Lake Humuhumu

Lake Rotokawau

Lake Rototuna

Historic changes to water quality indicators in Poutō dune lakes

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Table of Contents

1 Executive Summary

Past changes to water quality indicators are summarised from three Poutō dune lakes (Northland, New Zealand; Lake Humuhumu, Lake Rotokawau, Lake Rototuna), focussing on changes during the last century to: (1) lake level and mixing; (2) nutrient availability; and (3) biological productivity and macrophyte dominance (Table 1.1-1.3 overleaf).

Have lake levels and/or mixing changed?

There is evidence for lake level decline at Lake Rotokawau from as early as ca.1977 AD but most definitively from ca.1990 AD, with limited (if any) recovery since. This suggests the lake was deeper than its current 12 m maximum depth. Importantly lake levels fell only after a decade or so of heightened erosion from ca. 1968 AD.

At Lake Humuhumu there is strong evidence for increased mixing from ca. 1870 AD but limited evidence of any lake level decline (currently 16 m max depth) – a decline in lake level may have occurred in the eastern basin ca. 1930 AD but was not sufficiently marked so as to alter open-water or exposed sediment habitat.

Since ca. 1935 AD, limited if any change to either lake mixing or level is evident in proxy indicators at Lake Rototuna whereas, the degree of mixing has since become consistently high whereas before this, it varied more frequently.

Has nutrient availability changed?

Nutrient availability appears to have changed little at Lake Rotokawau, with continued dominance of oligo/mesotrophic diatoms and little change to sedimentary nutrient content.

Nutrient availability has risen markedly at Lake Humuhumu since ca. 1960-70 AD until today, decades after the onset of increased erosional influx and lake mixing (ca. 1929 AD). Increases to nutrient availability were considerably more marked than at Lake Rotokawau or Lake Rototuna (trebling of sedimentary nutrient content).

Nutrient availability appears to have undergone little change at Lake Rototuna despite it also experiencing greater erosion from ca.1945-1962 AD. As at Lake Rotokawau, some increase in *water column* nutrient availability was expected (despite limited changes to *sediment* indicators), from the shift to greater algal biomass.

Has algal productivity changed?

All three lakes experienced relative increases (decreases) in algal (macrophyte) biomass during the last century.

Following a drop in lake level at Lake Rotokawau from ca.1977 AD, a shift to an algal-dominated state occurred until ca. 1990 AD (e.g., loss of submerged and/or emergent macrophyte cover). Since ca. 1990 AD, macrophyte biomass has recovered, most likely in submerged rather than fringing emergent areas.

In Lake Humuhumu, greater nutrient availability since ca. 1968 AD was accompanied by a shift away from stable macrophyte-dominance to greater algal contribution (e.g., TOC/TN from 18 to 10 today). Meanwhile, organic matter build-up in the lake has risen markedly with sediments nearly twice as organic matter-rich whilst accumulating at rates greater even than earlier during the heightened erosion phase.

In Lake Rototuna, biological productivity appears to have changed little over the past 400 years. However, an erosive interval from ca.1945 to 1961 AD drove a shift away from stable macrophyte to algal dominance (e.g., TOC/TN from 14 to 10 today).

Table 1.1 Summary of past changes to lake level & mixing, nutrient availability and biological productivity at Lake Rotokawau.

Approximate dates (AD)	Changes to lake functioning and state
Pre-1968	**Interpretation**: Macrophyte-dominated, low catchment erosion and deep lake with extensive fringing littoral swamp - oligotrophic **Palaeolimnological evidence**: Less sand, more silt, less Ti, higher TOC/TN ratio, greater Fe/Mn ratio and planktic (oligotrophic) diatoms dominant
1968 to 1997	**Interpretation**: Algal-dominated, high catchment erosion and shallower lake with loss of fringing littoral swamp – oligotrophic/mesotrophic **Palaeolimnological evidence**: More sand, less silt, more Ti, lower TOC/TN ratio, lesser Fe/Mn ratio and rise of tychoplanktic and benthic (oligotrophic/mesotrophic) diatoms
Post-1997	**Interpretation**: Mixed algal/macrophyte, high catchment erosion and shallower lake with return of submerged macrophytes – oligotrophic/mesotrophic **Palaeolimnological evidence**: Continued more sand, less silt, more Ti, lesser Fe/Mn ratio and tychoplanktic and benthic (oligotrophic/mesotrophic) diatoms but moderate TOC/TN ratio

Table 1.2 Summary of past changes to lake level & mixing, nutrient availability and biological productivity at Lake Humuhumu.

Approximate dates (AD)	Changes to lake functioning and state
Pre-1870 to 1929	**Interpretation**: Macrophyte-dominated, low catchment erosion and deep lake with extensive fringing littoral swamp - oligotrophic **Palaeolimnological evidence**: Less sand, more silt, less Ti, higher TOC/TN ratios, higher Fe/Mn ratio and meroplanktic (oligotrophic) diatoms
1929 to 1978	**Interpretation**: Algal-dominated, high catchment erosion and more strongly-mixed lake – mesotrophic **Palaeolimnological evidence**: More sand, less silt, more Ti, lower TOC/TN ratios, lower Fe/Mn ratios and continued dominance of meroplanktic (oligotrophic) with benthic (mesotrophic) diatoms
Post-1978	**Interpretation**: Algal-dominated, low catchment erosion, considerably greater biological production and continued stronger-mixed lake – mesotrophic **Palaeolimnological evidence**: Less sand, more silt, more Ti, lower TOC/TN ratios, lower Fe/Mn ratios and continued dominance of meroplanktic (oligotrophic) with increasing benthic (mesotrophic) diatoms but notable rise in sediment organic matter content (x2-3 biological production)

Table 1.3 Summary of past changes to lake level & mixing, nutrient availability and biological productivity at Lake Rototuna.

Approximate dates (AD)	Changes to lake functioning and state
Pre-1945 to 1955	**Interpretation**: Shallow lake with submerged macrophyte and extensive fringing wetlands (formed 750 AD) and low/moderate catchment erosion with rising biological productivity

	Palaeolimnological evidence: Low but variable Fe/Mn ratios, rising sand content, stable organic matter content and higher C/N ratios
Post-1955	**Interpretation**: Shallow lake with higher catchment erosion, shift to algal dominance and considerably increased biological production (eutrophic) **Palaeolimnological evidence**: Low and stable Fe/Mn ratios, increased sand content, rising Ti, rising organic matter content and lower C/N ratios

2 Introduction

The Poutō dune lakes catchment is subject to a collaborative planning process, supporting a second generation regional plan change process to implement the National Policy Statement for Freshwater Management (NPS-FM, 2014). National policy requires the Northland Regional Council (NRC) to manage the quantity and level of water in lakes as well as the discharge of contaminants to land, air or water that alter water quality (RMA, 1991: Section 30). The NPS-FM extends this to directly require management of changes to total nutrient availability (nitrogen and phosphorus), algal biomass (Chl-*a*) and clarity in lakes (Secchi depth), through specifying objectives, policies, rules and limits for their sustainable management.

To support the definition and implementation of lake water quality objectives in the NRC's Waiora Northland Water programme of policy change, DairyNZ commissioned the University of Auckland to undertake a palaeolimnological investigation to gather evidence of past changes to lake mixing regime, nutrient availability and biological productivity. That is, changes in the frequency or intensity of bottom-water mixing, nutrient concentrations in the lake water column and to the biomass of as well as the balance between free-floating algae (phytoplankton) and multicellular, true plants (aquatic macrophytes).

Palaeolimnology is the reconstruction of past aquatic environments from their sedimentary records. By examining sedimentary records, palaeolimnology can provide detailed information on past water quality over considerably longer time periods than water column monitoring. This can extend well beyond the period of human occupation and use of the lakes and their catchments, with the length of the record and its usefulness for palaeolimnological research often variable, even between sediment records collected from different basins within the same lake.

Palaeolimnological applications for water quality management are common in Europe, Canada and the United States of America, helping to diagnose the cause(s) for change behind and management to meet water quality targets (e.g., Hall and Smol, 1996; Dixit et al., 1999; Bennion and Battarbee, 2007; Jeppesen et al., 2011). However, this approach is relatively novel for lake management in New Zealand, having only been applied for water quality reconstruction to Wainono Lagoon, Canterbury (Scallenberg and Saulnier-Talbot, 2014).

Regular water column monitoring of the Poutō dune lakes by NRC dates to 2005, whereas European land clearance and use in the upper North Island extends to the mid-19th Century (McGlone and Wilmshurst, 1999; Perry, et al., 2012). Earlier, Polynesian arrival in ca. 1200 AD was also associated with extensive fire-driven land clearance (e.g., McGlone, 1989). Research in New Zealand has demonstrated that over their histories of land use, many lowland lakes have subsequently undergone marked change in water quality status and behaviour (e.g., in response to natural or anthropogenic drivers) (Quinn et al., 1997; Drake et al., 2011). Reasons for this can include external (catchment-driven) and/or internal (lake water or sediment) processes interacting to alter nutrient availability, algal and macrophyte biomass and water clarity, with all three responses targeted for objective-setting by the NPS-FM. As monitoring records do not cover the centennial-scale of water quality changes lake sediment records can help us to understand sensitivity to, and mechanisms driving change that underpin objectives and policy for lake water quality in the Poutō dune lakes.

The Poutō dune lakes catchment is located on the Poutō Peninsula (the region stretching from ca.50km south of Dargaville to the northern head of the Kaipara Harbour) (Figure 2.1). It includes ca.50 dune lakes of ≥1Ha in extent. The Poutō Peninsula consists of loose to poorly consolidated sands deposited during the mid to late Holocene (last 7000 years), overlying older indurated Pleistocene windblown sand deposits (in an east-west gradient of Holocene-Pleistocene deposits) (Schofield, 1975; Kokich, 1991). The lakes currently display a wide gradient in ecosystem health, ranging from weakly impacted or highly natural, and macrophyte-dominated to severely degraded and algal-dominated states (Wells and Champion, 2015). The Poutō dune lakes are broadly representative of other lakes in Northland that include a large proportion of New Zealand's warm lowland lakes of outstanding cultural, ecological and environmental value (Verburg et al., 2010; Champion and de Winton, 2012). Similarly, the 34,678Ha of catchment across the Poutō Peninsula possesses a wide range of land use types split between pastoral (38.3%), exotic forestry (34.0%) and native scrub/forest (13.7%) (with a large area still in exposed dunes [8.3%] and open water [4.8%]) (LCDB3).

Nine Poutō dune lakes have been monitored on a monthly basis for water quality by the NRC since 2005 AD, from which three were selected for this study, on the basis of their current state and geomorphology (size, depth, mixing): Lake Humuhumu (mesotrophic, no change, outstanding ecology), Lake Rotokawau (mesotrophic, declining, outstanding ecology), Lake Rototuna (eutrophic, declining, moderate ecology) (Table 2.1).

Figure 2.1 Location of Poutō lakes along Northland's west coast and northern Kaipara Harbour, including the three lakes examined by this palaeolimnological study (Lake Rotouna, Lake Humuhumu, Lake Rotokawau). Lakes catchments are outlined in yellow with the Kaipara Harbour immediately east.

Table 2.1 Summary of Poutō dune lakes subject to palaeolimnological investigation by Rip (2016). Stratifies refers to thermal stratification frequency (regular = seasonally, monomictic; occasionally = for periods less than month with irregular frequency between years, polymictic; rare = for periods of less than a fortnight with irregular frequency between years). TLI = Trophic Level Index, a measure of lake health with higher values equating to greater eutrophy and lesser ecosystem health quality (state in brackets). TLI estimates derived from Hughes et al (2016) for period 2009-2014. Ecological status derived from NIWA lake surveys for 2015.

Lake	Catchment area (Ha)	Lake area (Ha)	Max depth (m)	Stratify *	Land use (%)			TLI	Status
					Pasture	Bush	Pine		
Rotokawau	125	26.4 (med)	12 (deep)	Occasional	25	18	46	3.3	Meso-trophic
Humuhumu	423	139.4 (large)	16 (deep)	Regular	27	16	42	3.7	Meso-trophic
Rototuna	28	8.9 (small)	5.5 (shallow)	Rare	15	0	80	4.8	Eu-trophic

*Note that stratification knowledge is limited to quarterly surveys of water column mixing.

3 Objectives

The objective of this study was to inform Poutō dune lake management and water quality objective setting by reconstructing **changes** and **likely cause(s)** at Lake Humuhumu, Lake Rotokawau and Lake Rototuna, to:

- Lake level and mixing
- Nutrient availability
- Algal and macrophyte productivity

4 Data Source & Supporting Research

The objectives were addressed by a multiproxy palaeolimnological investigation reported in a Master of Science thesis undertaken at the University of Auckland and co-funded by DairyNZ Inc. Please refer to Rip (2016) for further detail outside this report summary.

5 Approach and Methods

The multiproxy palaeolimnological approach at each lake involved standard:

1. Lake bathymetric surveying and collection of multiple lake sediment cores (28-30 April) – to select deeper basins for longer (older) and continuous (more informative) sediment records (see Figures 5.1-5.3);
2. Core sediment logging – to determine the best preserved sedimentary records from the multiple cores collected from each target lake;
3. Core sediment sequence dating – radiogenic isotopic dating (^{210}Pb, ^{14}C) focussed on the upper (more recent period) sediments in each selected core, applying the constant initial concentration method to ^{210}Pb dates and linear interpolation to older ^{14}C dates;
4. Core sediment multiproxy sampling and analysis – subsampling core sediment to conduct a range of hydrological, nutrient and productivity proxy analyses (see Table 5.1 for explanation);
5. Integrated dating with proxy evidence of change to determine changes in lake functioning and state.

All steps were carried out following referenced, peer-reviewed protocols (see Rip, 2016).

Table 5.1 Summary information on palaeolimnological proxy indicators, including the lake process recorded by each, employed for sediment records from Poutō dune lakes.

Process	Proxy (unit)	Interpretation
Lake level, water column mixing & erosion	Sediment accumulation rate (SAR) (mm/yr)	Records input of organic and inorganic matter. Proxy for erosion and biological productivity, which can drive changes to depth and/or result from altered land use or climate (e.g., Stephens et al., 2012a)
	Magnetic susceptibility (MS)	Greater MS equates to relatively greater supply of inorganic eroded material, largely ferromagnetic (Fe_3O_4, Fe_2O_3) or paramagnetic minerals from the catchment (Fe-Ti oxides, Fe-Mn carbonates, Fe sulphides) (Gale and Hoare, 1991). Decreased MS is associated with increased quartz, water or organic matter content (i.e., greater biological productivity or aeolian and catchment-derived sediment influx)
	Grain size (mean µm)	Changes in the proportion of sand (2-0.0625 mm), silt (0.0625-0.0039 mm) and clay (<0.0039 mm) can indicate changes in lake level as coarser sediment is associated with shallower depth (nearer the shoreline), stronger mixing (recirculation from littoral margins to deeper cored locations) and/or greater erosional input from the catchment under disturbance (e.g., forest clearance, harvesting, extreme rainfall/wildfire/wind-throw) (e.g., Smol, 2008)
	Titanium (Ti) concentration	Ti is a conservative element and derived from catchment soils/weathered bedrock. Increases in Ti in the lake sediment are driven by erosion of catchment soils.
	Total Sulphur (%TS)	TS records changes in production (input of organic-sourced sulphur) and benthic hypoxia (duration and intensity) that reduces the rate of organic matter decay (release of sulphur) and/or precipitation of iron sulphides (e.g., pyrite) (Talbot, 2001; Stephens et al., 2012a)

	Fe/Mn ratio	Manganese (Mn) is more soluble under reducing (anoxic) conditions than iron (Fe), meaning lower Fe/Mn ratios can be used to indicate reduced benthic hypoxia (Brown et al., 2007; Naeher et al., 2013). Lesser benthic hypoxia would be expected from a shallower water column, lesser intensity or duration of thermal stratification and/or reduced biological productivity (e.g., lesser detrital organic matter supplied to bottom waters). The opposite is equally true for increased Fe/Mn ratio and greater benthic hypoxia.
Nutrient availability	$\delta^{13}C$ (‰)	Stable carbon isotope content ($\delta^{13}C$) records changes in dissolved inorganic carbon (DIC) availability, which relates to productivity (demand) and stratification (supply) (Last and Smol, 2001). Over longer glacial-interglacial time-frames $\delta^{13}C$ also records changes to *p*CO2 (Stephens et al., 2012b). Likewise photosynthetic pathway fractionates $\delta^{13}C$ but fortunately, there is limited variation amongst primary producers native to New Zealand, meaning changes to $\delta^{13}C$ are more heavily driven by altered pH and DIC availability (i.e., higher pH or lesser DIC associated with stronger stratification/greater productivity, results in more enriched $\delta^{13}C$) (Meyers and Lallier-Verges, 1999)
	$\delta^{15}N$ (‰)	Stable nitrogen isotope content ($\delta^{15}N$) records changes primarily to lake stratification, through altered supply and form dissolved inorganic nitrogen under changes in ammonification, nitrification and denitrification (Last and Smol, 2001). However, the influx of N-fixing cyanobacteria can be indicated by relatively depleted $\delta^{15}N$ (0‰) compared to dissolved nitrate (+7-10‰) (Talbot, 2001). Very enriched signatures (+34‰) are indicative of ammonification under benthic hypoxia (Meyers and Teranes, 2001)
Biological productivity	Diatom community composition	Diatoms are algae whose siliceous frustules are readily preserved within sediment. Frustule abundance is a proxy for overall algal productivity whilst taxonomic presence/abundance indicates changes to lake littoral-pelagic extent, nutrient availability, clarity, depth, temperature and algal-macrophyte dominance (Round et al., 1990; Stoermer and Smol, 1999). Diatom communities vary from open water (planktonic), attached to aquatic plants (epiphytic), attached to exposed rocks (epilithon), eroded sands (epispammic) and exposed muds, generally devoid of macrophytes (epipelic) (Hall and Smol, 2001).
	Loss on ignition (%LOI)	LOI records the organic matter content of sediments and thereby, changes to production and/or erosional input from catchments (Dean, 1974).
	Total organic carbon (%TOC), Total Nitrogen (%TN)	Greater TOC and TN concentration records increased biological productivity and/or lesser erosional dilution by lake sediment influx (Last and Smol, 2001). Phytoplankton, periphyton and aquatic macrophytes produce lipids, carbohydrates and proteins in-lake, whilst terrestrial macrophytes can supply the same from the lake catchment. Hence, examination of the provenance of the organic matter is required before inferring changes to in-lake or in-catchment productivity (Meyers and Lallier-Verges, 1999)

	TOC/TN ratio (TOC/TN)	TOC/TN ratios are indicative of the source of organic matter. Values <10 indicate an algal dominated state, >20 dominantly terrestrial (vascular, cellulose-rich) inputs and values 10-20 indicate aquatic macrophyte dominance (Smol, 2008). TOC/TN ratios indicate changes to the dominance of in-lake (autochthonous) or in-catchment productivity (allochthonous) that in turn could reflect changes to nutrient loading or littoral habitat (e.g., disturbance, altered depth or clarity). Shifts in dominance of attached periphytic diatoms to planktonic forms, commensurate with reduced TOC/TN ratios are indicative of greater eutrophy and loss of macrophyte-dominated state (Hall and Smol, 2001)

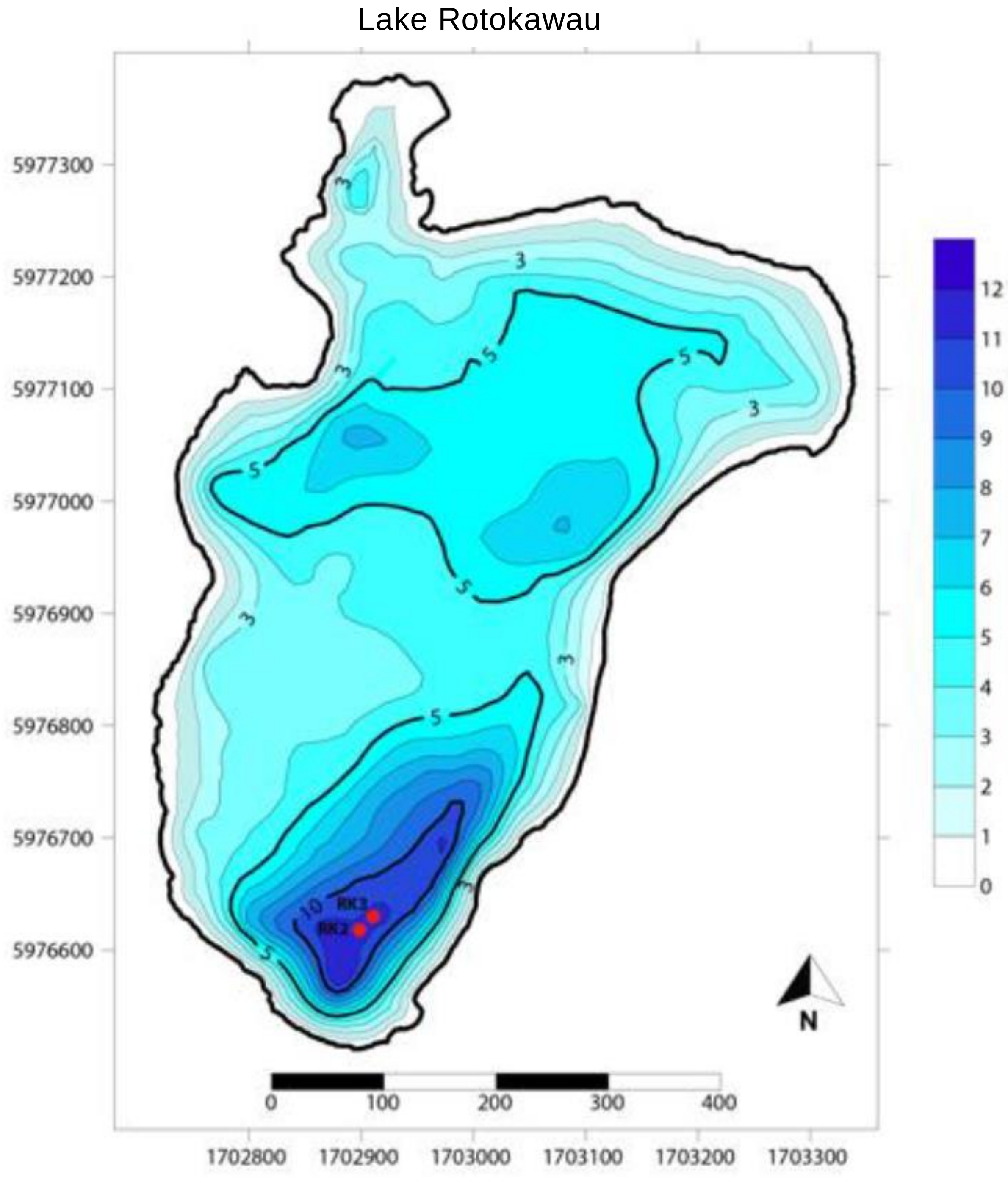

Figure 5.1 Bathymetry and coring location for RK2 and RK3 in Lake Rotokawau. Contours are recorded in metres relative to water level at the time of coring.

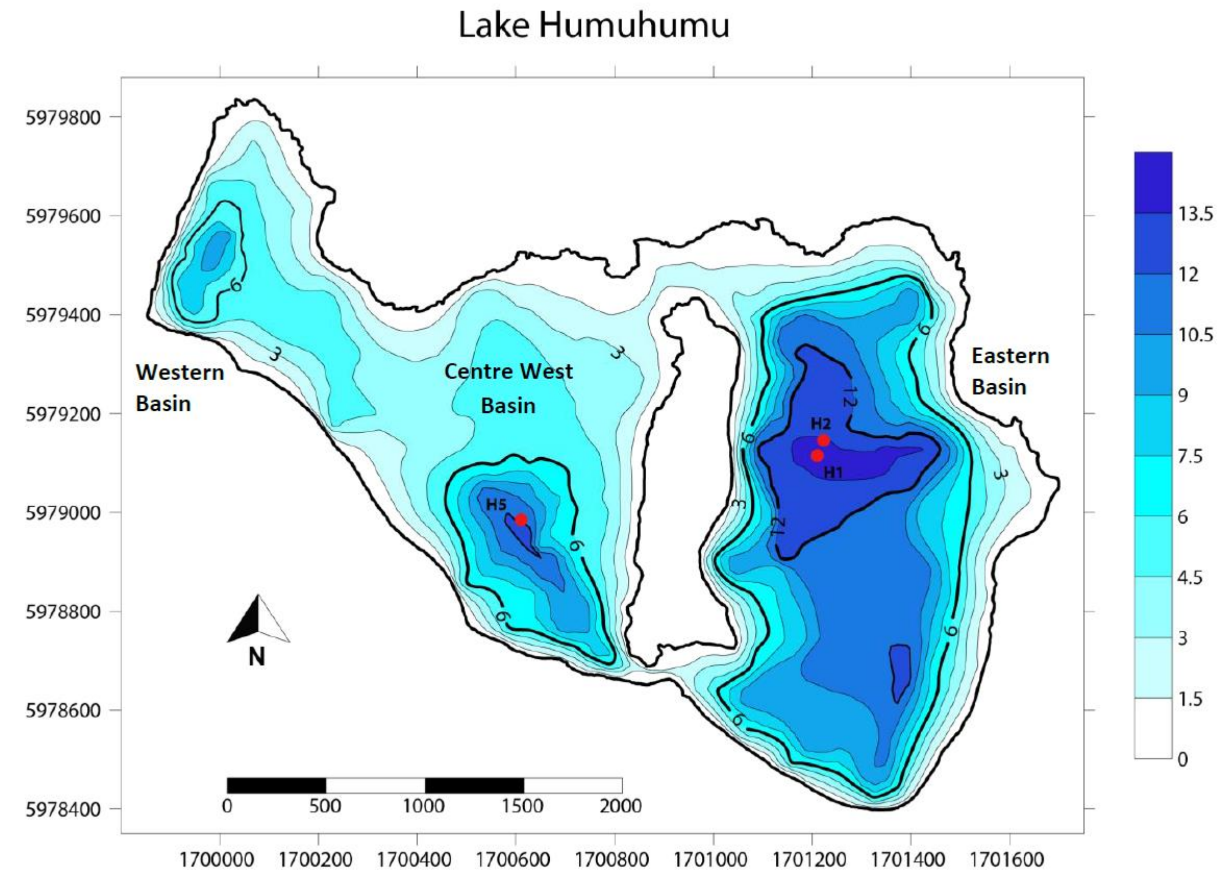

Figure 5.2 Bathymetry and coring location for H1, H2, and H5 in Lake Humuhumu. Contours are recorded in metres relative to water level at the time of coring.

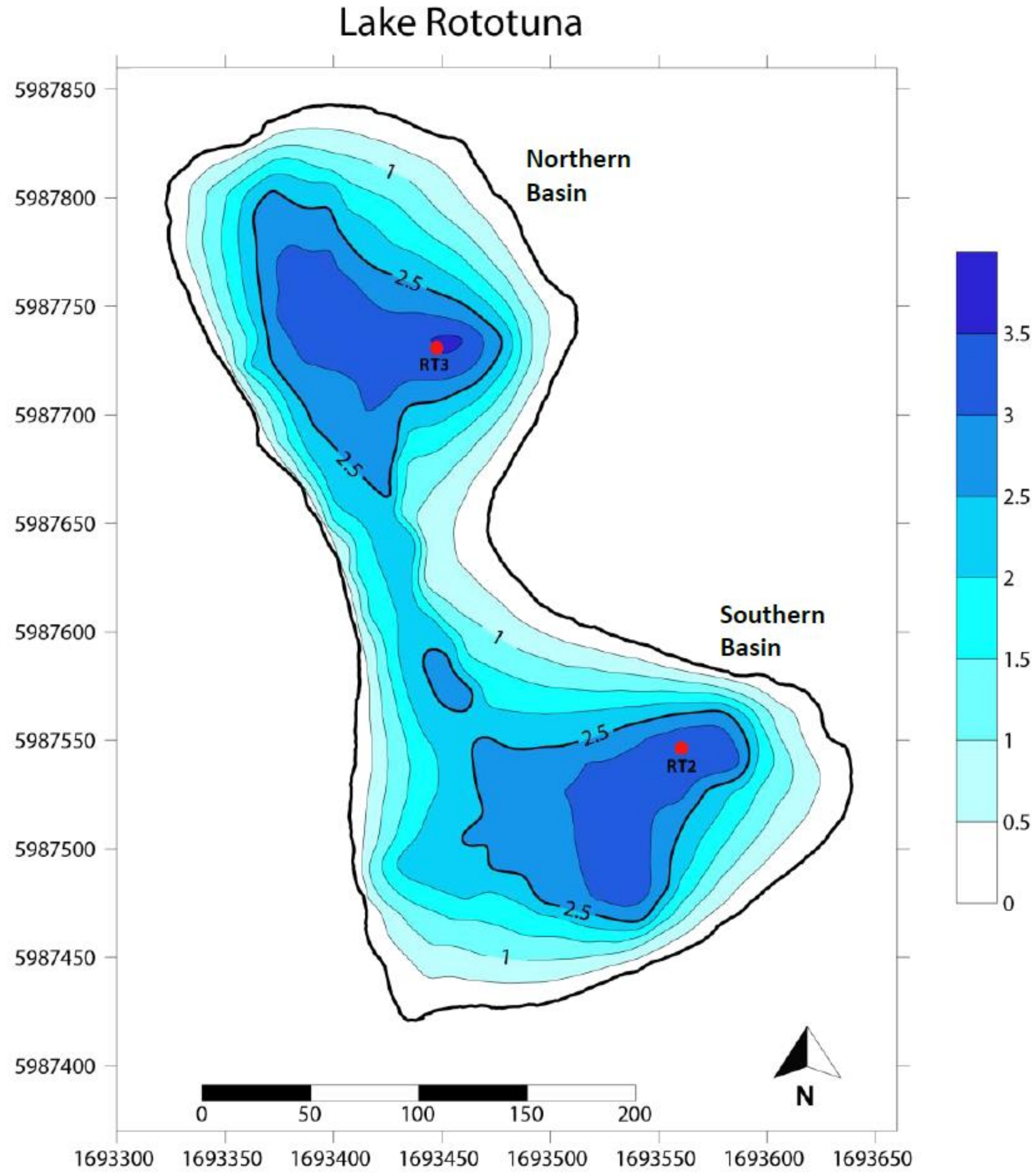

Figure 5.3 Bathymetry and coring location for RT2 and RT3 in Lake Rototuna. Contours are recorded in metres relative to water level at the time of coring.

6 Results & Discussion

Changes in sedimentation rates and their timing for Lakes Rotokawau, Humuhumu and Rototuna are reported in Tables 6.1-6.3 below. Stratigraphic plots of changes to proxy indicators of changing water quality are presented for the same Poutō dune lakes in Figures 6.1-6.7.

Table 6.1 Sediment accumulation rates (SAR) between dated sediment horizons in Lake Rotokawau (RK2 and RK3). SAR refers to period between date and preceding dated horizon (e.g., at 0 cm from 2015 AD to 2009 AD at 2 cm depth).

Depth (cm)	Core	Date (cal. yr BP)	SAR (mm/yr)
0	RK3	2015 AD (+66)	3.3
2	RK3	2009 AD (+60 ± 3): ^{210}Pb dating	4.0
4	RK3	2004 AD (+55 ± 1): ^{210}Pb dating	2.9
6	RK3	1997 AD (+48 ± 1): ^{210}Pb dating	3.6
10	RK3	1986 AD (+37 ± 1): ^{210}Pb dating	3.9
17	RK3	1968 AD (+19 ± 2): ^{210}Pb dating	3.3
18	RK3	1965 AD (+16 ± 3) ^{210}Pb dating	6.2
26	RK3	1947 AD (3 ± 2): ^{210}Pb dating	NA (sediment lost)
28	RK2	550 AD (1400 ± 42): ^{14}C dating	0.2
50	RK2	752 BC (2702 ± 71): ^{14}C dating	0.3
89	RK2	2144 BC (4094 ± 68): ^{14}C dating	NA (base of core)

Table 6.2 Sediment accumulation rates (SAR) between dated sediment horizons in Lake Humuhumu.

Depth (cm)	Core	Date (cal. yr BP)	SAR (mm/yr)
0	H2	2015 AD (+66)	0.7
1	H2	2000 AD (+51 ± 15): ^{210}Pb dating	0.5
2	H2	1978 AD (+29 ± 9): ^{210}Pb dating	0.6
3	H2	1962 AD (+13 ± 10): ^{210}Pb dating	0.6
4	H2	1946 AD (4 ± 12): ^{210}Pb dating	0.6
5	H2	1929 AD (21 ± 13): ^{210}Pb dating	0.3
35	H1	805 AD (1145 ± 52): ^{14}C dating	0.2
62	H1	721 BC (2671 ± 82) : ^{14}C dating	0.1
82	H1	2079 BC (4029 ± 59) : ^{14}C dating	NA (base of core)

Table 6.3 Sediment accumulation rates (SAR) between dated sediment horizons in Lake Rototuna. Note that the two cores are treated separately given their location in different basins and clear difference in SAR.

Depth (cm)	*Core*	*Date (cal. yr BP)*	*SAR (mm/yr)*
0	*RT2*	*2015 AD (+66)*	*0.2*
72	*RT2*	*1537 AD (413 ± 56): ^{14}C dating*	*0.01*
110	*RT2*	*2973 BC (4923 ± 54): ^{14}C dating*	*NA (base of core)*
0	*RT3*	*2015 AD (+66): ^{210}Pb dating*	*0.8*
35	*RT3*	*1560 AD (390 ± 44): ^{14}C dating*	*0.7*
70	*RT3*	*1032 AD (918 ± 41): ^{14}C dating*	*1.2*
120	*RT3*	*621 AD (1329 ± 20): ^{14}C dating*	*NA (base of core)*

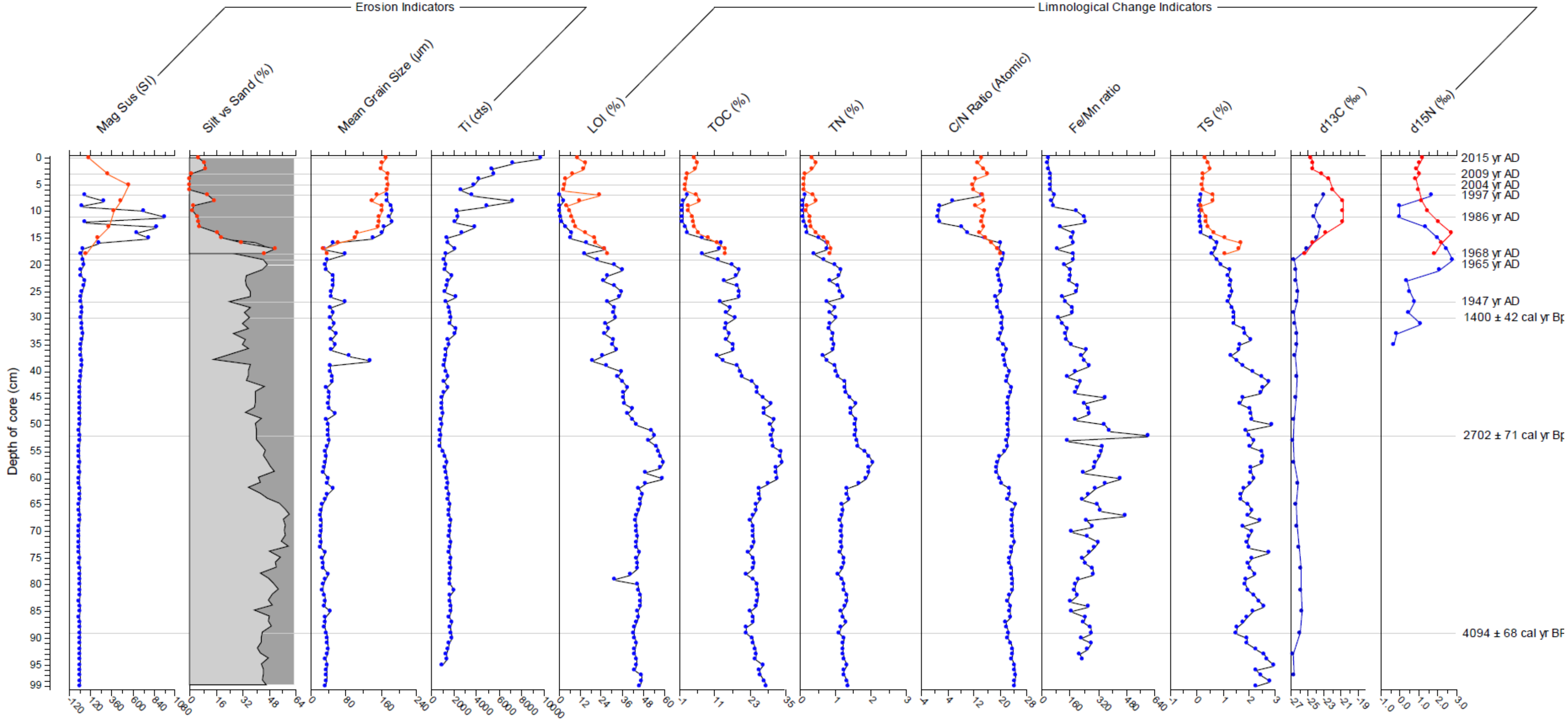

Figure 6.1 Lake Rotokawau palaeolimnological proxy indicators for cores RK2 (in blue) and RK3 (in red). ^{210}Pb and ^{14}C dates are listed on right, depth of core sample on left. Core samples are indicated by points on stratigraphic plots. Sand content is dark grey, silt light grey.

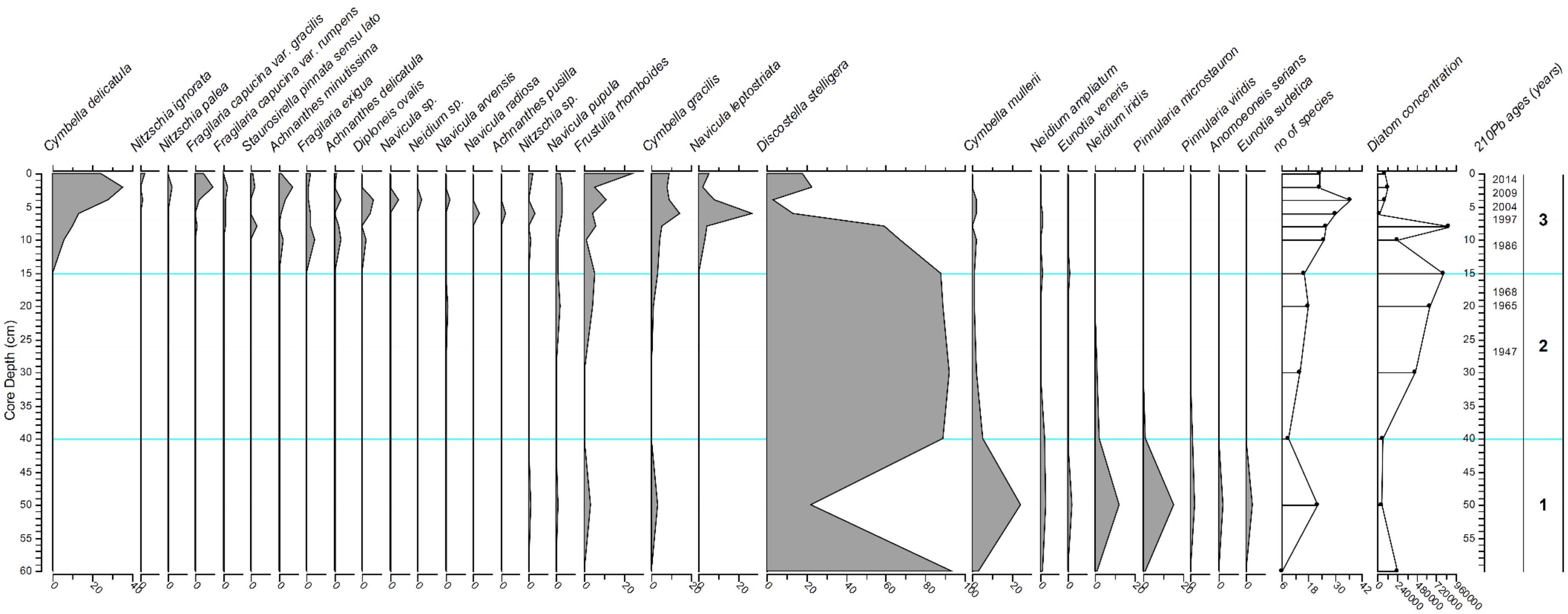

Figure 6.2 Lake Rotokawau palaeolimnological diatom indicators for cores RK2 (in blue) and RK3 (in red). ^{210}Pb and ^{14}C dates are listed on right, depth of core sample on left. Core samples are indicated by points on stratigraphic plots.

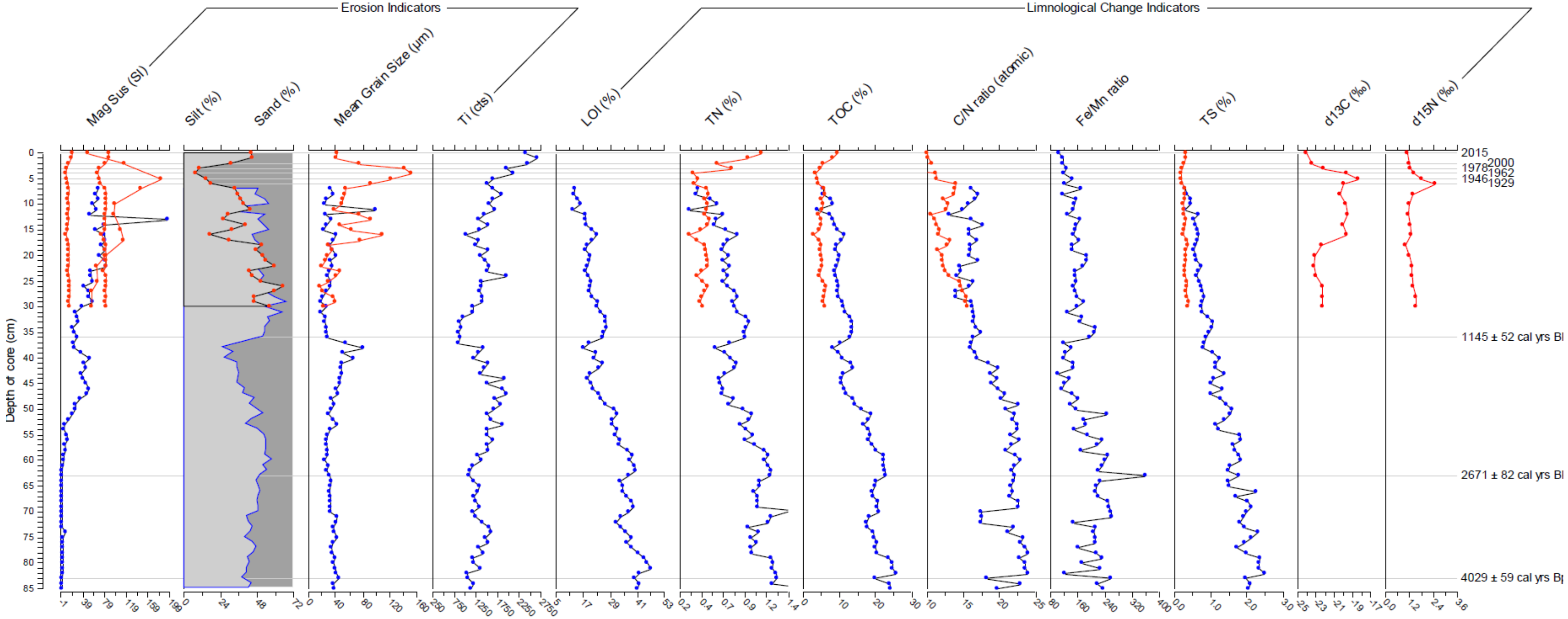

Figure 6.3 Lake Humuhumu palaeolimnological proxy indicators for cores H1 (in blue) and H2 (in red), eastern basin. ^{210}Pb and ^{14}C calibrated dates are listed on right, depth of core sample on left. Core samples are indicated by points on stratigraphic plots. Sand content is dark grey, silt light grey.

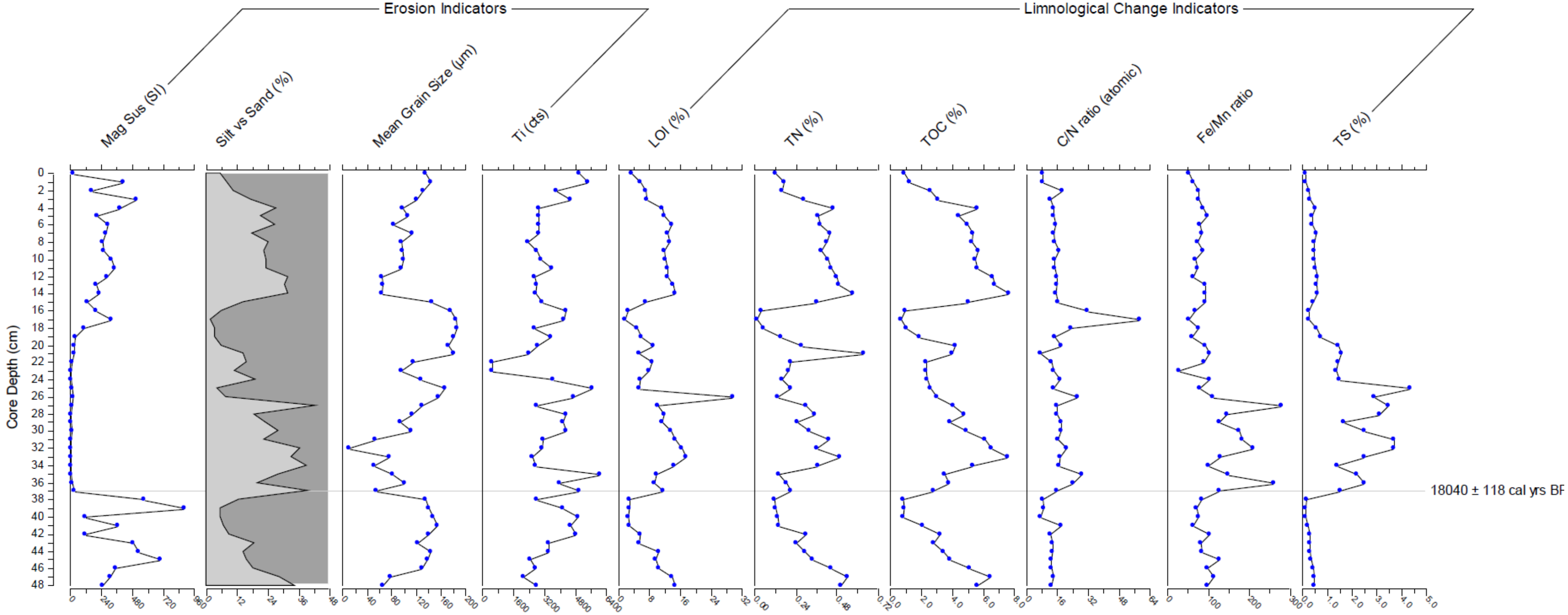

Figure 6.4 Lake Humuhumu palaeolimnological proxy indicators for core H5, centre west basin. ^{210}Pb and ^{14}C calibrated dates are listed on right, depth of core sample on left. Core samples are indicated by points on stratigraphic plots. Sand content is dark grey, silt light grey.

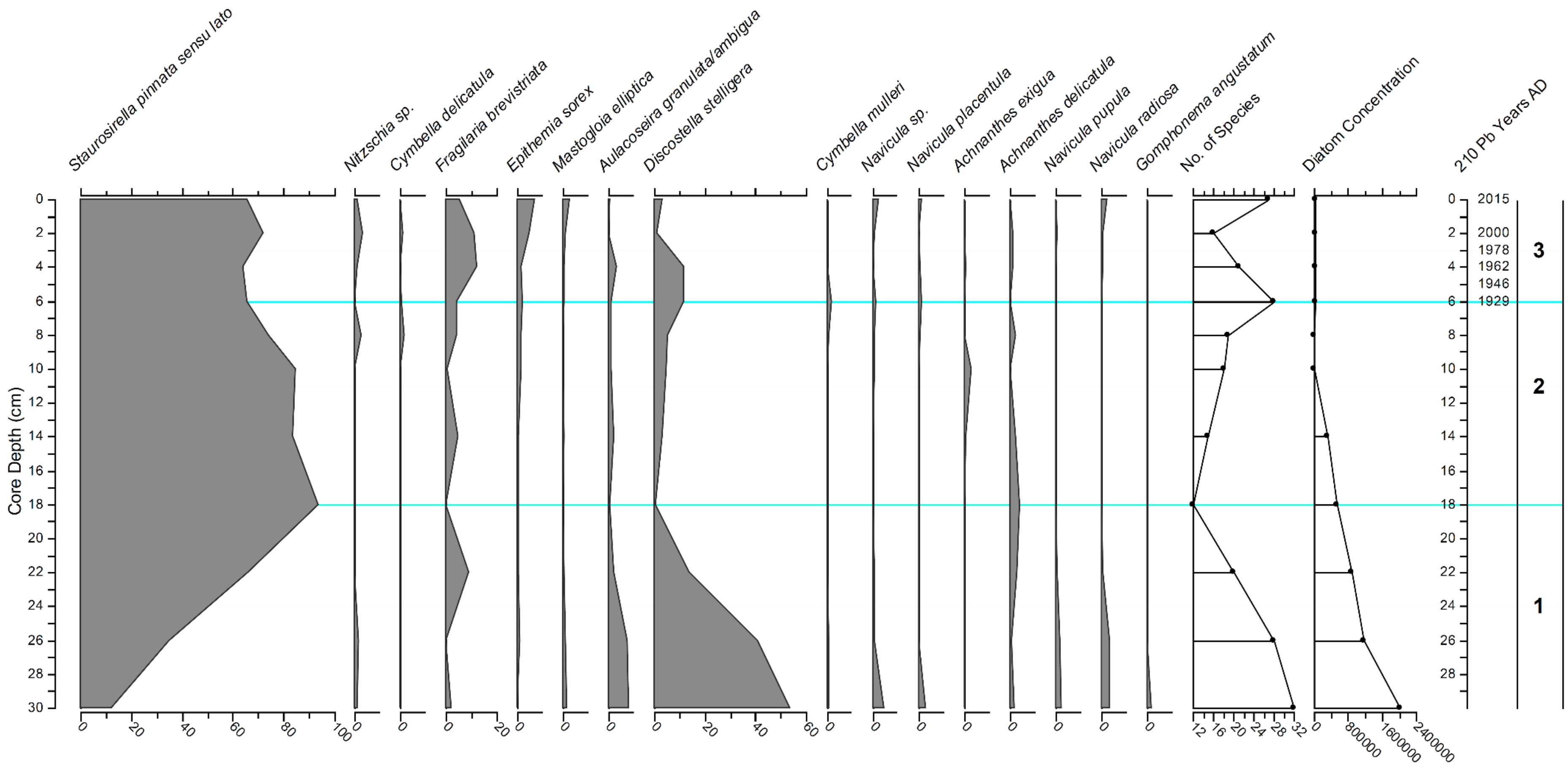

Figure 6.5 Lake Humuhumu palaeolimnological diatom indicators for core H2. ^{210}Pb and ^{14}C dates are listed on right, depth of core sample on left. Core samples are indicated by points on stratigraphic plots.

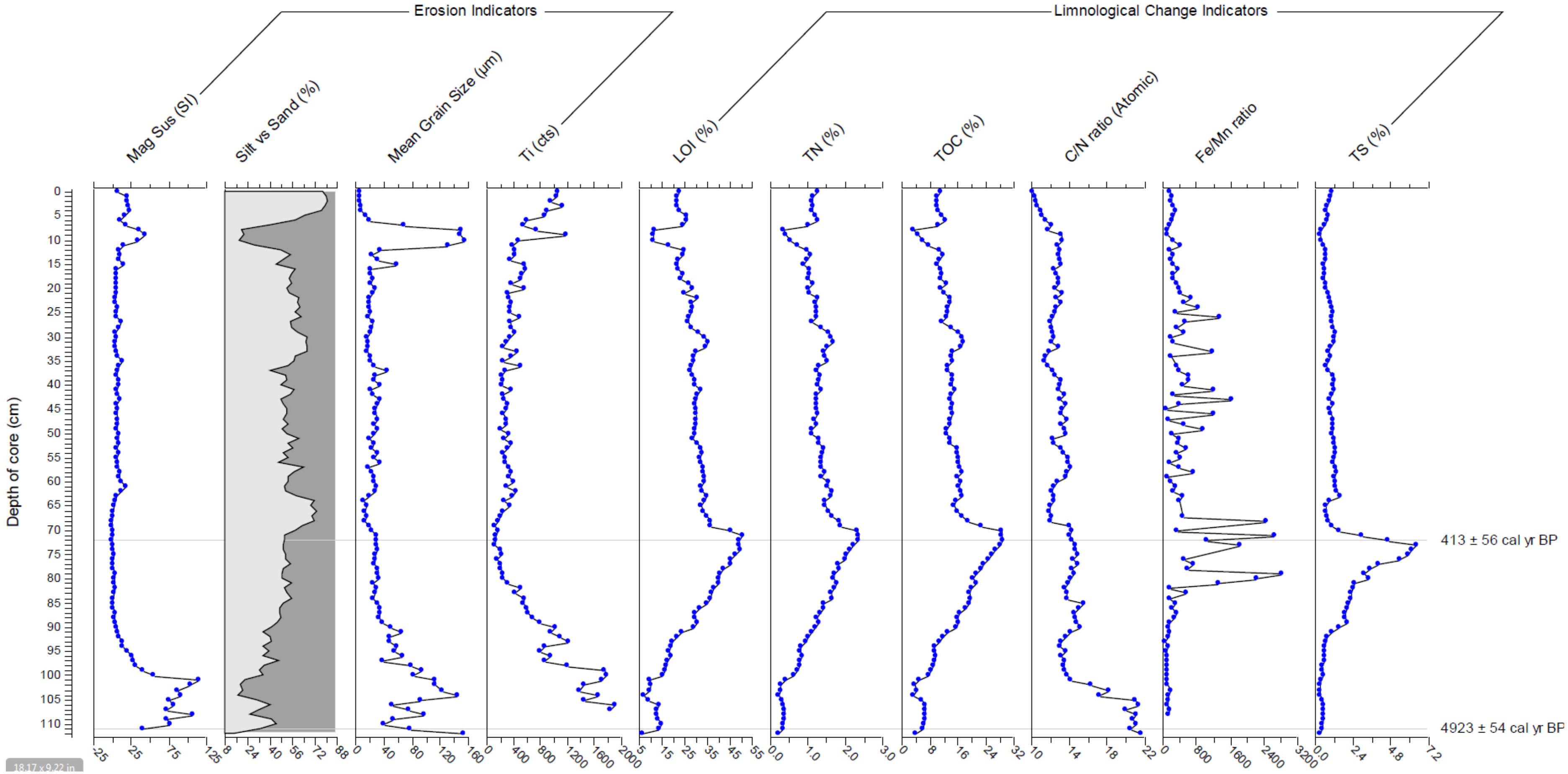

Figure 6.6 Lake Rototuna palaeolimnological proxy indicators for core RT2, southern basin. ^{210}Pb and ^{14}C calibrated dates are listed on right, depth of core sample on left. Core samples are indicated by points on stratigraphic plots. Sand content is dark grey, silt light grey.

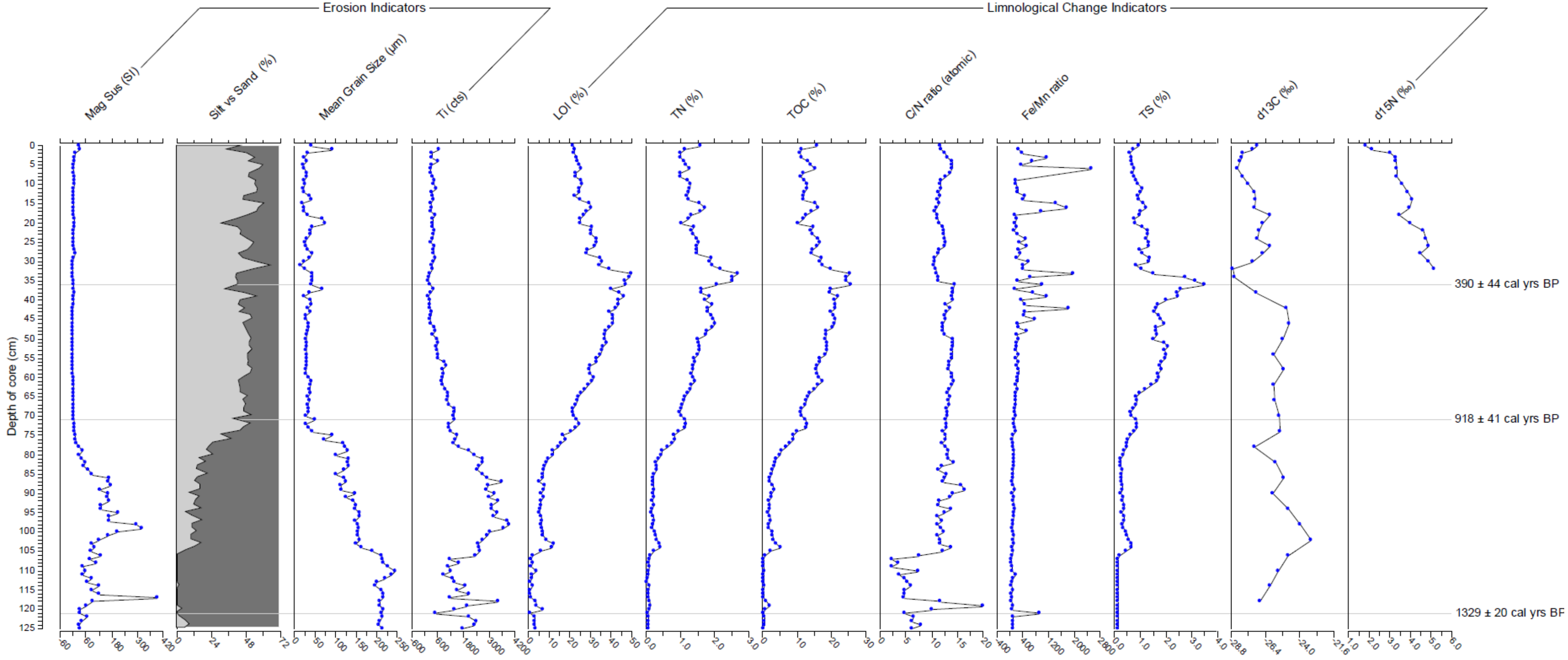

Figure 6.7 Lake Rototuna palaeolimnological proxy indicators for core RT3, northern basin. ${}^{210}Pb$ and ${}^{14}C$ calibrated dates are listed on right, depth of core sample on left. Core samples are indicated by points on stratigraphic plots.

6.1 Lake Rotokawau

Two cores were collected from the southern and deepest of three basins that extend back to ca. 4,000 cal. yr BP[1]. Both cores demonstrated similar multi-proxy profiles for the last century, suggesting **consistent water quality lake-wide over the recent past**. A hiatus in deposition or loss of core material occurred, limiting continuous interpretation until the last century to ca. 1947 AD (27cm), before resumption of sedimentation at ca. 1400 cal. yr BP (30cm).

Across all erosion indicators there were limited changes prior to ca. 1968 AD (18cm) whereupon Ti started to increase markedly and mean grain size increased from <40µm (silt) to ca.160µm (fine sand), coeval with markedly increased MS, and decreased %LOI. The latter have remained as such to today, albeit with two brief returns to higher silt and organic matter content in ca, 1990 AD and ca. 2010 AD – note these two events are not associated with a return to lower mean grain size so are likely the consequence of briefly increased biological productivity on a continued background of greater catchment erosion. The shift to greater sand content was marked by a slight decrease in SAR from 5.0 mm/yr (ca.1947-1968 AD) to 3.8 mm/yr (1968-Present). By contrast, SAR during the prior interval of ca.2700-1400 cal. yr BP (from 52-30cm depth) was an order of magnitude less, at 0.17 mm/yr (Table 6.1).

Lake level decline could have driven increased SAR and mean grain size since at least ca. 1968 AD (i.e., shallowing would reduce the distance between core location and littoral shoreline, encouraging coarser sediment deposition, focussing catchment sediment influx into a smaller lake basin and thereby increasing SAR). Indeed, Fe/Mn ratios declined markedly but only became consistently lower from ca.1990 AD. Consequently, increased erosion and mixing occurred well before drawdown in lake depth and/or reduced strength of thermal stratification that resulted in greater bottom-water oxygenation (and increased Mn relative to Fe)[2].

Following the onset of greater catchment erosion and before lake level drawdown, a clear change in stable state to algal-dominance is apparent from ca. 1977 AD to ca. 1997 AD. Despite reduced organic matter contribution overall (lesser TOC and TN), a TOC/TN ratio <5 and enriched $\delta^{13}C$ with depletion of $\delta^{15}N$, suggests increased algal productivity and dominance during this period (possibly including of N-fixing cyanobacteria) and a likely loss of fringing littoral vegetation that would otherwise raise TOC/TN ratios above 10. Greater algal-dominance from ca. 1977-1997 AD occurred at the expense of decreased diatom productivity, which has remained low from 1997 AD to today. Since ca. 1997 AD, SAR has continued at its peak rate but with greater organic-matter input and inorganic, erosional influx. For instance, TOC, TN and TS content rose modestly with a return to higher TOC/TN (>12) and depletion of $\delta^{13}C$. Together this suggests the return of macrophytes with monitoring data suggesting submerged forms, albeit at lesser biomass than prior to ca. 1977 AD and with little recovery in littoral fringing vegetation (Champion, pers. comm., 2016).

The changes in diatom taxa offer further information pertaining to the nature of recent water quality change. Diatom community composition only shifted well after the change in SAR and inputs of coarser sands, with a marked decline in *Discostella stelligera* ca. 1977 AD (from >85% dominance of diatom communities to ca.20% today). As *D.stelligera* is an oligotrophic planktic/euplanktic alga, its abundance is reliant on open-water habitat (i.e., the taxon spends its entire life-cycle suspended in the water column [Ruhland et al., 2008]). Replacement by a more diverse diatom community of tychoplanktic (life-cycle spent in turbulent, shallow water), meroplanktic (part of life-cycle suspended in water column, part on/in sediment) and benthic diatoms (spend entire life-cycle on/in sediment [Van Dam et al., 1994]), indicate the likelihood that first greater mixing (ca. 1977 AD) and later lake level decline (ca. 1990 AD) drove the shift to lower TOC/TN ratios, greater algal biomass and lesser benthic or littoral macrophyte vegetation. More recent diatoms are associated with a wider range of low-moderate nutrient availability (oligo-mesotrophic) than the earlier dominance of *D.stelligera* (oligotrophic) (Van Dam et al., 1994). Nutrient availability has also likely increased but since ca. 1977 AD, the most marked change to the diatom community is the rise of *Frustulia rhomboides* and *Cymbella* spp (Fig, 6.2). Both are benthic, **oligotrophic** species accounting for nearly 60% of diatoms in Lake

[1] Cal. yr BP refers to calibrated years since 1950, taken to represent Before Present (BP).
[2] A possible cause for lesser Fe/Mn, of reduced organic matter supply to bottom-waters, can be excluded as although this occurred it did so several decades earlier ca.1968 AD.

Rotokawau today (epipelic and epilithic taxa, respectively [Van Dam et al., 1994; Stone et al., 2011]). Hence, a change to exposed habitat and consequent reduction in aquatic macrophyte cover appears more marked than changes to nutrient availability would support and more likely, was driven by lake-level decline leading to physical disturbance on macrophytes. Given the majority of the lake extent is now <10m deep, this is feasible as the 10 m threshold appears to be a cut-off in Northland dune lakes between well and poorly-mixed systems (Hughes et al., 2016). If so, this also raises questions about whether the lake's current mesotrophic status was influenced both by external nutrient loading (given lower TOC/TN ratios and algal-dominated status predated lake level decline by several decades) and lake-level decline (promoting greater internal recycling of nutrients by wave-driven disturbance).

6.2 Lake Humuhumu

Three cores were collected from two different basins. Cores H1 and H2, collected from the eastern basin in 13m water depth, demonstrate similar patterns to each other and span to ca. 4,000 cal. yr BP (83cm length core). However, Core H5, obtained from the centre-west basin at 12m water depth, offers a considerably older record stretching to ca. 14-18,000 cal. yr BP (37cm length core). Given the marked difference in depths for core basal ages, the centre-west basin has either experienced considerably lower SAR or undergone a drying/hiatus in intervening years (e.g., lack of deposition or erosion of older sediments). More dating is required to determine which. So, Core H5 is not examined further below but in any case Cores H1 and H2 offer greater resolution of past water quality information through their greater SAR.

Over the last 4,000 years, SAR at the eastern basin of Lake Humuhumu has been equivalent to that at Lake Rotokawau (0.21mm/yr and 0.25mm/yr, respectively). Furthermore, like Rotokawau, the overall sedimentation rate has increased more recently. For instance, SAR since ca. 1929 AD has almost trebled (Table 6.2).

A marked increase in sand input occurred at 9cm depth (ca.1870 AD) associated with decreased organic matter content and increased MS, suggesting the cause lay in erosional inputs of minerogenic catchment-derived sediments. The latter continued until ca. 1978 AD whereupon a return to finer, organic-rich sediment occurred (e.g., lower MS, greater LOI, increased percentage of silt).

The early erosive period from ca. 1870-1978 AD was associated with a marked increase in Ti influx and modest enrichment of $\delta^{13}C$ but relatively greater enrichment of $\delta^{15}N$, suggesting increased demand on nutrients as well as regeneration/mineralisation of organic-N (i.e., causing its enrichment through ammonification and denitrification/nitrification [Talbot, 2001]). The coeval decline in TOC/TN from ca.15 to 10 highlights a shift in lake ecology away from earlier submerged or emergent macrophyte biomass to relatively greater algal contributions to the lake sediment record (Meyers and Lallier-Verges, 1999). Changes to smaller grain size and greater organic content since ca. 1978 AD were not associated with a recovery of the macrophyte community, with TOC/TN ratios remaining <10. Since ca. 1978 AD, TN concentrations have more than trebled whilst TOC concentrations have doubled, highlighting that current conditions of relatively greater algal production (or equally, reduced macrophyte production) have resulted in the present mesotrophic status of Lake Humuhumu. Unlike Lake Rotokawau, there is little evidence of a more recent increase in biomass of emergent or submerged macrophytes with continued decreasing TOC/TN to today.

Diatom remains add further detail to the picture of changing lake state. Whilst a notable decline in the dominance of the oligotrophic, planktic/euplanktic taxon *D.stelligera* occurred as per Lake Rotokawau, this change in Lake Humuhumu occurred pre-1929 AD (assuming constant sedimentation rates in down core, no later than 1840 AD) and involved a shift to a dominance of meroplanktic diatoms associated with open water (*Staurosira pinnata*) rather than benthic or sediment-dwelling diatoms. This change probably predates both European (18th Century) and Polynesian arrival (14th Century) (McGlone and Wilmshurst, 1999). Hence, this change is most likely climatically rather than land-use driven, although more age markers are required to assess this properly. An absence of marked change in Fe/Mn ratios until much later (ca. 1890 AD) highlights greater wind-driven mixing as the likely cause for the change to *S.pinnata*. Greater upper water column mixing in a 15m deep basin would have benefitted meroplanktic diatoms without necessarily impacting on benthic hypoxia under seasonal thermal stratification (e.g., without altering Fe/Mn ratios). However, by ca. 1890 AD, it is clear that benthic oxygenation increased which either corresponded to even greater wind-driven mixing and/or reduction in lake level. This trend has continued throughout the past century with Fe/Mn ratios at their lowest point in the last 4,000 years. The continued dominance of open-water associated diatoms, albeit mostly meroplankton, coupled to the absence of much (<20%) benthic or attached diatoms, prevents determination of whether greater benthic oxygenation resulted from lake level decline or greater wind-driven mixing[3]. For instance, the growth of the epipsamic diatom *Pseudostaura brevistriata* is associated with strong mixing and availability of sand (Schallenberg and Saulnier-Talbot, 2014), having risen to its greatest abundance during the more recent period of greater catchment erosion of sands to the lake (ca. 1870-1978 AD). However, the increased presence of both meroplanktic and benthic species of broad nutrient tolerance since ca. 1870 AD suggests that nutrient availability has also become more variable due to stronger mixing (e.g., *S. pinnata*, *P.breviata*, *Epithemia sorex* [Van Dam et al., 1994]).

Overall, Lake Humuhumu has likely experienced a pre-Polynesian increase in lake mixing from ca. 1140 AD, which was followed from ca. 1870-1978 AD by heightened catchment erosion. After ca. 1978 AD to today rising algal productivity was driven by a considerable increase to nutrient availability that drove a corresponding increase in internal (sedimentary) nutrient concentration through sharp rises in TN and TOC.

6.3 Lake Rototuna

Two cores were collected from Lake Rototuna's northern (RT3) and southern shallow basins (RT2), at 3-3.5m depth. Both were only coarsely dated offering limited information on the timing of events. However, sedimentation rates differed markedly between cores. The northern basin (RT3) experienced greater SAR from the core base at 120cm (ca. 1300 cal. yr BP) compared to the southern basin whose core (RT2) base is at 110cm (ca. 4,900 cal. yr BP). **These differences suggest altered lake behaviour and water quality between the basins**.

At the northern basin (RT3), a lake appears to have formed by ca. 750 AD. Older sediments are almost entirely sand with little to no organic matter content (i.e., indicative of active dunes locally, earlier than ca. 750 AD). Thereafter, reductions in mean grain size occurred until ca. 1000 AD accompanied by increasing biological productivity (rising %TOC and %TN), contributed by an aquatic macrophyte community (TOC/TN ca.12-14). Whilst little change to the aquatic plant community occurred from ca.1000-1560 AD, overall the lake became increasingly productive. During this period, there was limited change to Ti, SAR or grain size, suggesting limited change to catchment erosion. Whilst little change has occurred to erosional indicators in the last 450 years (suggesting limited change to erosional influx), the overall biological productivity of the northern basin declined between ca. 1560-1650 AD, returning to earlier if more variable levels, thereafter to today. Given the variability in biological production during the past 400 years, it is hard to discern any distinct event(s) but in the last 50-60 years mean grain size has risen and was associated with a decline in macrophyte biomass as TOC/TN ratios dropped to ca.10 (e.g., threshold to algal-dominated state). The latter has been associated with greater productivity (greater %TOC and %TN), increased demand on inorganic carbon (enriched $\delta^{13}C$) and increased inorganic nitrogen availability (depleted $\delta^{15}N$). Most recently, there has also been a short-lived erosion event contributing more sand ca. 1990 AD and which subsequently was associated with rapid increase to nutrient availability (greater %TOC and %TN).

At the southern basin (RT2), a lake appears to have formed by ca. 4,100 cal. yr BP. The basin became increasingly productive as signified by increasing TOC, TN and LOI until ca. 1550 AD, when TOC% and TN% declined markedly for a few decades. After ca. 1580 AD, biological productivity has remained broadly constant before dropping again at ca. 1900 AD for several decades. That event appears to have been linked to a marked increase in catchment erosion associated with greater MS, Ti and mean grain size. **Since ca. 1945 AD, organic matter**

[3] Land clearance for pasture would for instance increase the proportion of rainfall reaching the lake as runoff (Beets and Oliver, 2007). Clearance of remnant indigenous forest would however, increase wave height by increasing windspeed on the lake surface, especially if cleared on western margins (Collier, 1996).

entrainment has stabilised at earlier levels (e.g., as per ca. 45 to 410 cal. yr BP). Although, in this most recent period a **further reduction to submerged or emergent macrophyte biomass** has occurred as TOC/TN ratios have declined from 13 to 10 (i.e., moving to the threshold for an algal-dominated state)[4]. Despite this, there is little evidence of a change in SAR at the southern basin despite the greater relative algal productivity and its current eutrophic status.

Notably, in both cores RT3 and RT2 limited change to Fe/Mn ratios occurred despite marked reduction in lake level over the past century (Forester, pers. comm., 2016), suggesting that the geochemical proxy indicator is less sensitive in shallow lakes like Lake Rototuna (i.e., where changes in lake level can have lesser effect on already strong mixing).

[4] Note that no diatom or stable isotope analysis was conducted on sediment from the southern basin of Lake Rototuna, and on diatom analysis from the northern basin so that little more can be inferred about changes in algal production or nutrient availability.

7 Conclusions

Sedimentary records from Lakes Rotokawau, Humuhumu and Rototuna provide evidence for recent (last century) changes in lake condition. These recent changes are broadly similar within, but differ between lakes in terms of event timing, suggesting catchment rather than regional drivers are responsible (e.g., land use).

The general pattern is one of enhanced erosion preceding loss of macrophyte (submerged or emergent) biomass in favour of algae but limited change to nutrient availability or overall productivity until greater mixing and/or lake level decline many decades later.

The timing of enhanced erosion varied widely from ca. 1870-1978 AD at Lake Humuhumu and ca. 1905-1945 AD at Lake Rototuna, to being unabated since ca. 1960s AD at Lake Rotokawau.

The timing of relative shifts to lesser macrophyte and greater algal biomass also vary, from ca. 1977-1997 AD at Lake Rotokawau through to ca. 1870 AD at Lake Humuhumu and ca. 1945 AD at Lake Rototuna (at both latter lakes limited subsequent increase in macrophyte biomass has occurred since).

Stronger water column mixing leading to greater benthic oxygenation was evident only in the two deep lakes (>10 m), occurring from ca. 1870 AD at Lake Humuhumu and much later at Lake Rotokawau, from ca. 1977 AD (and especially from ca. 1990 AD). Whilst lake levels may have declined in both instances, this is only evident in changes to the diatom community at Lake Rotokawau, offering an explanation for increased coeval TOC/TN ratios as a response to expansion of littoral emergent vegetation on recently exposed lake margins, rather than a reduction in algal productivity amongst open-water.

Changes in biological productivity at each lake are equally hard to reconstruct – the shifts to greater algal biomass are likely to have altered the rate of sequestration of organic matter by sediments because more organic matter is likely to be recycled in the water column (Meyers and Lallier-Verges, 1999). Hence, even without change to TOC or TN, a shift in sedimentary TOC/TN to ≤10 might nonetheless record increased productivity. At Lake Rotokawau, declining TOC and TN occurred coeval with the shift in algal state after ca. 1977 AD. The same pattern occurred at Lake Humuhumu from ca. 1870 AD and at Lake Rototuna from ca. 1900 AD. All three could therefore have experienced greater and more variable nutrient availability in the water column from greater algal-based uptake/decay/recycling and reduced entrainment of organic matter. However, TOC and TN concentrations rose rapidly in Lakes Humuhumu and Rototuna after ca. 1978 AD and 1989 AD respectively, more definitively indicating increased nutrient availability at both thereafter. Lake Rotokawau, by contrast, has experienced little change in sedimentary nutrient indicators following reduced TOC/TN from ca. 1977-1997 AD, suggesting little change to external nutrient supply therein.

Again, differences in the timing of these events suggest that altered erosion, macrophyte biomass, lake mixing and productivity are likely due to catchment-scale changes in land use rather than regional climatic change. The timing of the inferred events ties well with known changes in land use, including the expansion of pastoral agriculture in the early 20th Century (Smale et al., 2009), and mass conversion of remnant bush and dune habitat into *Pinus radiata* plantations, beginning between 1968 and 1982 AD (Thode, 1983; Smale et al., 2009).

At Lake Humuhumu, indigenous forest clearance[5] and conversion to pasture coincide with initial increases to erosion and reduction in macrophyte biomass, whilst later pine forest conversion of remnant forest and dune systems coincides with a near trebling of nutrient availability[6], a shift to algal dominated state from ca. 1978 AD and return to greater fringing littoral

[5] Fire clearance of remnant kanuka (*Kunzea ericoides*) forest has been demonstrated to remobilise sands on Poutō dune lakes, indicating that it could have increased SAR (Ogle, 1997 in Collier, 1996).
[6] Exotic forests are associated with greater nutrient loss than mobile sands, particularly of phosphorus through mineralisation, remobilisation during harvesting and via pollen rain (Davis, 2005; Gibbs. pers. comm., 2015), but also nitrogen through initial colonisation of sites by N-fixing lupin and gorse, considerable top-dressing (e.g., up to 125kg P Ha/yr and 500kg N Ha/yr) (Williamson and Hoare, 1987) and later decay of root systems following harvesting (Collier, 1996). However, with the exception of pollen rain-sourced P, these nutrient losses are normally short-lived rather than continuous as at Lake Humuhumu.

macrophytes from ca. 2000 AD. At Lake Rotokawau, clearance and conversion to pasture also coincides with the early 20th Century peak in erosion and again, later forestry conversion coincides with the shift to algal-dominance from ca. 1977-1990 AD, before a recovery of fringing littoral macrophytes – the difference here being, that nutrient availability and overall productivity have not risen markedly unlike at Lake Humuhumu. At Lake Rototuna, the later and limited nature of changes suggest pastoral activities in the mid-20th Century are likely to have driven reduced macrophyte biomass throughout the shallow lake, and as per Lake Rotokawau, have changed nutrient availability and overall productivity little.

8 Recommendations for lake management

The mechanism(s) by which activities that accelerate catchment erosion can then also drive the loss of submerged macrophyte biomass, should be clarified for Poutō dune lakes. This will help **prevention of macrophyte loss in highest value** (macrophyte-dominated) dune lakes, but also, shed light on the lake processes to be managed in other **impacted** dune lakes so as to inform management to macrophyte objectives. Likely causal mechanisms include reductions to water clarity (from greater external sediments suspended in-column) and/or the physical disturbance of lake margins and littoral zones (by pest fish grazing, stock browsing/treading, heightened wave activity or enhanced bordering runoff velocities causing scour [Coffey, 1987; Johnson, 1987; De Winton et al., 2007]). Importantly, this indicates **a knowledge gap** given the focus of much lake research to date in New Zealand has been upon the role of nutrient availability and limitation of phytoplankton growth (e.g., Paul et al., 2008; Abell et al., 2010; Verburg et al., 2010; Trolle et al., 2014).

Reduced lake level and greater mixing was definitely associated with increased nutrient availability and algal biomass in Lake Humuhumu (from ca. 1977 AD) (and probably at Lake Rotokawau). The coincident timing with expansion of pine forestry raises the question of whether pine forestry drives lake level decline in Poutō dune lake (e.g., Collier, 1996). NRC (1991) have demonstrated this was the case for lakes on the Aupouri Peninsula in the 20-years following lupin and marram grass and then pine forest conversion of previously mobile dune sands (e.g., a 4.5m drop was recorded in groundwater near Hukatere; reduction in streamflow by 30-50%). Those figures tie with research in the central North Island where Beets and Oliver (2007) demonstrated that changes to *Pinus radiata* evapotranspiration and interception losses accounted for 30% of variation in local streamflow. Pine water yield was 100mm/yr less than under native bush and 160-260mm/yr less than pasture (Beets and Oliver, 2007). This research suggests reduced water yield poses a constraint on managing the water quality of dune lakes as changes to lake volume can alter residence time, benthic oxygenation, littoral disturbance, nutrient availability, algal biomass and therefore, macrophyte health (e.g., Wetzel, 2001).

To summarise, the knowledge gaps emerging from this study include the:

- Land use process responsible for historic changes to water clarity, linked to the loss of aquatic macrophytes (and from this ongoing or future land use practices linked to water clarity that should be managed for macrophyte objectives);
- Impacts of browsing stock on littoral emergent/submerged macrophytes and impacts of their exclusion on the latter (and from this effects of land management expected on water clarity, nutrient, algal and macrophyte objectives);
- Determining if exotic forestry is the cause of coincident lake level decline and greater nutrient availability in Pouto dune lakes (and from this if forestry land use and practices require management for water quality objectives);
- Relationships between lake hydrology and water quality indicators, particularly of changes in depth and changes to seasonal variation in depth (and from this if lake level and variability drive water quality responses).

9 References

Abell, J., Ozkundakci, D., and Hamilton, D. 2010. Nitrogen and phosphorus limitation of phytoplankton growth in New Zealand lakes: implications for eutrophication control. *Ecosystems*, **13**: 966-977.

Beets, P., and Oliver, G. 2007. Water use by managed stands of *Pinus radiata*, indigenous podocarp/hardwood forest, and improved pasture in the central North Island of New Zealand. *New Zealand Journal of Forestry Science*, **37**: 306-323.

Bennion, H., and Battarbee, R. 2007. The European Union Water Framework Directive: opportunities for palaeolimnology. *Journal of Paleolimnology*, **38**: 285-295.

Brown, E., Johnson, T., Scholz, C., Cohen, A., and King, J. 2007. Abrupt change in tropical African climate linked to bipolar seesaw over the past 55,000 years. *Geophysical Research Letters*, **34**: L20702.

Champion, P., and De Winton, M. 2012. *Northland lakes strategy*. Northland Regional Council, Whangerei. NIWA Client Report HAM2012-121.

Coffey, B. 1987. Submerged macrophytes: Survey, conservation and control. In Vant, B. (Ed.) *Lake Managers Handbook*, Water and Soil Miscellaneous Publication Number 103. Pp.92-103.

Collier, K., 1996. *Potential impacts of plantation forestry on dune lakes in Northland with interim guidelines for riparian management*. Department of Conservation, Wellington. NIWA Client Report DOC60204.

Davis, M., 2005. *Nutrient losses from forestry in the Lake Taupo catchment*. Environment Waikato, Hamilton. Centre for Sustainable Forest Management Client Report for Environment Waikato. Pp.12.

De Winton, M., Taumoepeau, A., and Clayton, J. 2002. Fish effects on charophyte establishment in a shallow, eutrophic New Zealand lake. *New Zealand Journal of Marine and Freshwater Research*, **36**: 815-823.

De Winton, M., and Dugdale, T. 2003. Coarse fish: the demise of plants and malaise of lakes. In *Managing invasive freshwater fish in New Zealand*. Department of Conservation workshop, May 2001. Pp.59-69.

Dean, W. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Research*, **44**: 242-248.

Dixit, S., Smol, J., Chalres, D., Hughes, R., Paulsen, S., and Collins, G. 1999. Assessing water quality changes in the lakes of the northeastern United States using sediment diatoms. *Canadian Journal of Fisheries and Aquatic Sciences*, **56**: 131-152.

Drake, D., Kelly, D., and Schallenberg, M. 2011. Shallow coastal lakes in New Zealand: Current conditions, catchment-scale human disturbance and determination of ecological integrity. *Hydrobiologia*, **658**: 87-101.

Gale, S., and Hoare, P. 1991. *Quaternary Sediments*. Belhaven Press, London. Pp. 323.

Hall, R., and Smol, J. 1996. Paleolimnological assessment of long-term water-quality changes in south-central Ontario lakes affected by cottage development and acidification. *Canadian Journal of Fisheries and Aquatic Sciences*, **53**: 1-17.

Hall, R., and Smol, J. 2001. Diatoms as indicators of lake eutrophication. In Stoermer, E., and Smol, J. (Eds.). *The Diatoms: Application for the Environmental and Earth Sciences*. Cambridge University Press, Cambridge.

Hughes, B., Stephens, T., Snelder, T and Kelly, D. 2016. *Lake FMU's for Northland. Recommendations for Policy development*. LWP/DNZ/Cawthron report to Northland Regional Council. Pp.88.

Jeppesen, E., Noges, P., Davidson, T., Haberman, J., Noges, T., Blank, K., Lauridsen, T., Sondergaard, M., Sayer, C., Laugaste, R., Johansson, L., Bjerring, R., Amsinck, S. 2011. Zooplankton as indicators in lakes: a scientific-based plea for including zooplankton in the ecological quality assessment of lakes according to the European Water Framework Directive (WFD). *Hydrobiologia*, **676**: 279-297.

Johnson, P. 1987. Marginal vegetation: Survey, management and conversation. In Vant, B. (Ed.) *Lake Managers Handbook*, Water and Soil Miscellaneous Publication Number 103. Pp.104-110.

Kokich, D. 1991. *Kai-Iwi-Poutō dune lakes water resources*. Whangerei, Northland Regional Council. Pp.48.

Last, W., and Smol, J. 2001. *Tracking Environmental Change Using Lake Sediments. Physical and Geochemical Methods*. Volume 2: Kluwer Academic Publishers: Netherlands.
Meyers, P., and Lallier-Verges, E. 1999. Lacustrine sedimentary organic matter reocrds of Late Quaternary paleoclimates. *Journal of Paleolimnology*, **21**: 345-372.
Meyers, P., and Teranes, J. 2001. Sediment Organic Matter. In: Last, W., and Smol, J. (Eds.) *Tracking Environmental Change Using Lake Sediments* Volume 2: Physical and Geochemical Methods. Kluwer Academic Press, Netherlands. Pp. 239-269.
McGlone, M. 1989. The Polynesian settlement of New Zealand in relation to environment and biotic changes. New Zealand *Journal of Ecology*, **12**: 115-129.
McGlone, M., and Wilmshurst, J. 1999. Dating initial Maori environmental impact in New Zealand. *Quaternary International*, **59**: 5-16.
Naeher, S., Gilli, A., North, R., Hamann, Y., and Schubert, C. 2013. Tracing bottom water oxygenation with sedimentary Mn/Fe ratios in Lake Zurich, Switzerland. *Chemical Geology*, **352**: 125-133.
NPS-FM. 2011. National Policy Statement for Freshwater Management 2014 issued by notice in gazette on 4 July 2014. MfE, Wellington. Pp.34.
NRC. 1991. *Aupouri Peninsula water resources assessment*. Northland Regional Council, Whangerei.
Ogle, C. 1997. *Sand movement and the protection of natural areas on Pouto Peninsula*, Northland. Department of Conservation, Whangerei. Conservancy Advisory Scientist Notes 145.
Paul, W., Hamilton, D., and Gibbs, M. 2008. Low dose alum application trialled as a management tool for internal nutrient loads in Lake Okaro, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, **42**: 207-217.
Perry, G., Wilmshurst, J., McGlone, M., McWethy, D., and Whitlock, C. 2012. Explaining fire-driven landscape transformation during the initial burning period of New Zealand's prehistory. *Global Change Biology*, **18**: 1609-1621.
Quinn, J., Cooper, A., Davies-Colley, R., Rutherford, J., and Williamson, R. 1997. Land use effects on habitat, water quality, periphyton and benthic invertebrates in Waikato, New Zealand hill-country streams. *New Zealand Journal of Marine and Freshwater Research*, **31**: 579-597.
Rip, B. 2016. A paleo-environmental reconstruction of the sedimentation, productivity, hydrology and geochemistry of the Pouto dune lakes Northland. Unpublished Master of Science Thesis, The University of Auckland. 127 pp.
RMA. 1991. Resource Management Act 1991. MfE, Wellington.
Round, F., Crawford, R., and Mann, D. 1990. *The Diatoms: biology and morphology of the genera*. Cambridge University Press, Cambridge. Pp.747.
Ruhland, K., Paterson, A., and Smol, J. 2008. Hemispheric-scale patterns of climate-related shifts in planktonic diatoms from North American and European Lakes. *Global Change Biology*, **14**: 2740-2754.
Scallenberg, M., and Saulnier-Talbot, E. 2014. Recent environmental history of Wainono Lagoon (South Canterbury, New Zealand). University of Otago Limnology Report No.12 prepared for Environment Canterbury. Pp.31.
Schofield, J. 1975. Sea-level fluctuations cause periodic post-glacial progradation, South Kaipara Barrier, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, **18**: 295-316.
Smale, M., Clarkson, B., Clarkson, B., Floyd, C., Cornes, T., Clarkson, F., Gilmour D., Snell, T., and Briggs, 2009. Natural areas of Kaipara Ecological District (Northland Conservancy). In R*econnaissance Survey Report for the Protected Natural Areas Programme*. Department of Conservation, Whangerei.
Smol, J. 2008. *Pollution of Lakes and Rivers: A paleoenvironmental perspective*. Arnold Publishers, Great Briatin.
Stephens, T., Atkin, D., Augustinus, P., Shane, P., Lorrey A., Snowball, I., 2012a. A Late glacial Antarctic climate teleconnection and variable Holocene seasonality at Lake Pupuke, Auckland New Zealand. *Journal of Paleolimnology*, **48**: 785-800.
Stephens, T. Atkin, D., Cochran, U., Augustinus, P., Reid, M., Lorrey, A., Shane, P., and Street-Perrott, A. 2012b. A diatom-inferred record of reduced effective precipitation during the Last Glacial Coldest Phase (28.8-18.0 cal. kyr BP) and increasing Holocene seasonality at Lake Pupuke, Auckland, New Zealand. *Journal of Paleolimnology*, **48**: 801-817.

Stoermer, E., and Smol, J.1999. *The Diatoms: Applications for the Environmental and Earth Sciences*. Cambridge University Press, Cambridge.

Stone, J., Westover, K., and Cohen, A. 2011. Late Plestocene paleohydrography and diatom paleoecology of the central basin of Lake Malawi, Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **303**: 51-70.

Talbot, M. 2001. Nitrogen Isotopes in Palaeolimnology. In: Last, W., and Smol, J. (Eds.) 2001. *Tracking Environmental Change Using Lake Sediments Volume 2: Physical and Geochemical Methods*. Kluwer Academic Publishes, Dordrecht. Pp. 401-439.

Thode, P. 1983. Northland's forest history and present resources. *New Zealand Journal of Forestry*. **28**: 203-224.

Trolle, D., Spigel, B., Hamilton, D., Norton, N., Sutherland, D., Plew, D., and Allan, M. 2014. Application of a three-dimensional water quality model as a decision support tool for the management of land-use changes in the catchment of an oligotrophic lake. *Environmental Management*, **54**: 479-493.

Van Dam., H., Mertens, A., and Sinkeldam, J. 1994. A coded check list and ecological indicator values of freshwater diatoms from the Netherlands. *Aquatic Ecology*, **28**: 117-133.

Verburg, P., Hamill, K., Unwin, M., and Abell, J. 2010. *Lake water quality in New Zealand 2010: Status and trends*. MfE, Wellington. NIWA Client Report HAM2010-107.

Wells, R., and Champion, P. 2012. *Northland Lakes Ecological Status 2012*. Northland Regional Council. NIWA Client Report HAM2012-069.

Wells, R., and Champion, P. 2013. *Northland Lakes Ecological Status 2013*. Northland Regional Council. NIWA Client Report HAM2013-088.

Wells, R., and Champion, P. 2015. *Northland Lakes Annual Report 2015*. Northland Regional Council. NIWA Client Report HAM2015-106.

Wetzel, R. 2001. *Limnology Lake and River Ecosystems*. Academic Press, San Diego. Pp.1006.

Williamson, R., and Hoare, R. 1987. Controlling nutrient loads and predicting resulting lake nutrient concentrations. In Vant, W. (Ed.) 1987. *Lake Managers Handbook*. Pp.158-166.