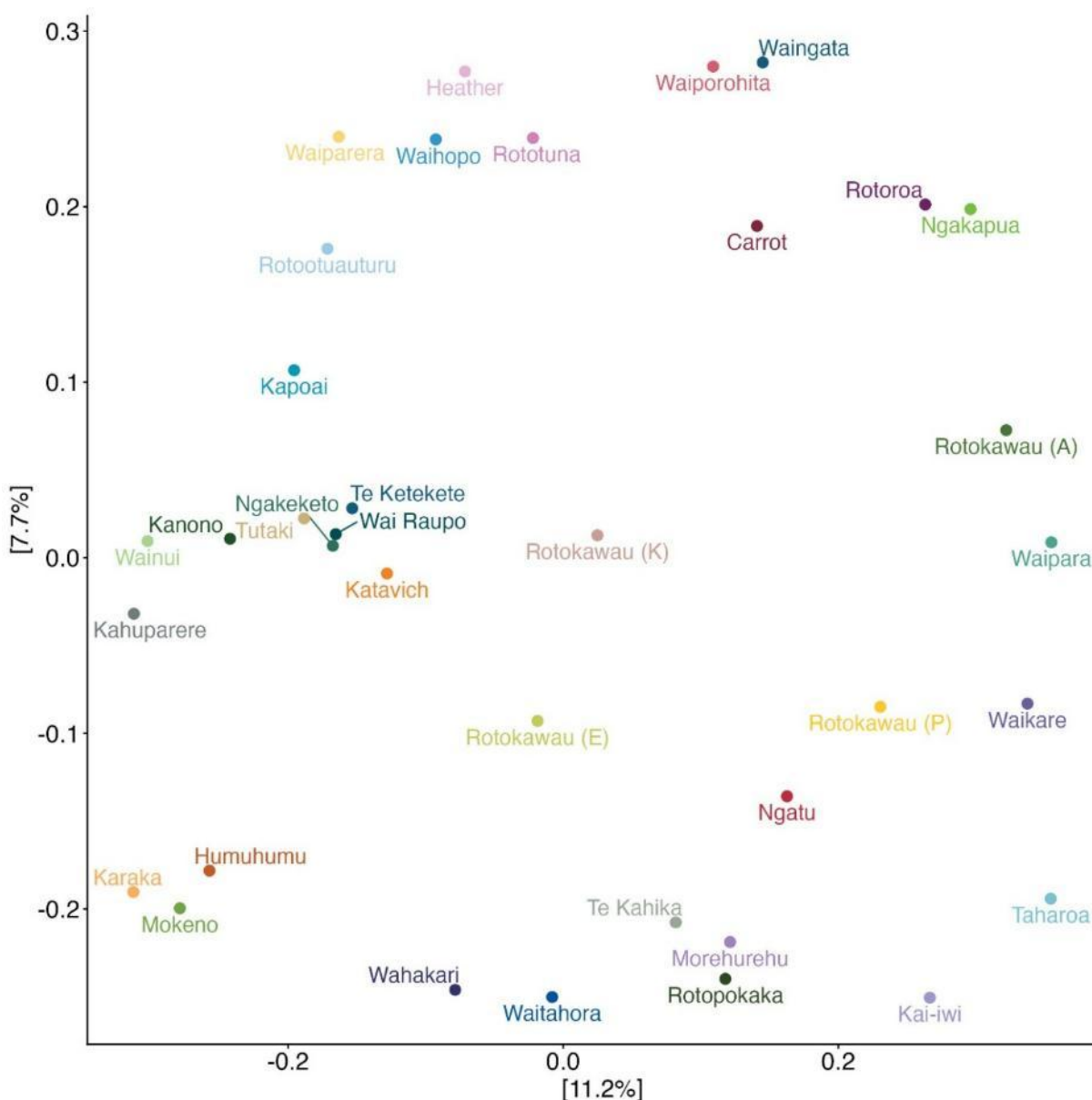


Figure 8. Principal coordinate analysis ordination plot of bacteria in the surface sediments of Northland lakes – the larger the distance between the dots, the greater the difference in bacterial community composition. A = Aupōuri, E = East, K = Karikari, P = Poutō.

Across most lakes, Gammaproteobacteria comprised the largest share of the surface-sediment bacterial community (Figure 9). Secondary contributors commonly included Bacteroidia and Anaerolineae, with Cyanobacteria, Acidobacteriae, and other classes present at lower but notable levels. A small number of lakes deviated from this pattern, showing comparatively higher contributions from classes such as Verrucomicrobiae, Desulfobacteria, or Dehalococcoidia. The “Other” category represented a substantial long tail of lower-abundance classes in many lakes (Figure 9).

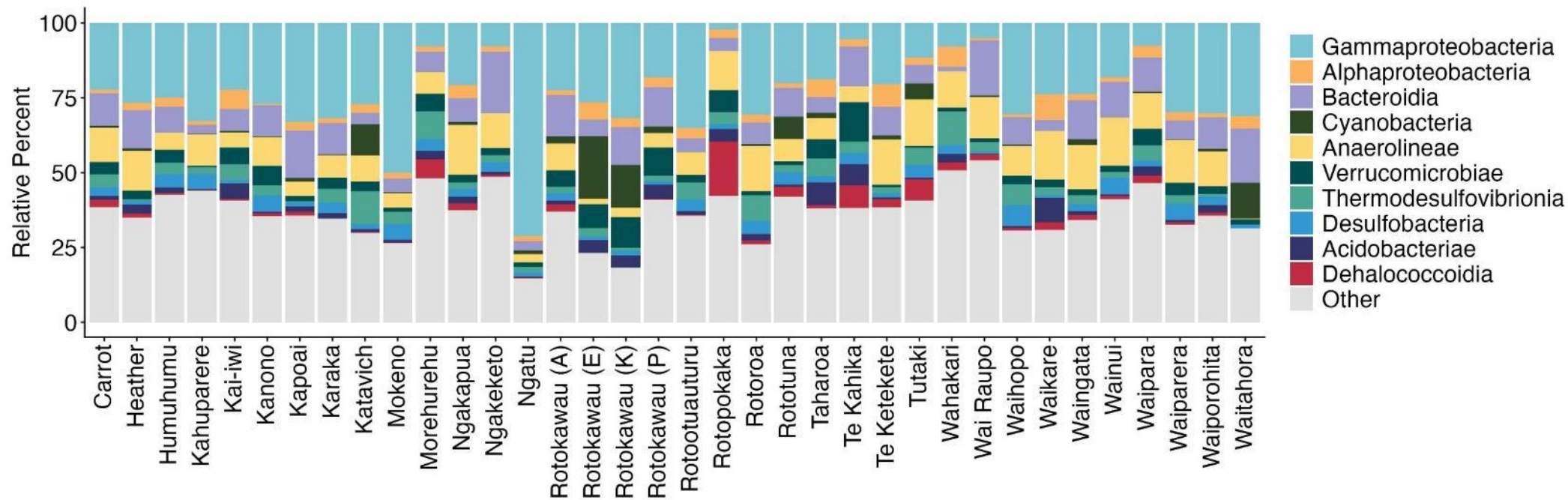


Figure 9. Bacterial taxonomic composition of surface sediments from Northland lakes, plotted at the class level. A = Aupōuri, E = East, K = Karikari, P = Pouto.

Surface sediment eukaryotic community composition

In contrast to the PCoA for bacterial communities, the eukaryotic community analysis grouped the lakes into three relatively distinct clusters (Figure 10). One cluster included lakes such as Kai-iwi, Taharoa, and Ngatu toward the lower-left, another comprised lakes including Carrot, Waipara and Ngakeketo on the right, while a third cluster contained lakes near the centre and upper-left (e.g., Kahuparere, Mokeno, and Wainui; Figure 10).

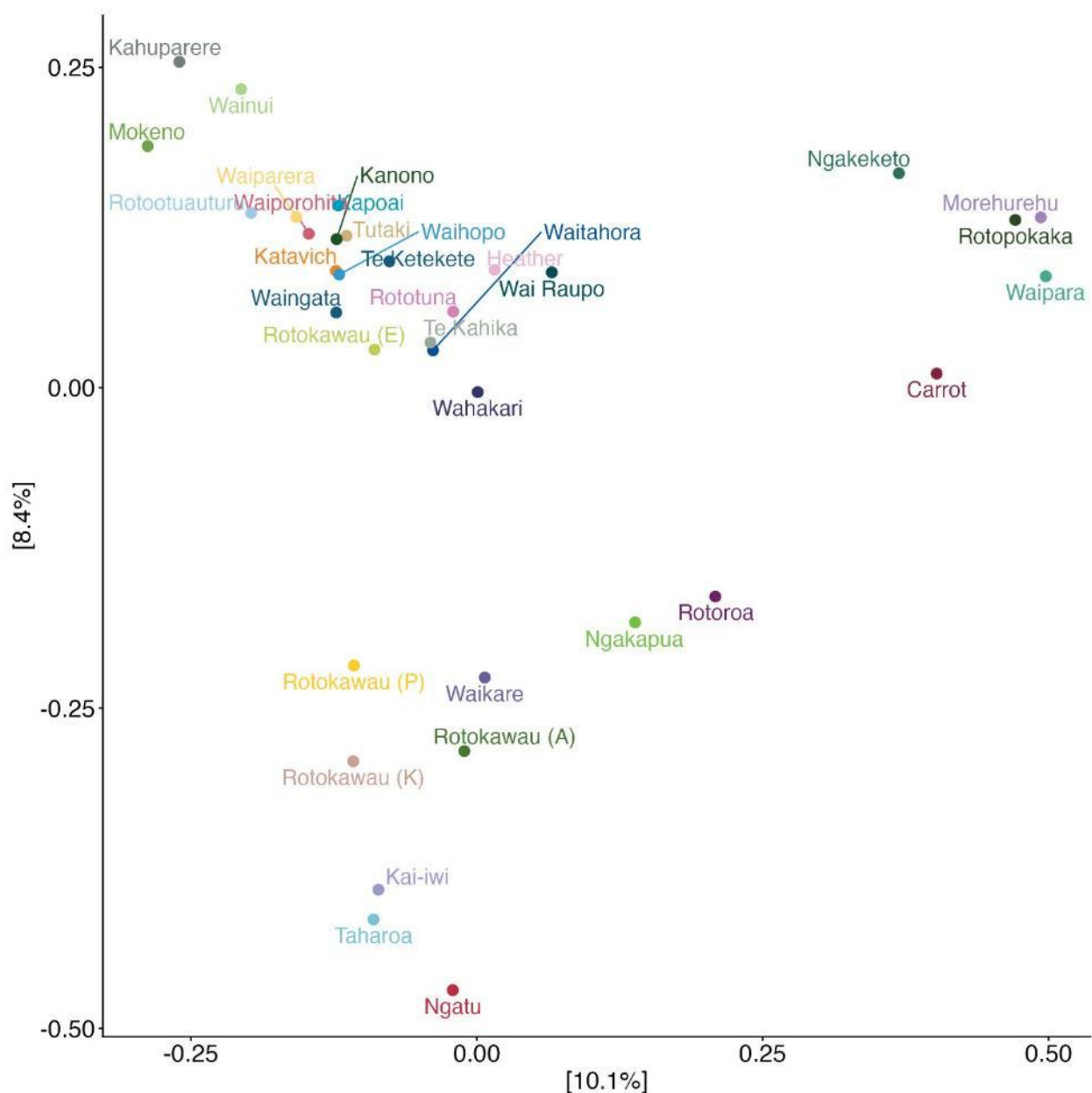


Figure 10. Principal coordinate analysis ordination plot of eukaryotes in the surface sediments of Northland lakes – the larger the distance between the dots, the greater the difference in the eukaryotic community composition. A = Aupōuri, E = East, K = Karikari, P = Pouto.

Across most lakes, Dinophyceae (dinoflagellates) dominated the assemblages, often comprising the largest proportion of eukaryotic reads (Figure 11). Chlorophyceae (green algae) were also common, typically appearing as secondary contributors. However, several lakes showed distinct profiles: for example, Ostracoda (crustaceans) were abundant in lakes such as Tutaki, Taharoa and Te Ketekete while Rhabditophora (flatworms) contributed substantially in Rotokawau (Karikari and Pouto) and Rotootuauru. Other groups, including Chromadorea (round worms), Clitellata (annelids – earth worms), Spirotrichea (ciliates), and Hexanauplia (small crustaceans), occurred at lower but notable levels in some lakes. The “Other” category represented a diverse set of low-abundance taxa across all sites (Figure 11).

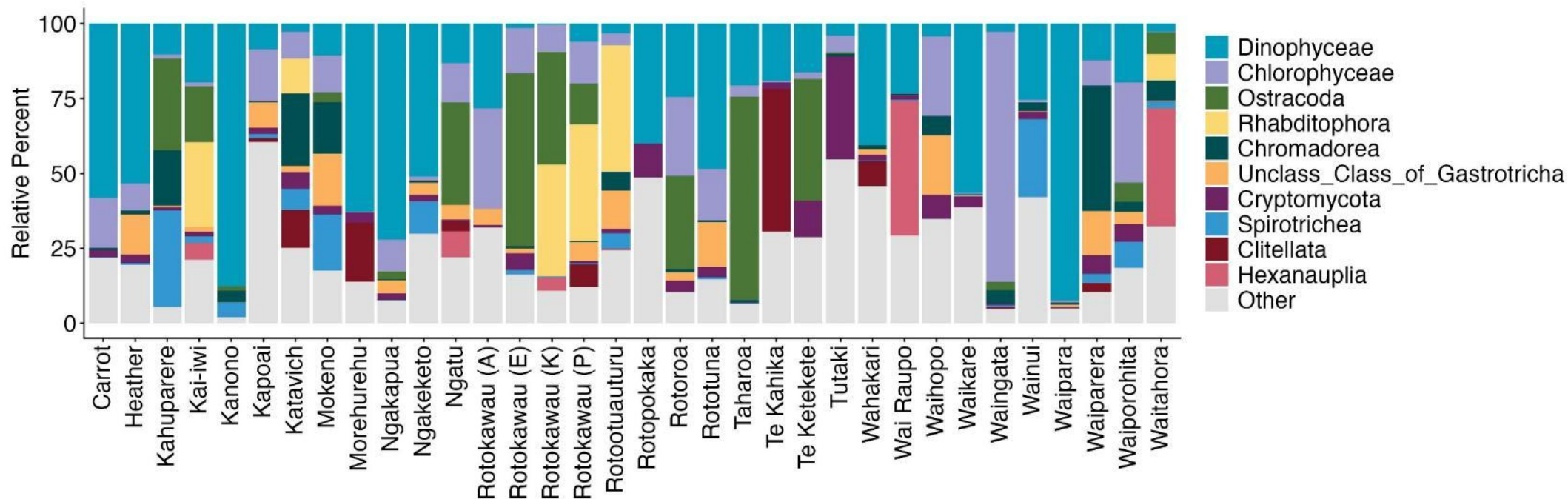


Figure 11. Eukaryotic taxonomic composition of surface sediments in Northland lakes, plotted at the class level. A = Aupōuri, E = East, K = Karikari, P = Pouto.

Sediment cores

Images of the ten analysed sediment cores are provided in Figures 12 and 13.

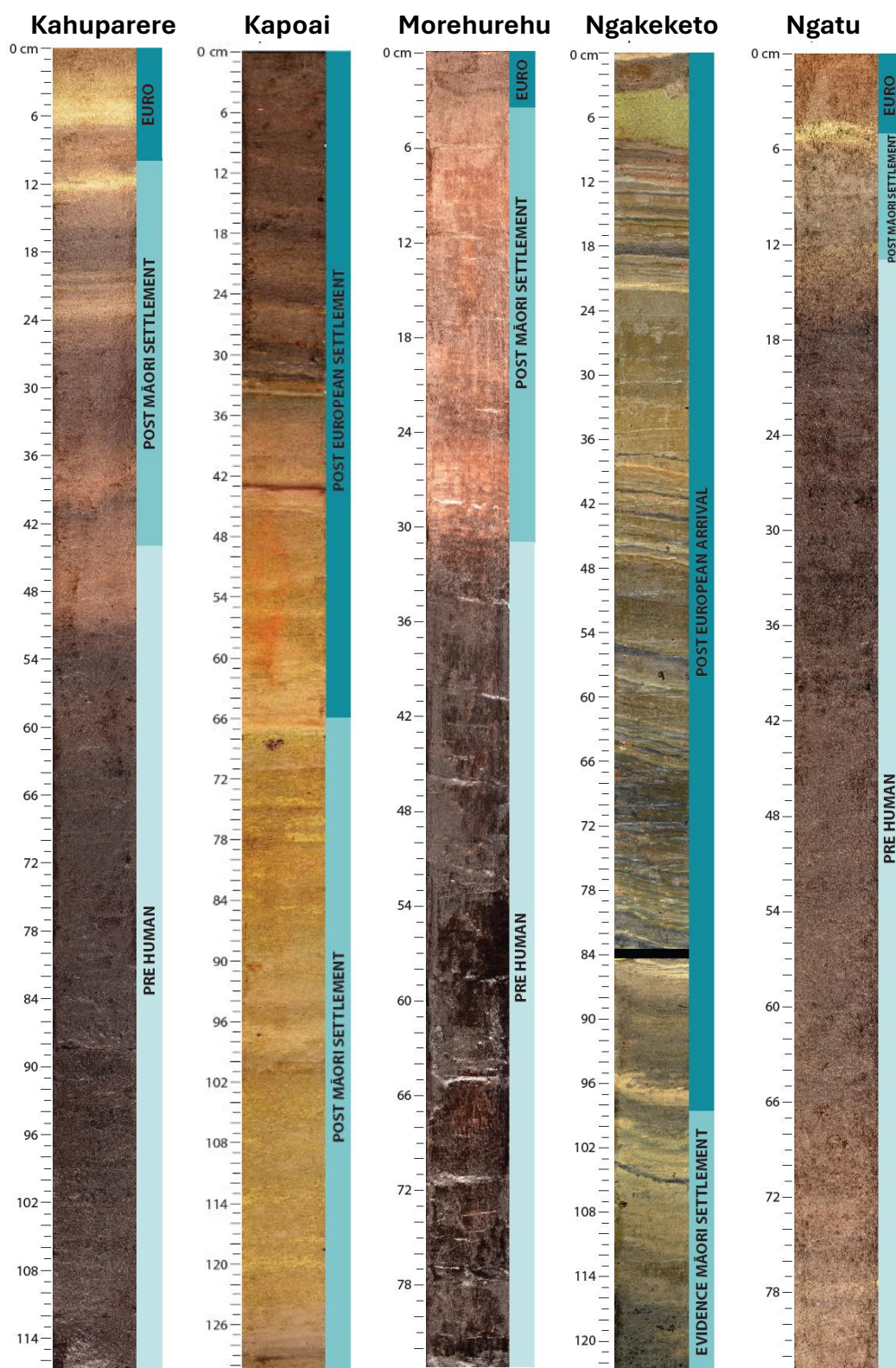


Figure 12. Images of sediment cores from Kahuparere, Kapoai, Morehurehu, Ngakeketo and Ngatu. Colours show approximate periods of human occupation.

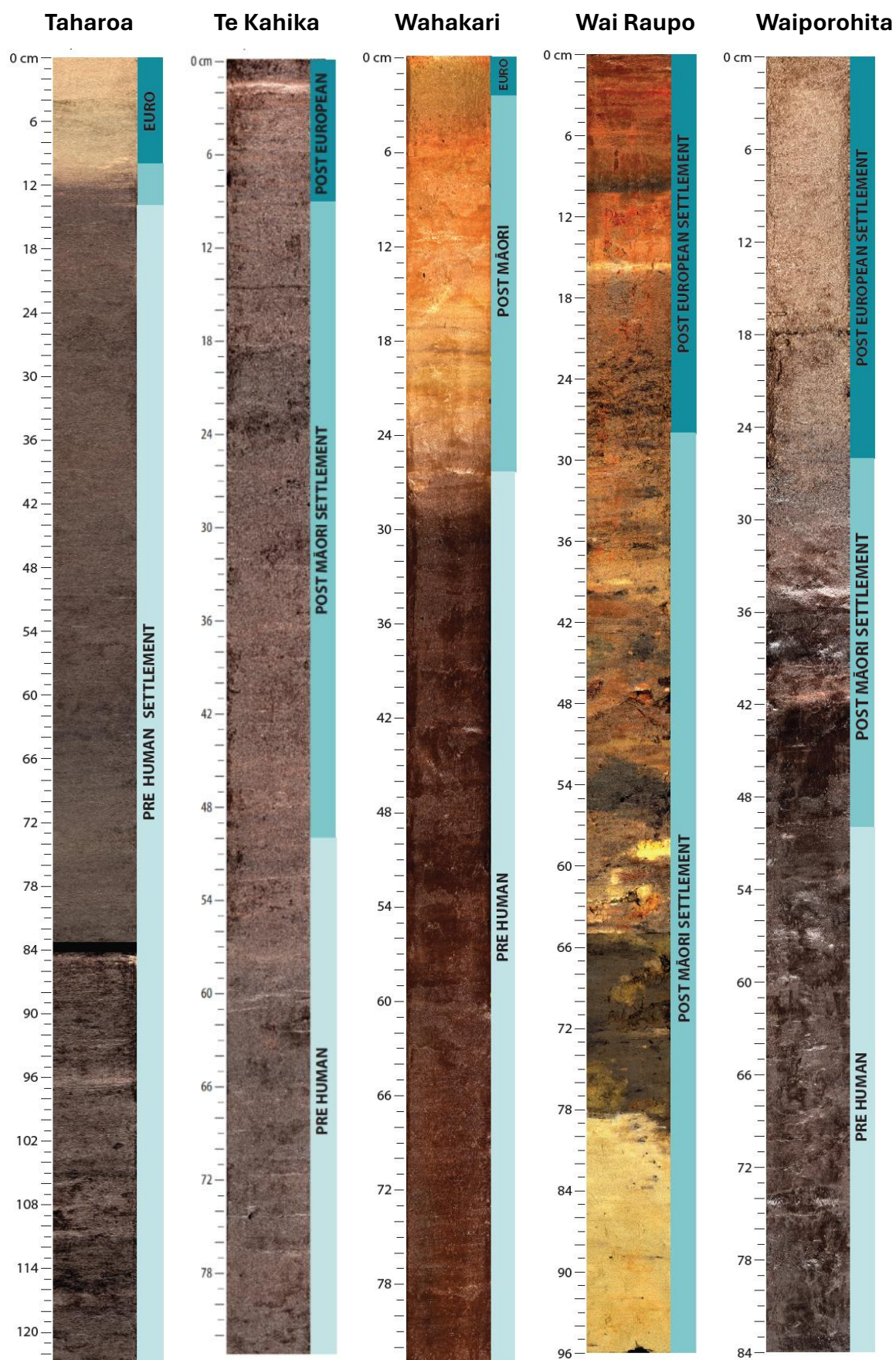


Figure 13. Images of sediment cores from Taharoa, Te Kahika, Wahakari, Wai Raupo and Waiporohita. Colours show approximate periods of human occupation.

Only a summary of the most abundant pollen types is provided for each lake. Full details will be included in an accompanying spreadsheet.

Lake Kahuparere

Pollen and Charcoal: The pollen and charcoal record indicate that prior to human arrival the lake catchment was dominated by native forest, with high abundances of podocarps, particularly rimu and kauri, and a substantial component of mānuka (Figure 14). This suggests a largely intact forested landscape with minimal disturbance. Following Māori settlement, tall native trees declined while bracken fern and charcoal increased, consistent with forest clearance and fire use, leading to more open vegetation. Sedges and raupō also increased, reflecting expansion of wetland or lake-edge vegetation. After European arrival, native forest taxa declined further and were progressively replaced by grasses, indicating widespread land clearance and pastoral development. Pollen from non-native trees, particularly pine, became increasingly abundant in the upper sediments (Figure 14).

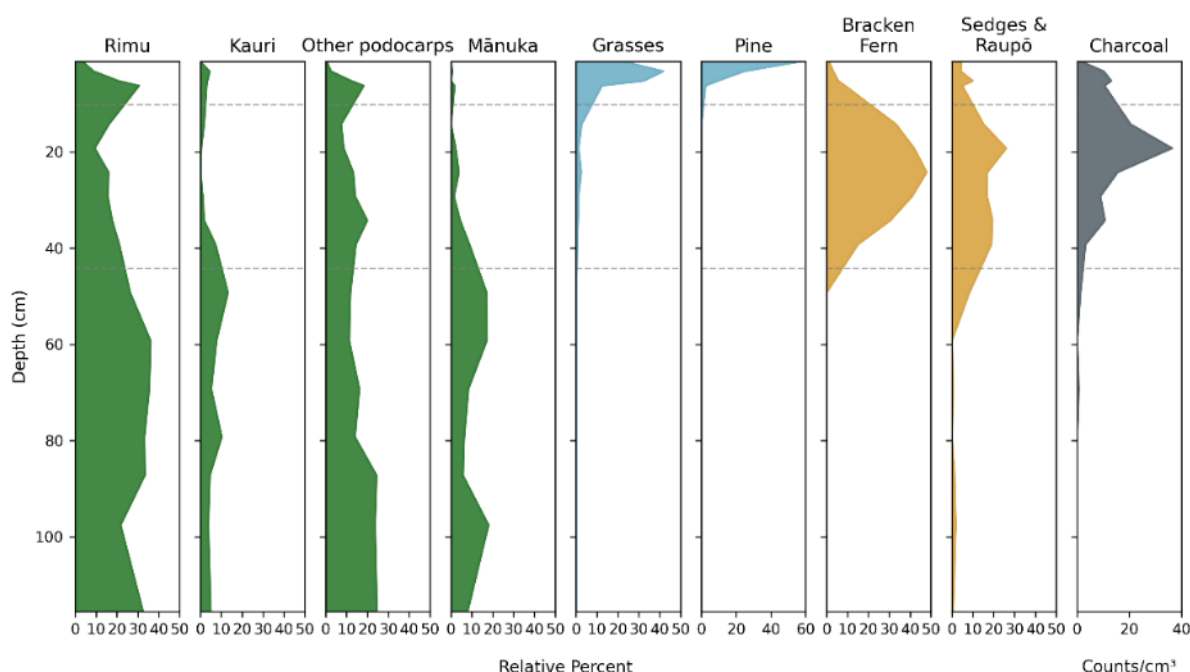


Figure 14. Downcore selected pollen and charcoal results for Lake Kahuparere. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement.

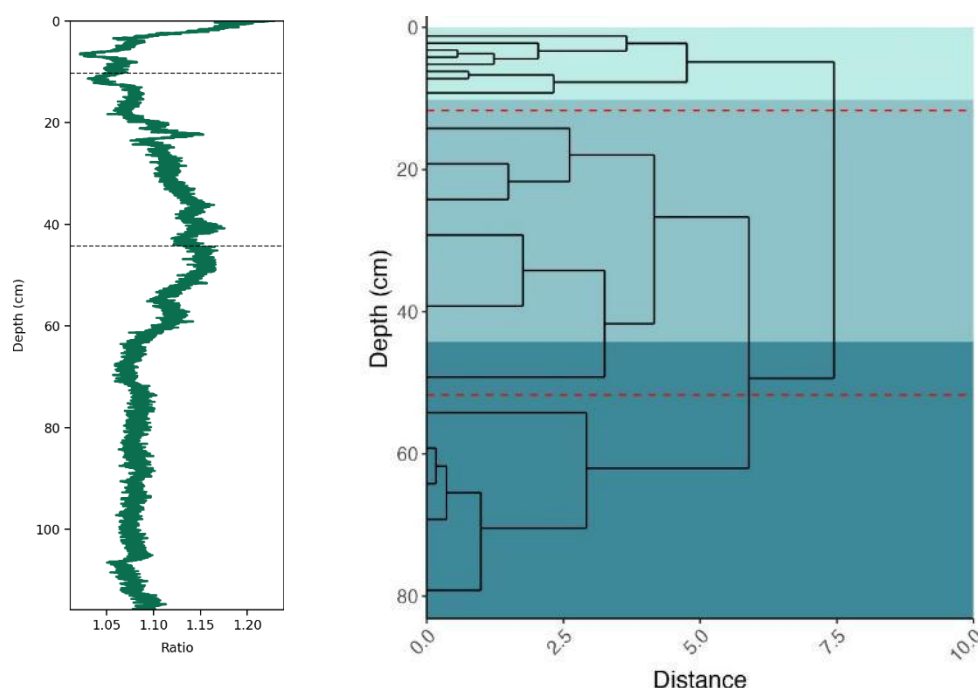


Figure 15. (Left) Downcore relative chlorophyll-a proxy ($RABD_{660:670}$) derived from hyperspectral analysis. Dotted horizontal lines mark midpoints between samples where pollen indicates transitions between human occupation periods (lower: pre-human to Māori settlement; upper: Māori to post-European settlement). (Right) CONISS plot of bacterial community composition. Colours denote human occupation periods, with light teal indicating the post-European period, medium teal indicating Māori occupation, and dark teal indicating the pre-human period. Red dashed lines indicate significant compositional change points. The x-axis represents dissimilarity between samples calculated using CONISS (sum of squared deviations), where larger values indicate greater compositional differences among samples.

Chl-a hyperspectral ratio: The Chl-a hyperspectral ratio remained relatively stable during the pre-human period, with only minor fluctuations (Figure 15). An increase is evident prior to Māori settlement, after which it declines. There is a more pronounced rise in the upper ~10 cm, reflecting changes after European settlement and suggesting an increase in algal abundance (Figure 15).

Bacterial community structure: The most pronounced significant shift in bacterial community structure occurred around the time of European settlement (Figure 15).

Lake Kapoai

An age model was developed for Lake Kapoai; however, it spans only approximately the last 500 years. As the other datasets cover roughly 1,000 years, the data below are not presented on an age scale. The age model was instead used to estimate the approximate timing of key changes in several proxies following European settlement.

Pollen and Charcoal: The pollen and charcoal record from Lake Kapoai indicate that prior to human arrival the surrounding catchment supported native vegetation with podocarps a dominant component, particularly rimu (Figure 16). Following Māori settlement, there was a marked increase in bracken fern and charcoal, alongside reduced representation of tall forest taxa, indicating forest clearance and repeated burning. Sedges and raupō increased during this period, suggesting expansion of wetland or lake-margin vegetation as forest cover declined. After European arrival, grasses increased markedly, reflecting widespread shifts to pastoral land use. Pine pollen was consistently present, indicating the establishment of exotic trees in the region (Figure 16).

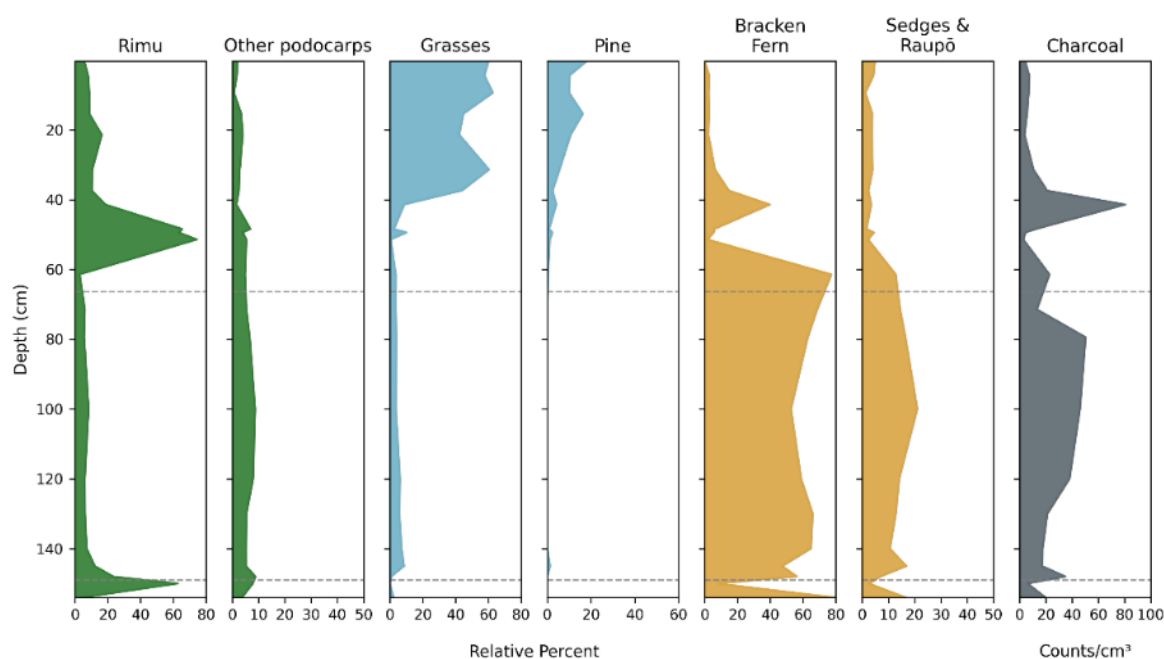


Figure 16. Downcore selected pollen and charcoal results for Lake Kapoai. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement.

Diatoms: Prior to European arrival, the diatom community of Lake Kapoai was dominated by small araphid taxa that inhabit both the benthic and pelagic zones (Figure 17). The two most abundant species in Lake Kapoai, *Staurosira construens* and *Staurosirella pinnata*, are globally associated with waters spanning from oligo- to eutrophic conditions; however, in Aotearoa New Zealand, *S. pinnata* has been recorded to be more abundant in deep, clear water lakes.

Following European arrival, the community dominance shifted to the centric, planktonic species *Discostella stelligera* (Figure 17). This species is abundant in Aotearoa New Zealand lakes and is tolerant of a wide range of conditions. There were simultaneous increases in meso- to eutrophic

and epiphytic taxa (e.g., species from *Encyonema*, *Encyonopsis*, and *Cocconeis* genera) several of which are common in Aotearoa New Zealand wetlands as well as lakes. These, along with an increase in *Humidophila contenta*, a species typically associated with soils or moist habitats, suggests increased catchment disturbance and potential expansion or development of marginal/wetland habitats. After its initial increase, *D. stelligera* declined, as epiphytic and meso-eutrophic taxa became more abundant.

Around 1950 CE, the community underwent a further major shift consistent with progressive eutrophication (Figure 17). Initially, the increasing abundance of eutrophic *Achnantidium minutissimum* and incursions of *Asterionella formosa* and *Ulnaria acus* indicate increasing nutrient concentrations. A subsequent increase in eutrophic and pelagic *Aulacoseria granulata* var. *angustissima*, followed by rapid increases in eutrophic *Aulacoseria ambigua* and *Pseudostaurosira trainori*, along with simultaneous declines in epiphytic taxa indicate progressing eutrophication and potential loss or reduction of host macrophytes. Most recently, *A. formosa* has become the dominant species.

Metals: Cadmium and lead concentrations remain low during the pre-human and Māori eras but increase markedly about 1950 CE (Figure 18). Following European settlement, the Mn:Fe ratio begins to fluctuate, likely reflecting episodes of anoxia. The Ti:Inc ratio is relatively stable earlier in the record but declines after ~1950 CE, suggesting that despite increased sedimentation (data not shown) likely driven by in-lake productivity, terrestrial inputs decreased from this time (Figure 18).

Chl-*a* hyperspectral ratio: The Chl-*a* hyperspectral ratio was generally stable throughout the Māori settlement phase (Figure 18). There was a marked increase during European settlement at about 1950 CE and a more pronounced change since about 2010 CE (Figure 18).

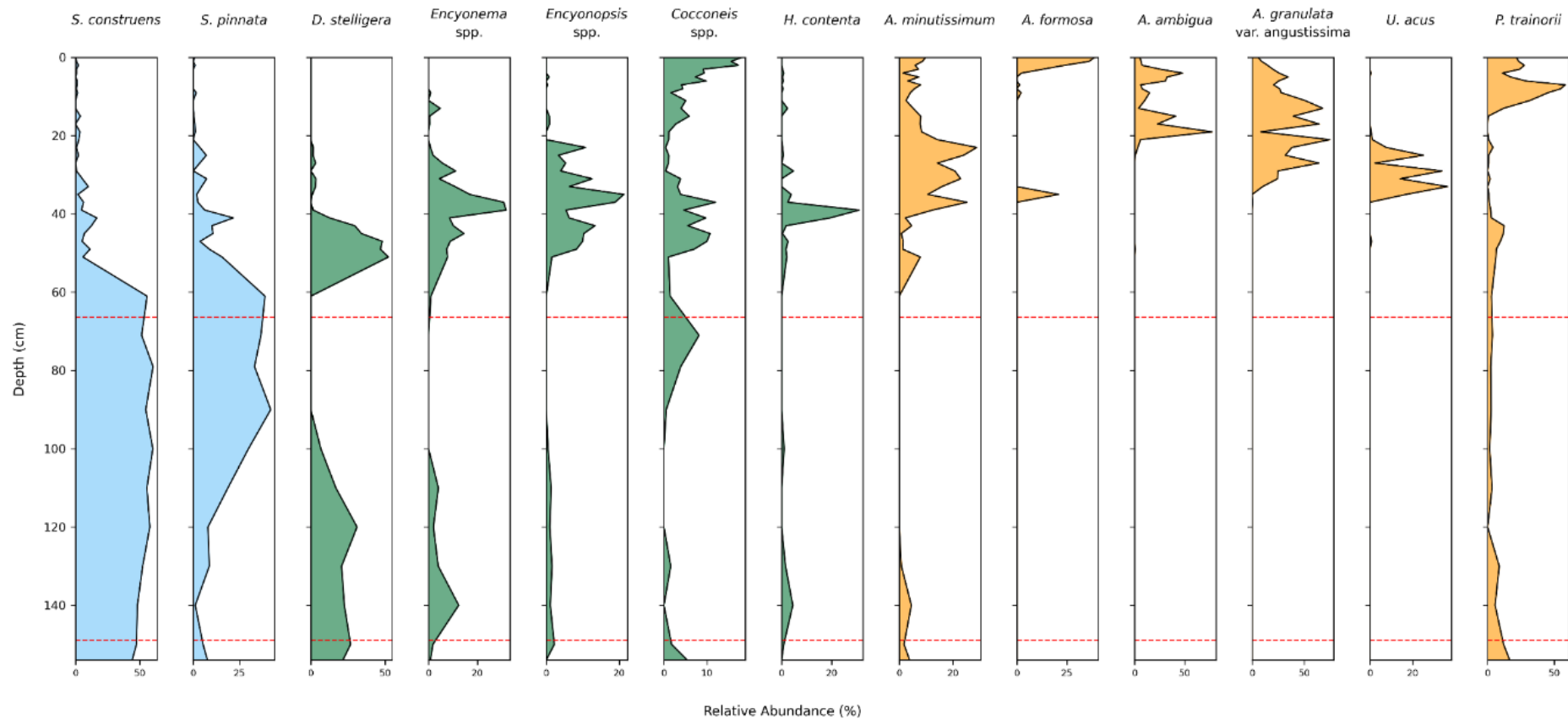


Figure 17. Relative abundances of selected Diatoms downcore for Lake Kapoai. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement. *S. construens* = *Staurosira construens*; *S. pinnata* = *Staurosirella pinnata*; *D. stelligera* = *Discostella stelligera*; *Encyonema* spp.; *Encyonopsis* spp.; *Cocconeis* spp.; *H. contenta* = *Humidophila contenta*; *A. minutissimum* = *Achnantheidium minutissimum*; *A. formosa* = *Asterionella formosa*; *A. ambigua* = *Aulacoseira ambigua*; *A. granulata* var. *angustissima* = *Aulacoseira granulata* var. *angustissima*; *U. acus* = *Ulnaria acus*; *P. trainorii* = *Pseudostaurosira trainorii*.

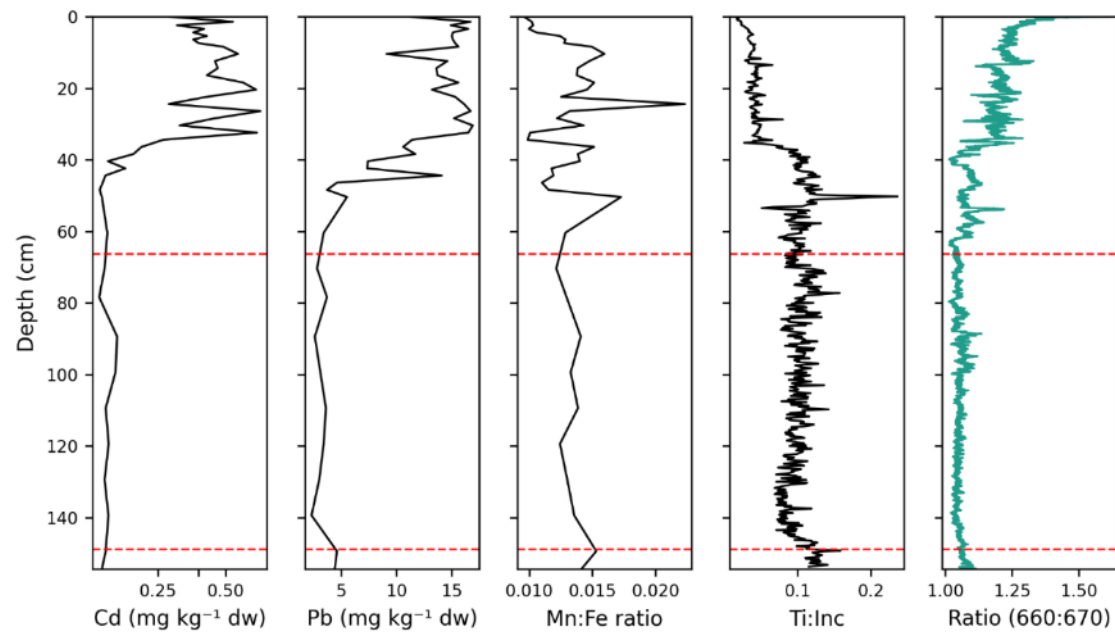


Figure 18. Lake Kapoai downcore cadmium (Cd) and lead (Pb) concentrations, manganese-to-iron (Mn:Fe) ratio (a proxy for anoxia), titanium-to-incoherence (Ti:Inc) ratio (a proxy for terrestrial erosion), and a relative chlorophyll-*a* proxy derived from the hyperspectral RABD660_670 ratio. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement.

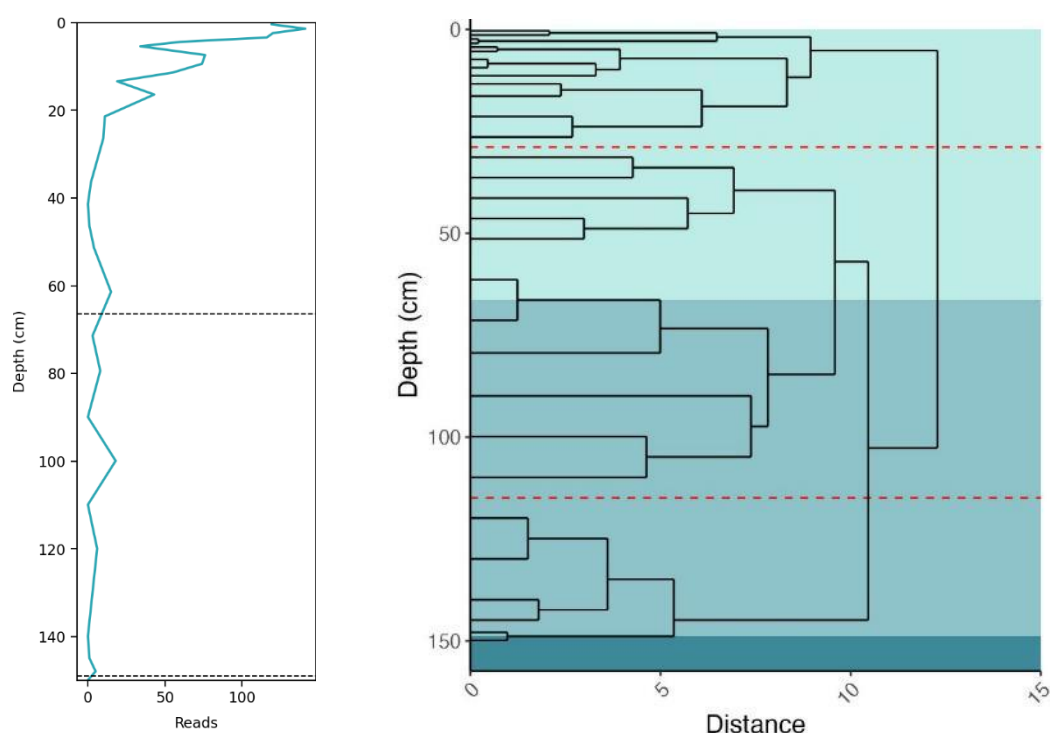


Figure 19. (Left) Cyanobacterial environmental DNA reads. Dotted horizontal lines mark midpoints between samples where pollen indicates transitions between human occupation periods (lower: pre-human to Māori settlement; upper: Māori to post-European settlement). (Right) CONISS plot of bacterial community composition. Colours denote human occupation periods, with light teal indicating the post-European period, medium teal indicating Māori occupation, and dark teal indicating the pre-human period. Red dashed lines indicate significant compositional change points. The x-axis represents dissimilarity between samples calculated using CONISS (sum of squared deviations), where larger values indicate greater compositional differences among samples

Cyanobacteria and bacterial community structure: Cyanobacteria are consistently present throughout the core, with a strong increase in the upper ~20 cm (Figure 19). The most pronounced significant shift in bacterial community structure occurs in the top ~25 cm (~1980 CE) with the second occurring after Māori settlement (Figure 19).

Lake Morehurehu

Pollen and Charcoal: The pollen and charcoal record from Lake Morehurehu indicate that prior to human arrival the catchment was dominated by native forest, with a mix of rimu, other podocarps, and celery pine, and minimal evidence of disturbance (Figure 20). Following Māori settlement, the relative abundance of forest taxa declined, while bracken fern, sedges, and charcoal increased, consistent with forest disturbance and burning. After European arrival, which was recorded only in the top few centimetres due to very low sedimentation rates, native forest pollen reduced and was replaced almost entirely by pine and grasses, reflecting extensive land clearance and the introduction of pine plantations near the lake (Figure 20).

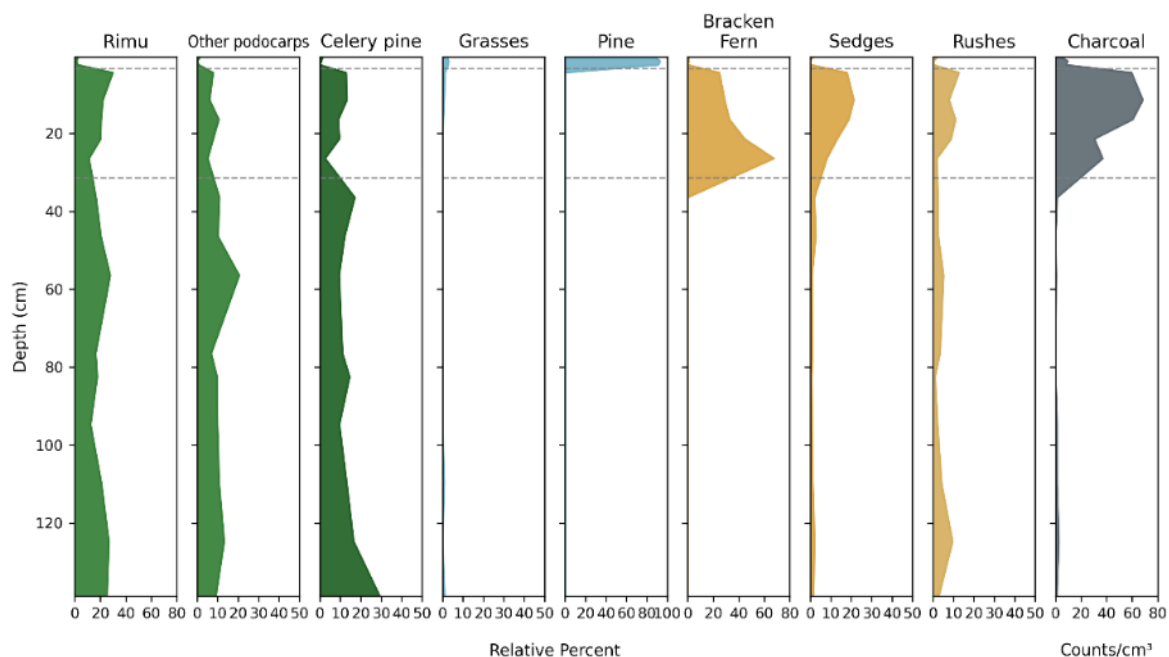


Figure 20. Downcore selected pollen and charcoal results for Lake Morehurehu. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement.

Chl-*a* hyperspectral ratio: There was some variability in the pre-human Chl-*a* hyperspectral ratio (Figure 21). In contrast it was relatively stable during the period of Māori settlement, with a slight increase post-European settlement (Figure 21).

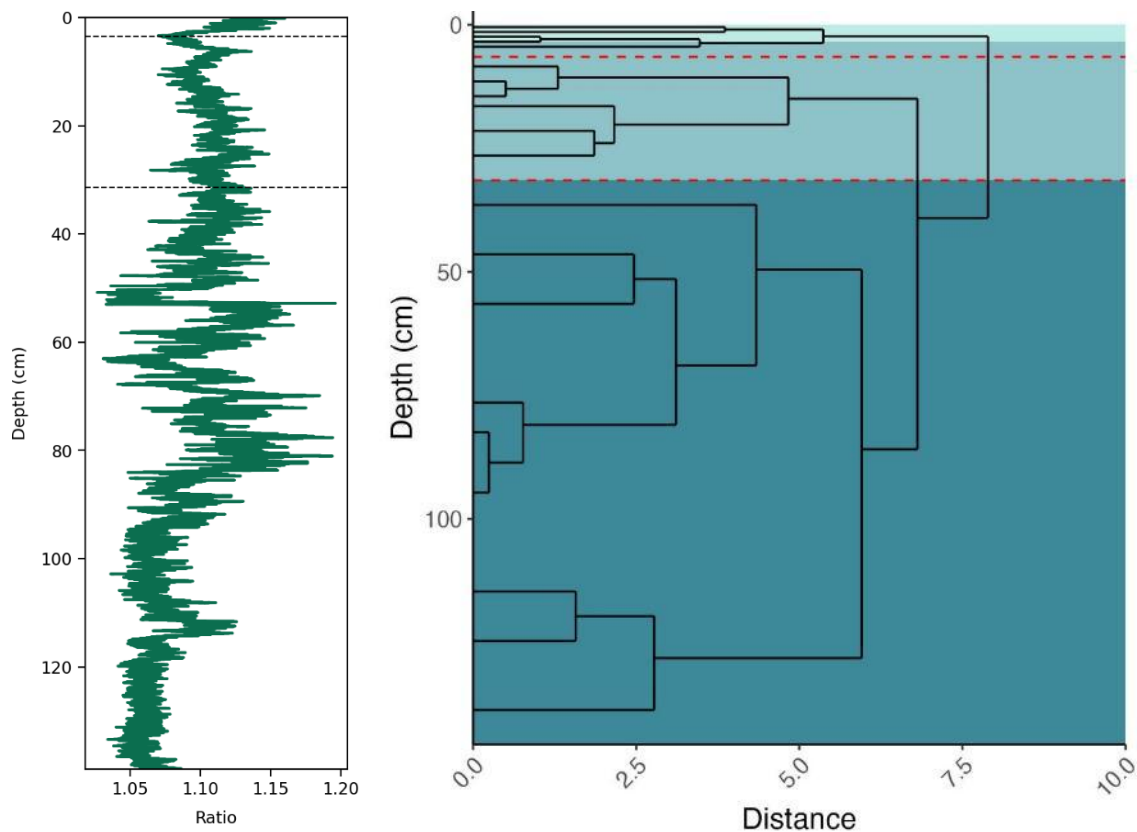


Figure 21. (Left) Downcore relative chlorophyll-a proxy (RABD_{660:670}) derived from hyperspectral analysis. Dotted horizontal lines mark midpoints between samples where pollen indicates transitions between human occupation periods (lower: pre-human to Māori settlement; upper: Māori to post-European settlement). (Right) CONISS plot of bacterial community composition. Colours denote human occupation periods, with light teal indicating the post-European period, medium teal indicating Māori occupation, and dark teal indicating the pre-human period. Red dashed lines indicate significant compositional change points. The x-axis represents dissimilarity between samples calculated using CONISS (sum of squared deviations), where larger values indicate greater compositional differences among samples

Bacterial community structure: The most pronounced significant shift in bacterial community structure aligned with the pre-European settlement period, and the second with the Māori settlement period (Figure 21).

Lake Ngakeketo

Pollen and Charcoal: The pollen and charcoal record from Lake Ngakeketo spans Māori and European settlement periods, with no pre-human sediments preserved (Figure 22). During Māori occupation, native taxa such as rimu and tree fern were prominent, while bracken fern reached very high abundances as did charcoal concentrations, indicating frequent burning and extensive vegetation disturbance. Following European arrival, pine and grass pollen became dominant, reflecting widespread land clearance and plantation forestry. Sedges and raupō occurred throughout the core with variable abundance (Figure 22).

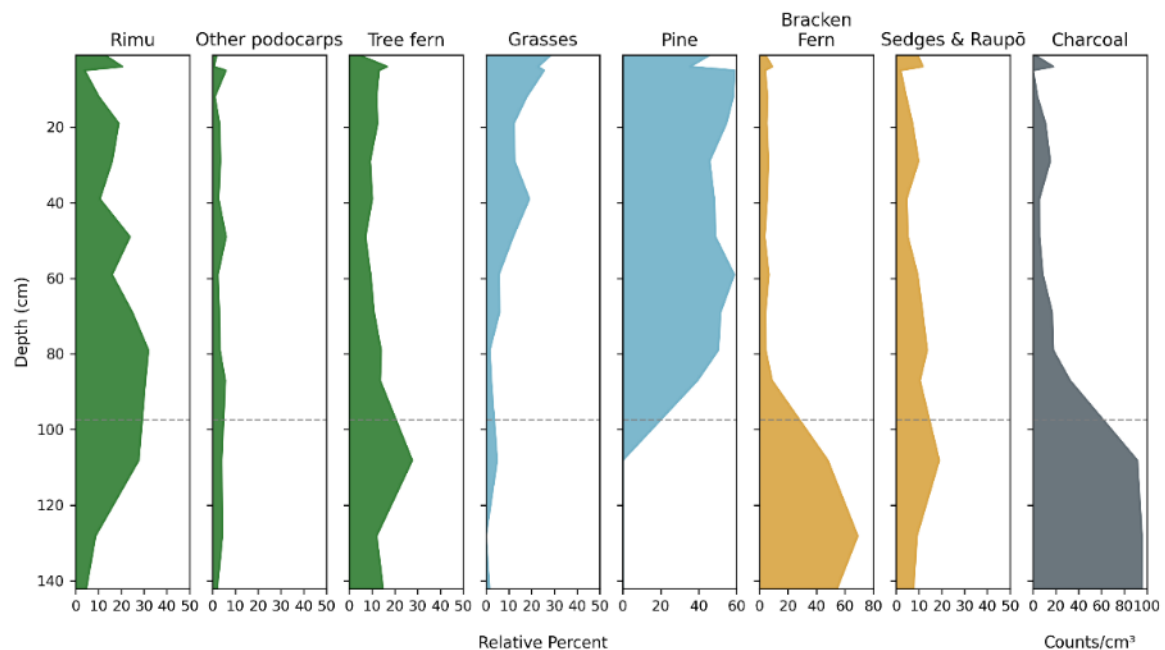


Figure 22. Downcore selected pollen and charcoal results for Lake Ngakeketo. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; transition from Māori settlement to post-European settlement.

Chl-*a* hyperspectral ratio: The Chl-*a* hyperspectral ratio was only available for the European settlement period (Figure 23). It shows a slight gradual increase through the upper section of the core, with very low or flat values in intervals corresponding to a large sand layers. A marked rise is observed in the top few centimetres (Figure 23).

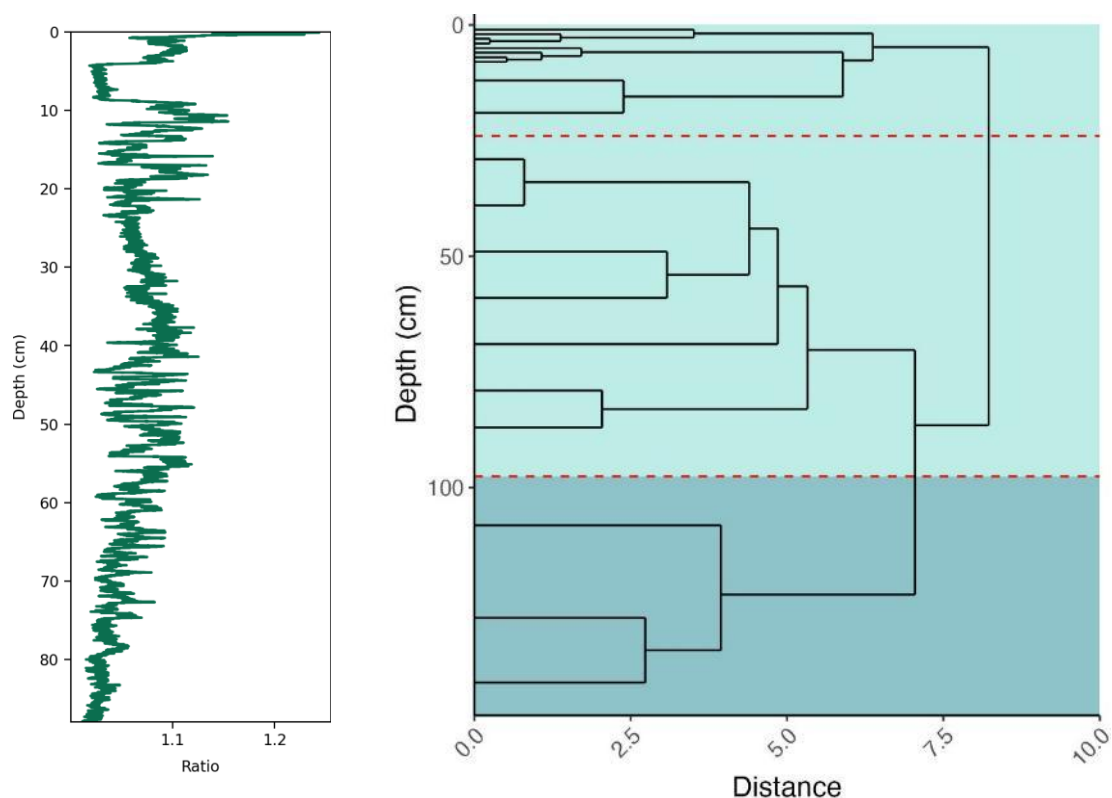


Figure 23. (Left) Downcore relative chlorophyll-a proxy (RABD_{660:670}) derived from hyperspectral analysis. Note only data from the top 90 cm is available. (Right) CONISS plot of bacterial community composition. Colours denote human occupation periods, with light teal indicating the post-European period and medium teal indicating Māori occupation. Red dashed lines indicate significant compositional change points. The x-axis represents dissimilarity between samples calculated using CONISS (sum of squared deviations), where larger values indicate greater compositional differences among samples.

Bacterial community structure: The most pronounced significant shift in bacterial community structure occurred in the top ~20 cm, with the second significant shift aligned with European settlement (Figure 23).

Lake Ngatu

Pollen and Charcoal: The pollen and charcoal record from Lake Ngatu show that prior to human arrival, the catchment was dominated by native forest, with consistently high proportions of rimu, other podocarps, and celery pine, indicating an intact forest and minimal disturbance (Figure 24). During Māori occupation, native taxa remained prominent, but bracken fern increased substantially, and charcoal concentrations rose sharply, consistent with forest disturbance and frequent burning. Following European arrival, pine pollen became dominant, and grasses also increased to more than 15%, reflecting widespread land clearance and plantation forestry. Native forest taxa declined but persisted at moderate levels (Figure 24).

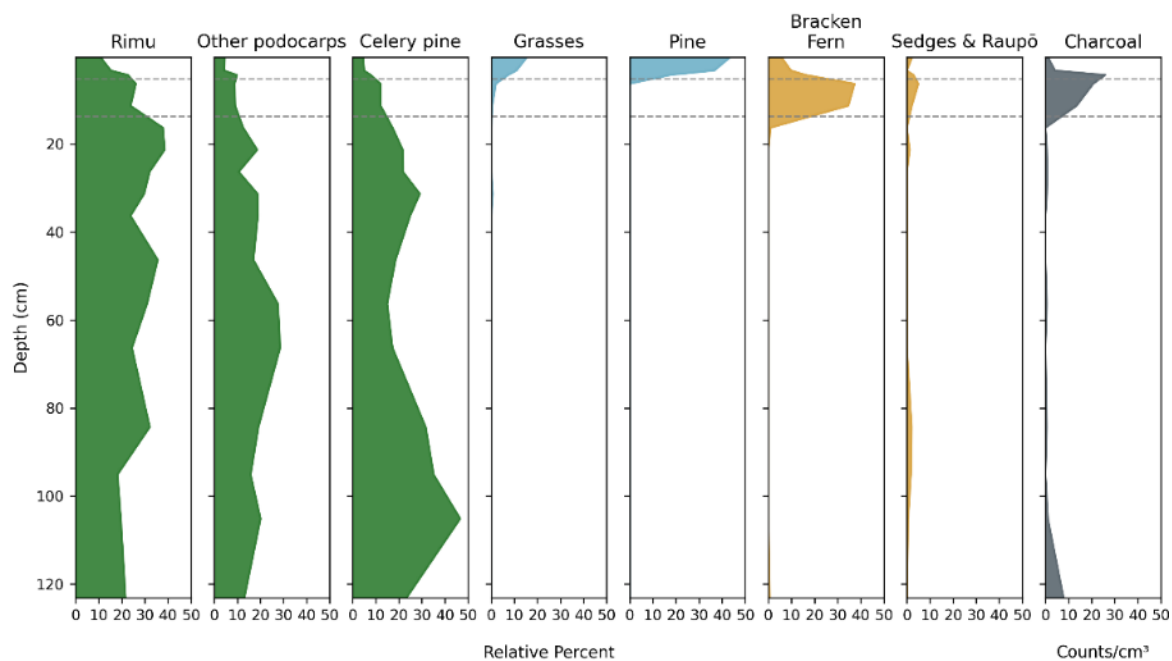


Figure 24. Downcore selected pollen and charcoal results for Lake Ngatu. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement.

Chl-*a* hyperspectral ratio: The pre-human Chl-*a* hyperspectral ratio is marked by stability (Figure 25). A slight increase occurs around the time of Māori settlement, and a strong rise is evident in the upper ~5 cm, corresponding to shortly after European settlement (Figure 25).

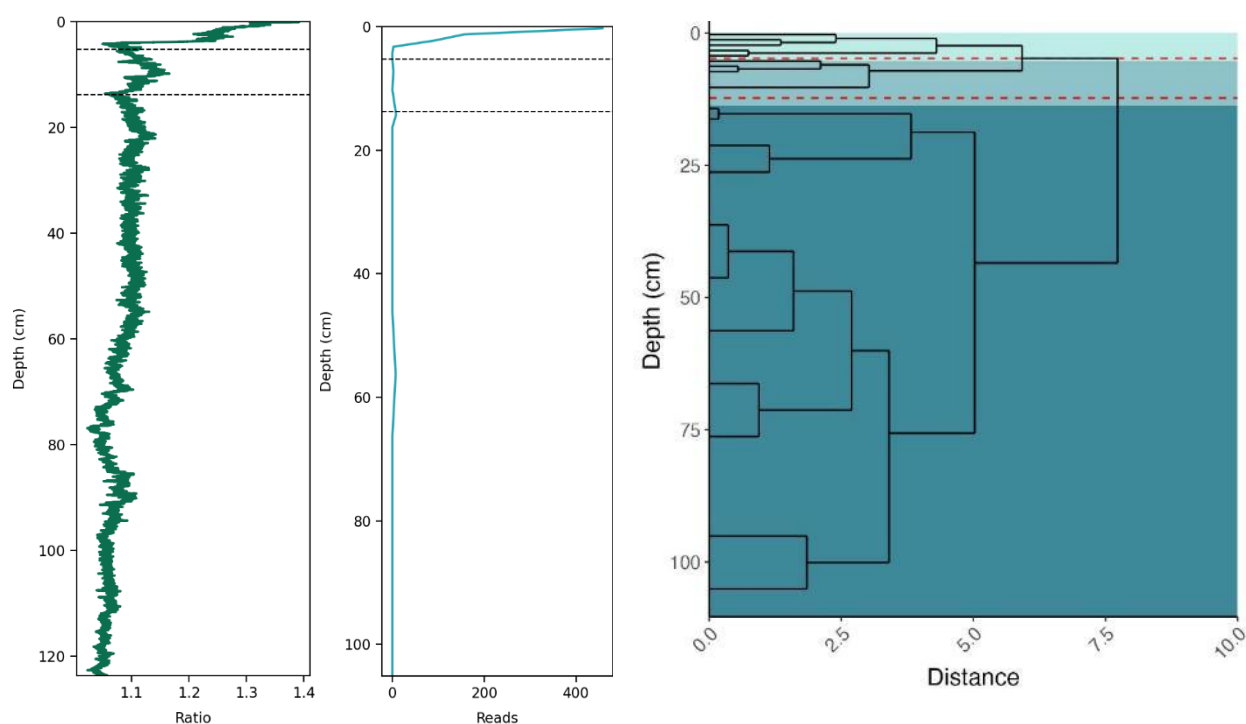


Figure 25. (Left) Downcore relative chlorophyll-a proxy ($RABD_{660:670}$) derived from hyperspectral analysis. (Middle) Cyanobacterial environmental DNA reads. Note different depths are shown on these two plots. On both plots, dotted horizontal lines mark midpoints between samples where pollen indicates transitions between human occupation periods (lower: pre-human to Māori settlement; upper: Māori to post-European settlement). (Right) CONISS plot of bacterial community composition. Colours denote human occupation periods, with light teal indicating the post-European period, medium teal indicating Māori occupation, and dark teal indicating the pre-human period. Red dashed lines indicate significant compositional change points. The x-axis represents dissimilarity between samples calculated using CONISS (sum of squared deviations), where larger values indicate greater compositional differences among samples.

Cyanobacteria and bacterial community structure: Cyanobacteria were absent from most of the core but increased markedly in the top ~5 cm (Figure 25). The bacterial community structure shifted significantly around the time of Māori occupation, and there is a further less pronounced change after European settlement (Figure 25).

Lake Taharoa

Pollen and Charcoal: Based solely on vegetation change, it is difficult to establish the depth or timing of Māori settlement in the area around Lake Taharoa. Based on pollen, this transition is estimated at approximately 14 cm, indicating very low sedimentation during the period from Māori settlement to European arrival. Some preliminary age modelling suggests it might instead occur around 20 cm. For the description below, the 14 cm delineation has been used.

Prior to human arrival, the catchment was dominated by podocarps, particularly kauri and rimu (Figure 26). During the period of Māori occupation, kauri and rimu remained dominant, with a slight increase in bracken fern and small amounts of charcoal, suggesting localised burning and minor vegetation change. Following European settlement, pine pollen increased markedly, alongside bracken fern and grasses, reflecting land clearance, establishment of exotic forestry, and more frequent burning. Native forest taxa persisted but generally declined through the European period (Figure 26).

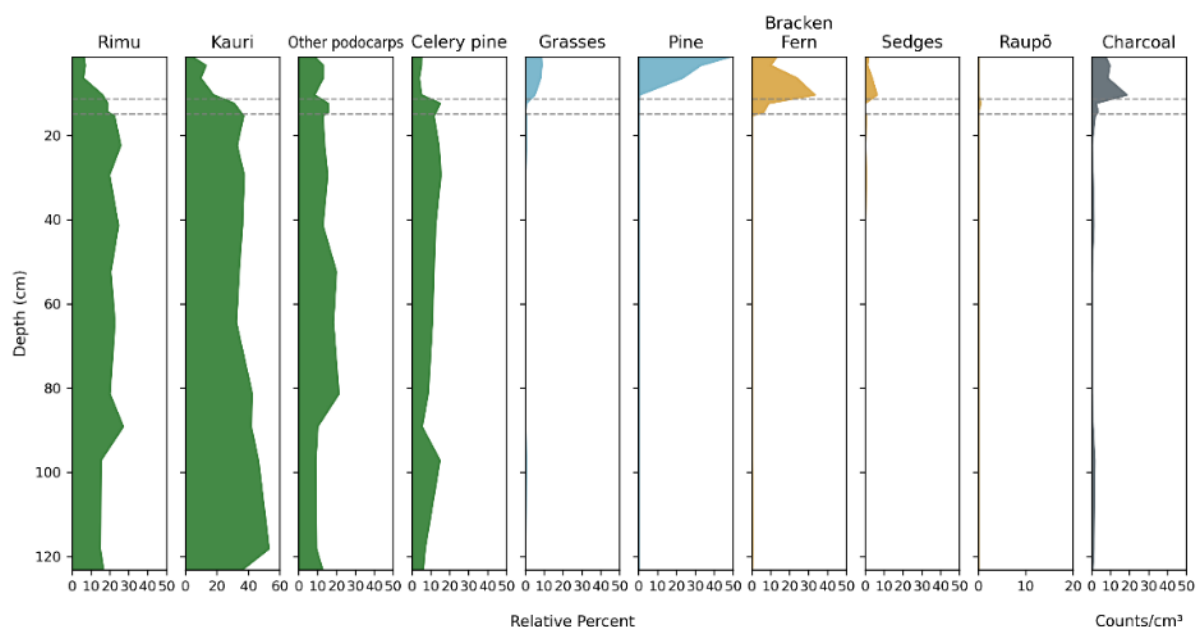


Figure 26. Downcore selected pollen and charcoal results for Lake Taharoa. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement.

Chl-*a* hyperspectral ratio: The Chl-*a* hyperspectral ratio was stable during the pre-human and Māori periods (Figure 27). There is a marked increase in the upper ~11 cm during the post-European settlement period, albeit this decreases over the last ~3 cm (Figure 27).

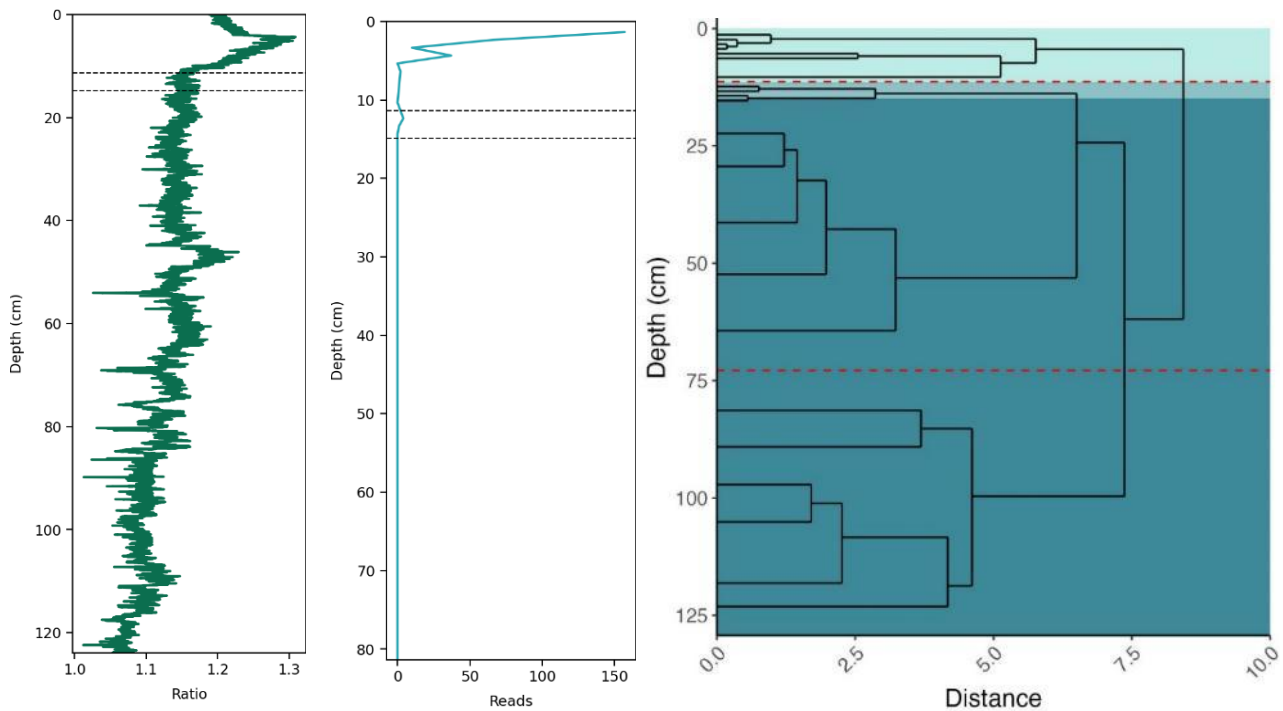


Figure 27. (Left) Downcore relative chlorophyll-a proxy (RABD_{660:670}) derived from hyperspectral analysis. (Middle) Cyanobacterial environmental DNA reads. Note different depths are shown on these two plots. On both plots, dotted horizontal lines mark midpoints between samples where pollen indicates transitions between human occupation periods (lower: pre-human to Māori settlement; upper: Māori to post-European settlement). (Right) CONISS plot of bacterial community composition. Colours denote human occupation periods, with light teal indicating the post-European period, medium teal indicating Māori occupation, and dark teal indicating the pre-human period. Red dashed lines indicate significant compositional change points. The x-axis represents dissimilarity between samples calculated using CONISS (sum of squared deviations), where larger values indicate greater compositional differences among samples

Cyanobacteria and bacterial community structure: Cyanobacteria were absent from most of the core but increased markedly in the top ~5 cm (Figure 27). The bacterial community structure changes significant during the prehuman period, but the most pronounced change occurs post European settlement (Figure 27).

Te Kahika

Pollen and Charcoal: The pollen and charcoal records from Lake Te Kahika indicate that prior to human arrival, the catchment was dominated by native forest, with high proportions of kauri and rimu, and negligible charcoal, suggesting an intact forest with minimal disturbance (Figure 28). Following Māori settlement in the region, native taxa persisted, but bracken fern became abundant and charcoal concentrations increased markedly, reflecting repeated burning and forest disturbance. Rimu remained common, though forest composition became more variable, and sedges expanded, suggesting wetland development. During the European period, pine pollen became dominant, while grasses increased and native flora declined sharply (Figure 28).

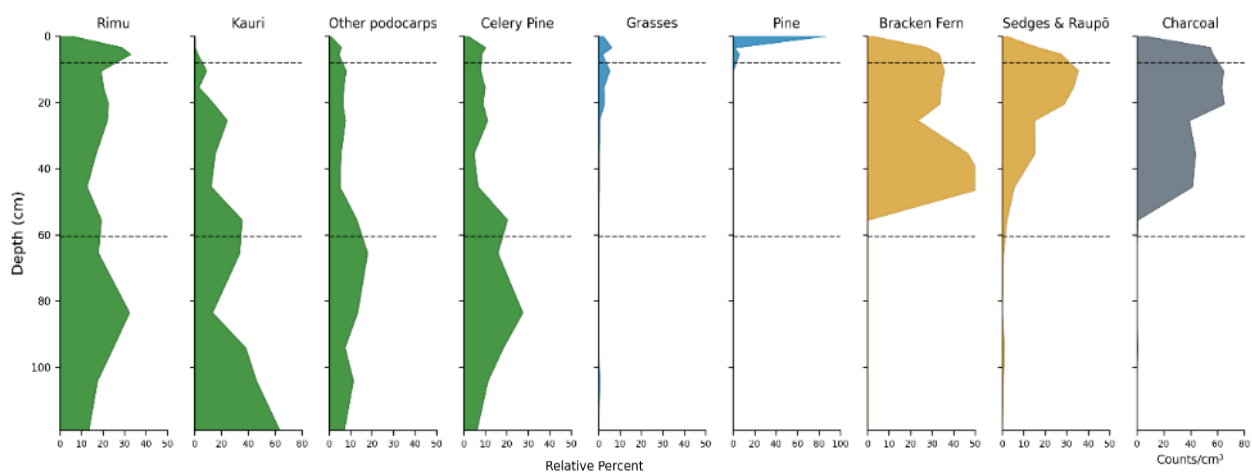


Figure 28. Downcore selected pollen and charcoal results for Lake Te Kahika. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement.

Chl-*a* hyperspectral ratio: The Chl-*a* hyperspectral ratio was relatively stable in pre-human sediments (Figure 29). A gradual increase begins during the Māori settlement period, and a small rise occurs in the upper ~8 cm during the post-European settlement period, albeit with considerable variability in this part of the sediment core (Figure 29).

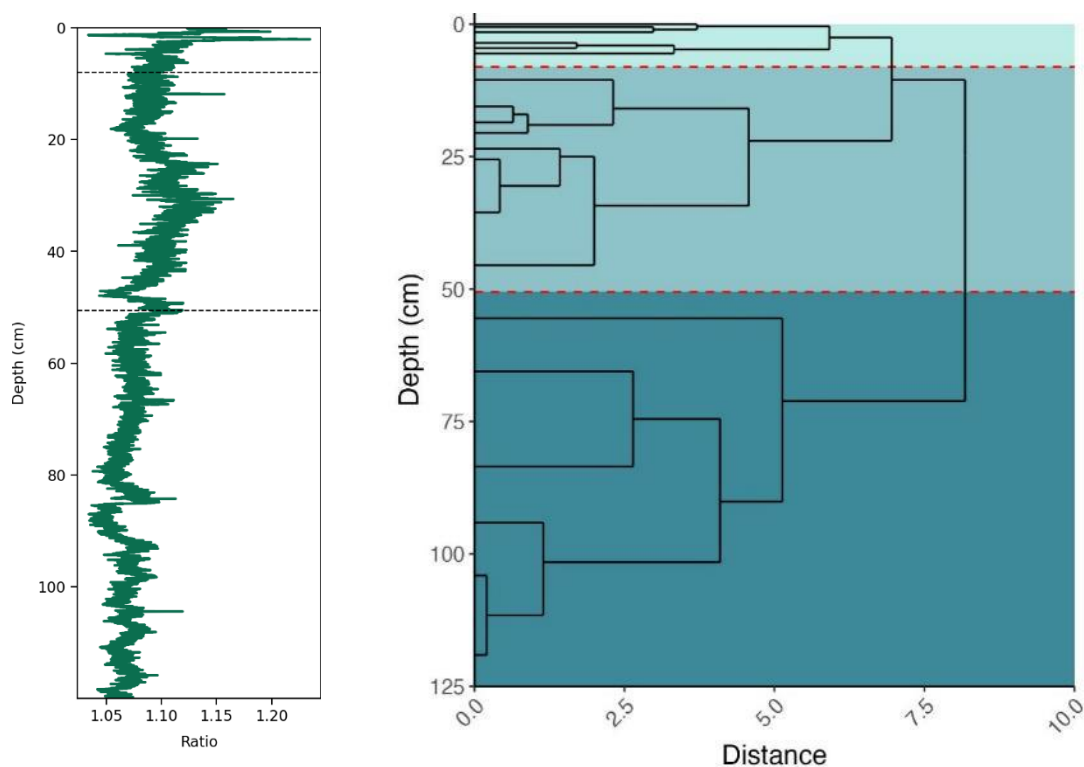


Figure 29. (Left) Downcore relative chlorophyll-a proxy ($RABD_{660:670}$) derived from hyperspectral analysis. Dotted horizontal lines mark midpoints between samples where pollen indicates transitions between human occupation periods (lower: pre-human to Māori settlement; upper: Māori to post-European settlement). (Right) CONISS plot of bacterial community composition. Colours denote human occupation periods, with light teal indicating the post-European period, medium teal indicating Māori occupation, and dark teal indicating the pre-human period. Red dashed lines indicate significant compositional change points. The x-axis represents dissimilarity between samples calculated using CONISS (sum of squared deviations), where larger values indicate greater compositional differences among samples.

Bacterial community structure: Bacterial community structure in the pre-human period differed significantly from that following Māori settlement, with a second significant shift occurring after European settlement (Figure 29).

Lake Wahakari

Pollen and Charcoal: The pollen and charcoal record from Lake Wahakari indicate that prior to human arrival, the catchment was dominated by native forest, with high and stable proportions of rimu, kauri, other podocarps, and celery pine, and very low charcoal concentrations, suggesting an intact forest with minimal disturbance (Figure 30). During Māori occupation, native forest taxa remained abundant; however, there were marked increases in bracken fern, accompanied by pronounced peaks in charcoal, indicating episodes of burning and vegetation disturbance. Rimu remained dominant through this period, although greater variability in forest composition is evident. Following European arrival, which is captured only in the upper few centimetres of the sediment core suggesting very low sedimentation rates, pine pollen became overwhelmingly dominant, comprising more than 80% of the assemblage, while grasses also increased (Figure 30).

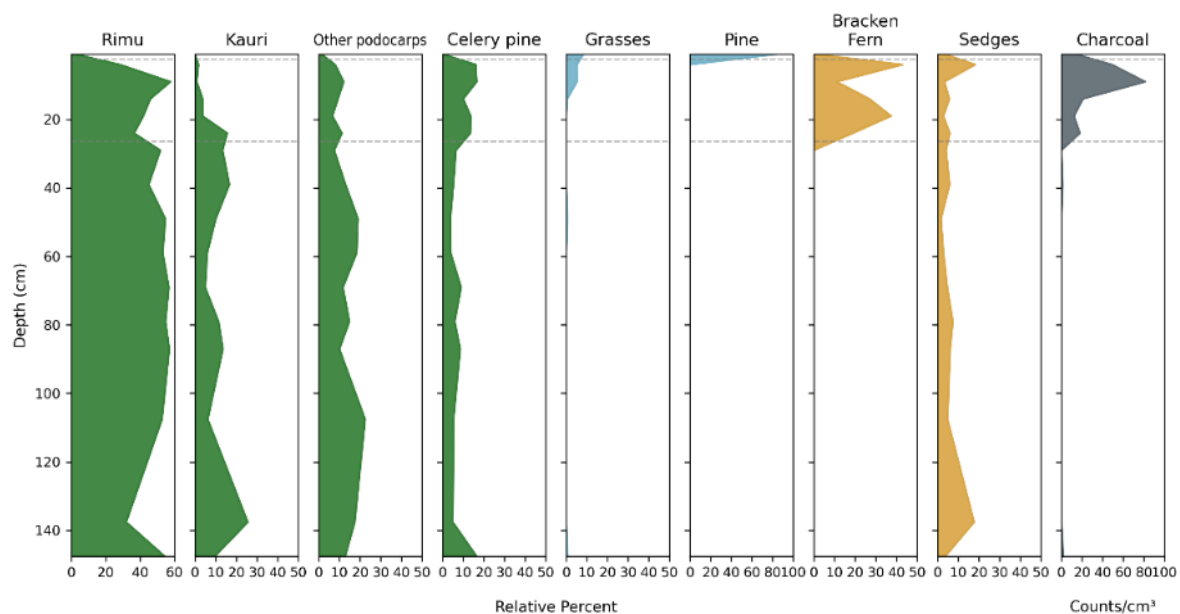


Figure 30. Downcore selected pollen and charcoal results for Lake Wahakari. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement.

Chl-*a* hyperspectral ratio: The Chl-*a* hyperspectral ratio increases gradually across the pre-human period and then decreases markedly following Māori settlement (Figure 31). There is a strong upward trend starting at the end of the Māori settlement period (about 8 cm) which continues to the top of the sediment core (Figure 31).

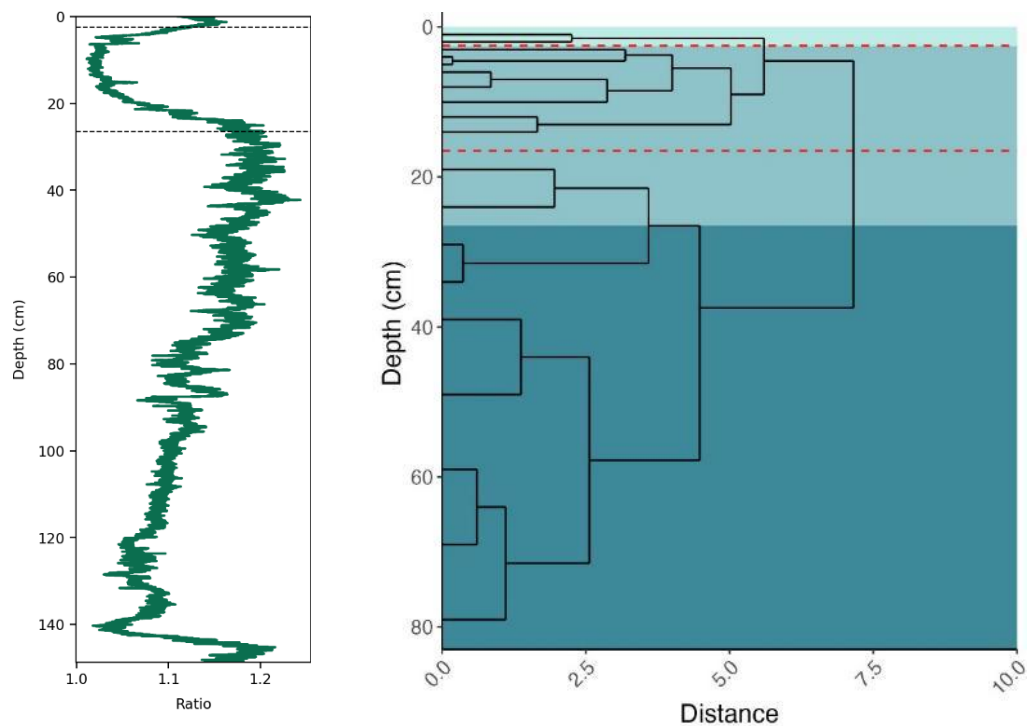


Figure 31. (Left) Downcore relative chlorophyll-a proxy ($RABD_{660:670}$) derived from hyperspectral analysis. Dotted horizontal lines mark midpoints between samples where pollen indicates transitions between human occupation periods (lower: pre-human to Māori settlement; upper: Māori to post-European settlement). (Right) CONISS plot of bacterial community composition. Colours denote human occupation periods, with light teal indicating the post-European period, medium teal indicating Māori occupation, and dark teal indicating the pre-human period. Red dashed lines indicate significant compositional change points. The x-axis represents dissimilarity between samples calculated using CONISS (sum of squared deviations), where larger values indicate greater compositional differences among samples.

Bacterial community structure: Bacterial community structure shifted significantly during the period following Māori settlement, with a second, smaller shift aligned with the European settlement period (Figure 31).

Lake Wai Raupo

Pollen and Charcoal: The pollen and charcoal record from Lake Wai Raupo spans the Māori and European periods only, with no pre-human section captured in the sediment core, suggesting fast sedimentation rates (Figure 32). During the Māori period, the catchment was dominated by native forest taxa, particularly rimu and tree ferns; however, bracken fern also abundant, and charcoal concentrations were consistently high, indicating frequent burning and substantial vegetation disturbance. Following European arrival, pine pollen became a major component of the assemblage, particularly in the upper sediments, while grasses increased, reflecting land clearance and the establishment of pasture and plantation forestry in the region. Native forest taxa persisted but declined through the European period (Figure 32).

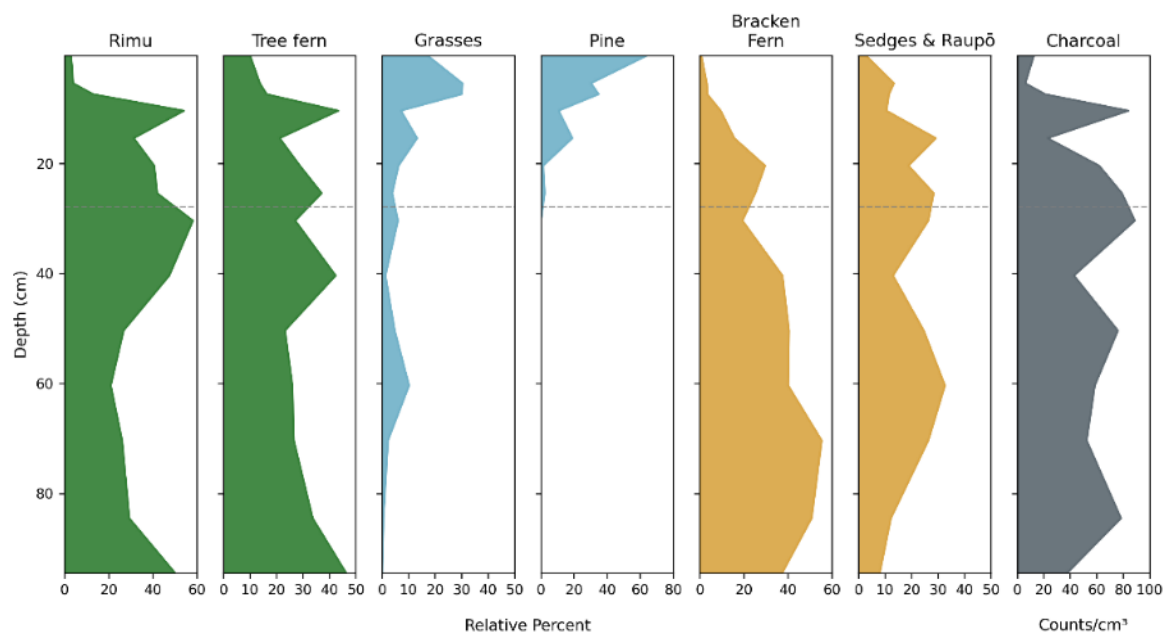


Figure 32. Downcore selected pollen and charcoal results for Lake Wai Raupo. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras: transition from Māori settlement to post-European settlement.

Chl-*a* hyperspectral ratio: The Chl-*a* hyperspectral ratio remains relatively stable during the period of Māori settlement (Figure 33). A clear increase occurs in the upper ~8 cm during the latter part of the post-European settlement phase, with the strongest rise near the surface (Figure 33).

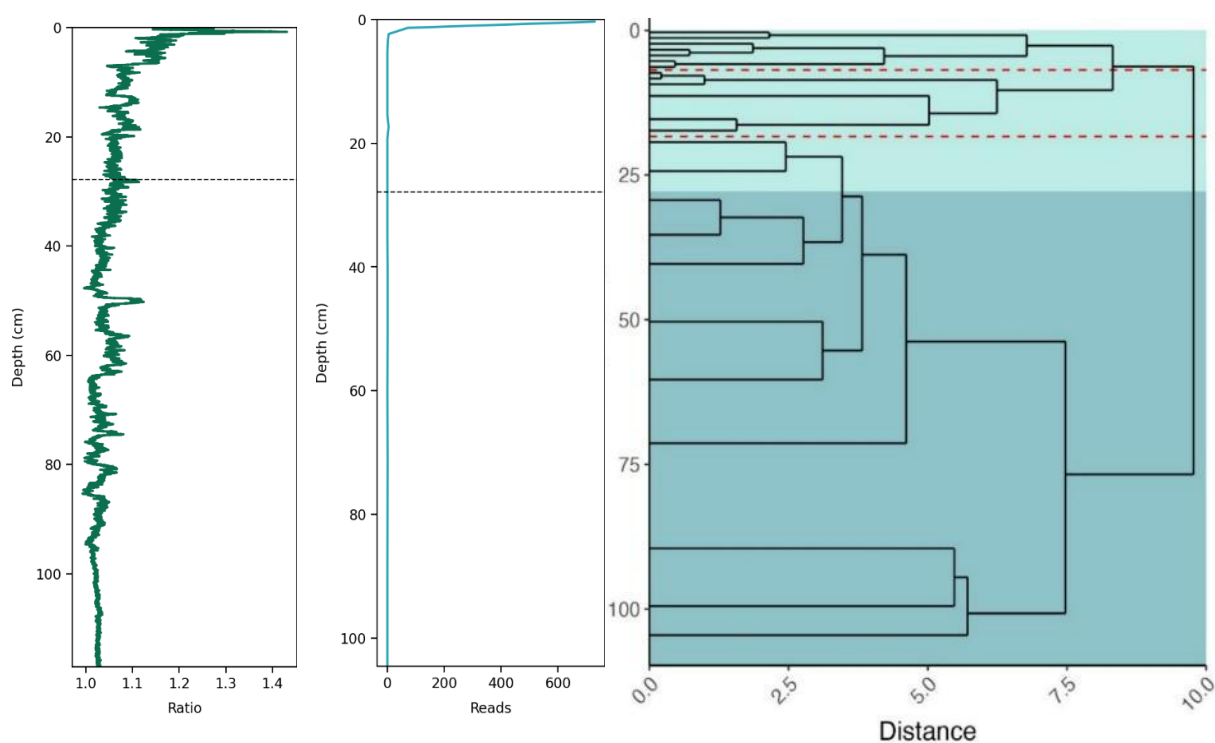


Figure 33. (Left) Downcore relative chlorophyll-a proxy (RABD_{660:670}) derived from hyperspectral analysis. (Middle) Cyanobacterial environmental DNA reads. Note different depths are shown on these two plots. On both plots, dotted horizontal lines mark midpoints between samples where pollen indicates transitions between Māori to post-European settlement occupation periods. (Right) CONISS plot of bacterial community composition. Colours denote human occupation periods, with light teal indicating the post-European period and darker teal indicating Māori occupation. Red dashed lines indicate significant compositional change points. The x-axis represents dissimilarity between samples calculated using CONISS (sum of squared deviations), where larger values indicate greater compositional differences among samples.

Cyanobacteria, and bacterial community structure: Cyanobacteria appear only in the most recent sediments (Figure 33). The two most significant shifts in the bacterial community structure in this core occur post European settlement, the most recent being in the top ~5 cm, though we note that this core does not extend to the pre-human phase (Figure 33).

Lake Waiporohita

Pollen and Charcoal: The pollen and charcoal records from Lake Waiporohita indicate that prior to human arrival, the catchment was dominated by native forest, with high proportions of beech, rimu, and other podocarps, and low charcoal concentrations, indicating relatively undisturbed conditions (Figure 34). During the period when Māori settlement is evident in the region, native forest taxa remained abundant; however, bracken fern increased and charcoal concentrations were elevated, suggesting episodes of burning and vegetation disturbance. Beech and podocarps persisted but showed greater variability, indicating changes in forest composition. Following European arrival, grasses and pine became prominent components of the pollen assemblage, reflecting land clearance, pasture development, and plantation forestry in the region (Figure 34).

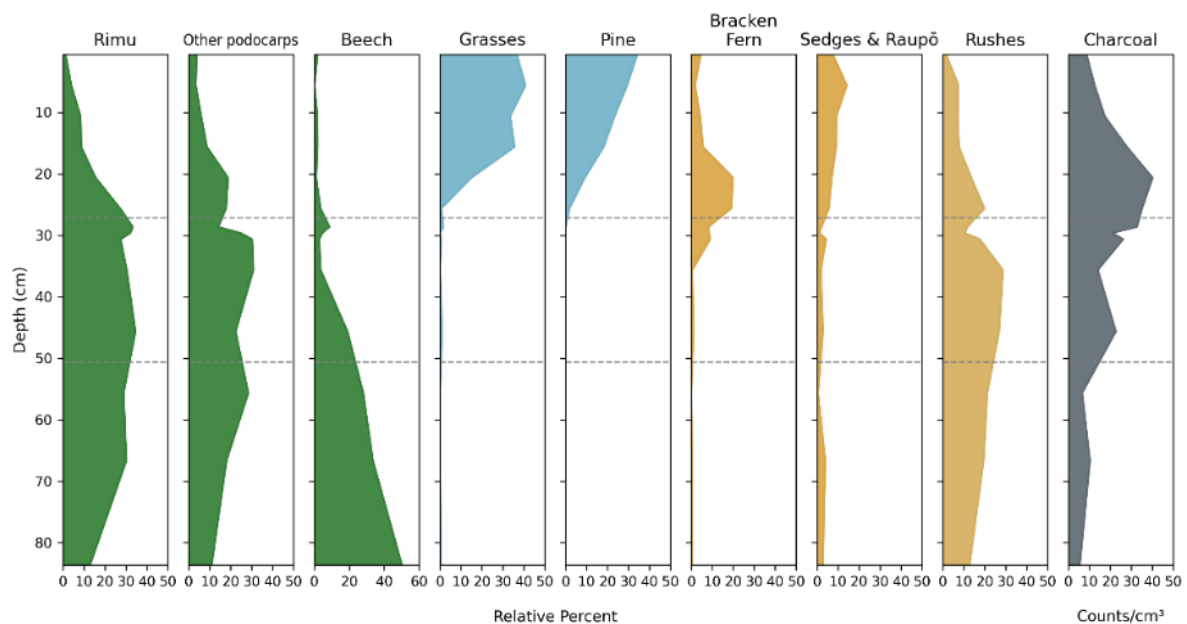


Figure 34. Downcore selected pollen and charcoal results for Lake Waiporohita. The dotted lines cross the midpoint between the two samples with pollen indicative of the different human occupation eras; bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement.

Chl-*a* hyperspectral ratio: The Chl-*a* hyperspectral ratio remains relatively stable during the pre-human period (Figure 34). A gradual increase begins after Māori settlement, and a sharp rise is evident in the upper ~20 cm during the post-European settlement period (Figure 34).

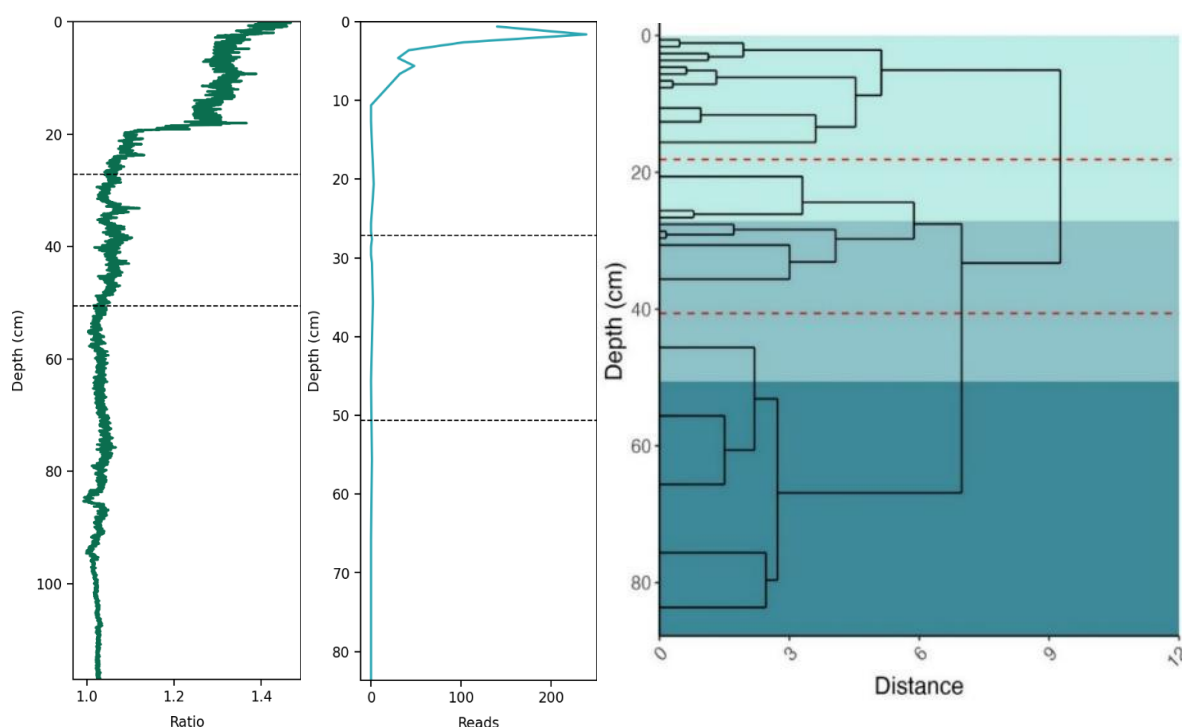


Figure 35. (Left) Downcore relative chlorophyll-a proxy ($RABD_{660:670}$) derived from hyperspectral analysis. (Middle) Cyanobacterial environmental DNA reads. Note different depths are shown on these two plots. On both plots, dotted horizontal lines mark midpoints between samples where pollen indicates transitions between human occupation periods (lower: pre-human to Māori settlement; upper: Māori to post-European settlement). (Right) CONISS plot of bacterial community composition. Colours denote human occupation periods, with light teal indicating the post-European period, medium teal indicating Māori occupation, and dark teal indicating the pre-human period. Red dashed lines indicate significant compositional change points. The x-axis represents dissimilarity between samples calculated using CONISS (sum of squared deviations), where larger values indicate greater compositional differences among samples.

Cyanobacteria and bacterial community structure: Cyanobacterial abundance increased markedly in the upper 10 cm of the sediment core (Figure 35). The most significant shift in bacterial community structure occurred post-European settlement, approximately aligned with the strong increase in Chl-*a* hyperspectral signal. A second significant shift occurred during the post-Māori settlement period (Figure 35).

Discussion

This report brings together contemporary water chemistry, surface sediment geochemistry, and paleolimnological evidence from the Lakes380 project to provide information on current condition and historical changes of lakes in the Northland region.

Although the Lakes380 programme applied standardised sampling methods across sites, it is important to recognise that all water chemistry measurements from the programme represent single time-point observations. Water chemistry is highly dynamic in both time and space and must therefore be interpreted with caution and, where possible, contextualised against longer-term regional monitoring datasets (e.g. NRC data). Some long-term data is available for 21 of the 37 lakes sampled for Lake380 which includes quarterly monitored discrete water quality data ([Environmental data hub](#)), and we recommend this is viewed alongside this report. In contrast to single-time-point samples, surface sediments integrate environmental conditions over months to years, while sediment cores extend this perspective over decades to centuries. It should be noted however, that surface sediment samples represent a single site and hence may not reflect the spatial variability common in sediment geochemistry.

Key findings

- Despite extensive catchment modification, about fifteen dune lakes are likely oligotrophic or mesotrophic, representing nationally rare and significant ecosystems. However, this classification is uncertain. Limited long-term data is available (not analysed in this report) from NRC for some lakes, thus our assessments mostly rely on the SBTI which is an eDNA-derived metric. In lakes where both datasets were available, discrepancies were sometimes observed.
- The risk of internal nutrient loading is elevated in many lakes, with sediments containing large pools of potentially mobile phosphorus. Of particular concern are oligotrophic and mesotrophic lakes with high amounts of biologically available phosphorus, such as Kai-iwi, Rotokawau (Aupōuri) and particularly Waikare. These systems may be especially vulnerable to further degradation.
- Elevated metal concentrations were detected in surface and hypolimnion water samples, as well as in surface sediments from some lakes. As these data are based on single time-point sampling, further monitoring is recommended to confirm these results. However, the findings likely indicate contamination from catchment-derived sources. Some concentrations approach levels that may pose risks to aquatic organisms.
- Paleolimnological records show significant catchment vegetation change over the last 500-1000 years, consistent increases in algal abundance and shifts in bacterial community composition. While broad trends are consistent across sites, important site-specific differences are evident, likely reflecting variation in catchment geomorphology, land use, and stressors such as non-native species.

Trophic level, water chemistry and zooplankton

Determining the trophic class of a lake traditionally requires monthly or seasonal measurements of nutrients, water clarity and Chl-*a*, which are then used to calculate the TLI. Best practice

recommends data collection for at least three years. While this approach provides robust assessments, it is not feasible for assessing large numbers of lakes. As an alternative, the Lakes380 team developed an eDNA-based tool that uses bacterial communities in a surface sediment sample to estimate trophic status. This method, known as the SBTI, was applied in this study. Thirteen lakes assessed using SBTI also had corresponding TLI data, enabling direct comparison of methods. Marked discrepancies were observed, which was unexpected given that the two approaches have previously shown strong congruence (Pearman et al., 2022). This may reflect a stronger coastal or saline influence in these lakes, which has been shown to affect SBTI performance. We recommend further validation of the index in this region prior to wider application.

Using combined TLI and SBTI assessments, about fifteen dune lakes are likely oligotrophic or mesotrophic. Oligotrophic and mesotrophic dune lakes are rare, and this finding supports ongoing work by NRC to protect these lakes from nutrient enrichment and the spread of non-native species (e.g., the Kai Iwi Lakes Management Plan).

Limitations

As noted above, the water-chemistry data generated through Lakes380 were collected from single time-point samples, which limits the ability to characterise temporal variability. Fortunately, for multiple Northland lakes which were assessed in Lakes380, long-term data exist for nutrients and several other parameters such as TSS and VSS. In lakes where such datasets are unavailable, the single time-point Lakes380 samples provide useful first indications of likely concentrations and can help identify sites where further monitoring may be warranted. For example, Lake Katavich had very high concentrations of most nutrients, suspended solids, and organic carbon in the Lakes380 samples, yet is not currently part of any routine monitoring programme.

High trace metals detected

Trace metals are rarely measured in lakes in Aotearoa New Zealand, meaning that although the Lakes380 sample set is based on one-off measurements, these data can serve as a preliminary screen for potential areas of concern. Among the trace-metal results, Lake Waitahora stood out, however, these results must be interpreted with caution. Access to the main basin of the lake was not possible due to an extensive raupō margin, and sampling therefore occurred at the lake outlet, which was estuarine. A saline influence is likely, meaning that the trace-metal concentrations from this site probably reflect a mixed freshwater–estuarine signal rather than true lake conditions.

Outside Waitahora, several lakes water and the surface or hypolimnion showed elevated trace-metal concentrations that may warrant further investigation:

- Arsenic was found to be above the national median in some lakes, most notably in Lake Kanono. In Lake Rotokawau (Poutō) the hypolimnion sample had slightly elevated arsenic concentrations observed are likely attributable to sediment release under low-oxygen conditions in this relatively deep lake. Given the low magnitude of enrichment, these levels are unlikely to pose a significant risk to biota such as kākahi, although further targeted studies would be required to confirm this

- Chromium, copper and lead were substantially elevated in Lake Rotopokaka. This may relate to catchment geology or, less likely, legacy industrial contamination, as the catchment contains no urban land.
- Lead exceeded the national median in several lakes, most notably Katavich and Rotopokaka. This is possibly linked to leaded petrol (phased out in ~1996). Lead concentrations in both lakes (0.82–0.92 mg/m³) were well below the New Zealand drinking-water maximum acceptable value of 10 mg/m³ indicating negligible risk to human health and livestock, as well as the ANZG trigger values for aquatic ecosystems (3.4 mg/m³), suggesting that immediate ecological risk is likely low.
- Nickel and zinc were elevated in the hypolimnion of Lake Te Kahika, which may indicate redox-mediated mobilisation from sediments under reducing conditions.

In all these cases, we recommend resampling over multiple months, complemented by efforts to reconstruct the environmental history of each lake and its catchment. This may require interviews with local community members, iwi and hapū, and review of grey literature and archived reports. Such work was beyond the scope of this project but would significantly strengthen interpretation. A further option to determine whether elevated trace-metal concentrations are recent or long-standing would be to analyse sediment-core samples, which can reveal historical levels to help distinguish between natural and anthropogenic sources.

Zooplankton

Daphnia was only detected in 12 lakes. The non-native *D. pulicaria/pulex* complex was found in Kapoai and its presence warrants further attention given the potential for it to outcompete native species and alter grazing pressure and food-web dynamics. A Lincoln University PhD student is currently using eDNA to characterise the full zooplankton communities in these samples, with results expected in 2027.

Surface sediment

Several lakes showed distinct geochemical signatures that warrant further consideration.

- Sulphur was particularly high in sediments from Waiparera, potentially indicating active sulphate reduction and low oxygen conditions.
- Elevated zinc in Carrot and Rotootuauru, along with high lead in Waikare and Rotoroa, could reflect contributions from historic land uses or localised point sources.
- High cadmium in Waiporohita may be linked to the legacy of cadmium-rich phosphate fertilisers.
- Enhanced copper in a subset of lakes (Carrot, Kai-iwi, Rotokawau ((Aupōuri), Rototuna, Waiporohita) may reflect contributions from underlying geological sources and/or catchment influences.

We recommend additional sampling to verify these concentrations, ideally incorporating spatial replication within each lake, alongside the sediment core analyses and environmental history reconstruction outlined above. The recently published *Northland's Landscape Driven Erosion Map* (Gunn and Rissmann, 2025) could also be used to assess whether underlying geological erosion risk helps explain the elevated metal concentrations observed in some lakes.

Sediment eDNA results

The sediment eDNA results highlight that Northland lakes support distinct microbial communities, likely reflecting differences in catchment influence, trophic state, sediment chemistry, and physical habitat conditions. The clear separation of sites in the bacterial ordination suggests that even lakes located within the same geographic region can maintain markedly different benthic microbial assemblages. Dominance by Gammaproteobacteria in many lakes is consistent with communities adapted to organic-rich, often anoxic sediment environments, while the presence of groups such as Verrucomicrobiae, Desulfobacteria, or Dehalococcoidia lakes hints at more specialised processes such as sulphur cycling, degradation of complex organic matter, or strongly reducing sediment conditions.

In contrast, the eukaryotic assemblages showed clearer differences between lakes than the microbial communities. This suggests that each lake has its own distinct community, likely influenced by things like macrophytes, habitat type, or the presence of introduced species. Most lakes were dominated by algae that use sunlight for energy, which is typical of healthy lake systems. However, in some lakes we found ostracods, flatworms, or nematodes, which can indicate differences in lake-bed sediment, oxygen levels, or food-web structure.

Phosphorus-fractionation

Results indicate that many lakes contain substantial pools of potentially available phosphorus. The most available fraction is the Ex-P fraction which is generally very low and highly seasonal in its availability.

- In several systems (for example Heather, Kahuparere, Kanono, Karaka, Rotootuauru, and Waikare), the *redox-sensitive P-pool* is elevated, suggesting an increased likelihood of internal loading during periods of low dissolved oxygen.
- In many of the Northland lakes including Carrot, Kai-Iwi, Rotokawau (Aupōuri, East, Karikari), Rotootuauru, Rotoroa and Rototuna, Waipara, Waiporohita, the *organic P pool* is large. The release from this fraction is generally relatively slow during organic degradation but does represent a significant source of P which may be incorporated into internal P loading cycles.
- The *elevated pH-extractable fractions* implies that significant release could occur under high pH conditions, such as during intense phytoplankton blooms. While sediments in deeper lakes are less likely to be affected by elevated pH, several shallow (≤ 4 m) Northland lakes e.g. Katavich, Rotokawau (East, Karikari), Rototuna and Waiporohita have high levels of pH-P and are likely vulnerable to pH driven P cycling. This is consistent with the mechanisms described by Waters et al. (2021), where elevated pH associated with photosynthetic activity promotes phosphorus desorption from Fe- and Al-oxide surfaces through hydroxyl competition and surface charge effects, enhancing the mobilisation of sediment-bound P into the water column.
- Of particular concern are oligotrophic and mesotrophic lakes that contain large stores of *biologically available phosphorus*, including Kai-iwi, Rotokawau (Aupōuri), and Waikare. The potentially mobile P pools in Kai-Iwi and Rotokawau

(Aupōuri) are dominated by organic-P, somewhat reducing immediate internal loading risk. However, Waikare has a relatively large redox sensitive P content and is likely to be very susceptible to changes in dissolved oxygen concentrations. These systems are at heightened risk of transitioning to more eutrophic states. Preventing further decline is far easier than reversing it once internal loading becomes entrenched; however, standard catchment-focused measures such as riparian planting and reducing diffuse nutrient inputs may not be sufficient on their own if sediments are already primed to release phosphorus.

Recommendations

To better understand the risk of internal nutrient loading, we recommend continuous water-column monitoring using temperature, pH, and dissolved-oxygen loggers placed at key depths (or at minimum, surface and bottom sensors). Such monitoring would help identify whether conditions conducive to redox- or pH-mediated desorption are occurring. Climate change is likely to exacerbate these risks, with projections indicating more frequent and prolonged droughts that will place small, shallow lakes under increased water-level stress, alongside more intense rainfall events that may deliver pulses of nutrients and sediments to lake systems in the region (Eveleens et al. 2025). Catchment responses may further compound these pressures, as land-use changes such as plantation forestry can reduce flows and contribute to declining lake levels, increasing the vulnerability of these systems to internal nutrient loading and ecological degradation.

Because internal loading can sustain eutrophication for many years even after external inputs are reduced, any mitigation strategy should consider options that directly reduce internal cycling, ranging from sediment capping and alum dosing to targeted sediment removal. These approaches have been used with varying degrees of success in lakes around Aotearoa New Zealand, including alum dosing in small, eutrophic lakes such as Lake Okaro (Rotorua region), where reductions in epilimnetic phosphorus concentrations and improvements in trophic state have been observed (Tempero 2023). These decisions need to be guided by lake-specific feasibility, risks, and cultural consideration, e.g. recent work supporting alum dosing at Lake Moawhiti, Rangitoto ki te Tonga / D'Urville Island, by Kelly et al. (2019) and Schallenberg et al. (2024). It is important to note that the Lakes380 fractionation data come from a single sediment sample per lake and this data should not be used in isolation to guide restoration decisions. A spatially distributed study of phosphorus fractions within each lake is required to provide a more robust basis for management planning.

Paleolimnological insights

Although 37 lakes were sampled in the Lakes380 project, only 10 cores were processed due to resource limitations. Of the sediment cores processed, only Lake Kapoai has undergone detailed multi-indicator analysis, restricting interpretation for the remaining lakes. The Kapoai core clearly demonstrates the depth of insight that full paleolimnological processing can provide. Lake Kapoai was selected for detailed analysis as part of a broader study examining lakes in areas of high-intensity agricultural land use. Within the Northland lake set, Kapoai was chosen because it

exhibits one of the highest sedimentation rates during the post-European settlement period, providing an extensive sediment record for analysis.

Expanding detailed analyses to additional cores would substantially improve our understanding of long-term ecological change across the region. Comprehensive paleolimnological approaches (including diatom analysis, sedimentary ancient eDNA (sedaDNA) of organisms other than bacteria, and expanded geochemical profiling) could reconstruct past water quality, identify shifts in biodiversity, and distinguish between catchment-driven versus in-lake processes. For example, diatom assemblages provide robust indicators of historical nutrient status and trophic change, while sedaDNA enables reconstruction of higher trophic-level communities and biodiversity shifts over time. Additional geochemical analyses (e.g. trace metals) could further constrain changes in terrestrial sediment inputs, erosion processes, and redox dynamics such as the development of anoxia. Based on costs in 2026, full multi-proxy analysis is estimated at approximately NZ\$20-30,000 per core, with processing and interpretation typically requiring several months per lake depending on analytical scope.

A regional sequence of human impact

While each lake has its own unique sediment history, the available records reveal a set of broad regional patterns. Across the study lakes, pollen, charcoal, hyperspectral Chl-*a*, and eDNA datasets collectively record a broadly consistent sequence of environmental transitions. This regional pattern is strongly aligned with other paleolimnological studies from Aotearoa New Zealand that document the ecological change of pre-human, Māori, and European phases of landscape use (e.g., McWethy et al 2014, Wilmshurst et al. 1999; Woodward & Shulmeister 2006, Newnham et al. 2018, Short et al. 2022, Wheeler et al. 2024).

Pre-human sediments across the study lakes are characterised by:

- Intact podocarp–broadleaf forests, typically dominated by rimu, kauri, and other podocarps. A notable exception is Lake Waiporohita, where the core records a strong beech component throughout the pre-human period, highlighting regional variation in forest composition.
- Negligible charcoal, indicating limited fires in the landscape.
- Low and stable algal abundance as shown by the Chl-*a* hyperspectral ratios.
- Minimal cyanobacteria in eDNA records.

Following Māori arrival c. 750–700 years ago, most cores show:

- Sharp increases in bracken fern and charcoal, signalling widespread fire and forest disturbance.
- Declines in tall forest taxa.
- Expansions of sedges and raupō around lake margins, likely reflecting increased light availability following forest clearance and the trapping of nutrient-rich and fine sediment by wetland vegetation. This pattern is consistent with national-scale research showing that raupō abundance increased at approximately 87% of sites across Aotearoa New Zealand after Māori arrival (Li et al., 2024).

- Small but detectable increases in algal abundance or a decrease in the stability of this proxy.

Post European settlement, more pronounced ecological changes are observed in and around all lakes.

- Pine and grass pollen rapidly dominate, reflecting plantation forestry and pastoral conversion.
- Hyperspectral Chl-*a* ratios sometimes increased steeply, often beginning c. 1950 CE, a timing consistent with fertiliser expansion and intensified land use across rural Aotearoa New Zealand.
- Cyanobacteria increase in eDNA datasets, sometimes forming sustained peaks in the upper sediments.
- Marked shift in the bacterial composition.

Despite these shared regional patterns, each lake exhibits its own nuanced set of responses. Fully resolving these differences, and understanding their drivers and precise timing, would require more detailed, multi-proxy analysis like that undertaken for Lake Kapoai, where an age model, diatoms, geochemistry, eDNA, metals and hyperspectral data provided a high-resolution reconstruction.

One notable example of lake-specific variation is the very low post-European sedimentation rates observed in four lakes. Lakes, Wahakari, Morehurehu, Ngatu, Te Kahika, Kahuparere and Taharoa each record < ~10 cm of sediment for the last ~200 years compared to the other lakes (Table 9). Although this may appear counter-intuitive given the dramatic vegetation change, burning, pasture establishment and pine forestry that occurred following European arrival, it is consistent with the physical characteristics of these lake catchments. Some of these lakes have small catchment-to-lake area ratios (Table 9), low catchment slopes, and / or highly permeable sandy substrates, features typical of Northland dune-lake landscapes that strongly limit sediment delivery to the basin.

Table 9. Approximate sediment depth corresponding to the onset of European settlement (c. AD 1800–1850) in ten Northland dune lakes. Lake area, catchment area, and catchment-to-lake area ratios are shown for comparison. Depth Euro = est. sediment depth corresponding to European arrival, ha = hectares.

	Depth Euro (cm)	Lake area (ha)	Cat. Area (ha)	Ratio
Wahakari	1.0	84	797	9.5
Morehurehu	2.4	49	316	6.5
Ngatu	4.3	55	172	3.1
Te Kahika	5.5	14	302	20.9
Kahuparere	6.2	7	257	37.5
Taharoa	10.3	210	423	2.0
Wai Raupo	25.3	20	200	10.2
Waiporohita	25.6	6	62	10.1
Kapoai	61.4	3	253	88.6
Ngakeketo	87.0	9	246	27.6

From a paleolimnological perspective, these low sedimentation rates impose important constraints on interpretation. When two centuries of environmental change are compressed into only a few centimetres of sediment, it becomes difficult to conduct fine-scale temporal analyses, such as identifying the timing and ecological impacts of non-native species introductions or detecting the impact of shifts in land-use practices. High-resolution reconstructions are most effective in lakes where the European period is represented by 10 cm or more of sediment, allowing for sufficient sample density and robust age–depth modelling to resolve decadal-scale change.

Lake Kapoai case study: a multi-proxy record of eutrophication

Lake Kapoai provides the most complete multi-proxy reconstruction of ecological change from the Lakes380 study in Northland, enabling a robust link between catchment transformations, in-lake responses, and the emergence of internal feedbacks over the last ~1000 years. The sediment core analysis included pollen/charcoal, diatoms, hyperspectral pigments, trace metals and elemental ratios (Mn:Fe, Ti:Inc), and eDNA, providing a coherent narrative of progressive eutrophication through the 20th century.

- The diatom record shows an early dominance of small taxa inhabiting benthic and mixed habitats (e.g., *Staurosira construens*, *Staurosirella pinnata*), followed, after European settlement, by a shift to planktonic species (notably *Discostella stelligera*) and then eutrophic pelagic taxa such as *Aulacoseira ambigua* and *Asterionella formosa*.
- Concomitant declines in epiphytic (attached to the surfaces of aquatic plants) diatom species indicate macrophyte loss and rising pelagic production. This stepwise trajectory, initial pelagic shift then strengthening eutrophication, matches palaeolimnological reconstructions elsewhere in Aotearoa Zealand where multi-proxy evidence ties post-1960s productivity increases to land-use intensification (e.g., Short et al. 2022, Gregersen et al. 2022, 2023, Wheeler et al. 2024).
- Hyperspectral Chl-*a* and cyanobacterial eDNA reads increase markedly in the upper core, aligning with the diatom shift toward eutrophic plankton and confirming a whole-lake transition from a macrophyte-supported state to a plankton-dominated, higher-productivity regime post ~1950 CE.

Cadmium (Cd) and lead (Pb) increase markedly around the 1950 CE, consistent with superphosphate fertilizer legacies and population/transport signals (Pb). Mn:Fe variability starting about 1650 CE signals intermittent anoxia. Ti:Inc declines after about 1960 CE imply that, relative to rising autochthonous (in lake) production, the proportion of terrestrially derived material decreased.

The addition of multi-gene eDNA analysis to this core could be valuable for reconstructing the historical biodiversity of the lake, as well as identifying which non-native species are present, when they arrived, and their potential impacts. Similar studies have been undertaken very effectively in lakes across Aotearoa New Zealand, demonstrating, for example, losses of native fish species and the key drivers of these changes (e.g., Thomson-Laing et al. 2024), and the impact of non-native fish on food webs (Schallenberg et al. 2023). Further analyses of eDNA

samples from the Lake Kapoai core are currently being undertaken as part of the ‘Our Lakes, Our Future’ MBIE Endeavour project, with results expected in late 2026. These analyses will provide additional insights into historical changes in microalgal and macrophyte communities, as well as other microeukaryotes, including ciliates, nematodes, and other aquatic organisms. The results will help further reconstruct ecological changes within the lake over time and complement the palaeoecological findings presented here.

Future opportunities and key recommendations

Further work could expand analyses of the existing sediment cores presented in the report using approaches such as multi-gene eDNA and diatom analyses. Priority should be given to cores containing well-resolved post-European sediments (>10 cm), such as those from Lake Waiporohita and Ngakeketo. To date, only bacterial eDNA has been analysed; however, a growing suite of assays are now available to target a wide range of ecologically important groups, from fish to less-understood taxa that have shown strong responses to changing lake health. These include both metabarcoding assays targeting multiple groups (Thomson-Laing et al. 2024, Schallenberg et al. 2023) and species-specific assays (e.g Thomson-Laing et al. 2021, Steiner et al. 2022). Some of these approaches may provide early warning indicators of ecological change, particularly in oligotrophic and mesotrophic lakes (e.g., Gregersen et al. 2023).

Additional sediment cores could also be selected from the Lakes380 archive and existing hyperspectral scans analysed. While most cores have been scanned, much of this data has not yet been processed. This represents a relatively low-cost opportunity to identify lakes suitable for further paleolimnological analysis, including estimating the depth of European settlement horizons. Based on results from this project, many cores from the Poutō Peninsula appear well suited for further study. Selected cores could be analysed using a multi-proxy approach similar to that of Lake Kapoai.

As part of the ‘Our Lakes, Our Future’ MBIE Endeavour programme, specific lake sampling and analytical protocols are currently being optimised, which could support cost-effective, large-scale surveys and provide knowledge on biodiversity. These will be freely available once completed.

Potential application of the report findings

The findings presented in this report have several practical applications for lake management, restoration planning, and future research across Northland. First, the identification of lakes that are oligotrophic or mesotrophic provides a basis for prioritising protection efforts. These lakes represent nationally uncommon ecosystems and may benefit most from preventative management approaches aimed at limiting nutrient enrichment, invasive species establishment, and catchment disturbance.

The phosphorus fractionation results can be used to identify lakes at greatest risk of internal nutrient loading and future eutrophication. This information can help guide monitoring programmes and support decisions regarding the need for interventions such as enhanced catchment management, oxygen monitoring, alum dosing, sediment capping, or other restoration measures.

The trace metal data provide an initial screening tool to identify lakes where further investigation may be warranted. Combined with catchment information, geological mapping, and environmental histories, these results can help distinguish between natural and anthropogenic sources of contamination, and guide future monitoring priorities.

The paleolimnological records establish long-term ecological baselines that can be used to assess the magnitude of environmental change since Māori and European settlement. These records provide valuable context for restoration targets by helping identify historical ecosystem states, rates of change, and the likely drivers of ecological degradation. In some cases, they may also help evaluate whether contemporary lake conditions reflect recent impacts or longer-term natural variability.

Finally, the sediment archives generated through the Lakes380 programme represent a significant resource for future research. Additional analyses, including diatoms, multi-gene eDNA, hyperspectral data, and geochemical proxies have the potential to improve understanding of biodiversity change, invasive species impacts, nutrient dynamics, and climate-related pressures.

Key recommendations

- Prioritise protecting and developing lake-specific management plans for oligotrophic and mesotrophic dune lakes.
- Conduct repeat water chemistry sampling, particularly in lakes exhibiting elevated trace metal concentrations, to determine whether observed enrichments are persistent or reflect short-term variability. Where elevated concentrations are confirmed, use catchment-scale tools such as the Northland Landscape Driven Erosion Map to help identify potential sources and pathways of metal inputs, and to distinguish between geological and anthropogenic drivers.
- Implement continuous in-lake monitoring (dissolved oxygen, temperature, pH) in lakes with elevated internal-loading risk (e.g., Kai-iwi, Rotokawau (Aupōuri), Waikare). This should be paired with further spatial surveys of the surface sediment geochemistry.
- Expand paleolimnological analyses using a multi-proxy approach, prioritising cores with well-resolved post-European sediments. This will help understand lake-specific trajectories, identify drivers of change, and detect impacts of non-native species or land-use intensification. Consider further analysis of the Northland sediment cores from the Lakes380 archive.

Acknowledgements

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Appendices

Appendix 1. Temperature, dissolved oxygen and chlorophyll-*a* profiles.

Profiles were not obtained for all lakes because some were too shallow to permit meaningful depth profiling, and in a small number of cases data were unavailable due to equipment malfunction during sampling.

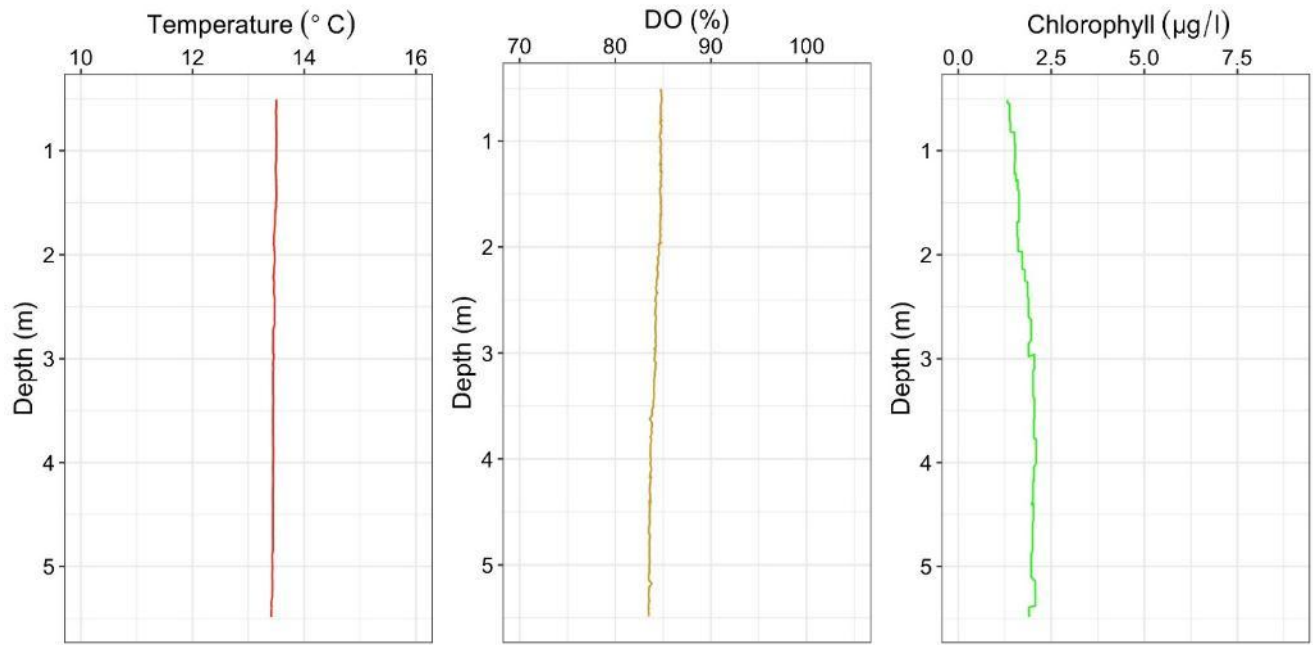


Figure A1. RBR profile for Lake Carrot.

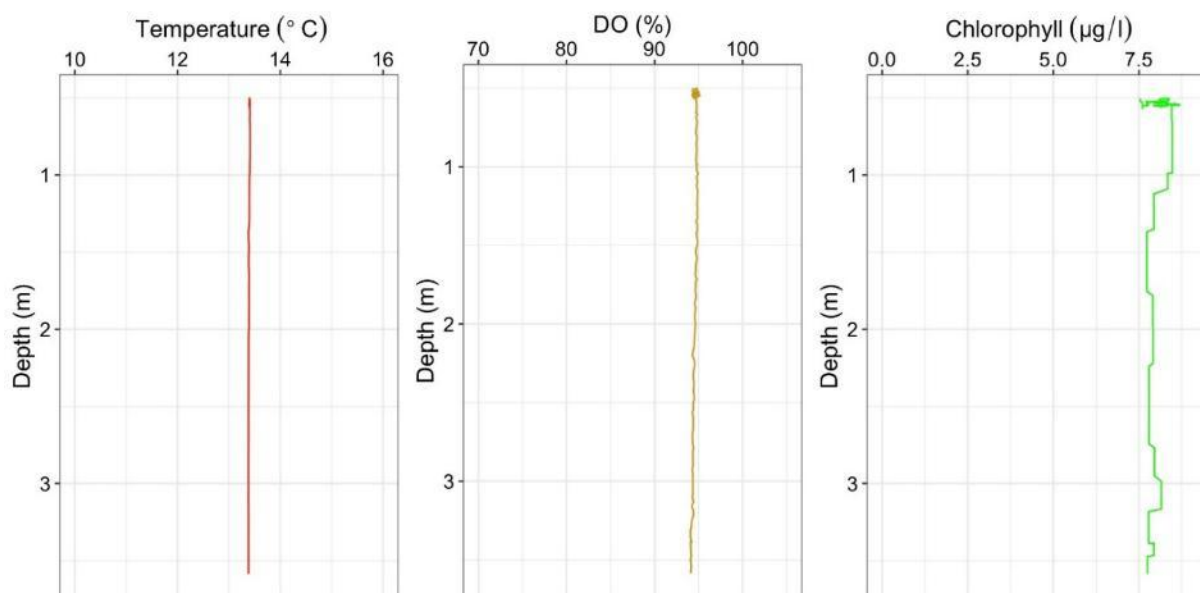


Figure A2. RBR profile for Lake Heather.

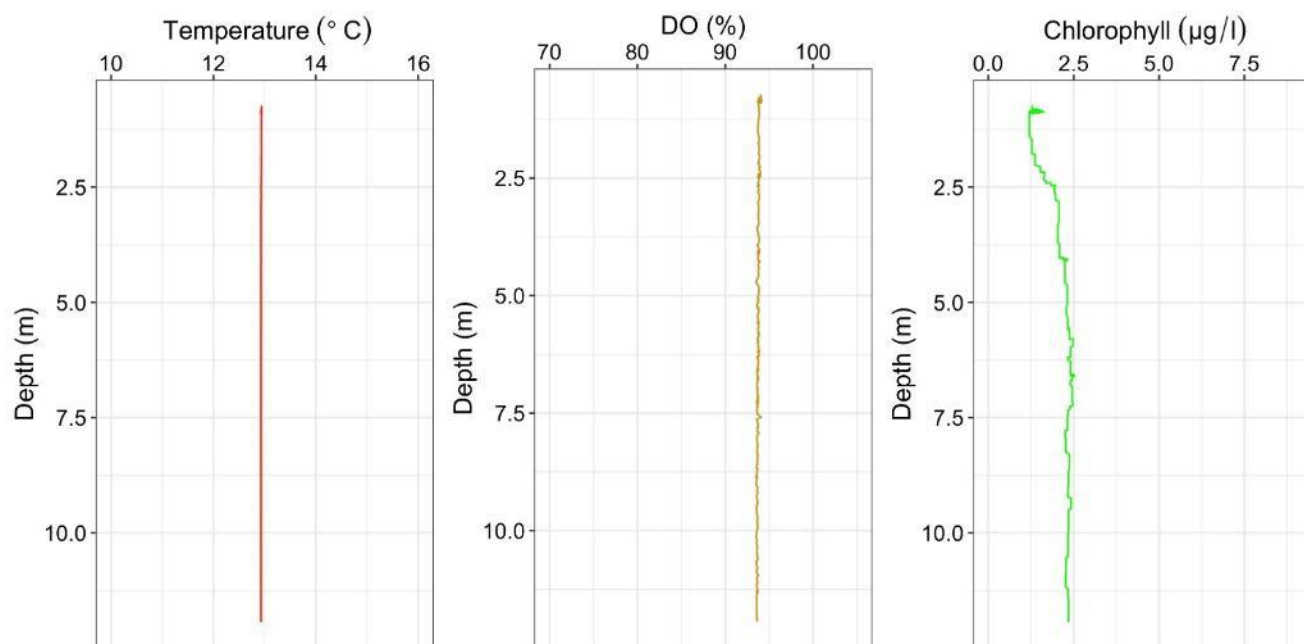


Figure A3. RBR profile for Lake Humuhumu.

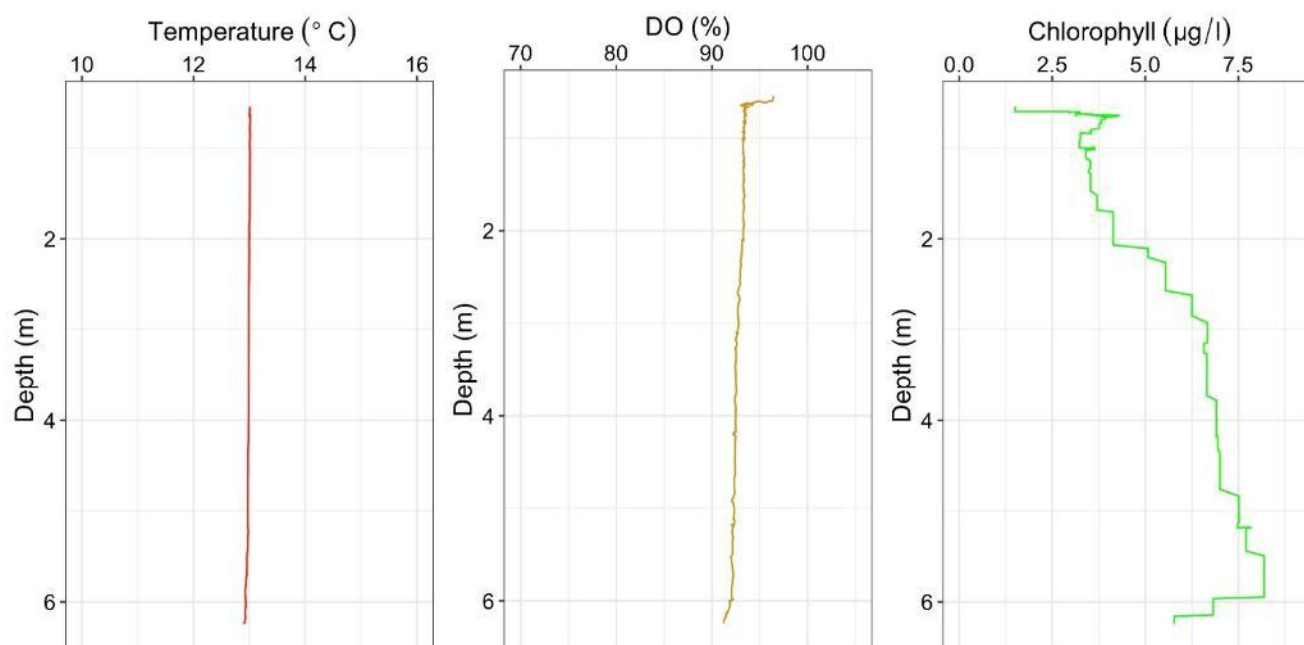


Figure A4. RBR profile for Lake Kahuparere.

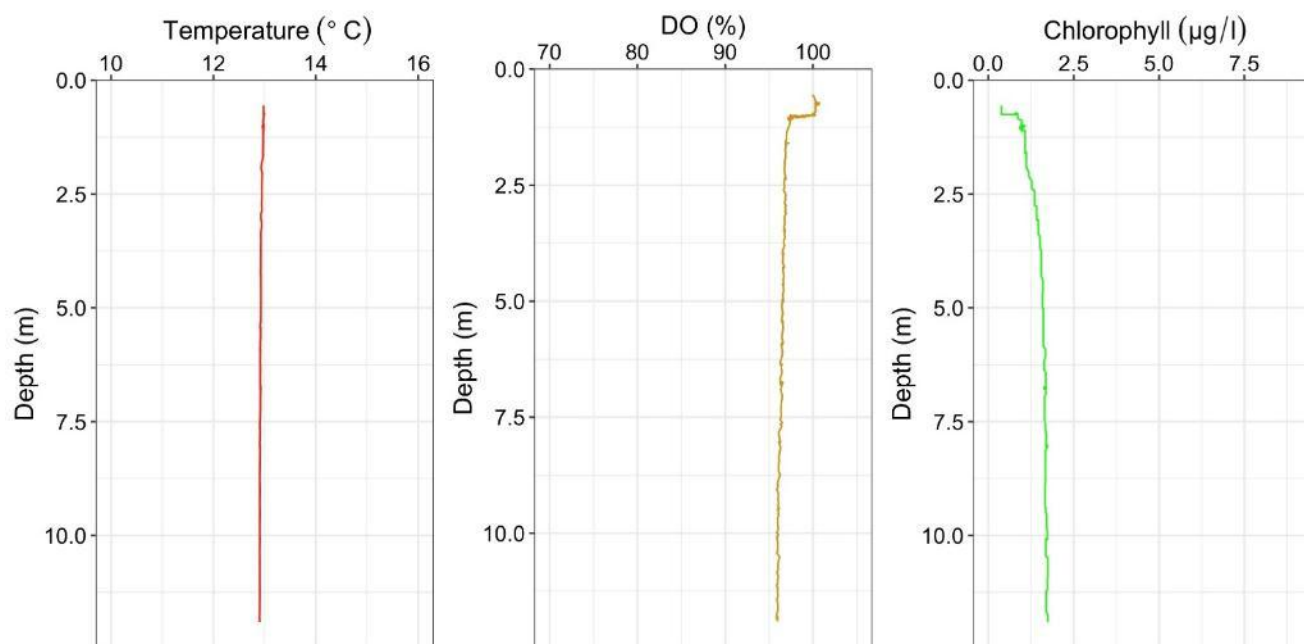


Figure A5. RBR profile for Lake Kanono.

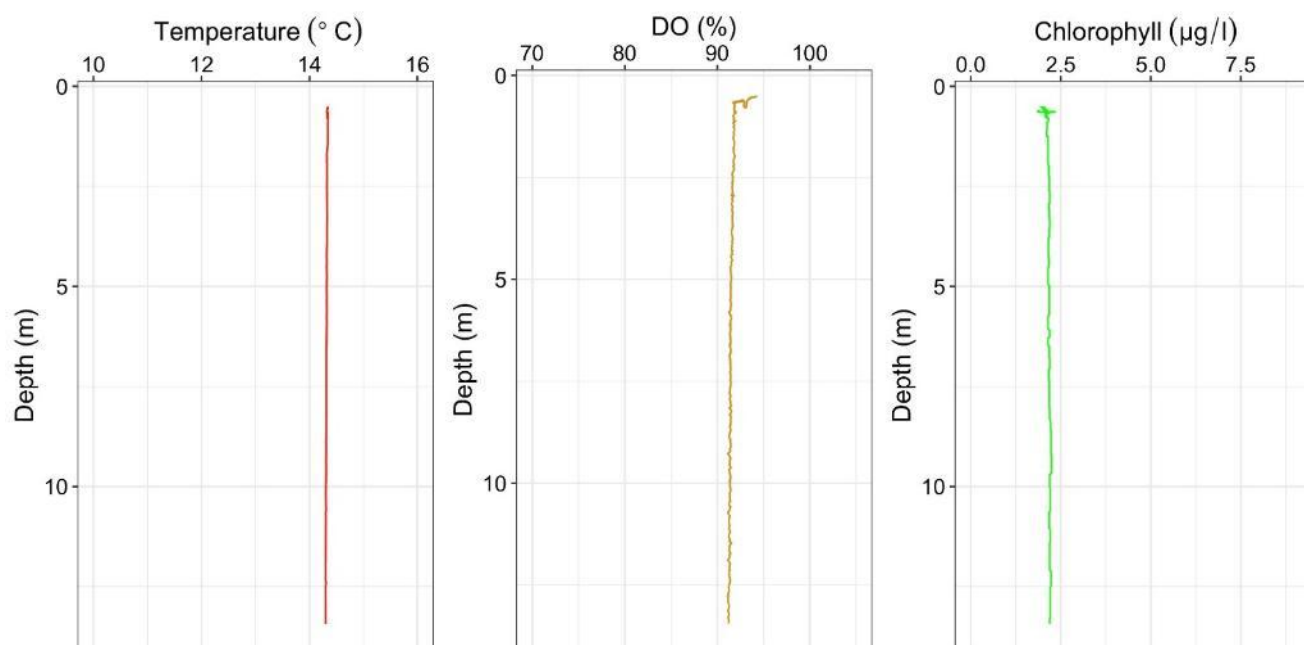


Figure A6. RBR profile for Lake Morehurehu.

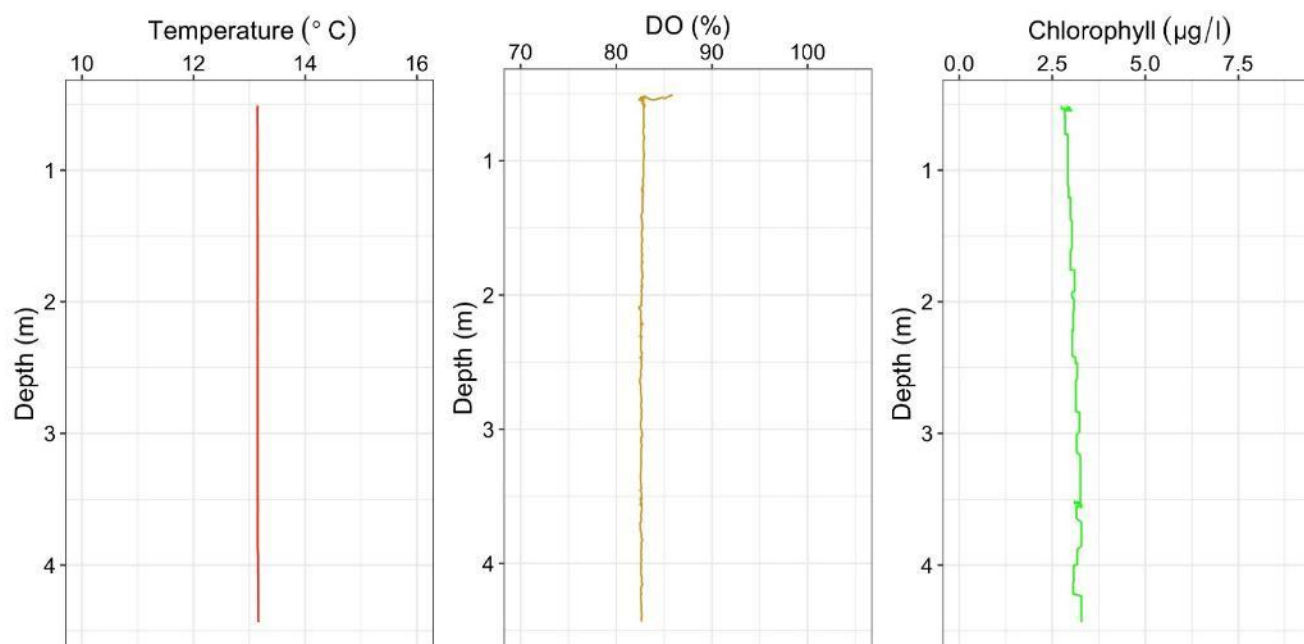


Figure A7. RBR profile for Lake Ngakapua.

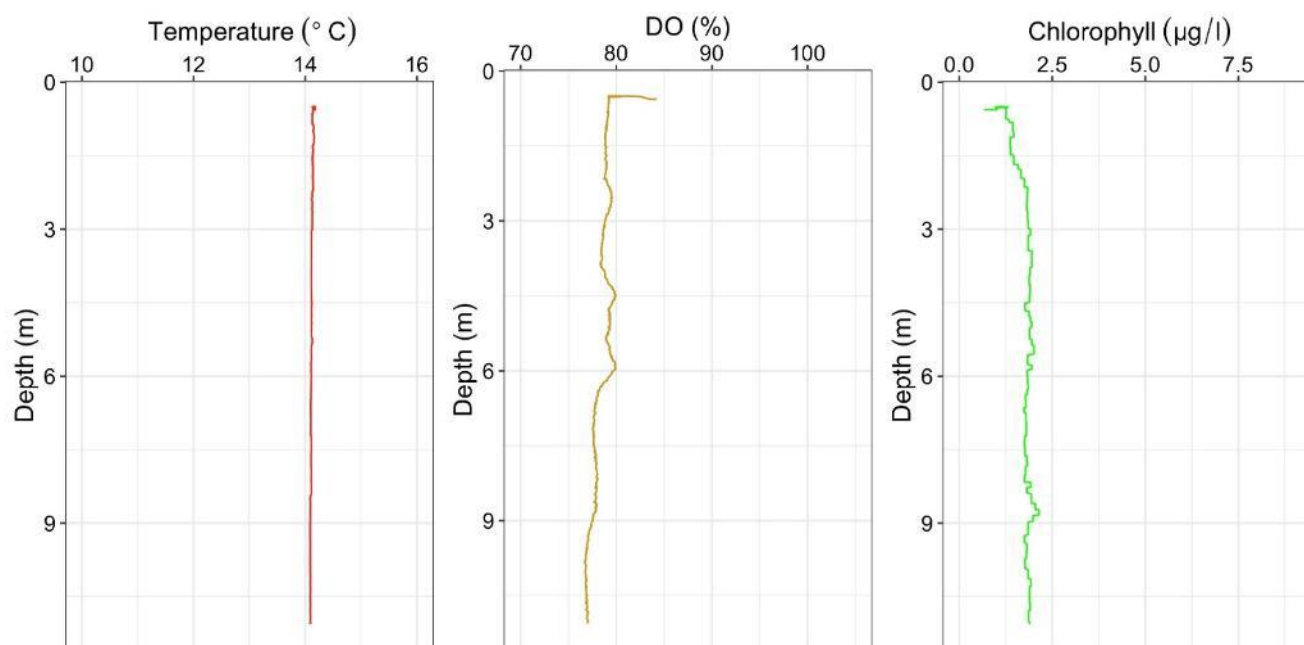


Figure A8. RBR profile for Lake Ngakeketa.

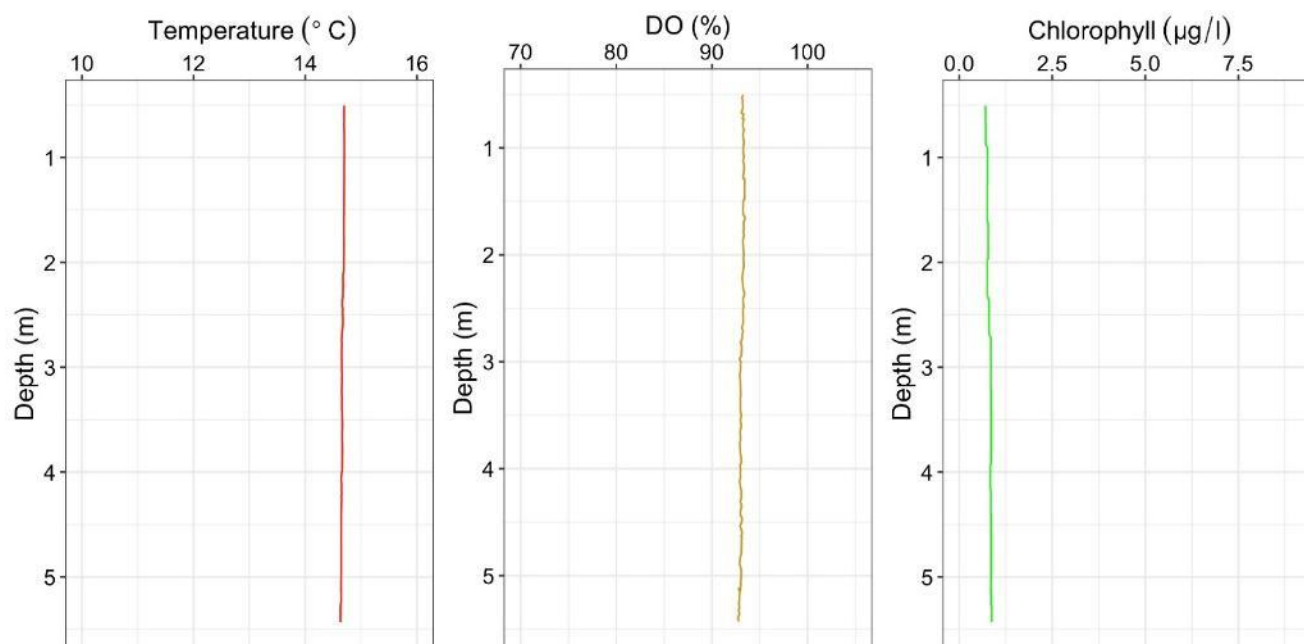


Figure A9. RBR profile for Lake Ngatu.

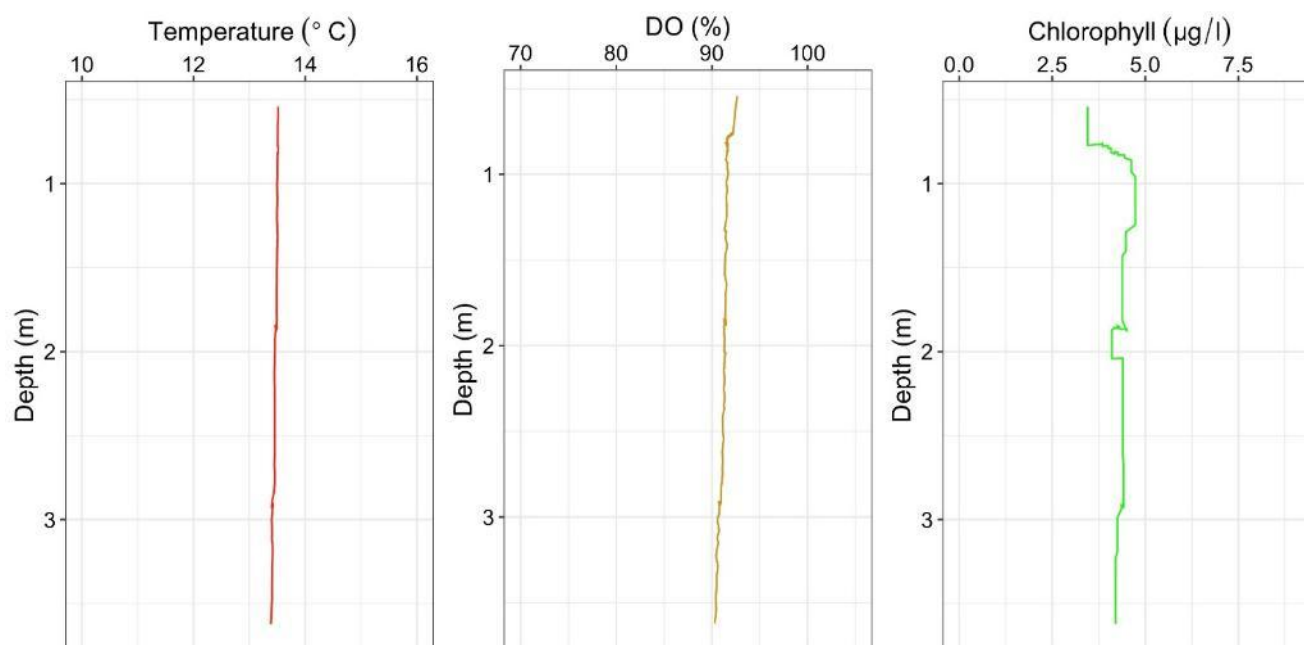


Figure A10. RBR profile for Lake Rotootuauru.

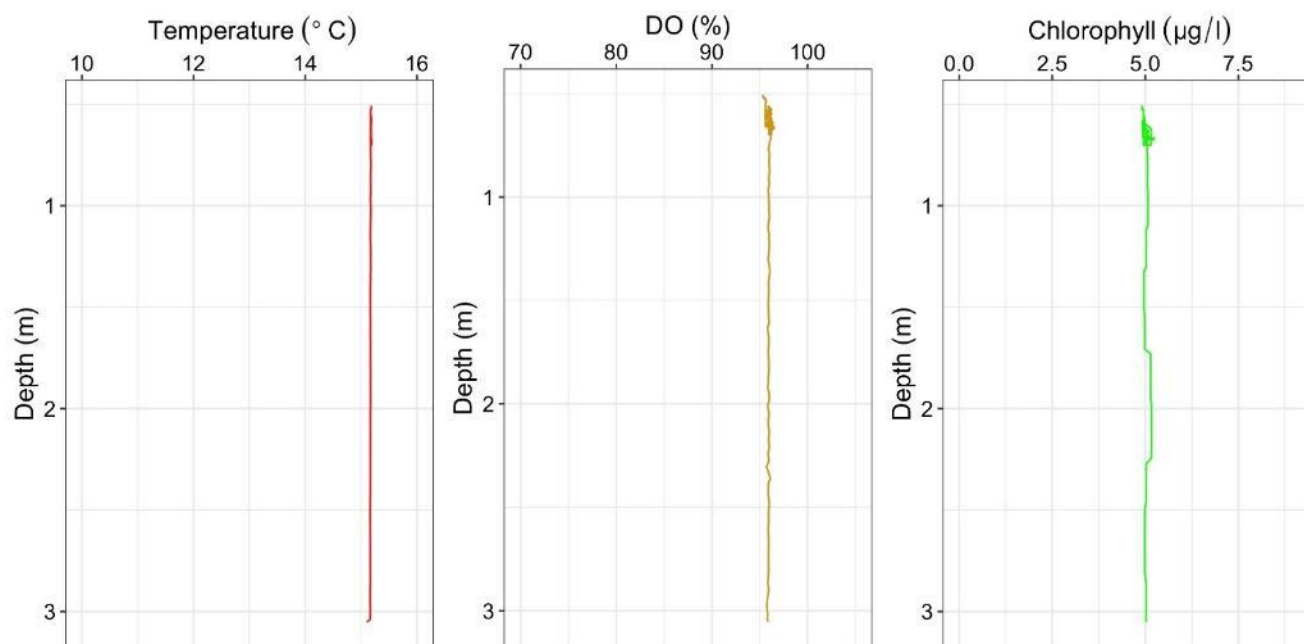


Figure A11. RBR profile for Lake Rotopokaka.

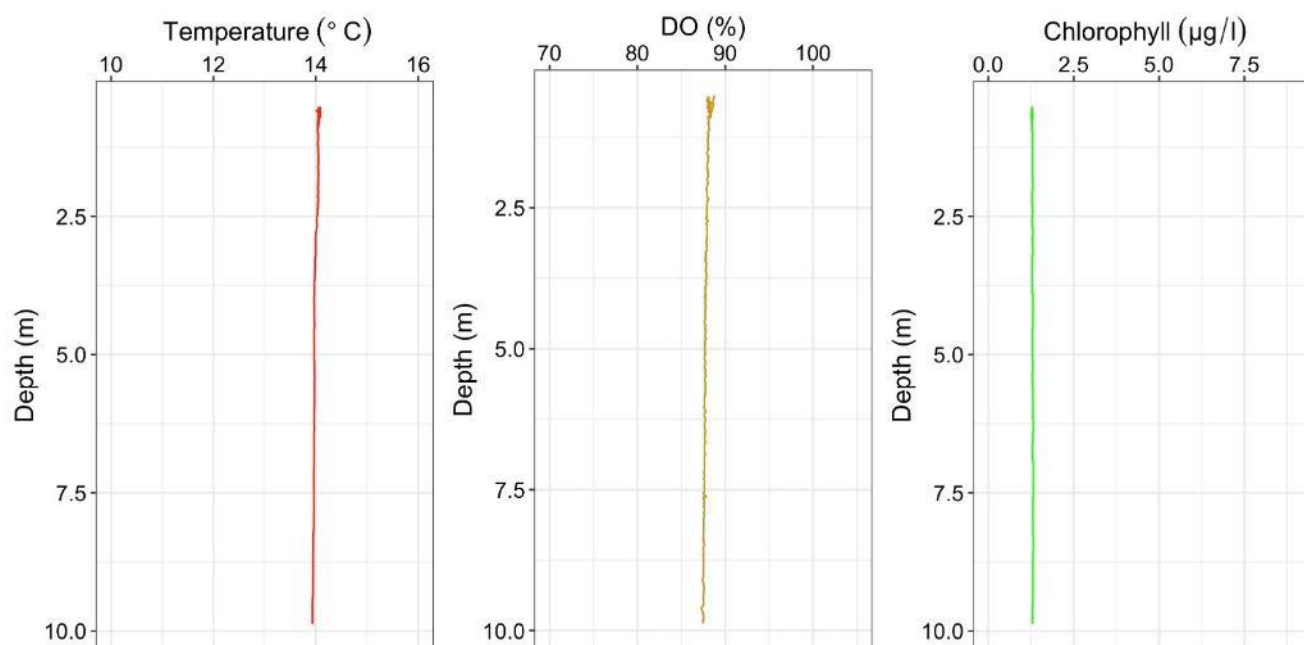


Figure A12. RBR profile for Lake Te Kahika.

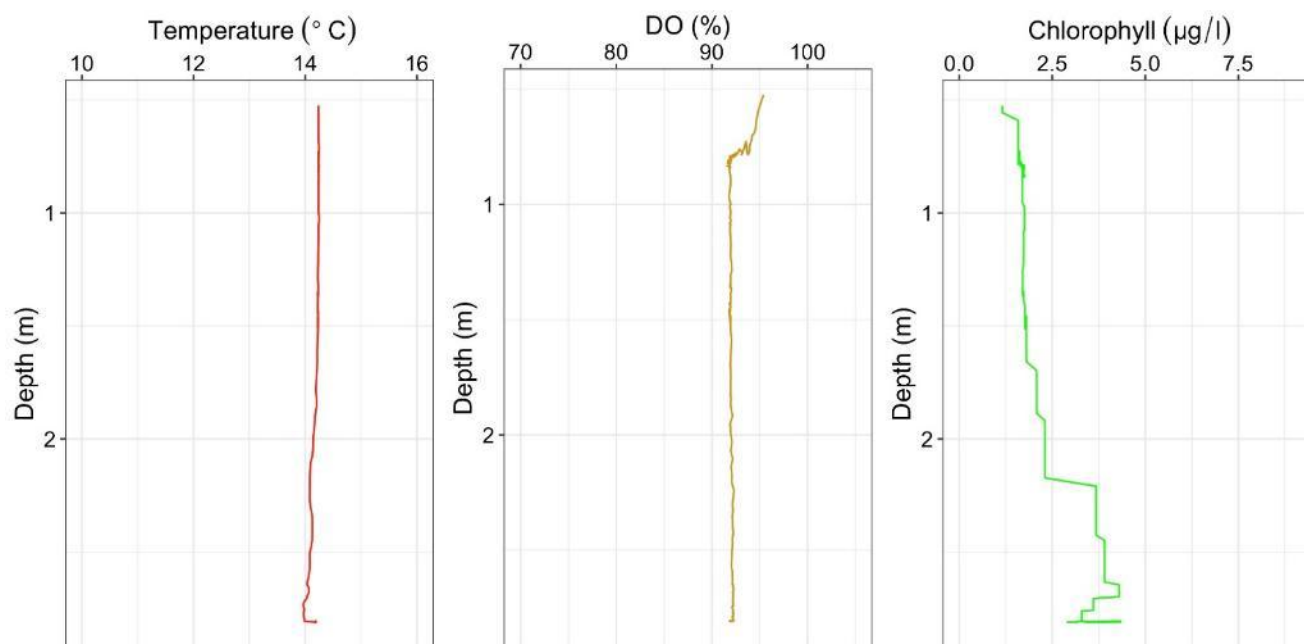


Figure A13. RBR profile for Lake Te Ketekete.

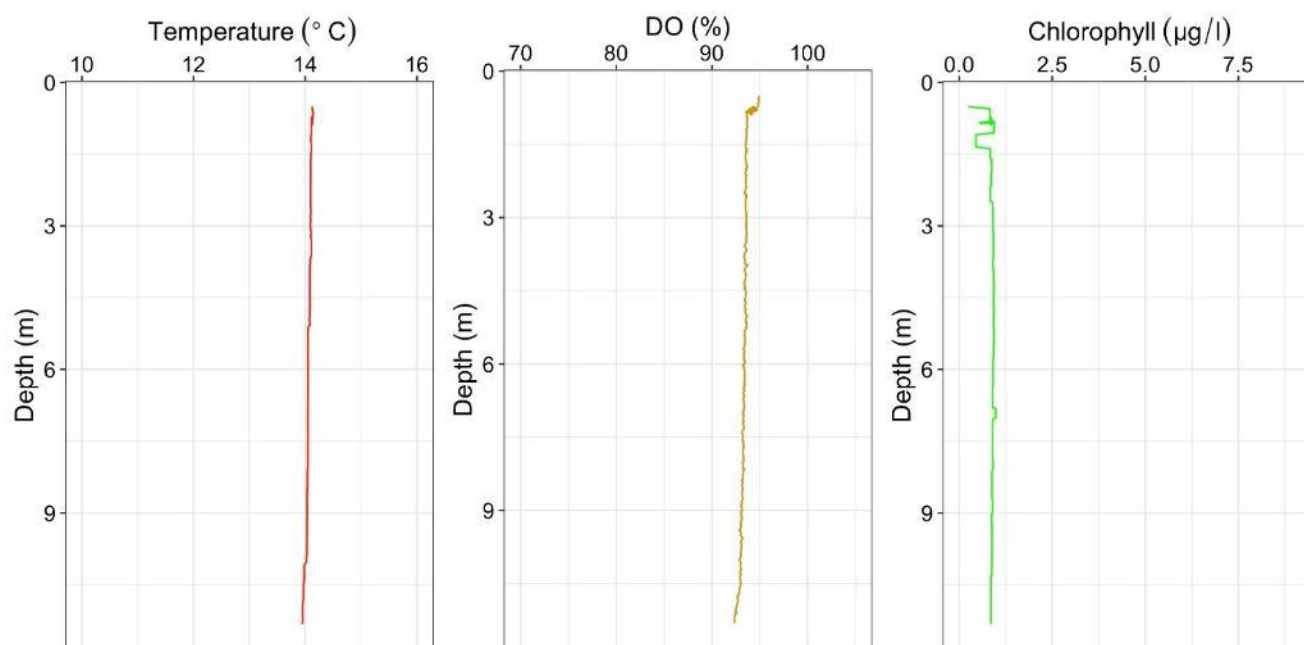


Figure A14. RBR profile for Lake Wahakari.

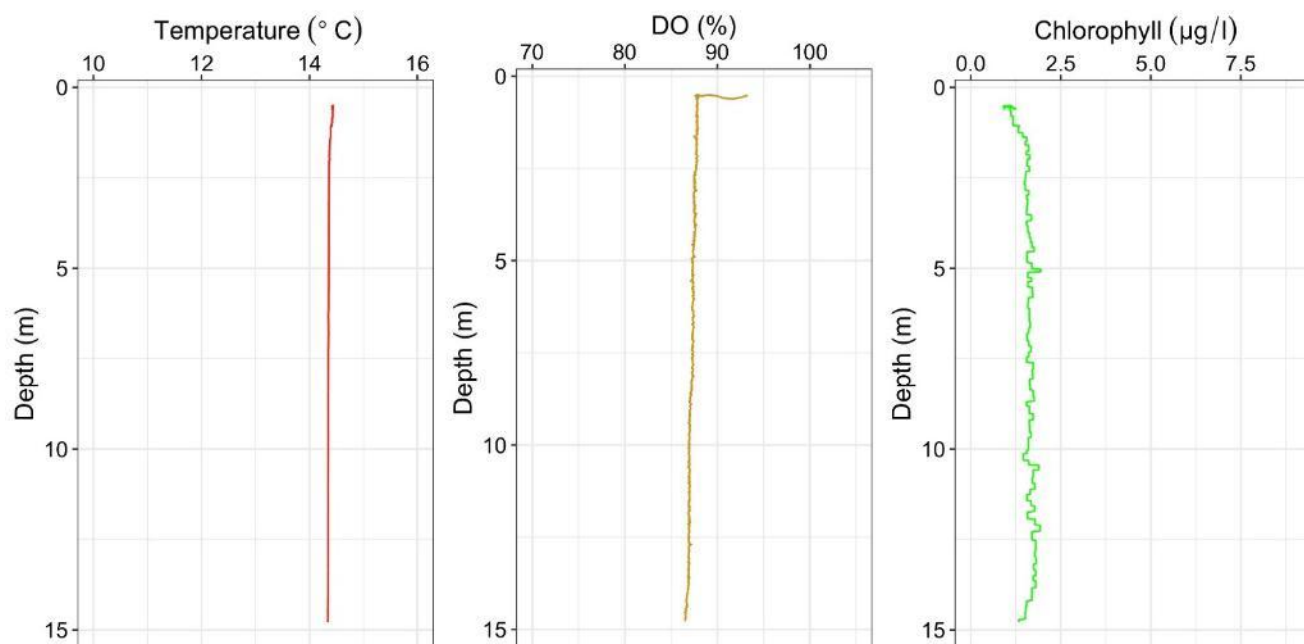


Figure A15. RBR profile for Lake Wai Raupo.

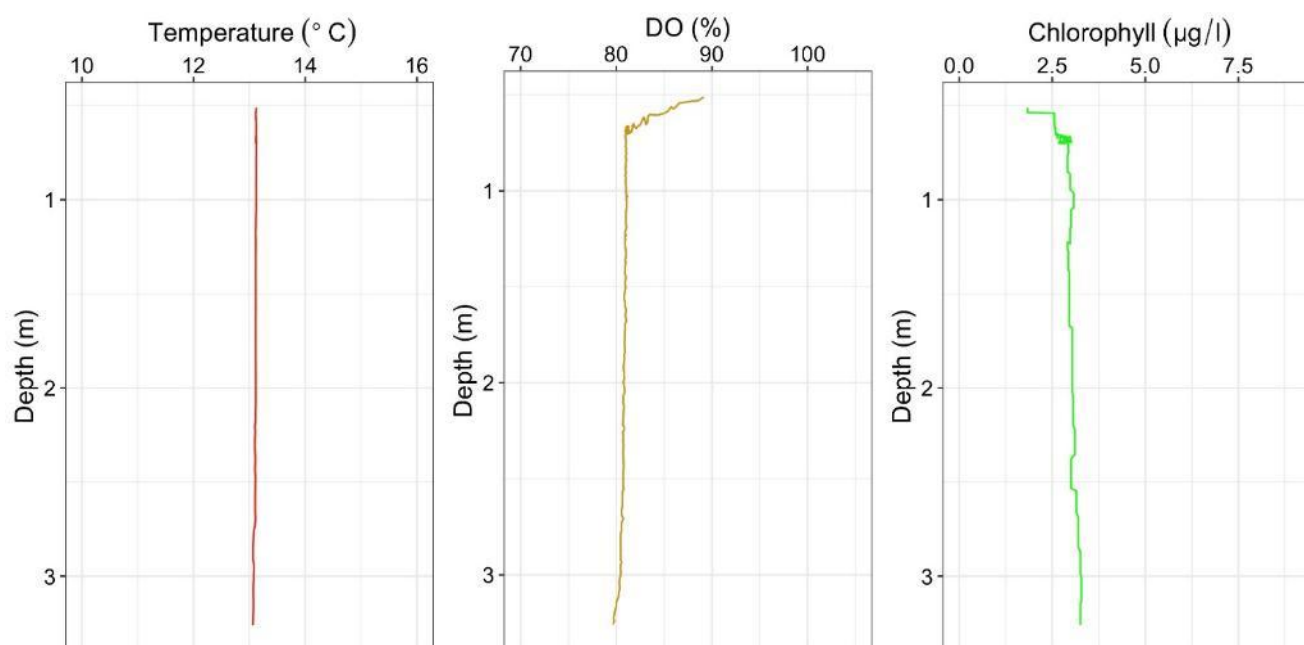


Figure A16. RBR profile for Lake Waihopo.

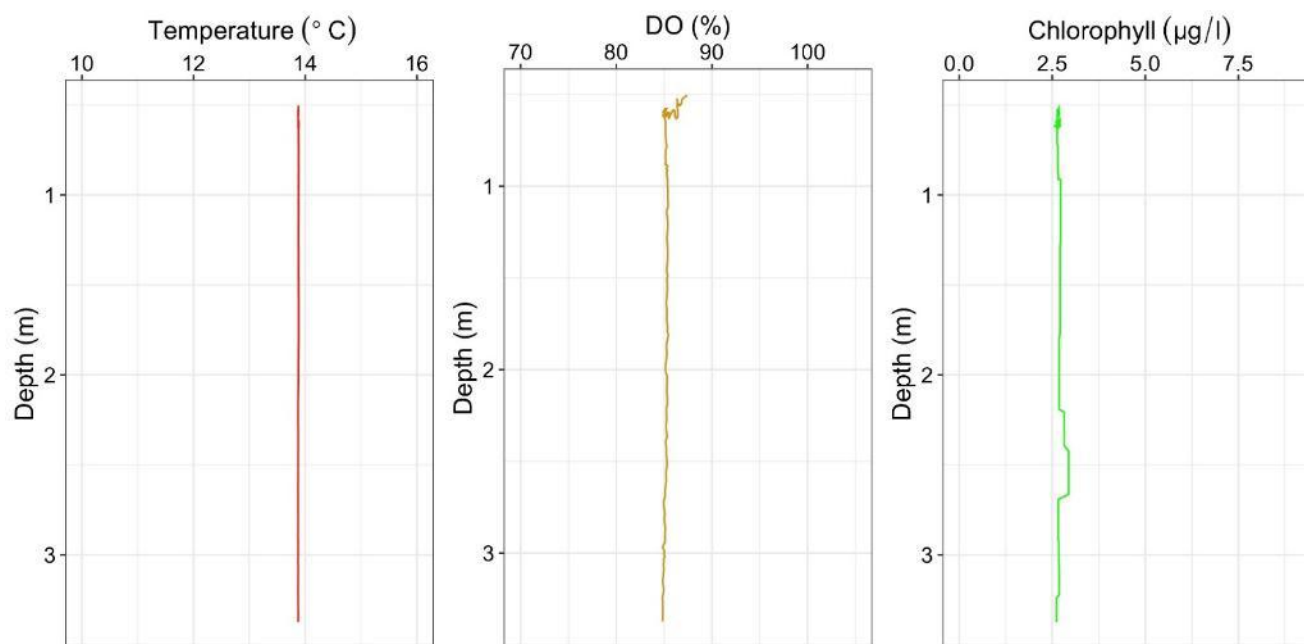


Figure A17. RBR profile for Lake Waiparera.

Appendix 2. Plots of water quality and chemistry data

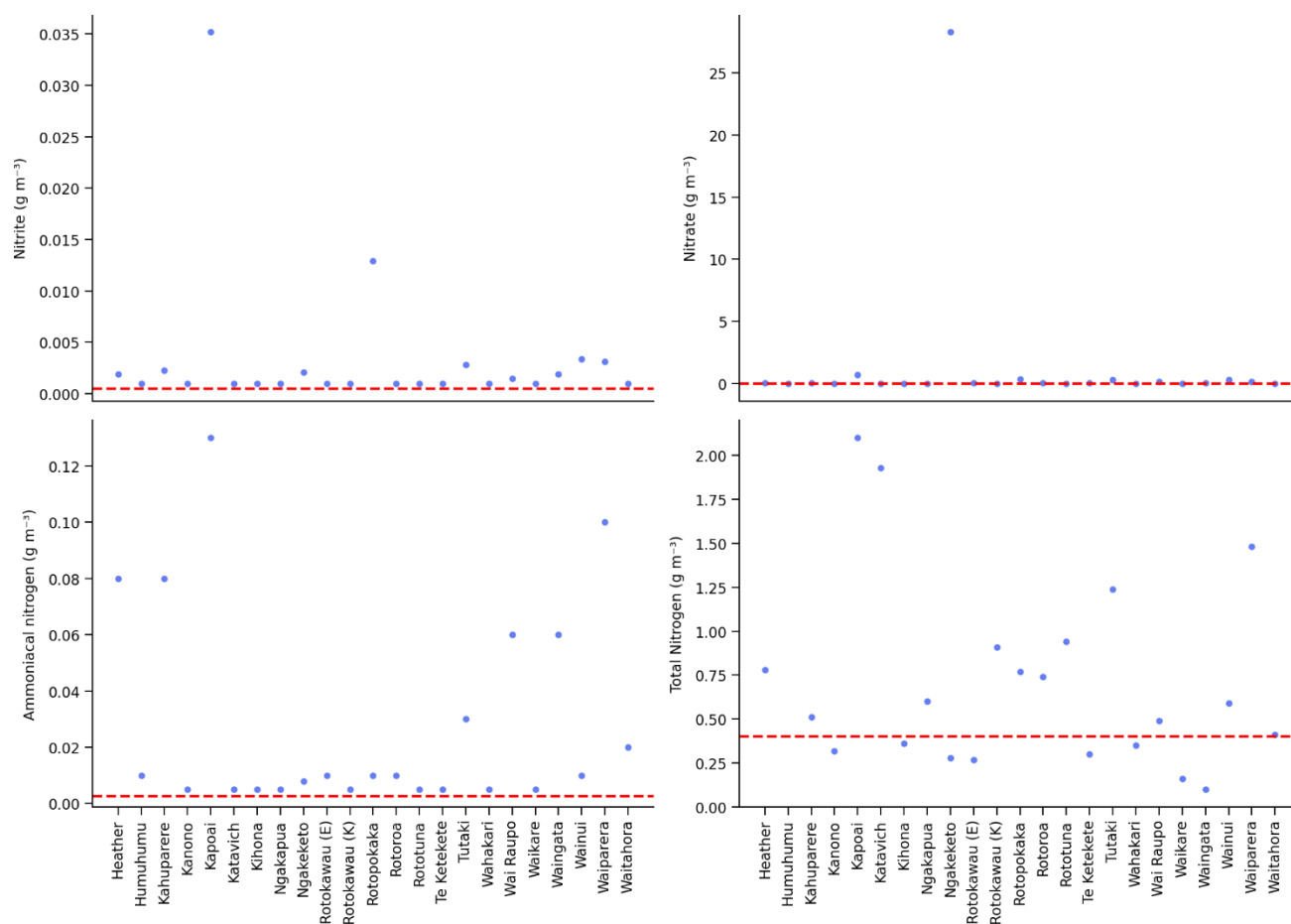


Figure A18. Dissolved and total nitrogen concentrations in surface water samples collected from lakes in the Northland Region compared to the national median for a selection of lakes in Aotearoa New Zealand shown as red dashed line. The total number of lakes in the national dataset varies between 226 and 260 depending on the variable measured. Note that the y-axis scale varies. * Where long-term data was available from Northland Regional Council this was used in preference to Lakes380 data and data shown are a median using all available data post 1 January 2020. A = Aupōuri, E = East, K = Karikari, P = Pouto.

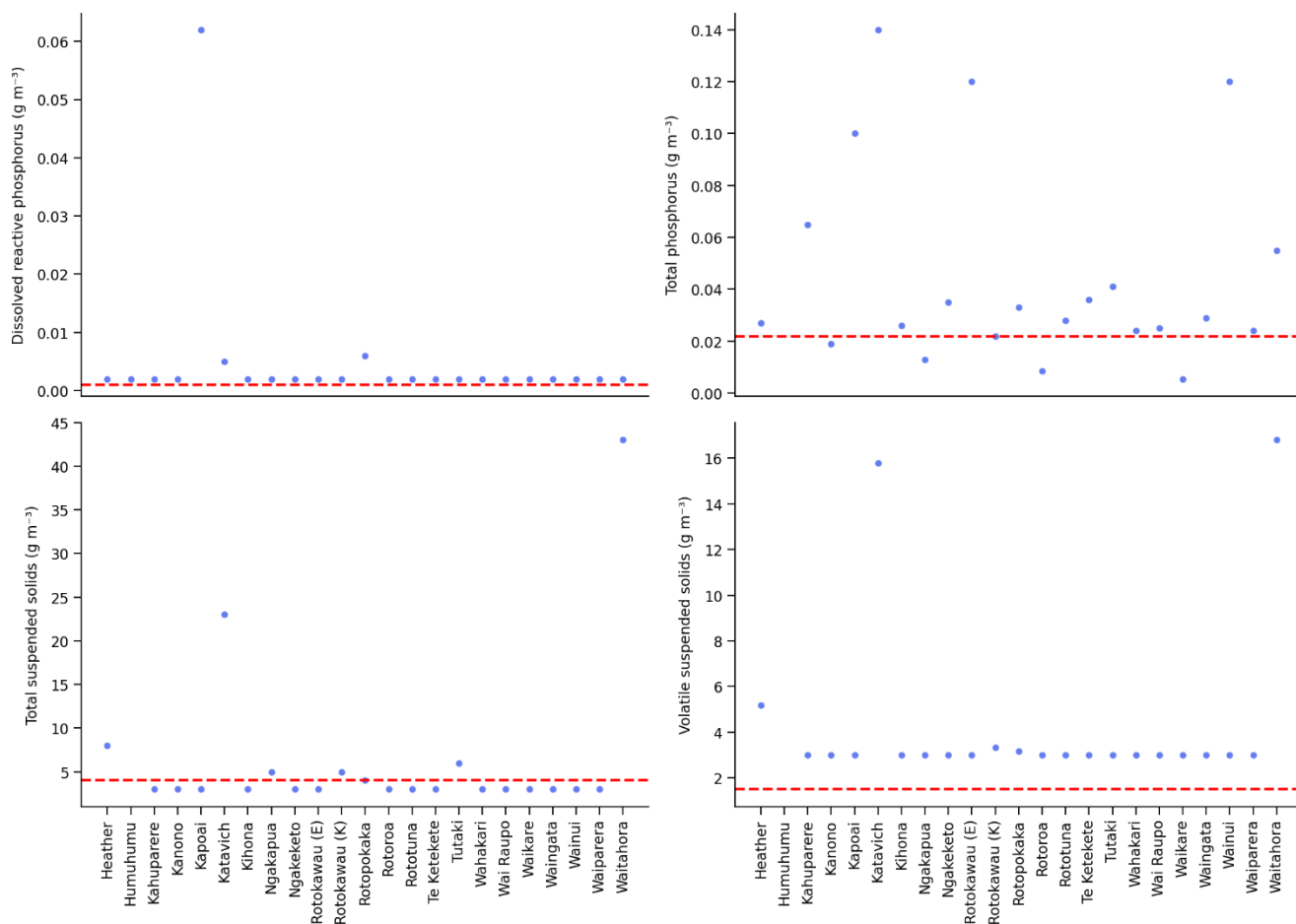


Figure A19. Dissolved and total phosphorus, and volatile and total suspended solid concentrations in surface water samples collected from lakes in the Northland Region compared to the national median for a selection of lakes in Aotearoa New Zealand shown as red dashed line. The total number of lakes in the national dataset varies between 226 and 260 depending on the variable measured. Note that the y-axis scale varies. * Where long-term data was available from Northland Regional Council this was used in preference to Lakes380 data and data shown are a median using all available data post 1 January 2020. A = Aupōuri, E = East, K = Karikari, P = Pouto.

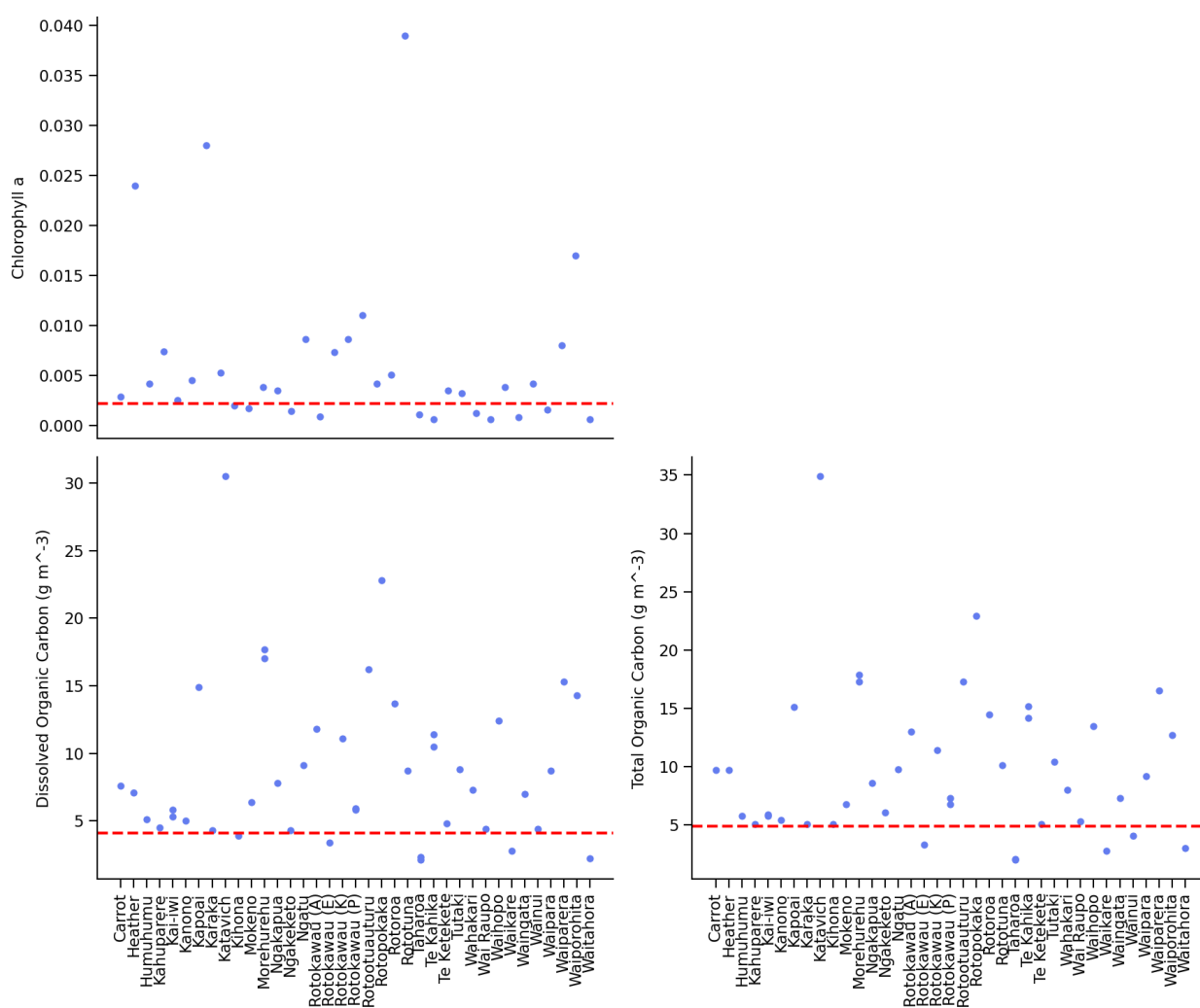
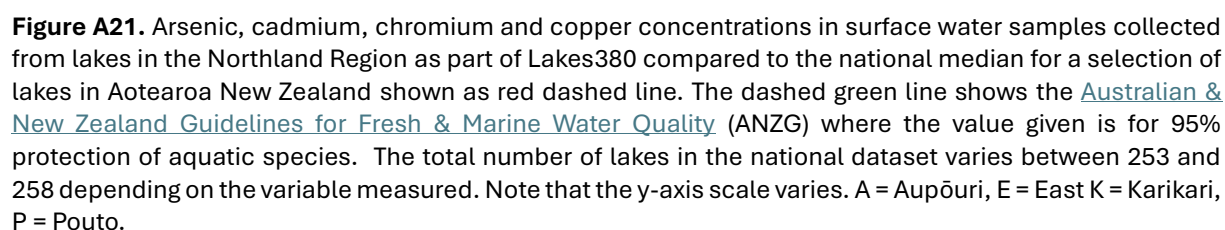


Figure A20. Total and dissolved organic carbon and chlorophyll-*a* concentrations in surface water samples collected from lakes in the Northland Region compared to the national median for a selection of lakes in Aotearoa New Zealand shown as red dashed line. The total number of lakes in the national dataset varies between 226 and 260 depending on the variable measured. Note that the y-axis scale varies. * Where long-term data was available from Northland Regional Council this was used in preference to Lakes380 data and data shown are a median using all available data post 1 January 2020. A = Aupōuri, E = East, K = Karikari, P = Pouto



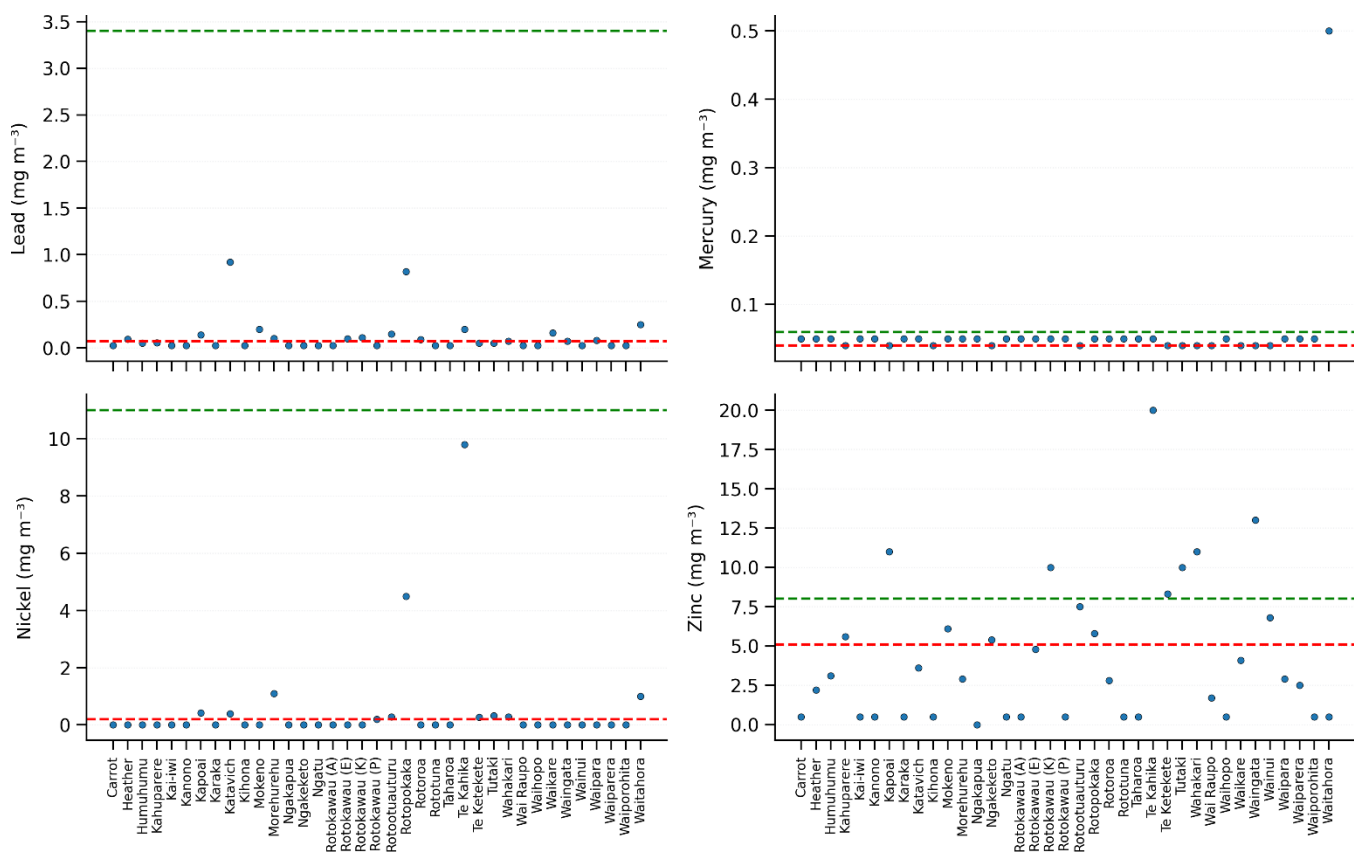


Figure A22. Lead, mercury, nickel and zinc concentrations in surface water samples collected from lakes in the Northland Region as part of Lakes380 compared to the national median for a selection of lakes in Aotearoa New Zealand shown as red dashed line. The dashed green line shows the [Australian & New Zealand Guidelines for Fresh & Marine Water Quality](#) (ANZG) where the value given is for 95% protection of aquatic species. The total number of lakes in the national dataset varies between 253 and 258 depending on the variable measured. Note that the y-axis scale varies. A = Aupōuri, E = East K = Karikari, P = Pouto.

Appendix 3. Plots of surface sediment chemistry data

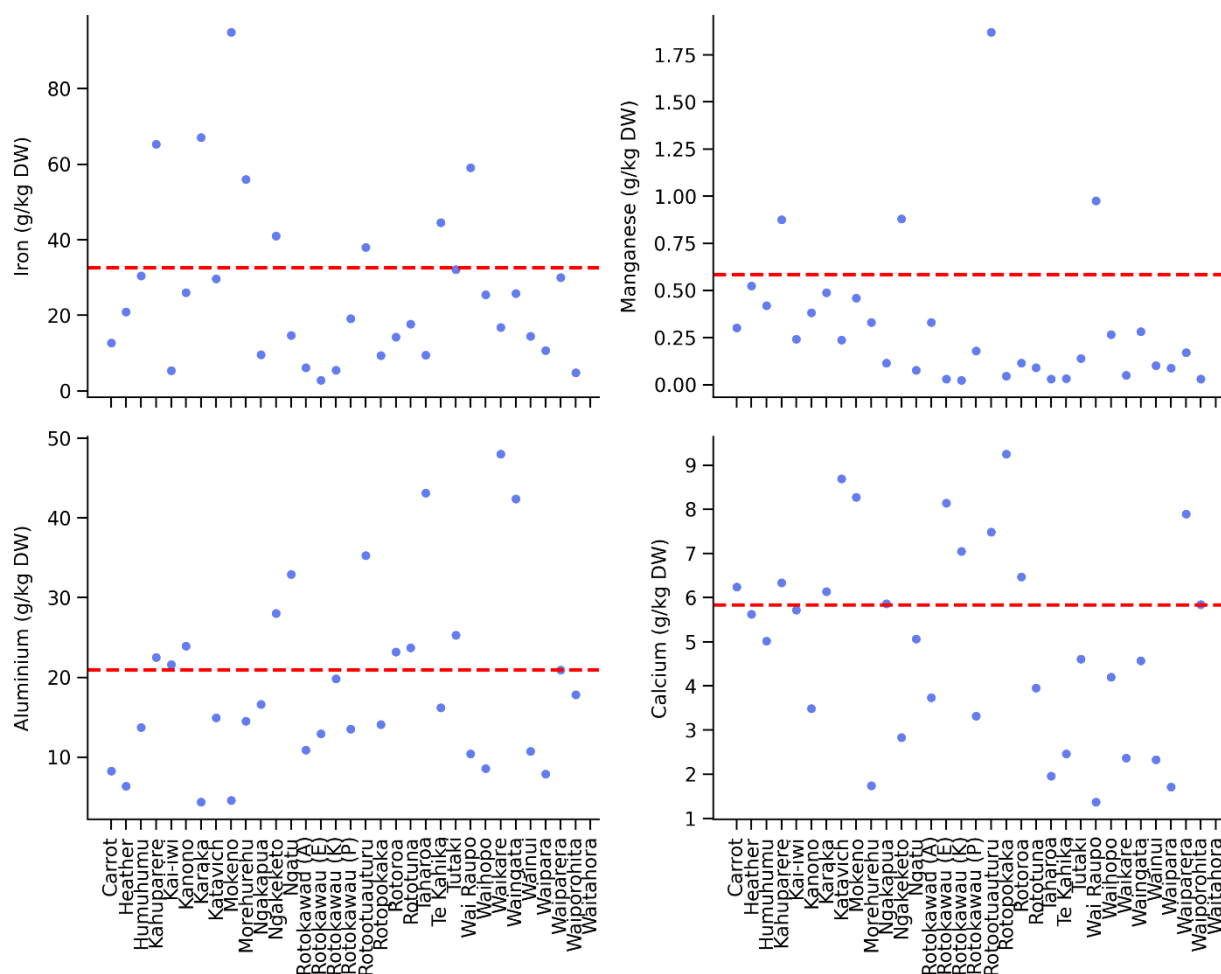


Figure A23. Metal concentrations in samples from the top 0–2 cm of the lakebed sediments collected from lakes in the Northland Region as part of the Lakes380 programme. Red dashed line indicates the national median for lakes in Aotearoa New Zealand sampled as part of the programme. The total number of lakes in the national dataset varies between 205 and 215 depending on the variable measured. Note that the y-axis scale varies. A = Aupōuri, E = East, K = Karikari, P = Pouto, DW = dry weight.

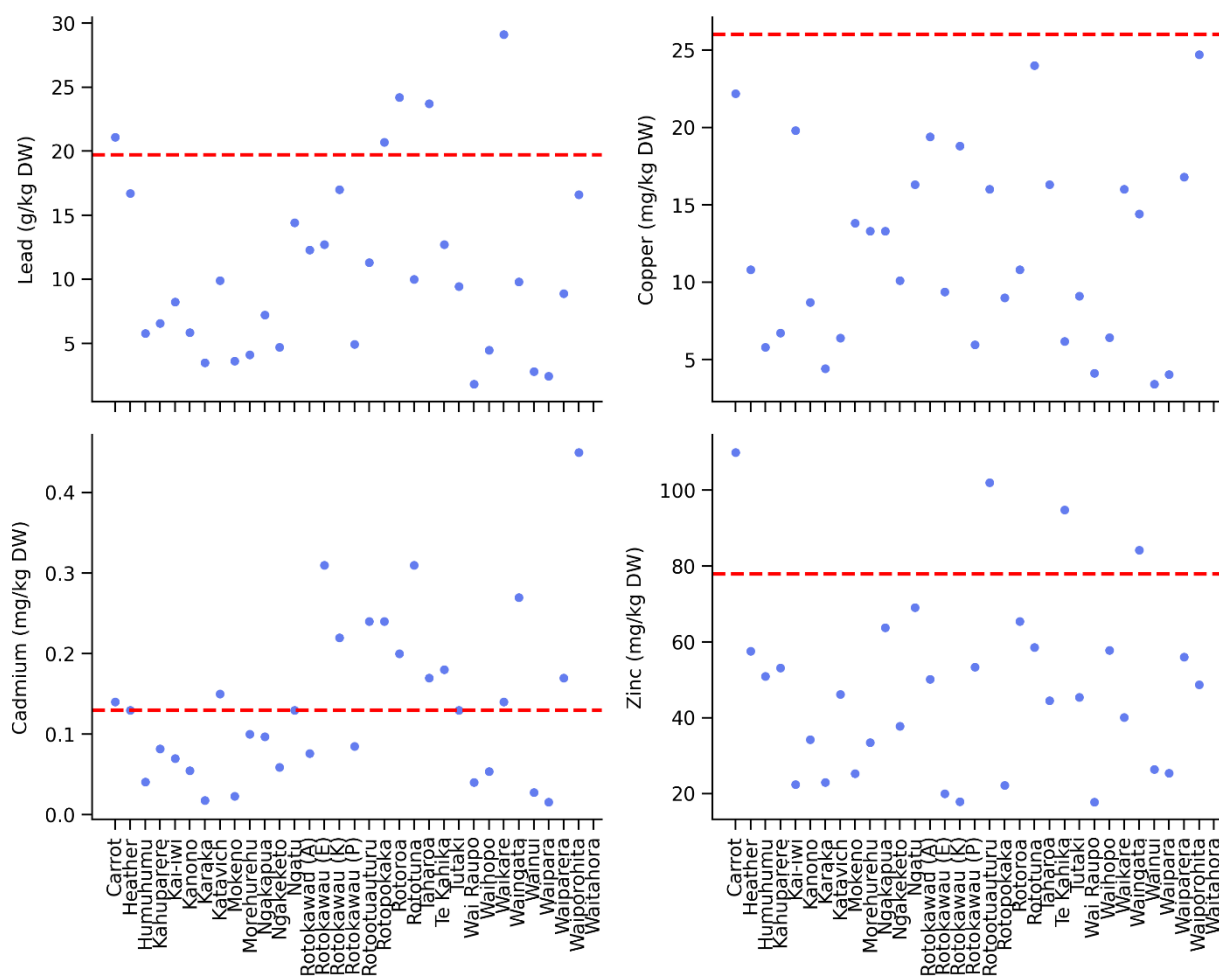


Figure A24. Metal and calcium concentrations in samples from the top 0–2 cm of the lakebed sediments collected from lakes in the Northland Region as part of the Lakes380 programme. Red dashed line indicates the national median for lakes in Aotearoa New Zealand sampled as part of the programme. The total number of lakes in the national dataset varies between 205 and 215 depending on the variable measured. Note that the y-axis scale varies. A = Aupōuri, E = East, K = Karikari, P = Pouto, DW = dry weight.

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