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A REVIEW OF THE CURRENT AND PAST HEALTH OF LAKES IN THE TASMAN REGION AND IMPLICATIONS FOR ONGOING MANAGEMENT AND PROTECTION

A REVIEW OF THE CURRENT AND PAST HEALTH OF LAKES IN THE TASMAN REGION AND IMPLICATIONS FOR ONGOING MANAGEMENT AND PROTECTION

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EXECUTIVE SUMMARY

Ten lakes in the Tasman Region were sampled as part of the national Our lakes' health: past, present, future programme, also known as Lakes380 (www.lakes380.com). The lakes sampled were: Tinawhu and Whupa (Kaihoka Lakes), Mangarākau, Otuhie, Rototai, Killarney, Lockett, Peel, Rotoiti and Rotoroa. This report was commissioned to ensure the data generated as part of this programme assist with management of lakes in the Tasman Region. The report provides analysis and interpretation of data generated from water, surface sediment and sediment core samples.

Very high concentrations of ammoniacal nitrogen (NH_3-N), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni) and zinc (Zn) were detected in the surface and / or hypolimnetic waters of Rototai, an unusual lake with a pH of 4. Other unusual values were high levels of arsenic in the surface and hypolimnetic waters of Lake Lockett, a high alpine lake, and high concentrations of Cr in the surface waters of Tinawhu, one of the coastal Kaihoka Lakes. The bottom waters of Lake Killarney, a supertrophic urban lake, had elevated levels of total nitrogen (TN), total phosphorus (TP), NH_3-N, Cd, Cr, Cu, Pb, Ni and Zn. Given the water chemistry results are based on a single time point, we recommend further sampling to confirm these results and explore potential sources or reasons for the elevated values.

High levels of Zn and Cd were detected in the surface sediment of Lake Otuhie, which might be related to previous gold mining activities in the catchment. High concentrations of three metals (Pb, Cu and Zn), commonly associated with urban and road run-off, were detected in the surface sediment of Rotoiti. These results are surprising, as both lakes have relatively unmodified catchments.

Surface sediment geochemistry analysis was undertaken to provide an initial indication as to whether nutrients bound to the surface sediment, especially phosphorus, are contributing to the nutrient loads of the study lakes. Potentially mobile phosphorus contents in the sediments of the Tasman lakes were generally above the national median, except for Mangarākau. Notably, the concentrations were particularity high in Lake Killarney.

The analysis of sediment core data provided new insights into how the catchment vegetation and water quality of each lake have changed over the last approximately 1,000 years (the period analysed varies based on the sediment core). The most pronounced changes were observed for Lake Killarney, where the landscape was transformed from a largely podocarp dominated forest to agricultural and urban developments. Correspondingly, there have been notable marked changes in the algal, cyanobacterial and bacterial communities in the lake. Similar changes in vegetation were observed in nearby Rototai. A small increase in algal concentrations and a shift in the bacterial community were observed post-European settlement in this lake; however, these changes were less pronounced than those observed in Lake Killarney. Productivity in this lake is likely limited because of the very unusual water chemistry and pH of 4.

Sediment core data from Tinawhu, Whupa and Mangarākau indicated moderate changes in the landscape around the lakes, with signs of relatively recent changes to the water quality of Tinawhu and Whupa, including increased cyanobacterial levels in Whupa. The catchments of Lakes Otuhie, Lockett, Peel, Rotoiti and Rotoroa have remained relatively unchanged over the last 1,000 years or more. Algal and cyanobacterial concentrations show little sign of change in these lakes. However, shifts in bacterial communities were observed in all lakes, although the reasons for these shifts, even in oligotrophic lakes, are unknown and are the subject of ongoing study. The shifts may indicate that global factors, such as climate change or atmospheric nitrogen deposition, are impacting all lakes in Aotearoa New Zealand.

The sediment core data provide useful insights into when and why changes in the water quality of lakes have occurred. The data are also valuable for determining informed restoration targets; for example, the algae and cyanobacteria data for Lake Killarney suggest that prior to about 1970, this lake likely had good water clarity. A return to this state would be an excellent restoration target for this lake. The pollen data from the sediment cores provide a useful resource to help guide planting plans for lakes where restoration of the catchments is required.

Based on the findings of this study, we recommend that:

- Water quality monitoring programmes should be established for Lakes Tinawhu, Whupa, Killarney, Otuhie, Mangarākau and Rotoiti.
- Further sampling and analysis of Lake Otuhie and Rotoiti surface sediment should be undertaken to enhance knowledge on the spatial distribution and concentrations of trace metals.
- Further surface sediment geochemistry surveys and bird surveys should be conducted at Lakes Tinawhu and Whupa to enhance knowledge on nutrient sources.
- Revitalisation / restoration plans should be developed for Lake Killarney following engagement with iwi and the local community.

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1. INTRODUCTION

The Tasman Region has a wide diversity of lakes including dune / wind, glacial, riverine, landslide, swamp / wetland lakes, and constructed reservoirs and dams (Leathwick et al. 2010). A significant portion of these lakes are alpine lakes and are within the northern regions of Nelson Lakes and Kahurangi National Parks.

To date, only limited sampling and monitoring of lakes in the Tasman Region have been undertaken. Schallenberg (2011) undertook a one-off assessment of Lakes Otuhie, Tinawhu (Kaihoka Lakes east) and Whupa (Kaihoka Lakes west), and these lakes were included as part of a national lowland coastal lake study (Drake et al. 2009; Drake et al. 2011). Sorrell et al. (2007) carried out an ecological assessment of Lake Matiri as part of the development of a hydro-electric power scheme. Lake submerged plant index (LakeSPI) assessments have been undertaken for Rotoiti and Rotoroa (lakespi.niwa.co.nz), and there has also been some sporadic monitoring of water quality in these lakes (Taylor 1971; Burns and Rutherford 1998; Smith 1999; Novis and Schallenberg 2021). Tasman District Council also undertook some sediment and water quality sampling at Lake Killarney in 2017 (Trevor James, unpublished)

Ten lakes in the Tasman Region were included in the national Our lakes' health: past, present, future programme, also known as Lakes380 (www.lakes380.com). As part of this programme, water, surface sediment and sediment core samples were collected. The water and surface sediment samples were analysed for nutrients, trace metals and environmental DNA (eDNA). The sediment cores were analysed using a range of techniques to explore if, how and why the lakes have changed.

The Tasman District Council recently commissioned the Lakes380 team to analyse and interpret the surface sediment, eDNA and selected water quality data. These data were used to predict the Trophic Lake Index for all lakes in the Tasman Region and provided advice to guide future monitoring (Wood et al. 2022).

Data from the sediment cores for selected lakes in the Tasman Region will be used in several scientific papers related to climate and land use change, as well as in several high-level papers documenting the current and historic health of lakes in Aotearoa New Zealand. However, the Lakes380 programme is not able to support regional-scale or lake-specific analysis and does not have resources to provide information on how the data can be used to support regional management decisions.

To ensure the data generated as part of the Lakes380 programme assist with the management of lakes in the Tasman Region, this Envirolink-funded project collates and interprets the data generated for 10 lakes in the region. This report provides analysis and interpretation of:

- Water chemistry
- Sediment nutrient geochemistry and implications for internal nutrient cycling
- Surface sediment microbial communities
- Information on changes in water quality and the surrounding landscape over the last approximately 1,000 years.

2. METHODS

2.1. Lake descriptions

Ten lakes in the Tasman Region were sampled as part of the Lakes380 programme (Figure 1 and 2). An aerial image of each lake with the sampling site are provided in Appendix 1.

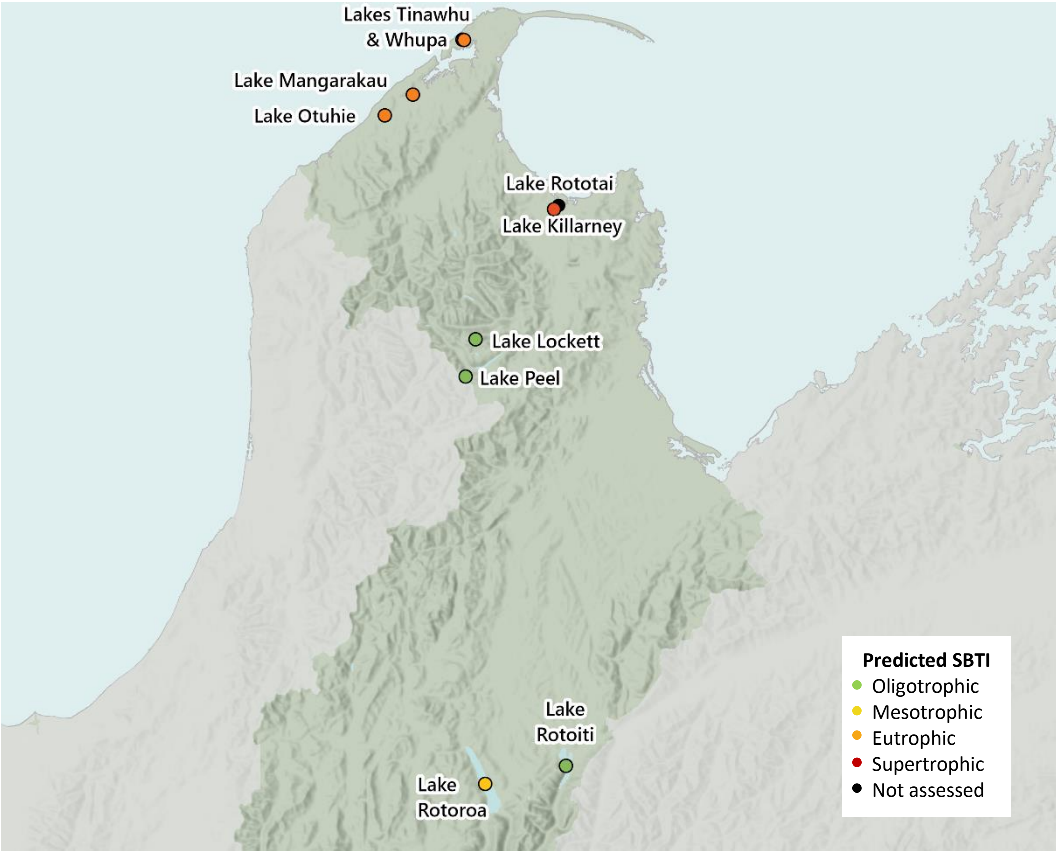

Figure 1. Locations of lakes studied in the Tasman Region as part of the Our lakes health: past, present, future research programme. The colour of the dots represents the lake trophic level as predicted using the Sediment Bacterial Trophic Index (SBTI; Pearman et al. 2022).

2.1.1. Lakes Tinawhu and Whupa

The Kaihoka Lakes have high ecological values and represent some of the last remaining relatively unmodified coastal lakes in Aotearoa New Zealand (Schallenberg 2011), thus protecting these lakes is of utmost importance. Tinawhu is currently eutrophic and Whupa is mesotrophic (Wood et al. 2022). Lakes Tinawhu and Whupa have a maximum depth of about 14.8 m and 13.5 m, respectively. Significant portions of the catchments of both lakes are in low-producing grassland (Tinawhu 51%, Whupa

43%). The lakes have no outlets or permanent inflows, with the hydrology of both lakes mainly controlled by rainfall and seepage (Schallenberg 2011).

2.1.2. Lake Mangarākau

Lake Mangarākau is a shallow lowland lake (4.6 m maximum depth) with an area of 15 ha. It is part of the Mangarākau wetlands, the largest remaining wetland in the Nelson and Marlborough Regions. Lake Mangarākau is likely an old river basin that formed through landslides. The lake water quality was monitored monthly for 2 years as part of the Lakes380 programme. The analysis of these data indicates the lake is mesotrophic with a TLI of 3.5 (Wood et al. 2022).

2.1.3. Lake Otuhie

Lake Otuhie is a large (85 ha), shallow (9 m maximum depth) coastal lake located between Westhaven / Whanganui Inlet and Kahurangi Point. The lake's catchment is influenced by limestone geology and was intensively mined for gold in the late 1800s, at which time Sandhills Creek was dammed, thus raising the water level of the outflow to lake levels and expanding the size of the lake (Schallenberg 2011). Currently, the catchment comprises 95% native vegetation and 5% pasture. Wood et al. (2022) estimated the lake is eutrophic, but the reasons for this are unclear, as only a small proportion of its catchment is in non-native vegetation (1.2% high-production grassland, 3% low-production grassland). The lake has a low water residence time and is flushed monthly, and there is no marine influence (Schallenberg 2011).

2.1.4. Rototai

Rototai, also called Blue Lake because of distinctive turquoise colour, is a small lake near Tākaka (14 m maximum depth). It is a sinkhole that was filled with groundwater but has no stormwater connections (James and McCallum 2015).

2.1.5. Lake Killarney

Lake Killarney is a small (0.8 ha, 12 m maximum depth) lake with no permanent in- or outflows. The lake is located within Tākaka township and is surrounded by parkland and residential houses. Stormwater flows into the lake, and it experiences severe algal blooms in summer (James and McCallum 2015). Previous data collected in 2017 showed anoxic bottom waters, and sediment analysis conducted concurrently indicated very high nutrient concentrations (total phosphorus (TP) = 5,850 mg kg^{-1}, total nitrogen (TN) = 29,000 mg kg^{-1}). It is highly likely that the release of nutrients from the sediment contributes significantly to the nutrient load in this lake.

2.1.6. Lake Lockett

Lake Lockett is a deep (57 m maximum depth) alpine cirque (bowl-shaped valley formed by a glacier) surrounded by steep rock, scree slopes and native forest in the

Kahurangi National Park. The remote location of this lake has meant that evidence of human presence or impact on this lake is minimal, and its catchment is over 95% native forest and grasses. In the late 1800s to about 1920, there was some very low intensity grazing of sheep and cattle in this region.

2.1.7. Lake Peel

Lake Peel is a small (4.7 ha), shallow (9 m maximum depth) alpine cirque lake in Kahurangi National Park, mostly surrounded by native alpine vegetation. As noted above, there was some very low intensity grazing of sheep and cattle in this region; however, its proximity to Lake Peel is unknown.

2.1.8. Rotoroa and Rotoiti

Rotoroa and Rotoiti are two large glacial lakes in Nelson Lakes National Park, and both were formed when rivers were dammed behind past glaciers' terminal moraines. The lakes lie in old glacial valleys and are surrounded by moderately steep to very steep hills, which are completely forested to the water's edge. The catchment of both lakes is predominately native vegetation, with a small amount of low- and high-producing grassland (Rotoiti 2.4%, Rotoroa < 0.4%).

Rotoroa is the larger of the two lakes, with an area of 2,361 ha and a maximum depth of 136 m. The Sabine and D'Urville Rivers flow into the southern end of the lake, and it is one of the sources of the Buller River, draining into the Buller via the Gowan River. Rotoiti has an area of 964 ha and a maximum depth of 82 m and is the source of the main stem of the Buller River.

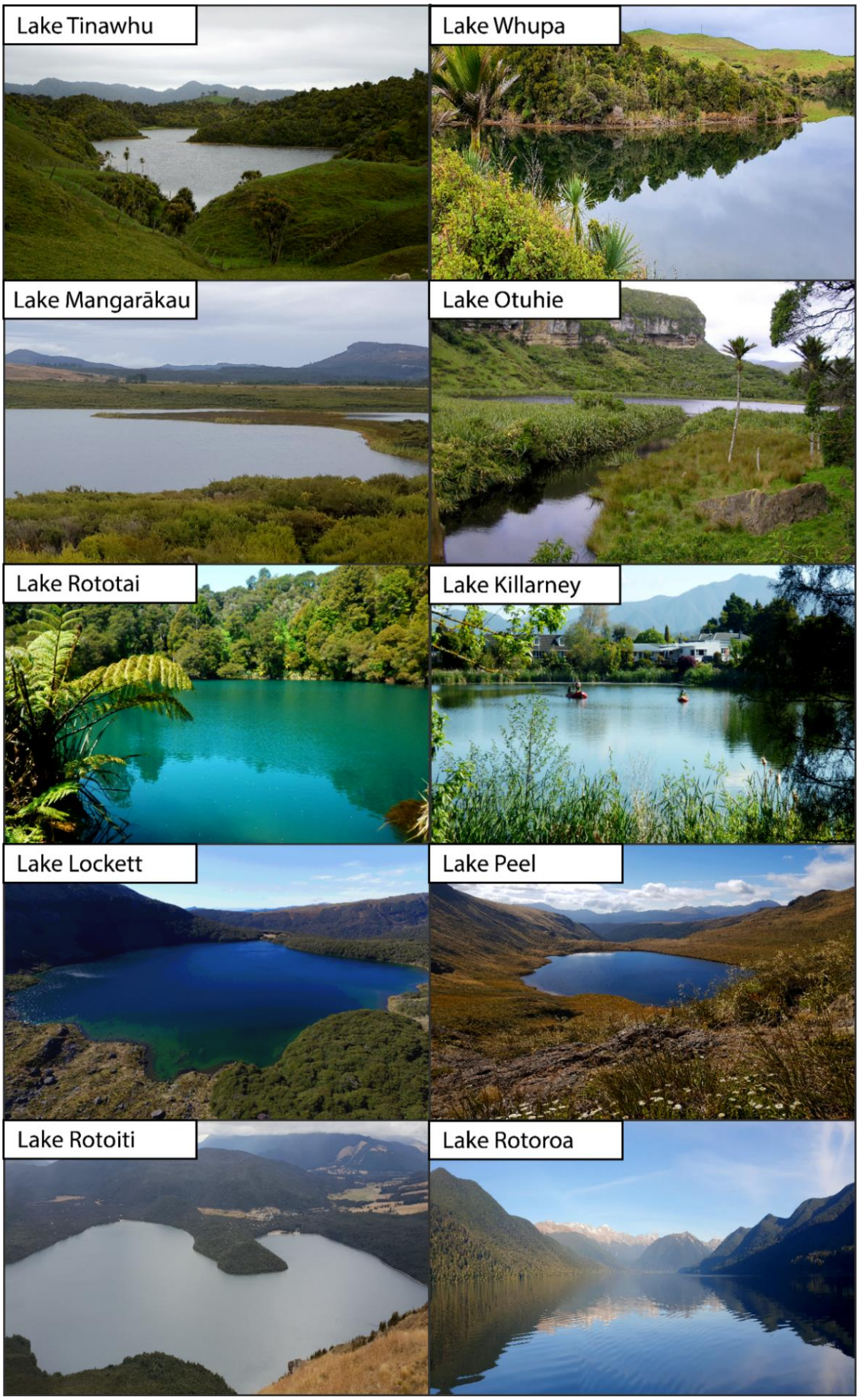

Figure 2. Photographs of the 10 study lakes

Table 1. Physical characteristics, catchment land use and Sediment Bacterial Trophic Index (SBTI; Pearman et al. 2022) for the 10 sampled lakes in the Tasman Region. ND = not determined.

	Max. depth (m)[1]	**Secchi Disc (m)[1]**	**Altitude (m)[2]**	**Area (ha)[2]**	**Lake geomorphic type[2]**	**Catchment (%)[3]**						**SBTI[1]**
						High productivity exotic grass	Low productivity exotic grass	Native	Native Forest	Urban	Other	
Lake Tinawhu	13.7	4	52	5.3	Dune	0.0	51.2	0.0	48.8	0.0	0.0	Mesotrophic
Lake Whupa	14.6	2.8	38	6.8	Dune	0.0	42.9	0.0	57.1	0.0	0.0	
Lake Mangarākau	4.6	1.68	14	15.3	Wetland	0.0	0.0	45.8	44.3	0.0	9.8	Mesotrophic
Lake Otuhie	9	0.97	5	84.7	Landslide	1.3	3.0	48.2	46.4	0.0	1.2	Eutrophic
Rototai	14	7.8		0.57	ND	80.5	0.0	0.0	19.0	0.5	0.0	
Lake Killarney	11.8	1.8	11	0.87	ND	54.2	0.0	8.5	0.8	36.5	0.0	Supertrophic
Lake Lockett	57	14	1285	27.4	Glacial	0.0	0.0	78.4	17.1	0.0	4.5	Microtrophic
Lake Peel	8.9	8.4	1353	4.7	Glacial	0.0	0.0	86.7	0.0	0.0	13.3	Mesotrophic
Rotoiti	82		595.53	964.4	Glacial	0.3	2.4	28.2	48.6	0.2	20.3	ND
Rotoroa	135.9		420.71	2361.5	Glacial	0.2	0.2	23.2	57.6	0.0	18.8	ND

1. Data from Our lakes' health: past, present, future (Lakes380) field sampling.
2. Data from Freshwater Ecosystems of New Zealand (FENZ) Geodatabase (Leathwick et al. 2010).
3. Data from Land Cover Database v5 (Landcare Research New Zealand Ltd https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/).

2.2. Physico-chemical analysis of water samples

Sampling of lakes in Golden Bay / Mohua was undertaken in October 2018 and Rotoiti and Rotoroa in May 2021. Prior to sampling, a side-scan sonar survey was used to determine the deepest part of each lake; however, sampling sites for Rotoiti were selected to avoid areas impacted by underwater landslides (which impact the sediment samples).

Secchi disc depth was recorded at all lakes, and water column profiles for temperature (°C), dissolved oxygen (DO % and mg L^{-1}), chlorophyll-*a* (Chl-*a*; µg L^{-1}) and photosynthetic active radiation (PAR) were measured using a RBRmaestro³ Multi-Channel Logger (Ruskin, USA) at the deepest point in the lake. Where available, these profiles are provided in Appendix 2. Note that these measurements were not taken at Rotoiti and Rotoroa.

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

Water samples (1 L) were collected using an integrated tube sampler through the surface mixed layer as determined by the RBR profile (hereafter referred to as surface samples). Sub-samples were taken for TN, TP and total organic carbon (TOC). A second set of sub-samples (40 mL) were filtered (low bleed 0.45 µm) for dissolved organic carbon (DOC). Analyses of total nutrients were undertaken using APHA 4500 methods on a flow injection analyser. Reporting limits for TN and TP were 0.1 g/m^3 and 0.005 g/m^3, respectively. Analyses of TOC and DOC were undertaken by combustion analysis at 850 °C using APHA 5310 B methods with reporting limits of 0.5 g/m^3. A further subset of samples was filtered (0.45 µm) and analysed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), based on the US Environmental Protection Agency (EPA) method 200.8 for arsenic (AR), cadmium (Cd), chromium (Cr), copper (Cu), Lead (Pb), mercury (Hg), Nickel (Ni) and Zinc (Zn). Reporting limits (mg kg^{-1}) were 0.005, 0.00001, 0.0002, 0.0002, 00005, 00008, 0002 and 0.001, respectively.

The RBR profile showed that seven of the lakes were stratified at the time of sampling; for these lakes a Van Dorn water sampler was used to collect a water sample (1L) from approximately 1 m above the lakebed. These samples were processed and analysed as described for the surface water samples.

2.3. Surface sediment analysis

2.3.1. Surface sediment collection for nutrient and elemental characterisation and microbial DNA

Samples for surface sediment geochemistry were collected by Uwitech gravity corer (90 mm diameter core). Five cores were taken, and the top 2 cm of sediment removed using a core cutter and combined in a 500 mL container. These were stored chilled (4 °C) and shipped to the laboratory within 48 hrs for nutrient and elemental characterisation. Analysis of surface sediment geochemistry was not conducted on Lake Killarney sediment during the Lakes380 programme. Instead, data from previously conducted analysis were utilised in this report. It should be noted that this was conducted in 2017, and only the top 1 cm of the sediment was sampled; therefore, the results are not directly comparable but are still considered useful in the context of this report.

Surface sediment samples for eDNA were taken in triplicate at each site. Using sterile spatulas, approximately 2 g of the undisturbed surface sediment layer (~top 1–2 mm) was placed in sterile tubes and stored in lifeguard (Qiagen, Germany) before being transferred to a -80 °C freezer in the laboratory for later DNA extraction (described below in Section 2.4).

2.3.2. Surface sediment nutrient and metal analysis

Surface sediment samples for nutrient and elemental analyses were homogenised, centrifuged (3000× g, 40 mins, 4 °C) and the pore water decanted. The sediments were analysed for metals using the methods described in Pearman et al. (2020). Briefly, the sediment was dried, passed through a 2 mm sieve and analysed for the following metals using acid digestion followed by ICP-MS, based on the US EPA method 200.8 for iron (Fe), manganese (Mn), aluminium (Al), calcium (Ca), Pb, Cu, Zn, Cd, phosphorus (P) and sulphur (S). Reporting limits (mg kg^{-1}) were 12.5, 0.125, 2.5, 12.5, 0.05, 0.075, 0.05, 0.005, 10 and 250, respectively. Total nitrogen and TOC were analysed using catalytic combustion (at 900 °C, O_2) and separated using a Thermal Conductivity Detector (reporting limit for both g/100 g). Oven drying of a known sediment volume was used to calculate bulk density, while oven drying followed by ashing (550 °C and 950 °C) and gravimetric determination were used to measure organic matter and carbonate content. Values were compared with the median values obtained from 201 lakes analysed nationally as part of the Lakes380 project.

2.3.3. Phosphorus fractionation analysis

To determine the forms of P bound in the sediment, chemical sequential extraction was undertaken on thawed sediment samples following a 'Psenner' type scheme modified from Rydin (2000) and Waters et al. (2021). In this sequential extraction scheme, sediments are shaken in a series of chemical reagents. The analysis provided the following P fractions:

- *Exchangeable phosphorus (Ex-P):* very loosely bound and soluble phosphorus.
- *Redox-sensitive phosphorus (Red-P):* phosphorus that may be mobilised by low dissolved oxygen in the surrounding water column. Commonly associated with reducible mineral phases such as Fe and Mn (hydr)oxides.
- *pH-sensitive phosphorus (pH-P):* phosphorus that can be mobilised by high pH in the surrounding water column. Commonly bound to the surfaces of mineral phases such as Al (hydr)oxides as well as the less reactive Fe and Mn (hydr)oxides, clays and organic particulates.
- *Organic phosphorus (Org-P):* easily degradable organic fraction.
- *Calcium-associated phosphorus (Ca-P):* the phosphorus fraction associated with Ca minerals, including apatite and carbonates as well as refractory metal oxides. This fraction is not considered to be bioavailable.
- *Residual phosphorus (Res-P):* consists of largely refractory organic material. This fraction is not considered to be bioavailable.
- *Total phosphorus (TP)*: determined by the sum of all fractions.

The Ex-P, Red-P and Org-P constitute the more mobile P fractions (Waters 2021) and are most likely to be, or become, bioavailable. The sum of these fractions is referred to as 'potentially mobile P'. Values were compared with the median values obtained from 201 lakes analysed nationally as part of the Lakes380 project.

2.4. Sediment core analysis

2.4.1. Sediment core collection

Four sediment cores were retrieved close to the deepest point of each lake (except Rotoiti and Rotoroa) using an Uwitech gravity corer with 2 m long, 90 mm diameter polyvinyl chloride barrels. Rotoiti and Rotoroa were sampled using a Mackereth corer with 6 m long, 50 mm diameter polyvinyl chloride barrels. All barrels were cleaned with 2% sodium hypochlorite (bleach) prior to coring. After retrieval, the cores were sealed, stored at 4 °C and in darkness for up to 4 weeks until sub-sampling. The cores were split lengthwise using a Geotek core splitter and a guillotine, and then photographed.

To prevent cross-contamination caused by the splitting of the cores, the top 2–3 mm of one half-core per lake was carefully removed with a sterile spatula. Sub-samples (~0.5 g) were taken from the centre of the half-core using a sterile spatula at various depths down the core. In general, sub-samples were taken every 1–2 cm in recent sediments and every 4–5 cm in older sediments. Sub-samples were kept frozen

(-20 °C) and in the dark until further DNA extraction. Sub-samples were also collected from a range of depths for pollen and charcoal analysis.

2.4.2. *Sediment core chronology*

Age models were developed for all lakes, except Rototai, Rotoiti and Rotoroa. Although age models are being developed for these three lakes, they were not available at the time this report was written.

A selection of samples from the upper part of each sediment core were extracted for $^{210}Pb_{ex}$ analyses. Total ^{210}Pb activity was estimated using alpha spectrometry at the ESR National Centre for Radiation Science. Terrestrial leaf macrofossils were extracted by picking *in situ* material from the split core surface. Macrofossils were cleaned and pre-treated using an acid–alkali–acid procedure to remove carbonates, fulvic and humic compounds (Norris et al. 2020). The pre-treated macrofossils were converted to CO_2 by combustion, graphitised and measured by accelerator mass spectrometry following Baisden et al. (2013). Conventional Radiocarbon Ages were converted to calendar years using the ShCaL20 calibration curve (Hogg et al. 2020), while those that returned modern ages were calibrated using the BHDCGO curve (Turnbull et al. 2017).

A bayesian framework was used to conduct age-depth modelling using OXCAL 4.4 (Ramsey 2009). Briefly, for each studied site, a $^{210}Lead_{ex}$ age-depth model, pollen and charcoal biostratigraphy and calibrated ^{14}Carbon dates 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.

2.5. Hyperspectral imaging scanning

The cores were scanned using a Specim sCMOS-CL-50-V10E-SCB camera. Measurements were captured with a spectral resolution of 1.3 nm and a spatial resolution of 41 µm. This study analysed spectral data using RABD660/670, which is correlated with the sedimentary pigment Chl-*a* and its degradation products. The results were converted to a spectral index with values in the range of 1.0–2.5.

2.6. Environmental DNA analysis

DNA was extracted from approximately 0.25 g of surface sediments and from specific depths of the sediment cores. DNA was extracted using the PowerSoil kit (Qiagen). The V3–V4 region of the bacterial 16S rRNA gene and the V4 region of the eukaryotic nuclear 18S rRNA gene were amplified by polymerase chain reaction (PCR). The primers 341F: 5-CCT ACG GGN GGC WGC AG-3 and 805R: 5-GAC TAC HVG GGT ATC TAA TCC-3 (Herlemann et al. 2007; Klindworth et al. 2013) were used for the bacterial 16S rRNA gene, and eukaryotic-specific primers Uni18SF: 5-AGG GCA AKY CTG GTG CCA GC-3 and Uni18SR: 5-GRC GGT ATC TRA TCG YCT T-3 (Zhan et al. 2013) for the 18S rRNA gene. Conditions for the PCR reactions and subsequent library construction for sequencing on an Illumina Miseq are as described in Pearman et al. (2020). Raw reads from the sequencing machine were demultiplexed and processed using cutadapt (Martin 2011), and Amplicon Sequence Variants (ASVs) were inferred using DADA2 (Callahan et al. 2016) following the pipeline detailed in Pearman et al. (2020). Reads were taxonomically classified using the RDP classifier against the SILVA 138 database (Pruesse et al. 2007) with a minBoot threshold of 70.

Community compositions of both bacteria and eukaryotes were plotted at the class level for the surface sediment communities. Non-metric multi-dimensional scaling (NMDS) ordinations were plotted based on Bray-Curtis distance matrices to show community change over time and space. The functional profiles of the bacterial communities were inferred from the 16S rRNA composition using the software *paprica* (Bowman and Ducklow 2015). This places the 16S rRNA gene sequences into a phylogenetic tree containing bacteria with sequenced genomes. The probable metabolism is then predicted based on the functional capability of the nearest sequenced genomes in the phylogenetic tree. Genes encoding enzymes – related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction – were subsequently subset for analysis.

2.7. Pollen analysis

Pollens were identified using microscopy as described in Short et al. (2022). Briefly, pollen was extracted from 0.25 cm^3 using standard laboratory techniques that included 10% hot hydrochloric acid, acetolysis and 6-micron sieving. Exotic Lycopodium tablets were added to each sample to allow calculation of pollen concentrations. Pollen and spore identifications were made using standard texts and Aotearoa New Zealand reference collections.

Data are presented as relative frequency of a minimum pollen sum of 150 grains. This sum includes pollen from all dryland plants: trees, shrubs and herbaceous plants and non-native plant taxa. Bracken fern (*Pteridium esculentum*) is included in the dryland pollen sum because in a post-disturbance landscape its functional morphology is closer to a shrub than a fern, and a stand is ecologically equivalent to shrubland (McGlone et al. 2005). Pollen of other groups (wetland, aquatics, ferns, tree ferns and non-palynomorphs) were excluded from the sum, but their percentages were calculated as a proportion of dryland pollen, plus the respective group.

Pollen data in combination were used to delineate human occupation periods in the sediment downcore data. Bracken fern (*Pteridium esculentum*) is used across Aotearoa New Zealand as a chronological marker for the first presence of Māori activity and settlement, as it is both an indicator of landscape disturbance and a nutritional source (McGlone and Wilmshurst 1999; McWethy et al. 2010; Newnham et al. 2018). Pine (*Pinus* spp.), other non-native taxa [e.g. willow (*Salix* spp.), sheep's sorrel (*Rumex acetosella*) and alder (*Alnus* spp.)] were introduced by European colonialists and used to mark European activity in a landscape.

3. RESULTS

3.1. Surface water

3.1.1. Surface water nutrient and elemental analysis

The concentration of nutrients in the surface waters of the Tasman lakes were compared to the national average from the Lakes380 programme[1] (Figure 3). Ammoniacal nitrogen (NH_3-N), Cd, Cu, Pb, Ni and Zn were extremely high in Rototai compared to all other Tasman lakes and the national median values (well above the 95th percentiles). Lakes Otuhie and Killarney were higher than the national median values for TN, TOC and Chl-*a.* Lake Lockett was very high in As and Lake Tinawhu in Cr (both well above the 95th percentile of the national median).

[1] For nutrients in the surface waters, the number of lakes in the Lakes380 dataset ranged from 239 to 287 depending on the parameter measured.

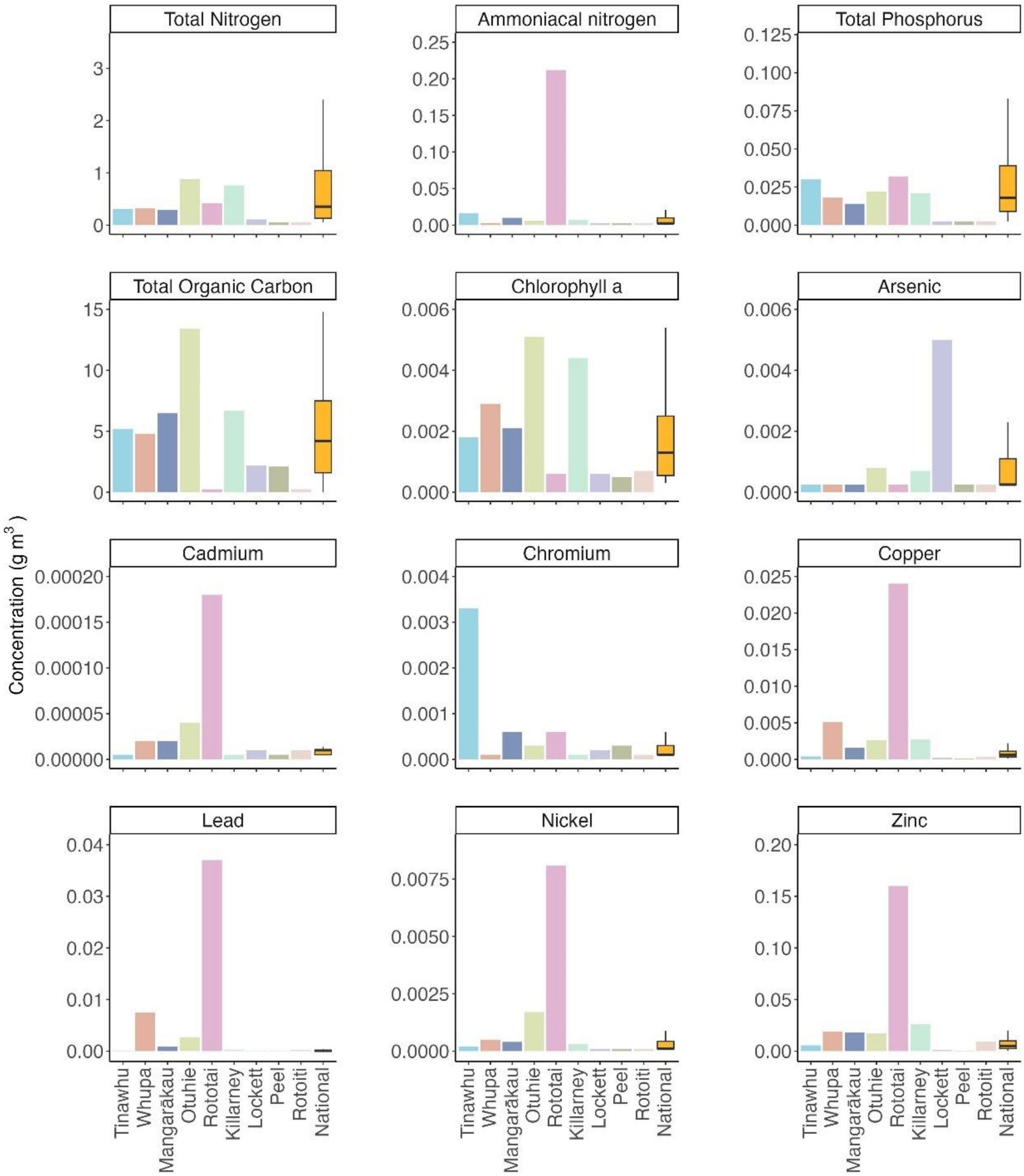

Figure 3. Nutrient and elemental concentrations in surface water samples collected from lakes in the Tasman Region compared to the national median for a selection of lakes in Aotearoa New Zealand (the total number of lakes in the national dataset varies between 239 and 287 depending on the variable measured). Note that the y-axis scale varies.

3.1.2. Hypolimnion nutrient and elemental analysis

For seven of the lakes, water was collected from the hypolimnion. The results were compared to the national average from the Lakes380 programme[2] (Figure 4). The hypolimnion water from Lake Killarney was extremely high in TN, TP, NH_3-N, Cd, Cr, Cu, Pb, Ni and Zn compared to the national median values (well above the 95th percentiles). As observed in the surface water results, Lake Lockett hypolimnetic water was very high in As, and Rototai was higher than the national median values for TN, NH_3-N, Cd, Ni and Zn. All the Tasman lakes sampled, apart from Rototai and Lake Lockett, were higher than the national median in TOC (Figure 4).

[2] For nutrients in the hypolimnetic waters, the number of lakes in the Lakes380 dataset ranged from 85 to 100 depending on the parameter measured.

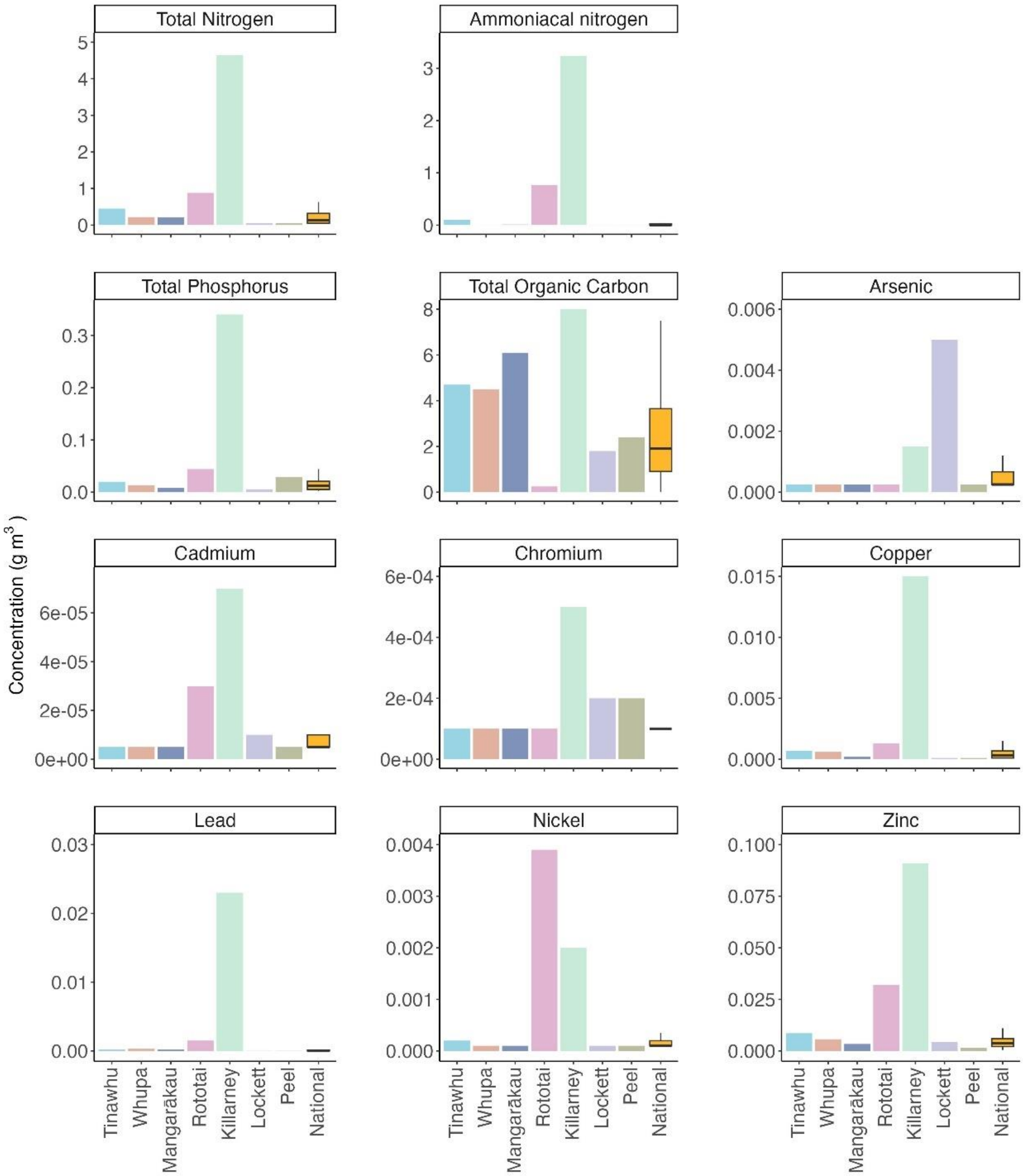

Figure 4. Nutrient and elemental concentrations in deep water samples (*n* = 1) collected from lakes in the Tasman Region and compared to the national median for selected lakes in Aotearoa New Zealand (the total number of lakes in the national dataset varies from 85 to 100 depending on the variable measured). Note that the y-axis scale varies.

3.2. Surface sediments

3.2.1. Surface sediment chemistry

The surface sediment chemistry of the study lakes was compared to the national statistics from 214 lakes analysed during the Lakes380 programme. Heavy metals were also compared to the Default Guideline Values (DGV) for sediment quality defined under the Australian and New Zealand guidelines for fresh and marine water quality (ANZECC and ARMCANZ 2000).

Heavy metals

All of the Tasman lakes were close to or below national median values for Pb (median = 18 mg kg^{-1}) except Rotoiti (51 mg kg^{-1}), which was in the top 10% of sampled lakes nationwide and was slightly higher than the DGV (Pb = 50 mg kg^{-1}; Figure 5). Copper contents were high (above the 75th percentile of the national dataset) in Lakes Peel, Lockett and Rotoiti, but these were below DGV concentrations. Zinc contents were elevated above the national 75th percentile in Lake Otuhie and Rotoiti but below DGV concentrations. Cadmium contents were above the 75th percentile in Lakes Peel and Lockett and were particularly elevated in Lake Otuhie, although they were below the DGV. The remaining lakes were near or below median values. Due to limited funding, analyses for these metals were not conducted on sediments from Lake Killarney or Rototai, which are lakes in proximity to urban areas or past industrial activities.

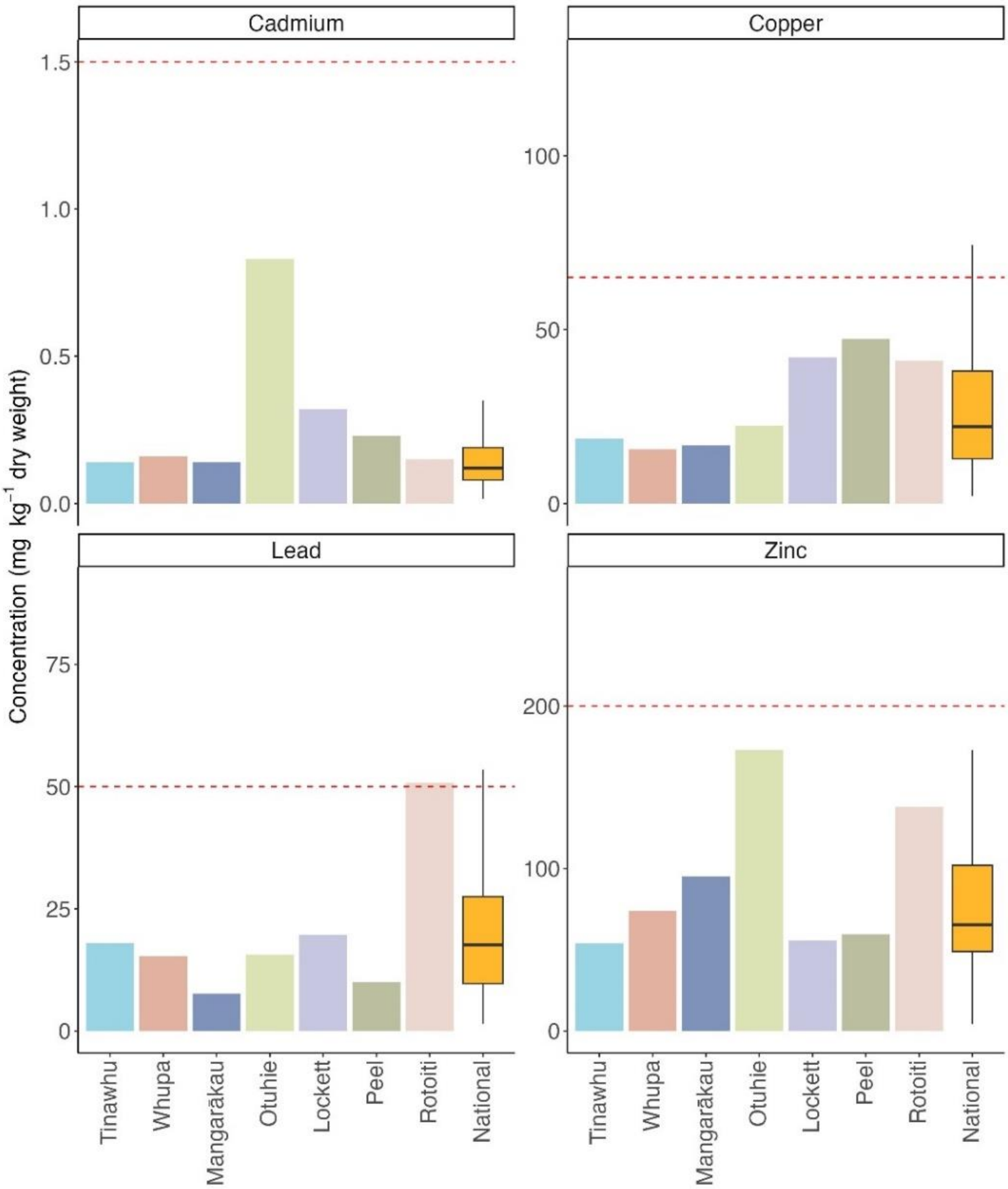

Figure 5. Sediment chemistry for samples from the top 0–2 cm of the lakebed sediments compared to the national median (*n* = 214 lakes) from selected lakes in Aotearoa New Zealand. Elemental results are total recoverable contents. Note that the y-axis scale varies.

Phosphorus geochemical parameters were compared with summary statistics from the national surface sediment (0–2 cm) dataset from the Lakes380 programme (*n* = 178; Figure 6). All Tasman lakes analysed, except Lakes Mangarākau and Otuhie, had TP contents in the surface sediments above the national median (1,568 mg kg^{-1}) but within the interquartile range. The exceptions to this were Lake

Tinawhu (2,319 mg kg^{-1}), which was just above the 75th quartile of the national dataset, and Lake Killarney (9,316 mg kg^{-1}), which was higher than the maximum TP content in the Lakes380 dataset (5,974 mg kg^{-1}). The Lake Killarney sediment was not analysed for P fractionation during the programme, and the sample reported here is for the 0–1 cm depth fraction as opposed to the 0–2 cm analysed during Lakes380. Hence, while it is not directly comparable, it is evident that the surface sediment of this lake is extremely enriched in P. Lake Otuhie sediment was notably low in TP content.

Potentially mobile P contents in the sediments of the Tasman lakes were generally above the national median (801 mg kg^{-1}), with the exception of Lake Mangarākau, which at 398 mg kg^{-1} was substantially lower. The potentially mobile P in the Tasman lakes was generally dominated by the elevated levels of organic P, especially in the alpine Lakes Peel and Lockett, but also in the Kaihoka Lakes (Tinawhu and Whupa). In contrast, the other main component of potentially mobile P, redox-sensitive P, was low in nearly all the lakes. The exception was again Lake Killarney – not shown in Figure 6 – which has an extremely high content of this P fraction (2,367 mg kg^{-1}). Due to limited funding, the potentially mobile P was not analysed in Lake Otuhie.

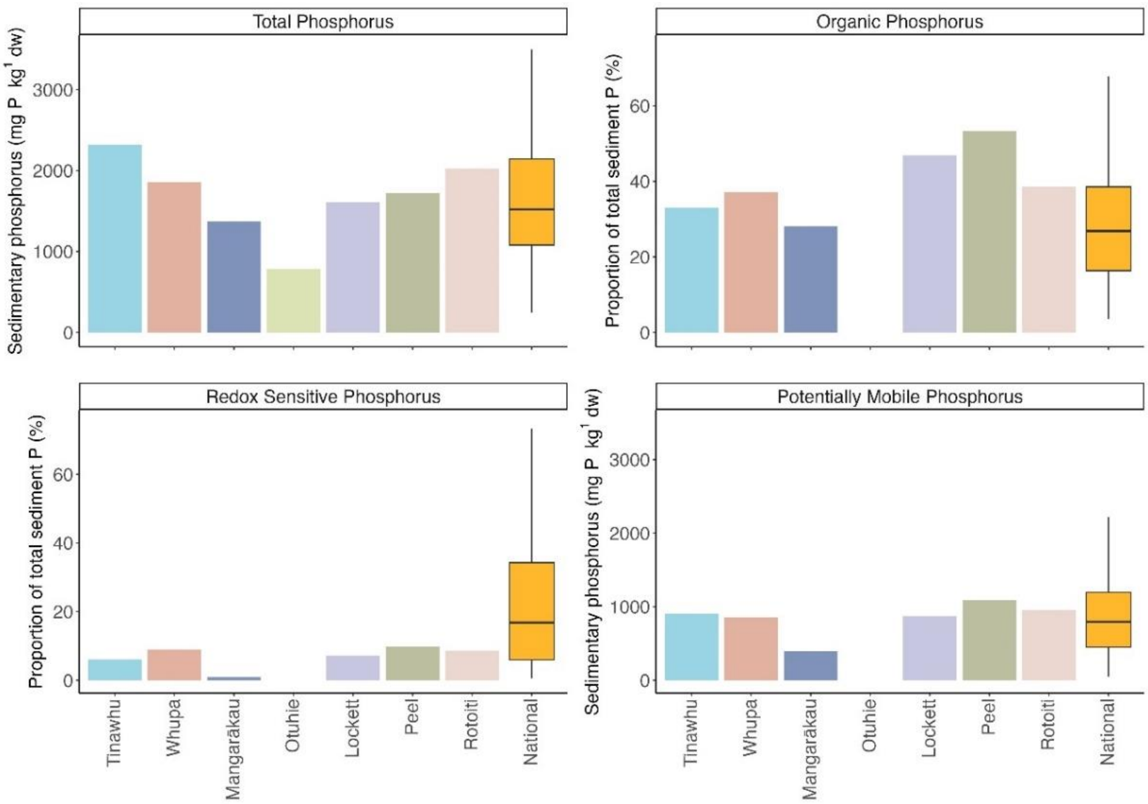

Figure 6. Phosphorus geochemistry (median value) in surface sediment of sampled lakes compared to the national median (*n* = 179 lakes) from the national Lakes380 dataset. Phosphorus fractionation analyses were not conducted on sediments from Lake Otuhie.

3.2.2. Bacterial community composition in surface sediment

The environmental DNA (eDNA) metabarcoding analysis of the surface sediments revealed different bacterial communities among the lakes (Figure 7A). The NMDS plot showed that Rototai and Lake Killarney have similar bacterial communities and Lakes Tinawhu, Otuhie and Mangarākau also cluster together. The bacterial community in Lake Lockett was very different to all other lakes.

Bacteroidia and / or Gammaproteobacteria were the dominant bacteria classes in the surface sediment of all lakes, except Lake Lockett where Nitrospira and Methylomirabilia were abundant (Figure 7B). Nitrospira play a pivotal role in nitrification and often occur in close association with ammonia-oxidising bacteria or archaea that convert ammonia to nitrite (Daims and Wagner 2018), while Methylomirabilia are denitrifying methanotrophs (Elul et al. 2021). Cyanobacteria represented a significant proportion of the community for Lakes Tinawhu, Killarney and Peel.

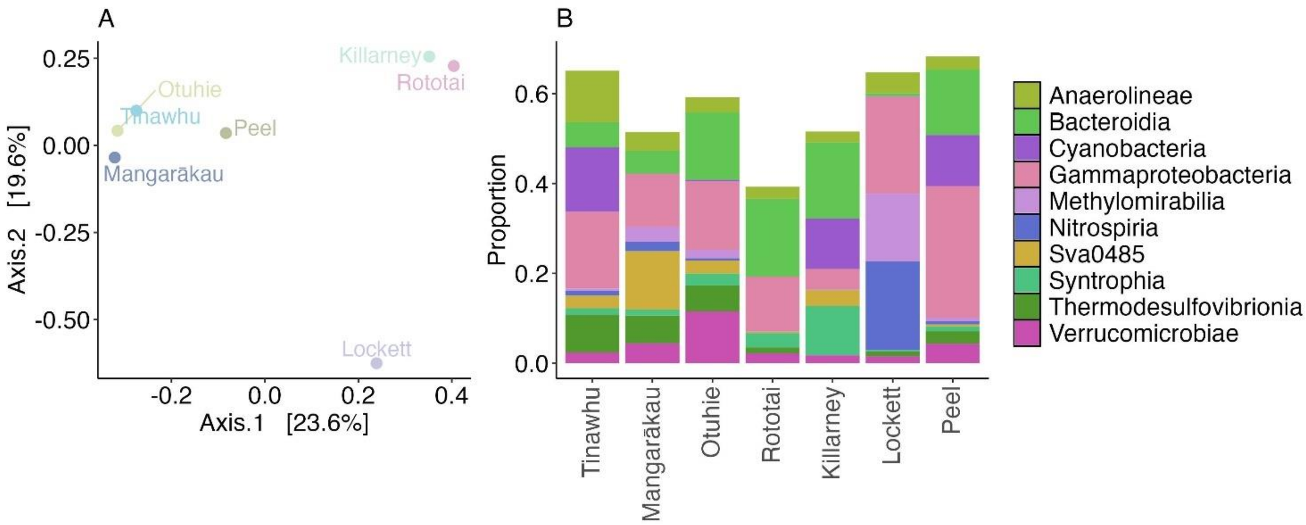

Figure 7. (A) Non-metric multi-dimensional scaling (NMDS) ordination plot of bacteria in the surface sediments of Tasman lakes – the larger the distance between the dots, the greater the difference in the bacterial community composition. (B) Bacterial taxonomic composition of surface sediments (plotted at the class level). The missing proportion represent 'Other' bacterial classes that were present in low abundance.

3.2.3. Eukaryotic community composition in surface sediment

The micro-eukaryotic communities varied among the lakes, with Lakes Lockett and Peel, and Mangarākau and Tinawhu, clustering together in the NMDS, indicating similar community structures (Figure 8A). The eukaryotic taxonomic composition (Figure 8B) revealed that despite the differences in community, Dinophyceae (dinoflagellates) and Spirotrichea (ciliate protozoa) were present in all lakes. Rototai was largely dominated by gastrotrichs (often referred to as hairybellies or hairybacks – a group of microscopic, cylindrical, acoelomate animals that are widely distributed and abundant in fresh water) and Lake Peel was dominated by Ostracoda (a crustacean that is also known as seed shrimps).

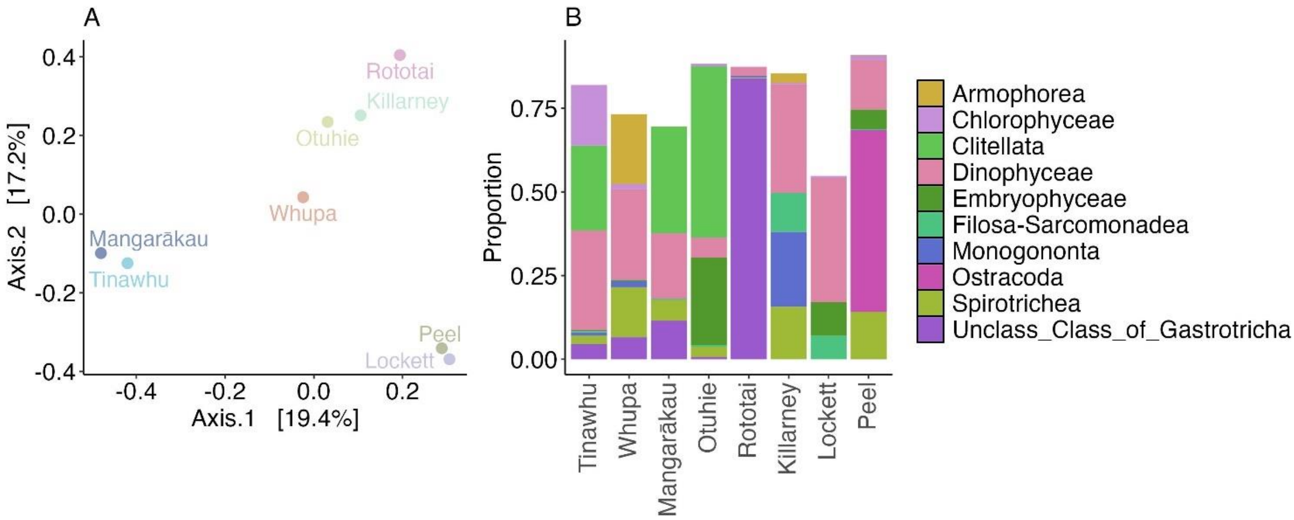

Figure 8. (A) Non-metric multi-dimensional scaling (NMDS) ordination plot of the micro-eukaryotic community in surface sediments – the larger the distance between the samples, the greater the difference in the community structure. (B) Eukaryotic taxonomic composition of surface sediments. The missing proportion represent 'Other' classes that were present in low abundance.

3.3. Downcore analysis

Images from a selection of the sediment cores are provided in Appendix 3.

3.3.1. Lake Whupa

The pollen and charcoal results from the Lake Whupa sediment core suggest that prior to human arrival, rimu, *Metrosideros* spp. (most likely rata), hutu and tree ferns were abundant in the region (Figure 9A). Post-Māori settlement, some vegetation disturbance occurred. This is highlighted in Figure 9A, which shows an increase in charcoal (burning) and bracken fern and a slow decrease in tall trees such as rimu, rata and beech. Post-European settlement, removal of tall trees in the region continued. While about 50% of the lake's catchment is now in regenerating native forest, the remainder of the landscape surrounding the reserve has been converted to farmland. This is reflected in Figure 9A by the increase in grasses. Raupō has probably always been present in the margins of this lake, but it increased markedly in abundance shortly after Māori settlement.

Algal concentrations have fluctuated in the lake, with a steady increase in the last approximately 50 years (Figure 9A). Post-European settlement, the cyanobacteria counts have increased markedly (Figure 9A). The NMDS plot highlights significant differences in the bacterial composition across the range of human occupation eras, in particular between the European and both the Māori and pre-human settlement eras (Figure 9B). The bacterial functional profiles related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction are variable over time but indicate a small increase in all enzymes in the post-European settlement era (Figure 9C).

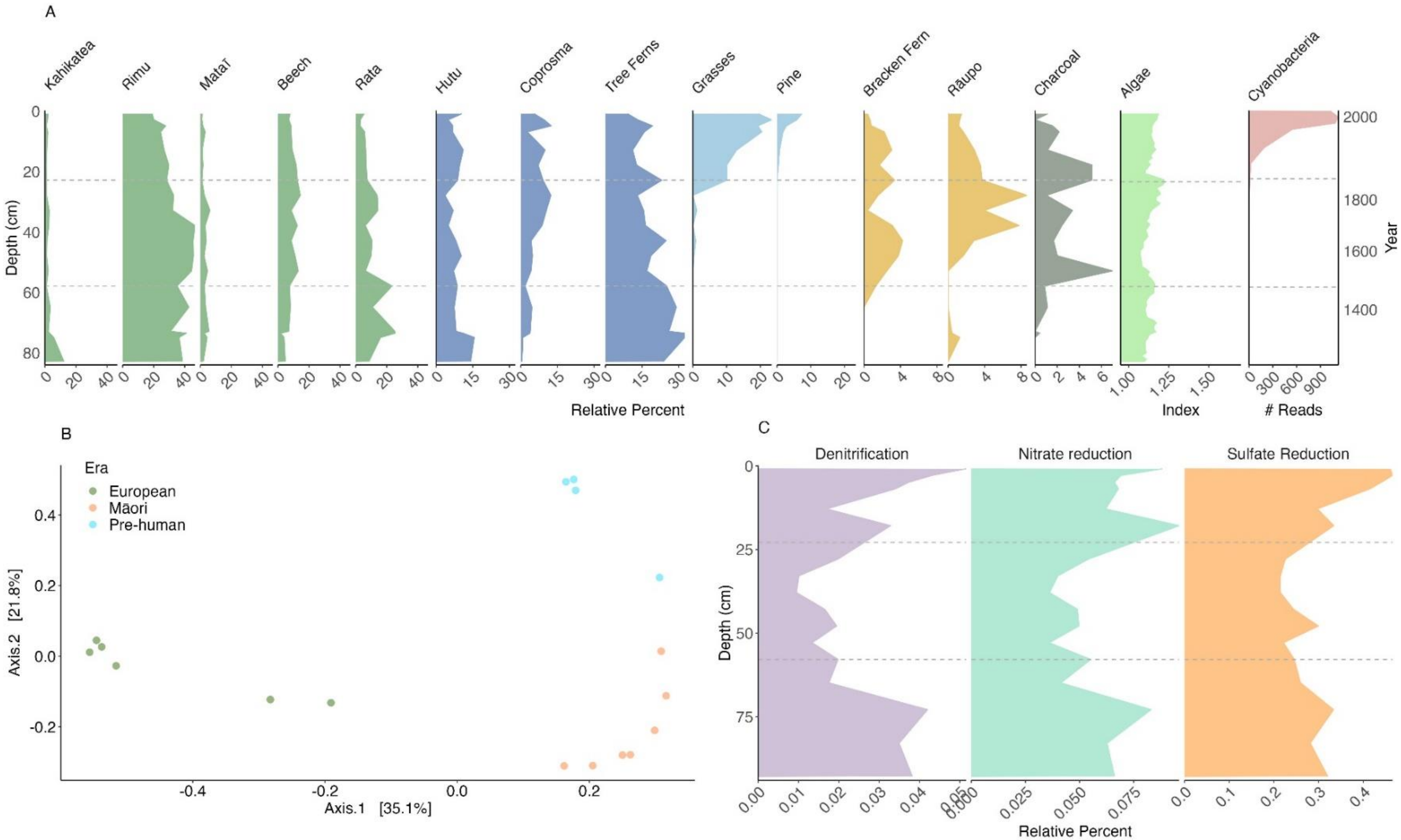

Figure 9. Downcore analysis results for Lake Whupa. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), RABD660-670 index from the hyperspectral analysis (proxy for algae), and number of metabarcoding reads of cyanobacteria. (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) Proportion of specific metabolic pathways (portion of functional read abundance) at different depths. The dotted lines represent the different human occupation eras (bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement).

3.3.2. Lake Tinawhu

The pollen and charcoal results from the Lake Tinawhu sediment core suggest that prior to human arrival, native forests of podocarps [mainly rimu and rata (*Metrosideros* spp.)], beech, tree ferns, and small trees and shrubs such as the endemic hutu were prevalent in the region (Figure 10A). After Māori settlement, there were some minor changes in the vegetation. These changes are identified by the presence of low amounts of charcoal (burning) and the appearance of bracken fern, which is often associated with landscape disturbance. Of note is the presence, and then relatively high abundance of raupō, which does not appear to have been growing around this lake prior to human arrival. Post-European settlement, some of the native vegetation in the region slowly decreased, and the increase in charcoal and bracken ferns suggests intensification of burning. While much of the lake's catchment is still in native forest, the land on the north-western lake margins has been converted to farmland. This is reflected in Figure 10A by the increase in grasses. Algae have always been present in the lake at low levels, and there has been a slight increase in cyanobacteria (albeit at very low levels) in the past 2 decades.

The NMDS plot highlights differences in the bacterial composition between human occupation eras. In particular, there is marked changes in the composition during the Māori and early post-European settlement eras (Figure 10B). The bacterial functional profiles related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction are variable over time, but there is a small increase in denitrification and nitrate reduction enzymes in the last approximately 20 years. However these results are not above the levels present prior to human arrival (Figure 10C).

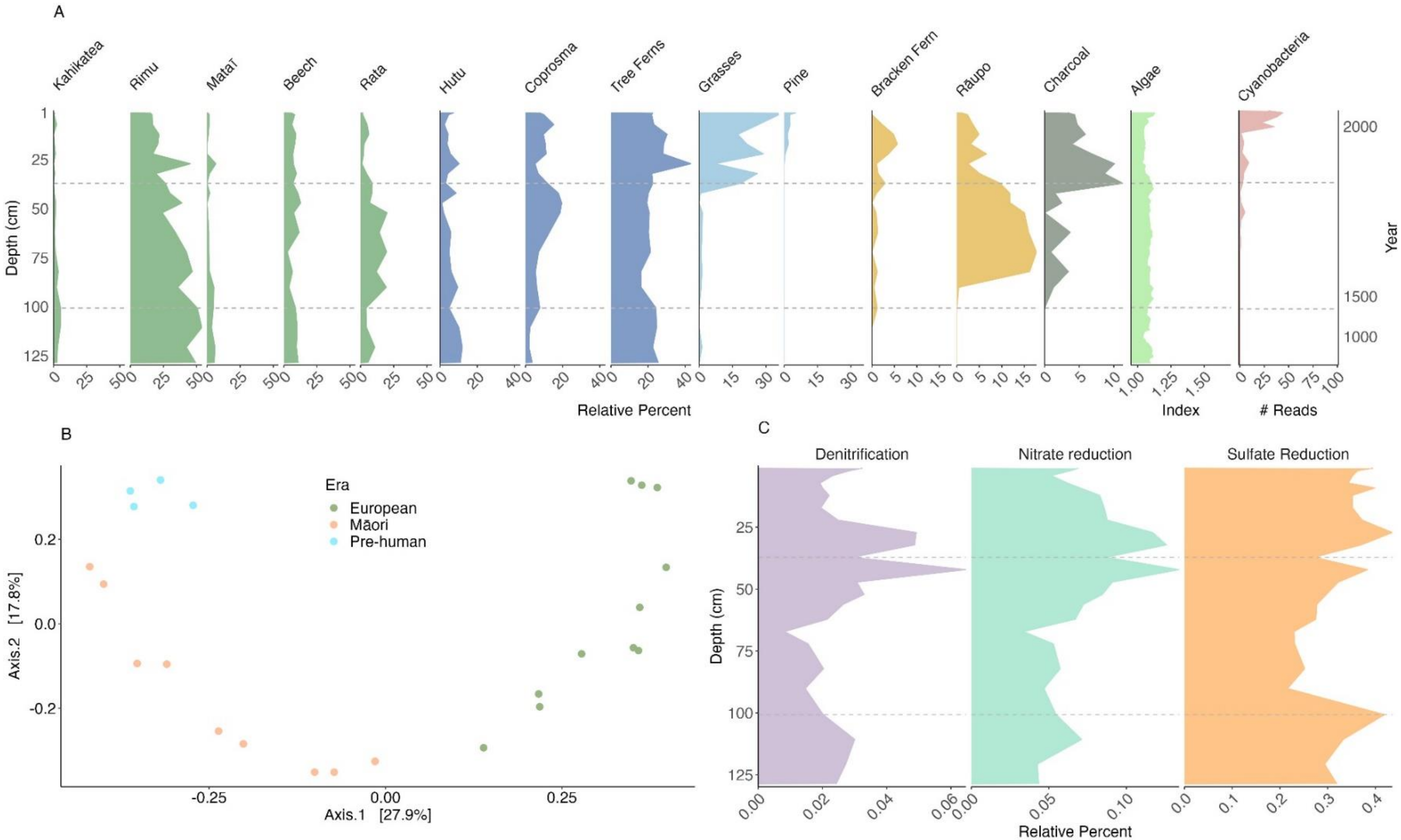

Figure 10. Downcore analysis results for Lake Tinawhu. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), RABD660-670 ratio from the hyperspectral analysis (proxy for algae), and number of metabarcoding reads of cyanobacteria. (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) proportion of specific metabolic pathways (portion of functional read abundance) at different depths. The dotted lines represent the different human occupation eras (bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement).

3.3.3. Lake Mangarākau

Results from the Lake Mangarākau sediment core suggest that before humans arrived in the area, the lake was surrounded by native forest abundant in podocarps (especially rimu), beech and tree ferns (Figure 11A). Post-Māori settlement, there was some minor vegetation clearance in the region, highlighted by an increase in charcoal and bracken fern, which is often associated with vegetation disturbance and burning. Post-European settlement, there was a further decline in some native trees (e.g. rimu, rata). In the wider region, farming became established, with grasses and pine pollen visible in the sediment record. Algae have always been present in low levels in the lake, and their abundance has been stable over the last 1,600 years (the period covered in the top metre of the studied sediment core). No cyanobacteria were present in the sediment core.

The NMDS plot highlights a shift in bacterial composition between human occupation eras, with the most significant difference between the pre-human and post-European settlement eras (Figure 11B). The bacterial functional profiles related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction were stable prior to human arrival and then increased during the Māori settlement era, before decreasing and then increasing again in the post-European settlement era (Figure 11C).

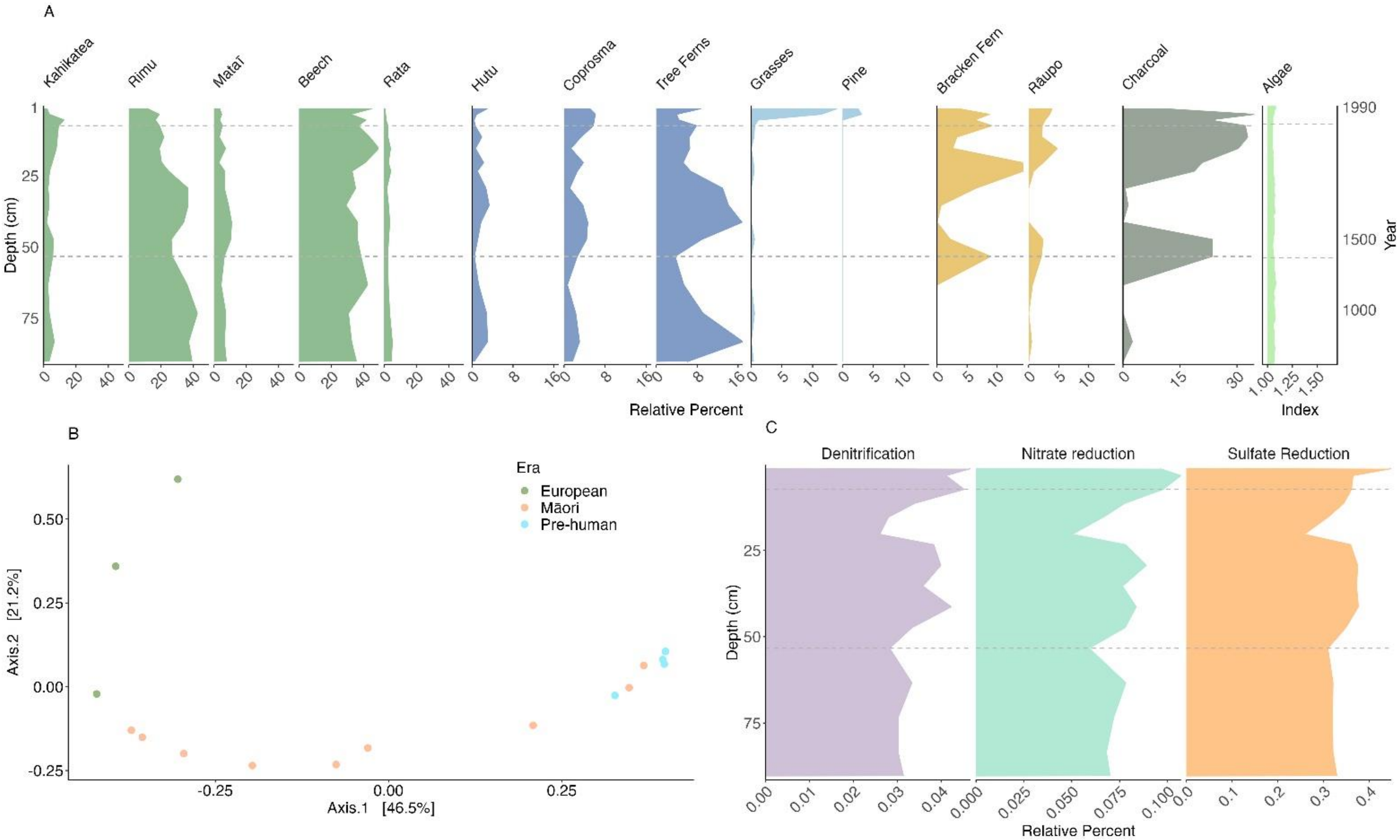

Figure 11. Downcore analysis results for Lake Mangarākau. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), and RABD660-670 index from the hyperspectral analysis (proxy for algae). (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) Proportion of specific metabolic pathways (portion of functional read abundance) at different depths. The dotted lines represent the different human occupation eras (bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement).

3.3.4. Lake Otuhie

The sediment core results from Lake Otuhie cover a period of about 1,400 years. The pollen data suggest that the vegetation in the catchment of Lake Otuhie has not changed markedly over time. The lake is still mostly surrounded by native forest abundant in podocarps, especially rimu and beech and tree ferns (Figure 12A). Post-Māori settlement, there was some minor vegetation change, with a small decrease in tree ferns, an increase in charcoal and the appearance of bracken fern, which are often associated with landscape modification. European settlement is signalled in the sediment core by some increased burning and the appearance of exotic pine pollen and grasses, which likely reflect an increase in farming in the wider region. Low amounts of algae have always been present in the lake, with little change over the studied period. There has, however, been a very small increase in cyanobacteria in the last decade.

The NMDS plot highlights marked differences in the bacterial composition between human occupation eras (Figure 12B), with a shift in the communities within the pre-human and post-European settlement eras. The bacterial functional profiles related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction have increased over time, with notable increases in all enzymes in the post-European settlement era (Figure 12C).

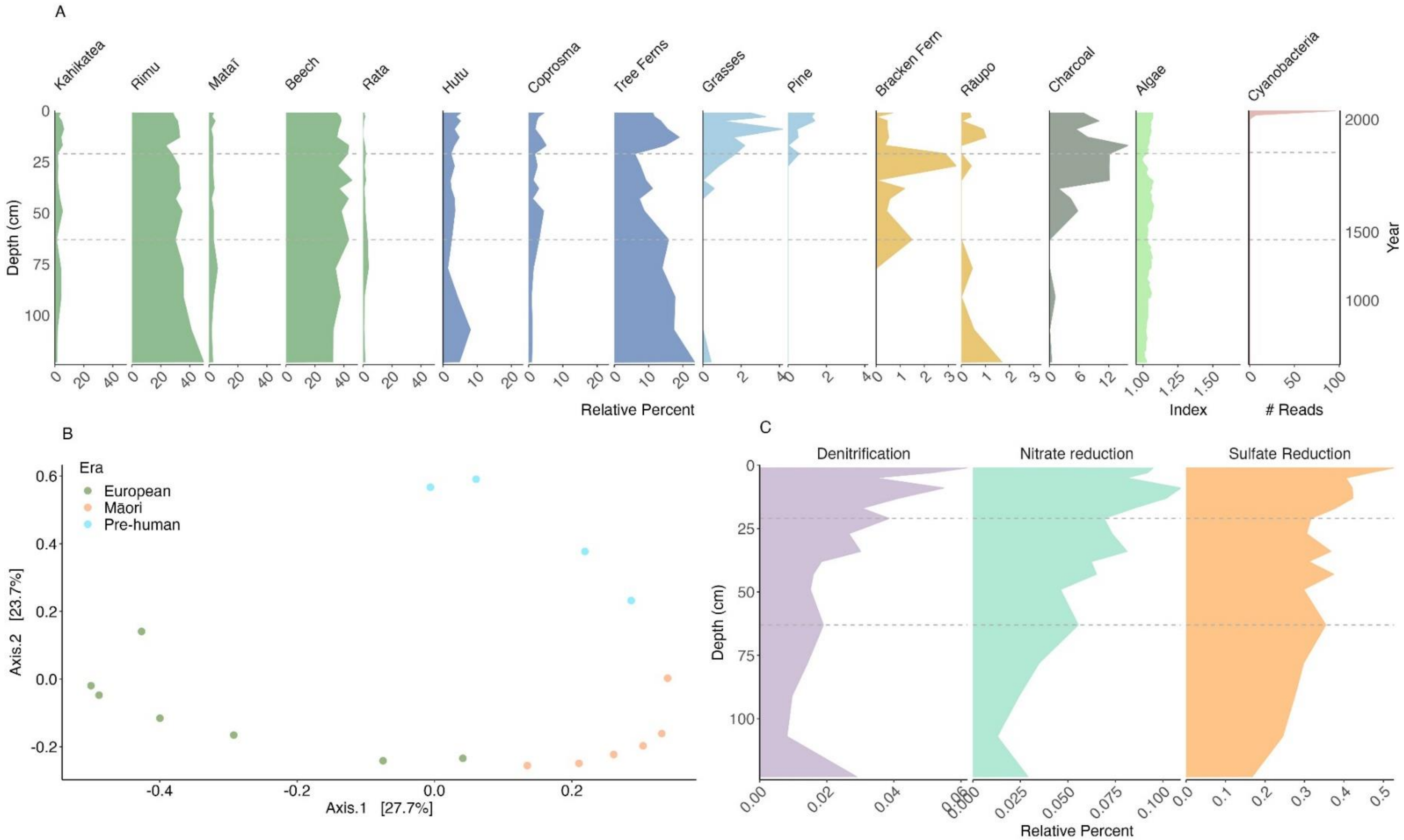

Figure 12. Downcore analysis results for Lake Otuhie. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), RABD660-670 index from the hyperspectral analysis (proxy for algae), and number of metabarcoding reads of cyanobacteria. (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) Proportion of specific metabolic pathways (portion of functional read abundance) at different depths. The dotted lines represent the different human occupation eras (bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement).

3.3.5. Rototai

The Rototai sediment core does not extend into the pre-human period. The pollen data from the sediment core indicate that prior to European settlement, the lake was surrounded by native forest abundant in beech and rimu, and small shrubs such as *Coprosma* and tree ferns (Figure 13A). Before European settlement, vegetation clearance began in the region, and this is shown by the presence of charcoal and bracken fern, which is often associated with landscape disturbance.

Post-European settlement, some native vegetation (beech and *Coprosma*) decreased, and the landscape surrounding the lake was converted to farmland, with grasses and exotic pine trees present in the pollen record. Algae have always been present in Rototai in low levels and have increased slightly post-European settlement. Cyanobacteria appear in the lake sporadically at very low levels.

There are marked differences in the bacterial composition between the Māori and post-European settlement eras (Figure 13B). The bacterial community, which had previously been relatively constant, changed markedly in the post-European period, particularly in the early years of settlement. The bacterial functional profiles related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction show a general increase post-European settlement (Figure 13C).

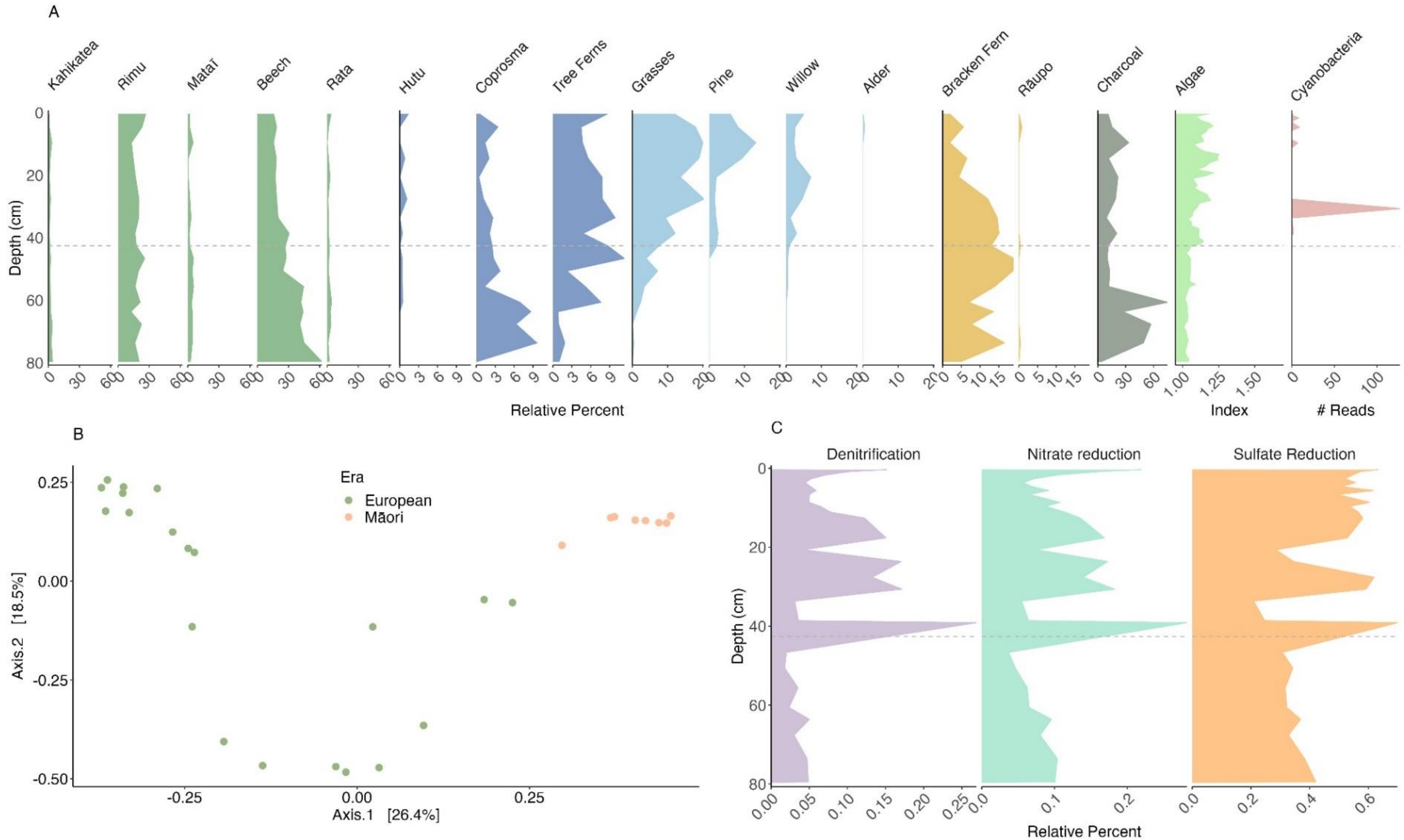

Figure 13. Downcore analysis results for Rototai. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), RABD660-670 index from the hyperspectral analysis (proxy for algae), and number of metabarcoding reads of cyanobacteria. (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) Proportion of specific metabolic pathways (portion of functional read abundance) at different depths. The dotted line represents the transition from Māori settlement to post-European settlement. No age model was available for this lake when the report was written.

3.3.6. Lake Killarney

The pollen data for Lake Killarney indicate that, prior to human arrival, the lake was surrounded by podocarp (in particular rimu) and beech forest, as well as tree ferns (Figure 14A). After human arrival, some vegetation clearance began in the region, highlighted by the increase in charcoal and bracken fern during this period and a decrease in tall trees and tree fern, particularly towards the end of this era. Post-European arrival, the native vegetation was almost completely replaced by pastoral land (i.e. grasses), and non-native trees such as pine, willow and alder were planted in the region. There was also a notable increase in total algae from about 1970, and the DNA analysis shows a corresponding marked increase in cyanobacteria.

The NMDS plot (Figure 14B) shows a very stable bacterial community during the pre-human era followed by a big shift in the periods of Māori and European settlement. The bacterial functional profiles related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction were relatively stable during the pre-human era and following Māori settlement, although a short increase is noted in about 1,600 AD. There has been a marked increase in all functional profiles post-European settlement (Figure 14C).

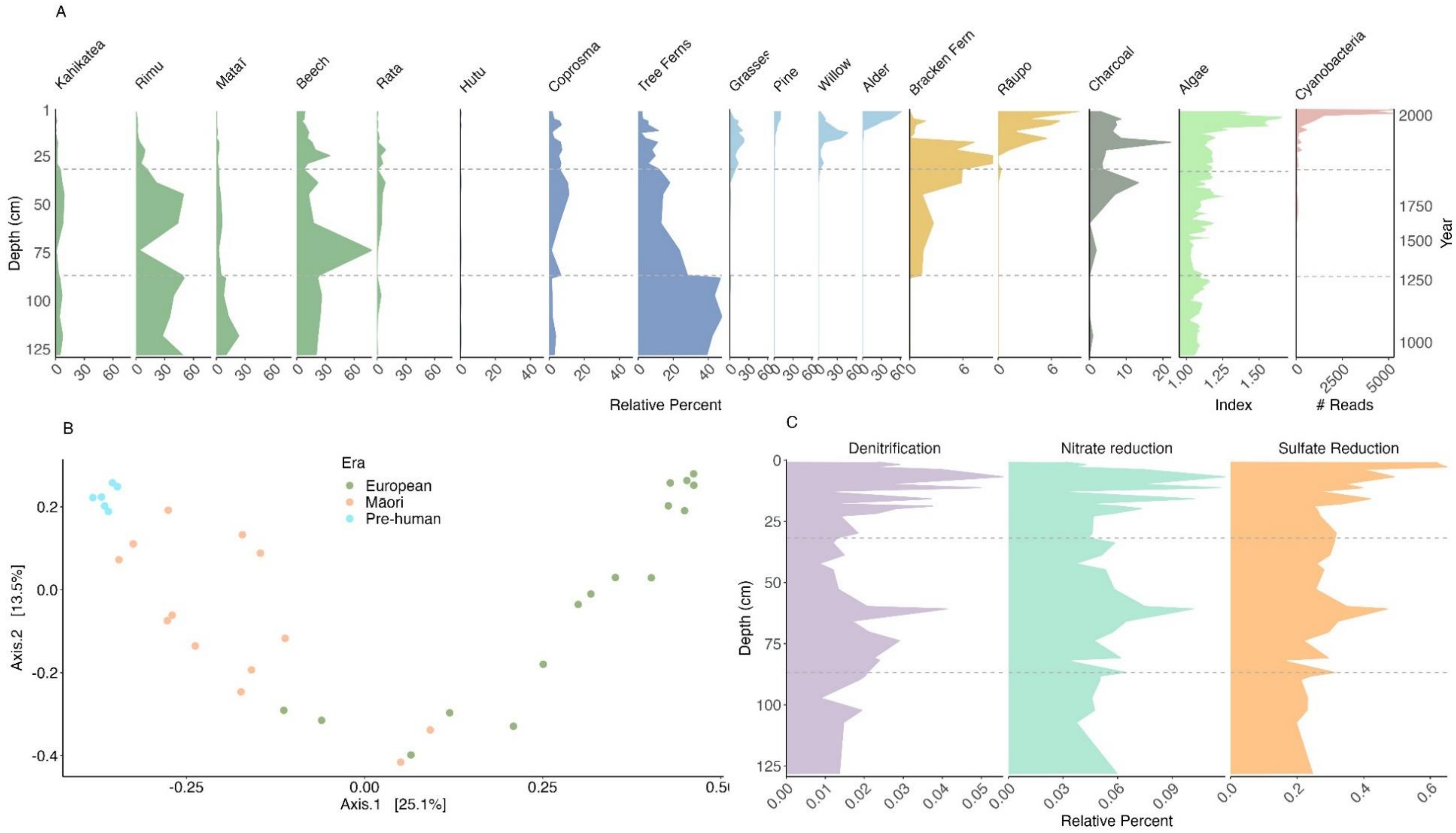

Figure 14. Downcore analysis results for Lake Killarney. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), RABD660-670 index from the hyperspectral analysis (proxy for algae), and number of metabarcoding reads of cyanobacteria. (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) Proportion of specific metabolic pathways (portion of functional read abundance) at different depths. The dotted lines represent the different human occupation eras (bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement).

3.3.7. Lake Lockett

The top 1 m of the Lake Lockett sediment core covers a period of about 8,000 years. The pollen results from the sediment core indicate that Lake Lockett was originally surrounded by a mix of alpine herbs and native forest, which was initially dominated by podocarps such as mataī and rimu. About 7,500 years ago, beech abundance increased while podocarps and native shrubs decreased (Figure 15A). The remote location of the lake within Kahurangi National Park has meant that evidence of human presence or impact on this lake is minimal. The age model for this lake indicates that the period post-European settlement (assumed to be approximately 1840 AD) is only captured in the top 4.7 cm of sediment. The pollen record shows an increase in herbs, grasses and bracken ferns post-human settlement, which are likely indicative of land use changes further afield in the region. Algal and cyanobacterial concentrations are low throughout the sediment record and there have been no marked changes.

The NMDS plots shows a gradual change in bacterial community structure over the 8,000 years of the sediment core (Figure 15B). Of note is the sharp increase in the bacterial functional profiles related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction beginning about 700 years ago (Figure 15C).

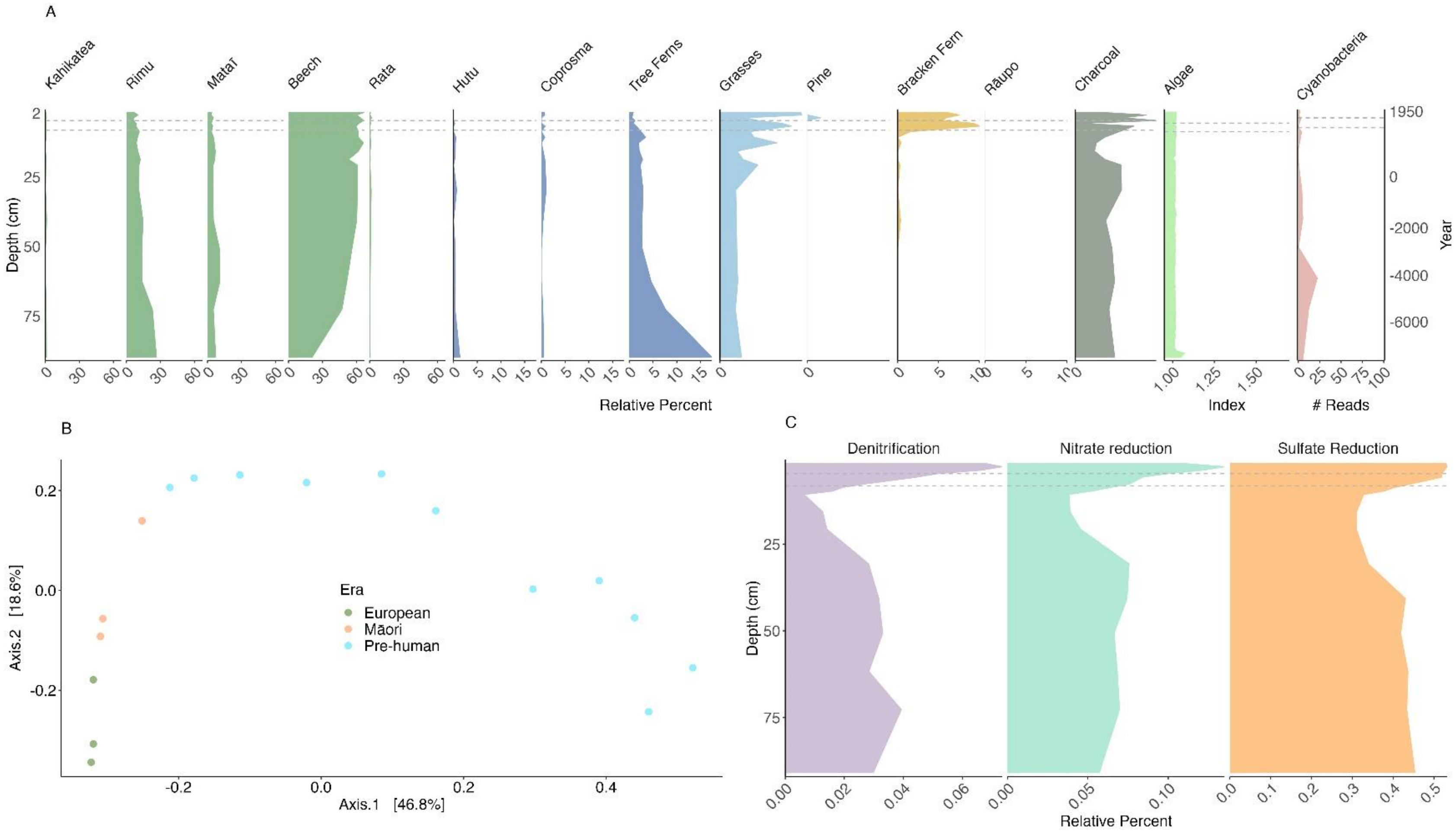

Figure 15. Downcore analysis results for Lake Lockett. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), RABD660-670 index from the hyperspectral analysis (proxy for algae), and number of metabarcoding reads of cyanobacteria. (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) proportion of specific metabolic pathways (portion of functional read abundance) at different depths. The dotted lines represent the different human occupation eras (bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement).

3.3.8. Lake Peel

The top 1 m of the Lake Peel sediment core covers a period of about 2,700 years. At 1,350 m altitude, Lake Peel has likely been above the tree line over the sediment core period, thus the pollen record will largely reflect the forest in the valleys below the lake. The pollen results indicate that the land in the valleys below Lake Peel was, and still is, dominated by beech and to a lesser extent podocarps such as mataī and rimu (Figure 11A). The remote location of the lake within Kahurangi National Park has meant that evidence of human presence or impact on this lake is minimal. The age model for Lake Peel indicates that the period post-Māori settlement (assumed to be ~1350 AD) is captured in the top approximately 30 cm, and European settlement (assumed to be approximately ~1840 AD) is only captured in the top 10 cm of the sediment. The pollen record shows a small increase in grasses, pine and bracken ferns post-human settlement, which are likely indicative of land use changes further afield in the region. Algal concentrations are low throughout the sediment record and there have been no marked changes. Cyanobacterial concentrations rose markedly in the last 20 years.

The NMDS plot shows three reasonably distinct clusters, which align with the periods of human occupation (Figure 11B). Of note is the increase in the bacterial functional profiles related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction early in the era following Māori settlement and then again beginning about 700 years ago (Figure 11C).

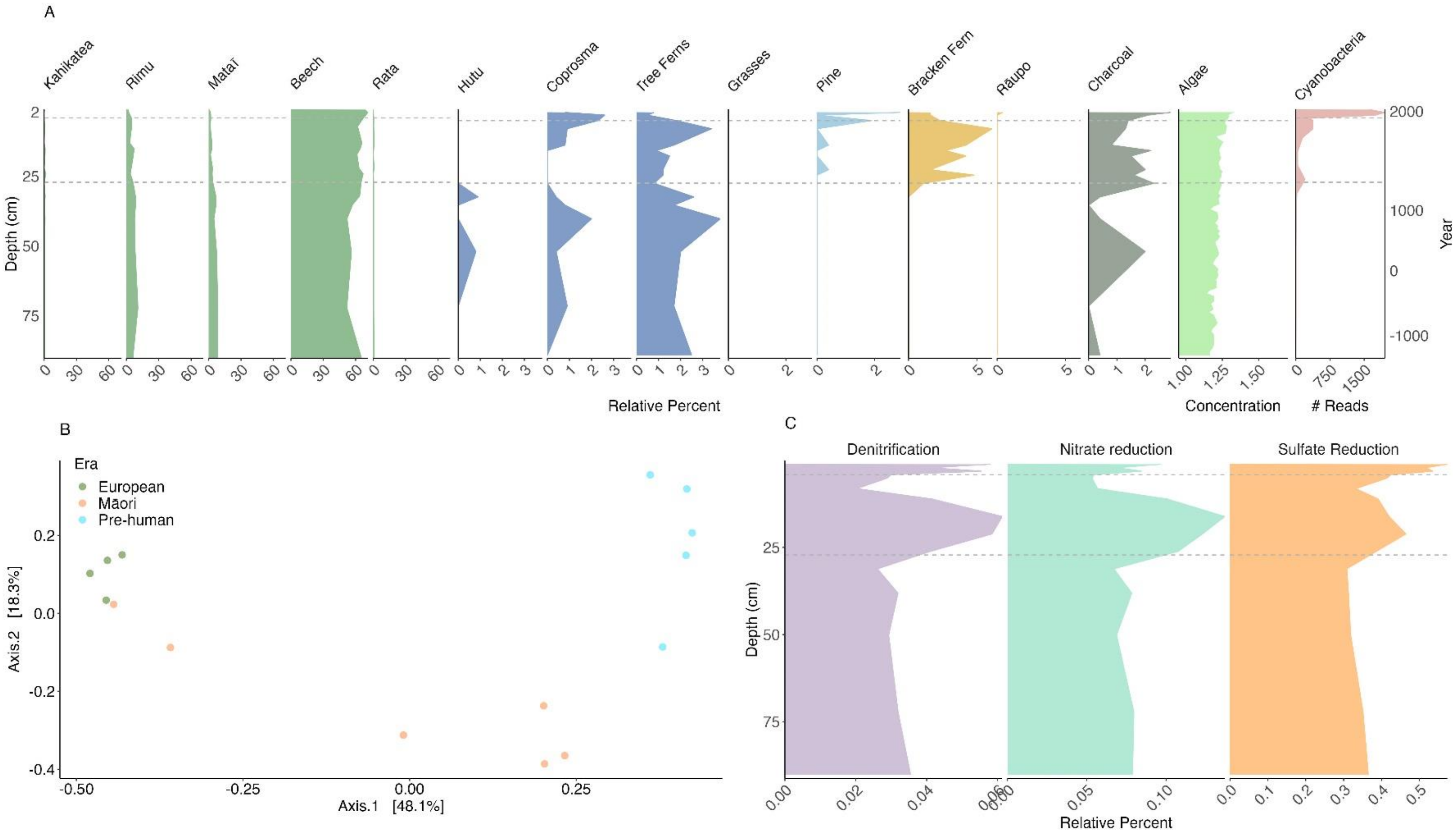

Figure 16. Downcore analysis results for Lake Peel. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), RABD660-670 index from the hyperspectral analysis (proxy for algae), and number of metabarcoding reads of cyanobacteria. (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) Proportion of specific metabolic pathways (portion of functional read abundance) at different depths. The dotted lines represent the different human occupation eras (bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement).

3.3.9. Rotoiti

The majority of the Rotoiti catchment is within Nelson Lakes National Park, and as such, there has been minimal human impact on the lake. However, there are small parts of the catchment at the southern end where the landscape has been modified.

The pollen and charcoal results from the Rotoiti sediment core show a dominance of beech forest in the catchment (Figure 17A). Following Māori settlement, some vegetation disturbance occurred in the wider region, with an increase in grasses, bracken ferns and charcoal. There was little change in the vegetation post-European settlement, albeit for the presence of some pine pollen, which was likely blown in from nearby regions where plantations or shelter belts were established. Algae and cyanobacteria have always been present in this lake at low concentrations and have not increased over time.

The NMDS plot highlights a marked shift in bacterial community composition between Māori settlement and the second half of the post-European settlement era (Figure 17B). The bacterial functional profiles related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction were relatively stable during the pre-human and the era following Māori settlement. However, there is a clear increase in the denitrification and nitrate reduction enzymes in the post-European settlement era, particularly the latter half (Figure 17C).

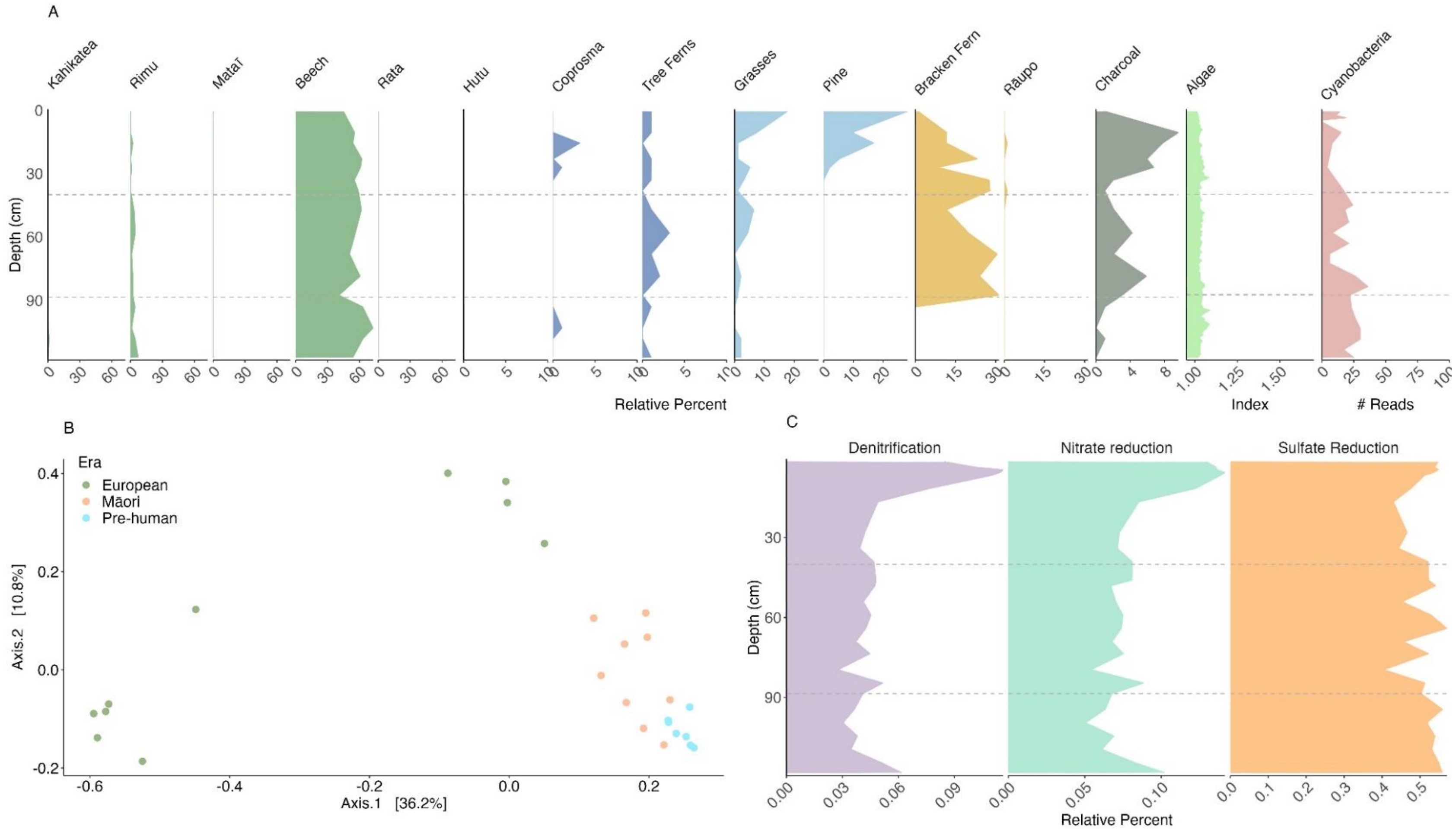

Figure 17. Downcore analysis results for Rotoiti. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), RABD660-670 index from the hyperspectral analysis (proxy for algae), and number of metabarcoding reads of cyanobacteria. (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) Proportion of specific metabolic pathways (portion of functional read abundance) at different depths. The dotted lines represent the different human occupation eras (bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement). No age model was available for this lake when the report was written.

3.3.10. Rotoroa

Most of the catchment of Rotoroa is within Nelson Lakes National Park, and there has been minimal human impact on the lake.

The pollen and charcoal results from the Rotoroa sediment core show the dominance of beech forest in the catchment (Figure 17A). Following Māori settlement, some vegetation disturbance occurred in the wider region, and this is visible in the sediment core as an increase in grasses, bracken ferns and charcoal. There was little change in the vegetation post-European settlement, albeit for the presence of some pine pollen, which was likely blown in from nearby regions where plantations or shelter belts were established. Algae and cyanobacteria have always been present in this lake at low concentration and have not increased over time.

The NMDS plot highlights a marked shift in bacterial community composition between Māori settlement and the later part of the European settlement eras (Figure 17B). The bacterial functional profiles related to denitrification, nitrate reduction and sulphate reduction have been variable over time, with a general increase particularly notable in the last 2 decades (Figure 18C).

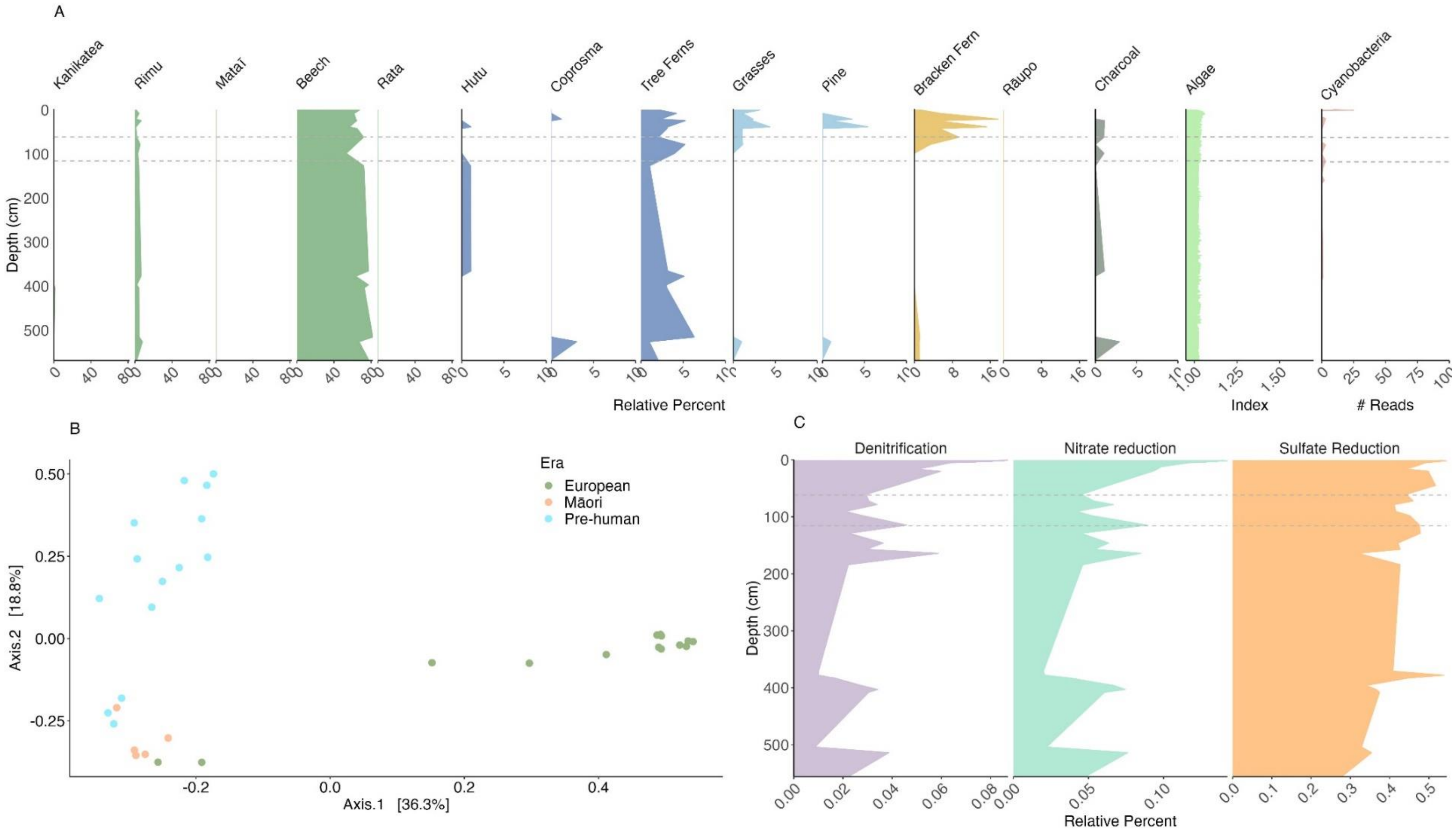

Figure 18. Downcore analysis results for Rotoroa. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), RABD660-670 index from the hyperspectral analysis (proxy for algae), and number of metabarcoding reads of cyanobacteria. (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) Proportion of specific metabolic pathways (portion of functional read abundance) at different depths. The dotted lines represent the different human occupation eras (bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement). No age model was available for this lake when the report was written.

4. DISCUSSION

This study focuses on 10 lakes in the Tasman Region that were sampled as part of the Lakes380 programme. The lakes are highly diverse and range from eutrophic lowland lakes to coastal lakes in good condition, and high alpine oligotrophic lakes.

This report provides analysis and interpretation of:

- Single time point surface water chemistry and, in some lakes, hypolimnetic water chemistry.
- Single time point surface sediment geochemistry and micro-organism diversity.
- Changes in bacteria, algae and shifts in the vegetation in the surrounding landscape over the last approximately 1,000 years obtained from analysis of sediment cores.

In this section, we provide a lake-by-lake discussion of these results. The water chemistry results are based on a single time point analysis. Water chemistry is temporally highly variable and is influenced by factors such as climate and lake stratification. Ideally, water samples would be collected monthly or bimonthly over 1–3 years to obtain an accurate overview of nutrient and water chemistry concentrations and dynamics within a lake; therefore, caution must be taken when interpreting these data.

In contrast, surface sediments provide a time-integrated representation of the within-lake conditions and organisms, as well as those in the catchment. However, the surface sediments can display spatial heterogeneity. More sampling is required to obtain spatially representative data, particularly for the larger lakes, i.e. Rotoiti and Rotoroa. The surface sediment geochemistry data are intended to provide an initial indication as to whether legacy nutrients, especially P, could potentially be contributing to the nutrient loads within a lake. While P is ultimately sourced from the wider lake catchment (external load), it can also be retained in lake sediments and then be released back to the water column under certain conditions such as low DO concentrations or elevated pH (internal loading). Such internal nutrient loading can fuel excess primary productivity, degrade water quality and delay lake recovery by decades following catchment restoration measures.

Currently, it is challenging to make ecological inferences about changes in the sediment surface and sediment core bacterial communities, as the ecology of most species remains largely unknown. In a first step to draw some ecological information from the sediment core data, we have converted the data to inferred functions. This has allowed us to explore changes in:

- Denitrification – the process that converts nitrate to nitrogen gas. An increase in the presence of bacteria able to perform this function could suggest an increase in nitrates in the waterbody.
- Nitrate reduction – the process that convert nitrate to nitrite. This is generally an anaerobic process. An increase in this profile could be indicative of increased nitrates and increase increased anoxia / low oxygen levels.
- Sulphate reduction – sulphate reducers derive their energy from the anaerobic oxidation of organic compounds. An increase in this profile may be indicative of increased anoxia / low oxygen levels.

4.1. Lakes Tinawhu and Whupa

The Kaihoka Lakes have high ecological values (Schallenberg 2011) and represent some of the last remaining relatively unmodified shallow coastal lakes in Aotearoa New Zealand. Protecting these lakes is therefore of utmost importance.

In Whupa, concentrations of Cd, Cu and Pb were higher in the surface water than the median from the Lakes380 national dataset. In Tinawhu, the surface water contained high concentrations of Cr. The natural weathering of minerals and anthropogenic activities are the main sources of these trace metals in freshwater bodies (Davutluoglu et al. 2011; Bartoli et al. 2012). Increased levels of these metals have been associated with agricultural activity (i.e. Cd and Cu are often found in fertiliser) and industrialisation. In high concentrations, these metals can have acute effects, such as mortality, on aquatic organisms, and chronic exposure can lead to adverse effects on growth, reproduction, immune and endocrine systems, development, and behaviour (Bartoli et al. 2012). More samples collected over a longer period of time are required to determine if the concentrations of these metals in the surface water of the Kaihoka Lakes pose a concern to the health of the aquatic organisms.

The physico-chemical depth profiling (undertaken with the RBR) by Lakes380 in October 2018 showed that Tinawhu and Whupa were thermally stratified with a thermocline at about 5 m, and temperature and DO were shown to decrease below this level (Appendix 2). These profiles suggest that a proportion of the lakebed could be becoming anoxic during summer stratification, releasing bound nutrients from the sediments into the overlying water. This is reflected in the slightly elevated TN and TP in the hypolimnetic waters of both lakes. The profile was taken in late spring, and oxygen levels will almost certainly decrease significantly through the summer months.

The TP content of the Kaihoka Lakes' sediments was higher than in the wider lake national dataset, suggesting some degradation, which is likely the result of modifications in the catchments or substantial nutrient inputs from other sources (i.e. waterfowl or aerial top dressing). The form in which this P is stored has important implications on how mobile it may be and thus how easily P may be recycled back to the water column. In this study, we have grouped the most mobile forms of P together as 'potentially mobile P'. The potentially mobile P pool is slightly elevated in both Tinawhu and Whupa sediments.

The sediment core results indicate that vegetation changes in the region began when the first Māori settled in the wider area, and then intensified post-European settlement, with 51% of the catchment of Tinawhu and 43% of the Whupa catchments now in low-producing grassland. Both lakes have extensive native vegetation around their margins (49% Tinawhu, 57% Whupa).

The algal profiles suggest little change in Chl-*a* concentrations in these lakes over the last 1,000 years. However, there are notable increases in cyanobacteria, particularly in Whupa. This suggests that the water quality of the lakes is degrading, and this change is also reflected in the SBTI and water chemistry data, indicating that the two lakes are likely either mesotrophic or eutrophic (note that current water quality data are insufficient to accurately determine the lakes' TLI).

The bacterial composition shows marked changes for both lakes across all human occupation periods. In Whupa, there was a clear delineation in the community composition between the three occupation periods. The bacterial functional profiles in both lakes are variable, but there has been a general increase in the last 50 years in all three functions, particularly in Whupa. Collectively, these data provide early indications of a decline in water quality over the last 50–100 years in both lakes, but most notably in Whupa.

Data on Cd concentrations in the sediment core from Tinawhu – which are not presented in this report – were also collected as part of the Lakes380 programme, and diatoms (a type of algae that leaves fossil remains in the sediment) were identified. Cadmium bioaccumulates in soils as a result of super phosphate fertiliser application and hence may provide a proxy for fertilisation and agricultural intensification. These data show a marked increase in Cd levels in the sediment core from about 2000 AD, suggesting that aerial top dressing / fertiliser application has recently impacted this lake. There have also been corresponding changes in the type and abundance of diatom species associated with increased nutrients in the last 20 years (Rose Gregersen, Victoria University of Wellington, unpublished data).

Collectively, the evidence presented in this report suggests relatively recent declines in the water quality of these two lakes. We strongly advocate for further research on the Kaihoka Lakes and that their protection is prioritised. Future work on these lakes should focus on identifying nutrient sources such as internal nutrient loading and the contribution of waterfowl. A long-term monitoring programme should also be established for these lakes. We support the suggestions in Wood et al. (2022) that this should include:

- Installation of a thermistor chain in both lakes. This should consist of temperature loggers positioned at approximately 2 m depth intervals tied to a buoy in the deepest part of the lake, and at least one DO logger should be installed 1 m from the lake bottom.
- Ideally, monthly (or bimonthly if the budget is restrictive) sampling of water from the epilimnion and hypolimnion. At each sampling, a CTD (conductivity, temperature, depth) cast should be undertaken to determine the depth of the thermocline. If a thermocline is present, a depth-integrated sample should be taken from the epilimnion and a second sample from 1 m above the lake bottom. A depth-integrated sample, including at least 10 m of vertical depth, should also be taken if no thermocline is observed.
- The water samples should be analysed for: dissolved reactive P, nitrate, nitrite, ammoniacal-N, Chl-*a*, TN, TP, total Kjeldahl nitrogen, total suspended solids, volatile suspended solids, dissolved Fe and Mn.

Once these data are available from a period of 18–24 months, we recommend applying a catchment modelling approach using the national CLUES (Catchment Land Use for Environmental Sustainability) model to estimate nutrient loads to the lakes (e.g., similar to approaches used in Kelly et al. 2014). In addition, more in-depth sampling and analysis of surface sediment is likely required, e.g. P fractionation and nutrient release experiments. We also recommend undertaking bird surveys and estimating their contribution to the external nutrient loads, following the approach used in Kelly et al. (2023). Molecular techniques applied to the sediment cores may also provide some useful insights into changes in bird species frequenting the lakes and possibly provide indications on their abundance.

4.2. Lake Mangarākau

The concentrations of most heavy metals in the surface waters of Mangarākau were higher than the national average; however, this pattern was not observed in the hypolimnion water samples nor the surface sediment. Gold and coal mining and timber and flax milling thrived around the lake / wetland at various times in the last 150 years (Friends of Mangarakau Swamp [date unknown]), and there is a small possibility that the evaluated levels could be related to legacy contaminants from these industries that are now leaching from the surrounding land into the wetland. Further sampling is required to confirm these results and explore conclusions on possible sources.

Both the surface and hypolimnion waters were high in TOC, which likely reflects that this lake is part of a large wetland complex. Wetlands are often high in TOC, and globally, wetlands are considered significant carbon sinks, estimated to hold twice as much carbon as the world's forests (Simmonds and Ferris 2022).

The surface geochemistry results do not suggest that any internal nutrient cycling is occurring in this lake. There were slightly elevated Zn concentrations, and as noted above, this could be related to previous anthropogenic activities in the wider catchment. However, more spatially representative sampling is required to explore this possibility.

The sediment cores show signs of some minor vegetation change in the wider area about 700 years ago, which corresponds with evidence of this region being settled by Māori (Native Forest Restoration Trust 2023). However, it is unlikely that the vegetation directly around Mangarākau was modified significantly during this period. As noted above, following European settlement, the area around Mangarākau was mined for gold and coal, and timber and flax were harvested and milled (Friends of Mangarakau Swamp [date unknown]). Multiple attempts were made to drain the wider Mangarākau wetlands, but these were largely unsuccessful (QEII National Trust 2005). These activities are broadly visible in the sediment core with reductions in native trees, such as kahikatea, observed in the post-European era; however, the low amount of sediment deposition makes it difficult to establish the timing of changes through this period.

No cyanobacteria were detected in the sediment core, which is unusual nationally and a good sign that the lake is in a healthy condition. Additionally, there are no marked changes in the Chl-*a* profiles over the sediment core. There are shifts in the bacterial community, the largest of these occurred post-European settlement. This is also mirrored by increases in the function profiles of denitrification and nitrate reduction, which could indicate changes in the amounts of nitrogen entering the lake. While caution should be taken when inferring change from the functional profiles, we note the observations in Wood et al. (2022). This study undertook preliminary analysis of 2 years of monitoring data from Mangarākau and found that the initial analysis of the TN and TP showed a step change in the TN concentrations in the second year – the cause for this could not be identified.

Mangarākau is part of the largest remaining wetland in the Nelson and Marlborough Regions and is almost as big as all the other wetlands in the Nelson area combined. Mangarākau is nationally significant, and although it is now largely protected, we support the recommendation of Wood et al. (2022) to undertake monitoring to increase knowledge on the seasonal variability in water quality, DO and temperature in this lake.

Wood et al. (2022) recommended:

- Installation of a thermistor chain with temperature loggers positioned at approximately 2 m depth intervals and a DO logger 1 m from the lake bottom.
- Monthly (or bimonthly if the budget is restrictive) sampling of water from the epilimnion and hypolimnion.
- Once these data are available from a period of 18–24 months, development of a catchment modelling approach to estimate nutrient loads to the lake.

4.3. Lake Otuhie

Based on SBTI results, the Lakes380 data indicate that Lake Otuhie is eutrophic (Wood et al. 2022), a finding that is further supported here by the elevated concentrations of TN, TOC and Chl-*a* in the surface water. We stress that these results are from a single time point and that further sampling is required. Schallenberg (2011) reported much lower TN and Chl-*a* levels, and concentrations of TN and Chl-*a* in samples collected in January 2023 were also markedly lower (0.32 g/m^3 TN and 0.0023 g/m^3 Chl-*a*; Wood et al. unpublished data).

TOC levels were similar among the samples and likely represent a high input of carbon from the largely vegetated catchment (95% native with only 1.2% high-production grassland and 3% low-production grassland).

Many of the trace metals were above the national median, including As, Cd, Cr, Cu, Pb and Zn. As noted above, caution should be taken when interpreting these results; however, Cd and Zn concentrations in the surface sediment were also extremely high, providing compelling evidence that further investigation is required. Schallenberg (2011) noted a need to explore mercury (not measured in this study) in this lake because of historical gold works in the Lake Otuhie catchment and the possible impacts on aquatic fauna.

Total P levels were low in the surface sediment, and although no measurements of the forms of P in sediments were undertaken, it seems unlikely that internal nutrient loading is a significant source of N and P in this lake.

The pollen results from the sediment core suggest minimal disturbance to the vegetation around Lake Otuhie, which is reflected by the current native vegetation in the catchment. Increases in grasses and non-native trees observed in the upper layers of the sediment core are likely the result of pollen been blown into the lake from the wider region.

Water quality appears to have remained very stable in this lake during the last approximately 1,000 years. There has been a very small increase in cyanobacteria in the last 10–20 years, but the levels are very low (i.e. low overall number of reads). The bacteria community has changed, with the most notable shift occurring in the post-European settlement era, which is also observed in small changes in the three functional profiles (denitrification, nitrate reduction and sulphate reduction). This likely indicates that the lake has undergone minor changes in the types of microbial processes that occur in the sediment, although this is yet to be observed as measurable / understandable changes in higher trophic levels.

Lake Otuhie is one of the least modified shallow coastal lakes in Aotearoa New Zealand, therefore protection of this lake is critical. Because of the uncertainty about the current water quality of Lake Otuhie, and some indication of progressive change from the sediment core data, we support the recommendations of Wood et al. (2022). This study suggested that a monitoring programme focusing on increasing knowledge on the seasonal variability in water quality and temperature should be established. The monitoring programme should include:

- Installation of temperature loggers positioned at the surface and if possible 1 m depth.
- Monthly (or bimonthly if the budget is restrictive) sampling of water.
- Once these data are available from a period of 18–24 months, a catchment modelling approach using the national CLUES model should be used to estimate nutrient loads to the lake.

Additionally, we suggest further sampling of water and sediment samples for trace metals.

4.4. Rototai

Rototai is an extremely unusual lake, as it is a flooded sink hole with a high surface area (0.57 ha) to depth ratio (14 m deep). The pH of this lake is extremely low (pH4), and the reasons for this remain unknown. The most likely reason, however, is that the lake is situated in a coal seam (although no evidence of this was observed). Lakes formed as part of coal mining activities are known to have low pH for a variety of reasons (see Blodau 2006 for a more detailed explanation). Further research into the history of this site and the reason for the unusual pH are recommended.

The water chemistry of Rototai is extremely unusual, and it is a clear outlier, both in the Tasman Region and nationally, with very high levels of NH_4-N, Cd, Cu, Pb, Ni and Zn (surface and hypolimnion samples). This is likely related to the pH and geology of the lake basin. Surface sediment geochemistry and nutrients for Rototai were not assessed in this study.

The bacterial and micro-eukaryotic compositions of the surface sediment were different in Rototai compared to all the other lakes, except Lake Killarney. The similarity in microbial communities between Rototai and Lake Killarney was surprising given the unique water chemistry of Rototai. This suggests that factors such as geographic location and lake type (Rototai and Lake Killarney are both flooded sink holes with high surface area to depth ratios) may play a part in driving microbial composition.

Rototai has a high sedimentation rate for a very small lake, with over 40 cm of sediment deposited in the lake since about 1840 AD. The pollen data indicate some removal of native trees during the post-European settlement era. This change is clearly evident on the western side of the lake, which is now largely in grass and non-native vegetation. The removal of native trees may have increased the sediment input into the lake. Additionally, the eastern side of Rototai is very steep. Historic imagery (Figure 19) suggests that this slope may have always been vegetation – primarily in beech trees. The steep topography and beech trees (which drop high volumes of leaves) may be the causes of high sedimentation in the lake. It is also possible that degradation processes are slow in the acidic water. There are also anecdotal reports that a furniture tanning factory was situated adjacent to the lake, although no documented evidence has been found to date. The presence of a factory may have had some impact on the lake.

Figure 19. Historical image of Rototai (left, orange arrow) and Lake Killarney (right, red arrow). Left image taken in 1942, right image taken in 1952. Images from retrolens.co.nz.

The algae, bacteria composition and functions suggest change pre- and post-European settlement. Because of the uniqueness of the lake, it is challenging to interpret these data. We did not analyse any other biological communities, but this approach would be extremely valuable, as Rototai may harbour unique or rare biota.

Nationally, Rototai is a unique lake. Because of the unusual water chemistry of Rototai, most national regulations and guidelines are not relevant, and the lake requires its own tailored management programme. Rototai is on private land and access is restricted. While we do not recommend resources are invested in monitoring Rototai, it would be extremely valuable for Tasman District Council (TDC) to engage with the landowner and facilitate protection and enhancement of this nationally unique waterbody. This could include improving the riparian planting on the western side of the lake and exploring the possibility of protecting the lake and land directly adjacent, for example, by placing it in a QEII National Trust or similar.

4.5. Lake Killarney

A previous assessment of Lake Killarney indicated that it is supertrophic and regularly experiences algal blooms (Wood et al. 2022). The single time point water samples taken in this study confirmed the lake is in a highly degraded condition. Of note were the extremely high levels of TN, TP, NH_3-N, Cd, Cr, Cu, Pb, Ni and Zn in the hypolimnetic waters. The profile taken during this study does not show the presence of a thermocline, but the DO profiles decrease rapidly below about 8 m (Appendix 2). This profile was taken in late spring, and oxygen levels will almost certainly decrease significantly as the thermocline strengthens during summer. Temperature and oxygen depth profiles were also collected by TDC in August and October 2017 and showed anoxic bottom waters and a strong thermocline in October 2017 (see Wood et al. 2022). These low oxygen levels likely facilitate the release of nutrients and trace metals from the sediments. There are reports that stormwater from the township of Tākaka has previously flowed into the lake during storm events, which may have contributed to the high levels of trace metals. Further investigation should be undertaken to ensure this is not still occurring.

Surface sediment analysis was not conducted during this study, but work undertaken for TDC in 2013 indicated very high nutrient concentrations (TP = 5,850 mg kg^{-1}, TN = 29,000 mg kg^{-1}). It is highly likely that the release of nutrients from the sediment contributes significantly to the nutrient loads in this lake, particularly as the lake has no permanent in- or outflows.

Pollen analysis of the sediment cores shows dramatic changes in vegetation in this region. The most significant change is the increase in grasses and non-native trees around the lake over the last 100 years. The retrolens images (Figure 19) show that in 1942, the land around the lake was almost complete de-vegetated. There are currently a number of large non-native deciduous trees around Lake Killarney, and this likely contributes the organic load in this lake. The sediment core analysis shows a very dramatic increase in algae and cyanobacteria, which began in about 1970. There are also corresponding decreases in the denitrification, nitrate reduction and sulphate reduction enzyme pathways. Although the water quality of this lake is now highly degraded, these changes have occurred relatively recently. Given its small size, close proximity to humans and lack of permanent inflows, this lake holds high potential for restoration. While further monitoring could be undertaken to refine knowledge on the nutrient dynamics in Lake Killarney, it would be pertinent to ensure that these data can be used to inform potential restoration options.

We suggest investigating:

- Gradual replacement or removal of deciduous non-native trees around the lake.
- Ensuring that there are no stormwater inflows into the lake.
- Approaches to reduced internal nutrient loading. There are multiple options, including techniques to destratify or aerate the water column, dredging of the high nutrient surface sediments (the sediment core could be used to guide the required depth), and sediment capping to prevent the release of nutrients from the sediment back into the water column.

There are benefits and caveats to each of these approaches, and further investigations and consultation with mana whenua and the community are strongly recommended to ensure an enduring outcome.

4.6. Lakes Lockett and Peel

As expected for high alpine lakes in unmodified catchments, the nutrients and trace metals were generally very low in the water samples from Lakes Peel and Lockett. The only exception was As, which was high in both the surface and hypolimnetic water samples from Lake Lockett. The most common sources of As (pesticides, industrial effluents as a contaminant from mining of gold and lead, and from the combustion of coal) would not affect this relatively remote lake. Arsenic can occur naturally where there are sulphide mineral deposits and sedimentary deposits deriving from volcanic rock; however, most of the geology in this region is sedimentary, laid down in an ancient sea and then faulted and uplifted. Further sampling should be undertaken to confirm this result and, if needed, explore the potential source.

The surface sediment of both lakes contained relatively high levels of potentially mobile P; however, the RBR profile (Appendix 2) shows that despite relatively strong temperature stratification in the lake, the bottom waters remain well oxygenated. This suggests that it is unlikely that internal nutrient cycling is occurring, although further measurements are required to confirm this.

The bacterial community composition in the surface sediment showed that Lake Lockett was very different to the other lakes studied. The bacterial community analysed in Lake Lockett was notably deeper (57 m), and it also had much higher As concentrations in the surface sediments, which likely impact the community composition.

The pollen records from both lakes indicate little change to the vegetation in their catchments over the last approximately 1,000 years. The occurrence of pollen from grasses, pines and bracken ferns likely comes from outside the direct catchments and indicates changes to the landscape in the wider region. The algae profiles are relatively stable, suggesting the water quality of these lakes have not changed markedly. There is a peak in cyanobacteria in the more recent core samples from Lake Peel. Picocyanobacteria were abundant in the samples, and this is a common finding in many oligotrophic lakes. The relatively recent increase may be indicative of changes in the condition of this lake.

The bacteria communities have changed, most notably in the last 200 years. There are also increases in the denitrification and nitrate reduction function profiles in both Lake Peel and Lake Lockett, which could be early indicators of subtle changes in the geochemistry / microbial functioning in these lakes.

The full sediment record (~13,600 years) from Lake Lockett was studied by a University of Otago master's student as part of the Lakes380 project to explore long-term climate changes (Lalor 2021). Lalor (2021) found evidence for high productivity during the early Holocene and indications that lake level was lower and weather conditions were warmer and drier. This is consistent with previous studies that attribute these differences to southward-shifted and / or weaker westerly winds.

4.7. Rotoiti and Rotoroa

The Rotoiti and Rotoroa catchments are largely within the boundaries of Nelson Lakes National Park and are considered at low risk of degradation by TDC.

No surface water or sediment samples were analysed for Rotoroa.

The single point samples from Rotoiti showed very low levels of nutrients and trace metals. Previous sporadic monitoring of these lakes has allowed some temporal analysis. Water samples from Rotoroa and Rotoiti were collected between June 2020 and May 2021 by Novis and Schallenberg (2021). Based on these data, they calculated the TLI of both lakes as 2.4 (oligotrophic). These authors compared their data to historical data from 1969–1971 (Taylor 1971) and suggested that the previous values measured overlap with the values recorded in their study. In contrast, TN concentrations in Rotoiti measured between February 1992 to June 1994 (Burns and Rutherford 1998) were much lower than those measured between 2020 and 2021, possibly indicating that TN has increased in the past 30 years in this lake. This might

also be due to difference in laboratory methods. We recommend that a longer-term and more regular monitoring programme is established at Rotoiti to monitor potential changes in water quality.
The surface sediment analysis for Rotoiti showed high levels of three key anthropogenic metals: Pb, Cu and Zn. The level of Pb in Rotoiti is amongst the highest measured in the national Lakes380 dataset and above the DGV guidelines. These metals are often associated with urban and road run-off, as they are commonly linked to vehicle brakes or tyres. We recommend further sampling of Rotoiti surface sediment to enhance knowledge on the spatial distribution of these trace metals. Additional sampling would also establish the potential impacts on aquatic organisms and identify any patterns around proximity to St Arnaud and potential sources.

The pollen record from both lakes indicates little change to the vegetation in the catchment of these lakes over the last approximately 1,000 years. The occurrence of pollen from grasses, pines and bracken ferns likely originates from outside the direct catchment and indicates change to the landscape in the wider region. The algae and cyanobacterial profiles are relatively stable and levels are low, suggesting the water quality of these lakes have not changed markedly. However, the bacteria communities have changed, most notably post-European settlement. There are also increases in the denitrification and nitrate reduction function profiles, which could be early indicators of subtle changes in the geochemistry / microbial functioning in these lakes.

Rotoiti and Rotoroa have also been impacted by natural disturbance events, with both severe storm and earthquakes in the region resulting in the rapid deposition of large amounts of terrestrial material on the lakebed. Research has shown that this influx of terrestrial sediments can have substantial impacts on lake biota (Brasell et al. 2021). However the impacts on the biota of Rotoroa and Rotoiti are unknown.

Based on the possibility that TN concentrations are increasing in Rotoiti and the detection of high levels of selected trace metals in the surface sediments, a monitoring programme should be developed for this lake in the near future, especially given its high cultural, social and ecological values.

5. RECOMMENDATIONS

Based on the findings of this study and the findings of Wood et al. (2022), we recommend that:

1. Water quality monitoring programmes should be established for Lakes Tinawhu, Whupa, Killarney, Otuhie, Mangarākau and Rotoiti. These data will provide new information on seasonal trends and valuable insights into nutrient-temperature-dissolved oxygen dynamics that can be used to guide future protection or restoration programmes.
2. Further sampling and analysis of surface sediments from Lake Otuhie and Rotoiti should be undertaken to enhance knowledge on the spatial distribution and concentrations of trace metals.
3. Further surface sediment geochemistry surveys and studies on the current and historical abundance of birds should be conducted at Lakes Tinawhu and Whupa to enhance knowledge on nutrient sources.
4. A revitalisation / restoration plan should be developed for Lake Killarney. Existing knowledge on the high levels of nutrients in the lake sediments should be used to guide the development of these plans. Further consultation with iwi and the local community may be required to select the most appropriate management option.

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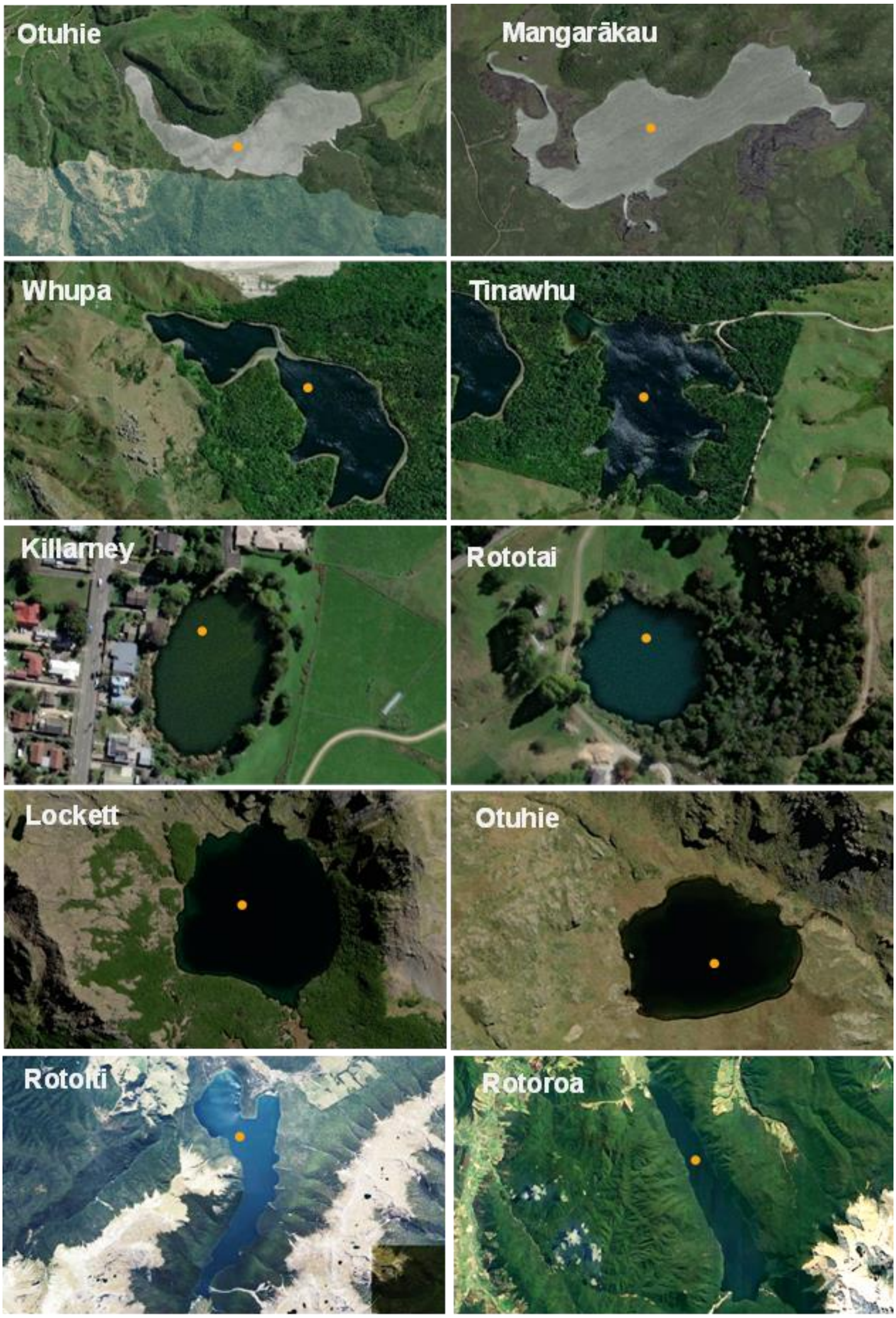
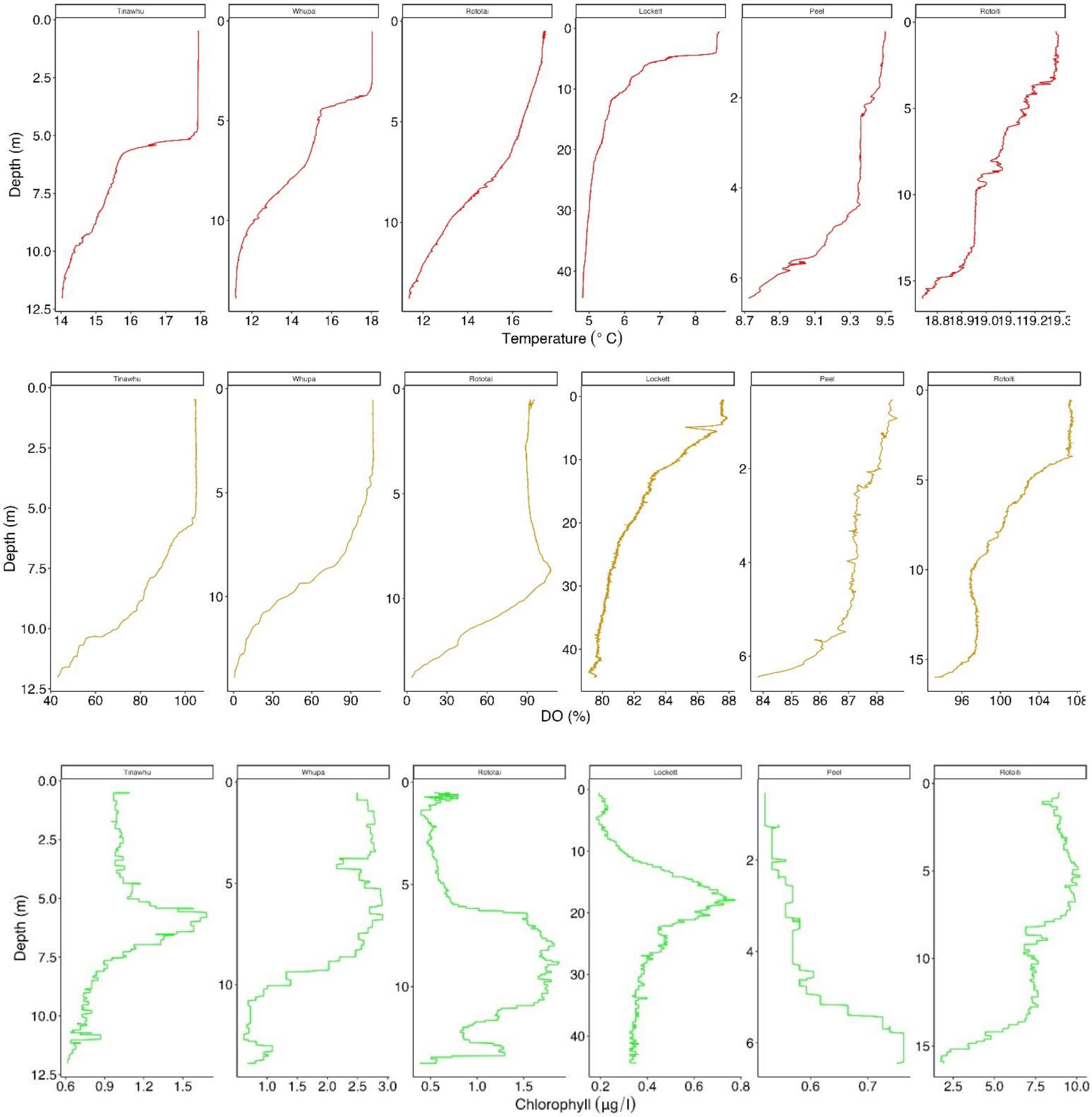
Appendix 1. Aerial image of study lakes showing sediment coring site (source: Google Earth).



Appendix 2. Water column (temperature, dissolved oxygen and chlorophyll-*a*) profiles for selected lakes.

Sampling dates: Lakes Tinawhu and Whupa = 24 October 2018, Rototai = 23 October 2018, Lake Lockett = 27 October 2018, Lake Peel = 29 October 2018 and Rotoiti = 8 May 2021.



Appendix 3. Images of selected sediment cores for five lakes.